The effects of emotion on involuntary attention in children and adults

Thesis

for the degree of

doctor rerum naturalium (Dr. rer. nat.)

approved by the Faculty of Natural Sciences of Otto von Guericke University Magdeburg

by M.Sc. Carolina Bonmassar

born on 25th March 1991 in Trento (Italy)

Examiner: PD Dr. Claudia Preuschhof

Prof. Dr. Erich Schröger

submitted on: 30rd August 2022 defended on: 18th April 2023

Abstract

Task-irrelevant sounds can lead to costs in performance due to the orienting of attention toward the distracting event. Under certain circumstances, motivationally significant sounds (e.g., emotional sounds such as a baby cry) can benefit performance because of an increase in arousal level. The main goal of the present doctoral thesis was to investigate the relation between the costs of orienting attention and the benefits of an increased arousal level from a developmental perspective in the involuntary auditory attention. For this purpose, I conducted a series of five experiments. In the first study, participants (children aged 7 to 10 years and adults) watched a silent video while listening to a sound sequence containing standard, emotional and neutral novel sounds, which were irrelevant to the video. I recorded attention-related event-related potentials (ERPs) and pupil dilation responses (PDRs). Results showed larger amplitudes in auditory involuntary attention components (P2, P3a) and larger PDR with the occurrence of novel sounds in children compared to adults. Both groups showed enhanced ERP and PDR amplitudes for emotional compared to neutral novel sounds. To follow up the costs and benefits issue on the behavioral level, participants (children aged 6 to 8 years and adults) performed a discrimination task while listening to a task-irrelevant sound sequence containing standard, emotional and neutral novel sounds. Reaction times (RTs) and PDRs were recorded in Studies II and III. The objective of these experiments was to find a direct relationship between enhanced arousal (i.e., larger PDR) and faster reaction times in the emotional trials compared to neutral trials. Results showed that highly arousing emotional novel sounds reduced distraction effects and this reduction was stronger in children compared to adults. However, the relationship between arousal and reaction times in the emotional trials was not confirmed by the multilevel analysis conducted on adults, probably reflecting partially distinct processes. During the Covid-19 pandemic, I conducted an online version of Study II on adults. RTs were recorded remotely. Results showed distraction effects even in more ecological environments, whereas the reduced distraction effects due to emotional information were not observed. Study V targeted the question in more detail of whether pupil dilation responses reflect the same attentional mechanisms commonly examined in EEG experiments. Adults listened to a sound sequence containing deviant sounds (e.g. pink noise, 750 Hz, 525 Hz high and low loudness deviants etc.) while watching a silent video. Results showed that, compared to standard sounds (500 Hz), only pink noise, moderate and strong frequency deviants and high-loudness sounds elicited significant PDRs in adults.

Overall, results indicated that children aged 8 to 10 years old are more sensitive to the occurrence of novel sounds but can process emotional novel sounds at an advanced level both on a behavioral and cortical level. Furthermore, the pupil can be used as an alternative method in attentional developmental research. This thesis proposes an updated version of the three-stage model of involuntary attention by including the effects of emotion on attention.

Table of contents

Abstract *2*

Table of contents *3*

List of figures *7*

List of tables *8*

Index of notation *9*

1. Introduction *11*

1.1 Attention as part of the executive functions and attentional networks in the development **12**

1.2 The oddball paradigm with novel and emotional novel sounds **14**

1.3 The three-stage model of distraction of attention and its corresponding ERPs in the development **16**

1.4 Distraction of attention as cost of orienting of attention and emotional information as benefit of arousal level in the development **18**

1.5 The LC-NE system **21**

1.6 Co-registrations of LC, PDR and attention-related ERPs (P300, P3a) **22**

1.7 The LC-NE system and attention networks **23**

1.8 Research questions and hypotheses **23**

2. Study I: Which steps (early/late P3a, LDN) of involuntary attention will be influenced by auditory emotional novels in elementary school children? Which developmental differences can be observed between children and adults? *29*

2.1 Introduction **29**

2.1.1 Processing of unexpected and task-irrelevant sounds reflected by ERPs 30

2.1.2 Processing of emotional unexpected and task-irrelevant sounds reflected by ERPs 31

2.1.3 Attention networks, the role of the locus coeruleus-norepinephrine system and pupil size 32

2.2 Materials and Methods: **33**

2.2.1 Participants 33

2.2.2 Stimuli 33

2.2.3 Procedure 34

2.2.4 EEG and Pupil Data recording 35

2.2.5 Data analyses 36

2.2.6 Statistical analysis 37

2.3 Results **41**

2.3.1 ERPs 41

2.3.2 Pupil diameter 45

2.4 Discussion **47**

2.4.1 Age effects on enhanced attention in response to novelty and emotion 47

2.4.2 Age effects on early and late processing of novelty and emotion 50

2.5 Limitation **51**

2.6 Conclusion **52**

3. Study II: How do costs of attention orienting and benefits in enhanced arousal evoked by task-irrelevant novel and emotional auditory stimulation influence performance in a task? *53*

3.1 Introduction **53**

3.2 Method **55**

3.2.1 Participants 55

3.2.2 Stimuli 56

Table 2: Descriptive statistics of the categories of sounds used in the experiment. *57*

Table 3: Independent t-tests of the categories of sounds used in the experiment. *57*

3.2.3 Procedure 58

3.2.4 Data Analysis 59

3.2.5 Pupil data processing 60

3.2.6 Behavioral data (reaction times, RTs) 61

3.2.7 Statistical analysis 61

Table 4: Overview of the 10 best BIC-selected models. *65*

3.3 Results **67**

3.4 Discussion **70**

3.5 Conclusion **73**

4. Study III: How do costs of attention orienting and benefits in enhanced arousal evoked by task-irrelevant novel and emotional auditory stimulation influence performance in a task? Which age differences can be observed between children and adults? *75*

4.1 Introduction **75**

4.2 Method **78**

4.2.1 Participants 78

4.2.2 Stimuli, procedure, data analysis, pupil data processing and behavioral data (reaction times, RTs) 78

4.2.3 Statistical analysis 79

4.3 Results **79**

4.4 Discussion **82**

5. Study IV: How do costs of attention orienting and benefits in enhanced arousal due to task-irrelevant novel and emotional auditory stimulation influence performance in a task? Are these effects visible also in an online study? *87*

5.1 Introduction **87**

5.2 Methods **89**

5.2.1 Participants 89

5.2.2 Stimuli 90

5.2.3 Procedure 90

5.2.4 Data Analyses 91

5.2.5 Statistical analysis 91

5.3 Results **91**

5.4 Discussion **93**

6. Study V: Can the distractor-dependent PDR be a marker for the attentional mechanisms in a context of pitch deviants and environmental sounds? *97*

6.1 Introduction **97**

6.2 Methods **100**

6.2.1 Participants 100

6.2.2 Stimuli ... 100
6.2.3 Procedure ... 101
6.2.4 Data Analysis ... 102
6.2.5 Statistical analysis ... 103

6.3 Results ... 103

6.4 Discussion ... 105

7. General discussion and conclusions ... 111

7.1 Answering our research questions ... 111

7.2 Integration of results within current neurophysiological models of attention in adults and in children ... 114

7.2.1 Development of attention in middle childhood ... 114
7.2.2 Emotional processing ... 116
7.2.3 Pupil responses to task-irrelevant stimuli ... 118
7.2.4 Updating the 3-stage model of attention ... 119

7.3 General conclusions ... 121

7.4 Future perspectives ... 121

8. Supplementary material ... 123

8.1 Study I: ... 123

8.2 Study II: ... 125

Supplement discussion ... 128

References ... 131

List of figures

Figure 1 16
Figure 2 35
Figure 3 39
Figure 4 43
Figure 5 44
Figure 6 46
Figure 7 58
Figure 8 68
Figure 9 69
Figure 10 70
Figure 11 81
Figure 12 82
Figure 13 93
Figure 14 105
Figure 15 114
Figure 16 119

Figure S 1 127

List of tables

Table 1: *Overview of the studies conducted in the present thesis.* 27

Table 2: *Descriptive statistics of the categories of sounds used in the experiment.* 57

Table 3: *Independent t-tests of the categories of sounds used in the experiment.* 57

Table 4: *Overview of the 10 best BIC-selected models.* 65

Table 5: *Coefficients for the mixed-effects model.* 66

Table 6: *Mean and standard deviation of the child and the adult group (Study II)* 79

Table 7: *T-tests novel vs. standard sound in the RTs and PDR (time window 1.5-1.7 s) in the child group* 80

Table 8: *Descriptive statistic: mean reaction times (rt) in milliseconds (ms) and standard deviations (SD) for standard, emotional and neutral novel sounds, hits and error rates for the online and the laboratory experiment.* 92

Table 9: *T-tests deviant vs. standard sound in the early time window (500-900 ms)* 104

Table 10: *T-tests deviant vs. standard sound in the late time window (1200-1600 ms)* 104

Table S 1 123

Table S 2 124

Table S 3 124

Table S 4 128

Index of notation

ANOVA	Analysis of variance
ACC	Anterior cingulate cortex
ADHD	Attention deficit hyperactivity disorder
ANS	Autonomic nervous system
BF	Bayes Factor
BIC	Bayesian information criterion
BOLD	Blood oxygenation level dependent
EEG	Electroencephalography
EOG	Electrooculogram
EKP	Ereigniskorrelierten Potenziale
ERP	Event-related potential
FEF	Frontal eye field
fMRI	Functional magnetic resonance imaging
ICA	Indipendent component
ICA	Indipendent component analysis
IADS	International affective digitized sounds
ISI	Interstimulus interval
IPS	Intraparietal sulcus
LDN	Late discriminative negativity
LMM	Linear mixed effect models
LC	Locus coeruleus
LC-NE	Locus coeruleus - norepinephrine
MMN	Mismatch negativity
MMR	Mismatch response
NE	Norepinephrine
PFC	Prefrontal cortex
PD	Pupil dilation
PDR	Pupil dilation response
RT	Reaction time
RON	Reorienting negativity
SARS-Covid	Severe acute respiratory syndrome coronavirus
SD	Standard deviation
SOA	Stimulus-onset asynchrony
SC	Superior colliculus
SNS	Sympathetic nervous system
tPCA	Temporal principal component analysis
TPJ	Temporoparietal junction
VFC	Ventral frontal cortex

1. Introduction

Let me introduce you to Tommy. Tommy is a lovely 8-year-old child, who is having a math test at school. He is extremely focused and nothing and nobody can distract him. Unusually, the classroom is very quiet. Suddenly a loud scream! One of Tommy's classmates slammed his hand against the edge of the table. In less than a second Tommy's attention is driven on a classmate and not on the test anymore. He had scared the pants off Tommy. But no worries, he is fine, just being a bit too theatrical…Tommy is motivated and comes back to work very quickly. All of a sudden, another classmate drops his keys on the floor! Of course, Tommy is hardly concentrated now. It is very difficult to complete the math test today!

This brief scene is useful to introduce the topic of the present thesis. What I have described above are two different types of distractor sounds that caught Tommy's attention: one had an emotional content (the scream) whereas the second one had a neutral content (the keys). Which sound has distracted Tommy the most? Did both sounds have the same impact on Tommy's performance on the math test? And if Tommy would be an adult, would he be less distracted?

Attention is considered to be a basic component of cognitive functioning and because of this role, attention in infancy and childhood is especially important. Attention can be captured by stimuli in all sensory modalities but in this project, I will focus on the effects of auditory stimulation on attention. In contrast to the visual modality, the auditory modality cannot be easily avoided, as an example we can close our eyes in order to stop visual processing but we cannot easily close our ears.
In the introductory example, Tommy's attention has been oriented toward new and task-irrelevant auditory stimuli that have impaired his performance. But under certain circumstances, the content of distracting events (for example emotion) may drive to better performance by enhancing the arousal level. Distraction of attention by unexpected and task-irrelevant sounds could comprise costs due to orienting of attention toward a distracting event and could benefit due to an increase in the arousal level evoked by the processing of such events (Max et al., 2015). In the present thesis I will investigate the relationship between those two factors in the development, because children seem to be more sensitive to auditory distractors and novel events occurring outside the focus of attention compared to adults (for a review Wetzel & Schröger, 2014). In fact, attentional processes may be less automatic in

children compared to adults, since the application of these processes has not become a routine yet (Norman & Shallice, 1986).

From an evolutionary aspect, potentially behavioral relevant stimuli (for example emotional stimuli) are able to signal a general relevance of a situation, irrespective of their relevance for the current task. Humans must be able to adapt behavior and transfer attention across sensory modalities in potentially dangerous situations (for a review Koelewijn et al., 2010). Thus, which attentional mechanisms are affected by task-irrelevant emotional sounds on both a neurophysiological and behavioral perspective in children and adults? I am going to investigate costs of orienting of attention toward a distracting event and benefits due to arousal level evoked by the processing of such events and for the first time combining different methods together in children (electroencephalography (EEG), pupil dilation responses (PDR) and reaction times (RTs)).

1.1 Attention as part of the executive functions and attentional networks in the development

Attention is part of the executive functions, which are higher cognitive processes including working memory, inhibitory control and cognitive flexibility (Miyake et al., 2000). The executive functions serve our ability to respond flexibly and adaptively to changes in the environment to accomplish long-term goals. Attention as part of the executive functions undergoes critical quantitative and qualitative changes during childhood and is rooted in neural circuitry that has a protracted developmental time course (Diamond, 2002; Fiske & Holmboe, 2019; Friedman & Miyake, 2017; Miyake et al., 2000; Miyake & Friedman, 2012). Early improvements in attention control emerge in their rudimentary form during the first year of life and continue to develop throughout childhood into adolescence (for reviews see Diamond, 2002; Jurado & Rosselli, 2007; Zelazo et al., 2008).

As many other higher cognitive functions, the development of executive functions and attention control has been tied to the maturation of the brain in the prefrontal and frontal cortex (e.g., Fuster, 2002, Posner, Rothbart, Sheese & Voelker, 2011; Rueda, Posner, Rothbart & Davis-Stober, 2004; Rothbart & Posner, 2001; see Garon, Bryson & Smith, 2008 and Diamond, 2002 for a review) but also in the parietal areas (for example, Luna et al., 2010; Skau et al., 2022; Wetzel & Schröger, 2014). Not only cortical areas but also structural aspects of the brain mature until young childhood, for example brain size, brain connectivity and synaptic density (Bunge et al., 2002; Giedd et al., 1999; Huttenlocher, 1979). Research with older children and adolescents has demonstrated that performance improvements on executive functions' tasks indirectly parallel the structural changes in grey matter (Sowell et al., 2003, 2004) and are directly associated with the structural changes in white matter (Nagy et al., 2004) that occur in the same fronto-parietal cortices that are recruited during executive functions' task performance. All these maturational changes determine an increase in velocity and capacity of information processing with increasing age (Casey et al., 2000; Olesen et al., 2007). Moreover, due to their frontal location, attentional networks are influenced by other distributed neural systems such as the emotional, motivational, arousal and motor system (e.g. Ruff & Rothbart, 1996).

An early influential model of attention, underpinning relations between attention and neurological networks was first proposed by Posner (1990). This model explains attention as a trinity of functionally and anatomically distinct networks, which however seem to interact with each other (Petersen & Posner, 2012): *Alerting, Orienting* and *Executive network.*

Alerting. Is the ability to maintain and increase readiness of preparation for an upcoming stimulus for even a short time. Alertness has been related to arousal and therefore is influenced by the chemical neuromodulator norepinephrine, which arises from the locus coeruleus. Its network includes frontal and parietal regions: the right dorsoparietal prefrontal cortex for monitoring and arousal in conjunction with the anterior cingulate cortex (ACC) and the right inferior parietal region for endogenous and exogenous alerting (Raz & Buhle, 2006). Developmental differences in the ability to increase response readiness evoked by external cues and sustained attention has been shown to be different between children and adults. Children seem to process warning cues less efficiently than adults (Pozuelos et al., 2014).

Orienting. Is the ability to select information in the surrounding among multiple sensory stimuli. Endogenous (top-down) and exogenous (bottom-up) orienting improve performance by enhancing the neural sensory activity. Its network includes the pulvinar, superior colliculus, superior parietal lobe, temporoparietal junction, superior temporal lobe and frontal eye fields. Developmental differences until late childhood have been shown in studies requiring disengagement of attention from the cue location toward the target and in studies contrasting reaction times to valid vs. invalid cued targets (Pozuelos et al., 2014).

Executive. Is the ability to focus attention on a specific task, planning or decision making, conflict resolution, error detection, regulation of thoughts and feelings and evaluation of conditions to be dangerous or not (Posner, 2011). Its network includes mainly the anterior cingulate cortex (ACC) for more higher-level tasks (for a detailed review see Raz & Buhle, 2006). Tasks requiring executive abilities have shown that these abilities develop during childhood and in particularly demanding tasks until early adulthood (Pozuelos et al., 2014).

Despite the initial belief of the independence between these networks, Petersen and Posner (2012) reviewed the interactions between networks and emphasized the role of the locus coeruleus especially in the *alertness* network.

A similar, but more recent neuroanatomical model of attention control by Corbetta & Shulman (2002) describes two frontoparietal networks which are activated also by salient, new events in the auditory modality: a dorsal and a ventral one. The dorsal frontoparietal network embodies the top-down control mechanism which biases the filtering of the signal based on current goals, expectations, preexisting information and task preparation in order to select appropriate stimulus features (exogenous orienting). To this network belong the bilateral intraparietal sulcus (IPS), prefrontal cortex (PFC), temporoparietal junction (TPJ) and the frontal eye fields (FEF) and shares common neuronal areas and functions with the *Alerting* network by Posner (1990, 2008). The ventral frontoparietal network, on the other hand, responds along with the dorsal network when behaviorally relevant stimuli occur in the surrounding (stimulus-driven reorienting, Corbetta et al., 2000). This network comprises the temporoparietal junction (TPJ) and ventral frontal cortex (VFC). An interaction between the two networks occurs when attention is reoriented back to an object of interest, the ventral network interrupts ongoing activity in favor of the dorsal network which shifts attention toward the new information (or task at hand, Corbetta et al., 2008; Sara & Bouret, 2012). The role of the ventral network in response to salient but task-irrelevant stimuli, is to prevent shifts of attention that could impair performance. Evidence from neuroimaging studies suggested that specific attention processes mature throughout childhood (Farrant & Uddin, 2015). For example, children showed greater activation in anterior cingulate cortex and lateral prefrontal cortices during selective attention (Booth et al., 2003) and response inhibition (Casey et al., 1997; Paulsen et al., 2015) compared to adults. Also, behavioral studies suggested that children are more susceptible to interference and less able to inhibit responses than adults (e.g., Bunge et al., 2002).

1.2 The oddball paradigm with novel and emotional novel sounds

Orienting and distraction of attention can be tested using the passive oddball paradigm, in which a repeated standard sound and a rare deviant or novel sound (oddball or distracter) are presented to participants who are explicitly told to ignore the sound sequence (e.g., Escera et al., 1998). A deviant is a repeated distracter sound, such as a 1000 Hz pitch sound rarely presented in a sequence of 500 Hz standard sounds, whereas a novel is a uniquely presented distracter sound, for example a 1000 Hz pitch sound presented just once in a sequence of 500 Hz standard sounds. Usually, novel sounds are environmental sounds, such as the sound of a crying baby or a door knock, etc. (Figure 2). Both deviant and novel sounds activate different mechanisms in the brain and yield to different event related (ERP) components, such as the mismatch negativity (MMN) and the N1 (see paragraph 1.3).

Most frequently, novel and deviant sounds can attract the attention and can impair the ongoing task. When novel sounds convey emotional information, their processing may be prioritized and they may receive privileged access to attention and awareness due to their high motivational relevance (Duncan et al., 1997; Lang et al., 1997; Pessoa, 2005; Poe et al., 2020; Schupp et al., 2003; Vuilleumier et al., 2001; Vuilleumier, 2005). However, recent studies suggested that novels may yield not only distraction, but also facilitation in a behavioral task (Ruhnau et al., 2010; SanMiguel, Linden, et al., 2010; SanMiguel, Morgan, et al., 2010; Wetzel et al., 2012), thus they may improve performance in novel versus standard trials. Similarly, emotional novel sounds may improve performance in emotional novel trials versus neutral novel trials in a task (Anderson & Shimamura, 2005; Lindström & Bohlin, 2011; Lorenzino & Caudek, 2015; Max et al., 2015). A plausible explanation for those opposing effects is that the orienting response toward salient sounds comprises not only attentional orienting, but also an alerting effect (Näätänen, 1992), which drives to enhanced arousal (SanMiguel, Linden, et al., 2010; Wetzel et al., 2012, 2013; see also Hoyer et al., 2021). Thus, it is assumed that novel sounds reflect the sum of both costs of attentional orienting and benefits by the alerting component of novels (Posner, 1990; Pozuelos et al., 2014; SanMiguel, Linden, et al., 2010). Importantly, the underlying processes driving to distraction or facilitation effects may follow a respective trajectory in children compared to adults.

1.3 The three-stage model of distraction of attention and its corresponding ERPs in the development

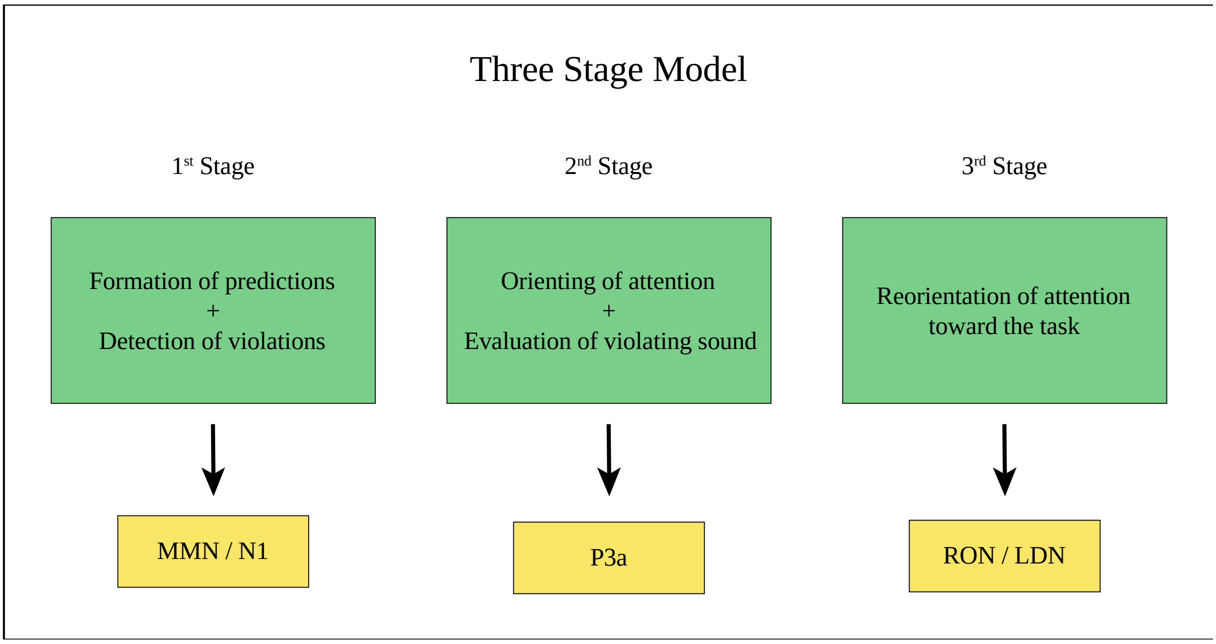

Figure 1: Overview of the original three-stage model of attention (Escera et al., 1998, 2000; Horváth et al., 2008; Schröger et al., 2000; for a developmental review Wetzel & Schröger, 2014).

The processes bringing to and following distraction have been described as a temporally serial three-stage model. The three stages of distraction of attention find corresponding neurophysiological evidence in the event-related potentials (ERPs) and have been investigated in both children and adults (e.g., Escera et al., 1998, 2000; Horváth et al., 2008; Schröger et al., 2000; for a developmental review Wetzel & Schröger, 2014; see Figure 1). *1st stage*. In this stage, characteristics of the recent auditory stimulus are assumed to be automatically integrated by the cognitive system, while participants are engaged in a primary task. A neuronal model is formed from the mental representation of the acoustic environment establishing a prediction of the upcoming sound (in the introductory example Tommy suddenly heard the distracting scream of a classmate). The automatic detection of prediction violation is reported as mismatch response (MMR) when small deviant sounds are presented (Schröger, 1998; Schröger & Wolff, 1996; Winkler, 2007; but see May & Tiitinen, 2010). MMR occurs around 100-200 ms after stimulus onset over central and frontal areas (Alho et al., 1990; Mueller et al., 2008). Positive and negative MMR have been observed even before birth (Draganova et al. , 2005), in infants (Fellman & Huotilainen, 2006; for a review see Kushnerenko et al., 2013), in kindergarten children (Morr et al., 2002; Mueller et al., 2008; Ponton et al., 2000), in school-age children (Mahajan & McArthur, 2015; Wetzel et al., 2006) and in adults (Näätänen et al., 2007). When novel sounds occur in the surrounding, the automatic detection of a prediction violation is reported as the N1. The auditory N1 cannot be consistently elicited in children under the age of 8 or 9 years, and it only becomes adult-like at about 16 years of age (Čeponiene et al., 2001, 2003; Ponton et al., 2000; Ruhnau et al., 2010). N1 amplitudes increase whereas N1 latencies decrease with increasing age from 5 to 19 years (Fuchigami et al., 1993; Mueller et al., 2008). In auditory oddball experiments, the N1 amplitude can be strongly modulated by attentional context and interstimulus intervals (ISI; Horváth et al., 2008; May & Tiitinen, 2010; Tiitinen et al., 1994).

2^nd^ stage. Attention can be shifted toward the task-irrelevant sound that violated the prediction and a further evaluation is implemented (Bendixen et al., 2007; Escera et al., 1998; Hughes et al., 2007; Näätänen, 1990; Näätänen et al., 2001; Schröger & Wolff, 1998; Sokolov, 1963). In the example above Tommy involuntarily allocated his attention toward the scream of the classmate. This can be observed in the P3a component, occurring around 250-400 ms after stimulus onset (Háden et al., 2009; Kushnerenko et al., 2007) over more frontal areas in younger children to more central-parietal areas in older children (Brinkman & Stauder, 2008; Čeponiene et al., 2004; Ruhnau et al., 2010, 2013; Wetzel et al., 2011; Wetzel & Schröger, 2007b). In active (with required behavioral response) but also passive oddball tasks (no behavioral response required), the P3a likely represents attentional orienting (Masson & Bidet-Caulet, 2019; also called novelty P3 Barry et al., 2016; Brinkman & Stauder, 2008; Escera et al., 1998; Yago et al., 2003). However, the rapid attentional shifts to the new and unexpected stimuli, may involve early evaluation of the stimulus as well, in order to determine whether further cognitive processing and behavioral response is necessary (Horváth, 2014; Horváth et al., 2009; Horváth, Winkler, et al., 2008). A component similar to the P3a has been observed already in toddlers (Putkinen et al., 2012), kindergarten children (Shestakova et al., 2003) and school aged children (Brinkman & Stauder, 2008; Čeponiene et al., 2004; Gumenyuk et al., 2001, 2004; Wetzel et al., 2011; Wetzel & Schröger, 2007b). Additionally, the P3a component in response to novel events frequently consists of two peaks: An early P3a around 200 ms at central areas is thought to represent stimulus specific processes (Brinkman & Stauder, 2008; Gumenyuk et al., 2001, 2004; Wetzel & Schröger, 2007b), whereas a late P3a around 300 ms at fronto-central areas is suggested to represent more general orienting of attention processes (Brinkman & Stauder, 2008; Escera et al., 1998, 2000; Wetzel & Schröger, 2007b).

3^rd^ stage. If the new stimulus is not behaviorally relevant, the focus of attention is reoriented back to the ongoing task. In the example above Tommy reallocated his attention to the math test. This relates to a late component, which is named late discriminative negativity (LDN) or in active paradigms also named reorienting negativity (RON, Hämäläinen et al., 2008; Putkinen et al., 2012; Shestakova et al., 2003; for a review see Cheour et al., 2001). The LDN peaks at approximately 450 ms after stimulus onset and has been observed in the fetus (Draganova et al., 2005) and in toddles (Putkinen et al., 2012) but decreases in amplitude until early adolescence (Cheour et al., 2001). The underlying neurocognitive functions of LDN are still speculative. It has been discussed to represent anticipation processes to the target or even attention related processes (Shestakova 2003), for example reorienting of attention toward a primary task (Čeponiene et al., 2004; Horváth et al., 2009; Shestakova et al., 2003; Wetzel et al., 2006).

While the three-stage model has been well investigated in adults, very little work has been conducted in children. Whether the developmental trajectory of attentional networks (orienting and evaluation processes to novel and emotional information) is still maturing in middle childhood, that is between the age of 6 and 10 years, has still to be investigated. However, typical ERP components (N1/MMN, P3a, RON/LDN) corresponding to the three stages of distraction of attention have been observed in children as well. Therefore, the three-stage model can be used in the investigation of developmental characteristics in the distraction and orienting of attention.

1.4 Distraction of attention as cost of orienting of attention and emotional information as benefit of arousal level in the development

Orienting of attention implies capacity limited processes and resources, which are subsequently not available for the completion of a task. In order to measure the behavioral distraction, an active task can be implemented in the experimental setup. Subjects are instructed not to pay attention to the task-irrelevant sounds or to specific sound features while performing a task, which can be visual (auditory-visual oddball paradigm) or auditory (auditory-auditory oddball paradigm, Hughes et al., 2007; Parmentier et al., 2008). The distraction effect on a behavioral level is calculated by subtracting the reaction times (RTs) of the standard trials from the RTs of the novel trials and is related to delayed reaction times and/or decreased hit rates during the task (Escera et al., 1998; Schröger & Wolff, 1998). Behavioral distraction effects are normally larger in younger children compared to older children or children compared to adults as the ability to shield from task-irrelevant information increases with age (e.g., Gumenyuk et al., 2001, 2004; Wetzel et al., 2006). However, depending on features of the paradigm (for example SOA between sound and target onset) and attentional task demands (working memory load), other studies showed no difference between age groups (Horváth et al., 2009; Ruhnau et al., 2013) and one study found the opposite effect (Ruhnau et al., 2010).

When novel sounds convey emotional information, their processing is prioritized and they receive privileged access to attention and awareness due to their high motivational relevance (Lang et al., 1997; Pessoa, 2005; Poe et al., 2020; Schupp et al., 2003; Vuilleumier et al., 2001; Vuilleumier, 2005). Affective content triggers a neural cascade activating areas of the limbic system, such as the amygdala (e.g., Frühholz et al., 2016). The cognitive brain regions in emotion overlap at a certain extend to areas involved in the control of attention. The prefrontal cortex (PFC) has a central role in affect and emotion processing (Pessoa 2008). Interestingly, the amygdala activates also the noradrenergic system through projections to the locus coeruleus modulating attention (Aston-Jones et al., 2000), but the role of this pathway is still unresolved.

In attentional research, most of the experiments make use of visual emotional stimuli, whereas auditory emotional stimulation is less used. Task-relevant visual emotional information seem to improve performance in a task (for example, Tartar et al., 2012; Zeelenberg et al., 2006). Task-irrelevant visual emotional information, on the contrary, capture attention which drives to impaired processing of non-emotional aspects of the stimulus or event (Anderson & Shimamura, 2005; Most et al., 2005; Pereira et al., 2006; for a review on visual emotional stimuli, see Bradley et al., 2012). In fact, if a certain amount of attentional resources is allocated to the emotional stimulus, less resources will be available for the processing of the neutral target thereby causing an impairment in target identification (Kanske, 2012). However, under certain conditions, task-irrelevant emotional information can facilitate task processing and performance (Anderson & Shimamura, 2005; Lindström & Bohlin, 2011; Lorenzino & Caudek, 2015; Max et al., 2015). From an evolutionary aspect, emotional stimuli are able to signal a general relevance of a situation, and humans must be able to adapt behavior and react in potentially dangerous situations (Lu et al., 2017; Tartar et al., 2012; for a review Koelewijn et al., 2010). In line with this idea, facilitation effects in a task may be obtained due to an increased arousal level (Anderson & Shimamura, 2005; Lorenzino & Caudek, 2015; Max et al., 2015). Emotional information triggers activity in the sympathetic nervous system which comes along with a higher arousal level, which in turn facilitates motor and behavioral responses (Aston-Jones & Cohen, 2005; Corbetta & Shulman, 2002). Thus, what might be reflected in behavior when task-irrelevant emotional information is presented might be the sum of both effects: costs of attentional orienting and benefits by the arousing component of the stimuli (Max et al., 2015). Only a handful of studies focused on the processing of auditory emotional non-linguistic stimuli and the developmental trajectory has been either fragmentary or inconsistently described in the literature. Behavioral and physiological studies have provided evidence that within the first year of life, infants are able to discriminate between happy, sad, angry and fearful facial expressions (for example, Grossmann, 2013; Kotsoni et al., 2001) and respond accordingly to other peers' emotional vocalizations by showing signs of distress when listening to other infants' crying but not to other non-affective sounds (Dondi et al., 1999). Moreover, infants already respond with increased arousal to emotional stimuli within the first 15 months of postnatal life (Geangu et al., 2011; Wetzel, Buttelmann, et al., 2016). Evidence about the influence of emotional information on attention remains sporadic in school aged children and it is difficult to draw conclusions due to differences in the experimental setup, the task to perform and modality presentation. Although emotion recognition occurs very early in life, its categorization from short bursts of non-linguistic affective vocal expressions improves in school aged children between 5 and 17 years (Grosbras et al., 2018), indicating a long-lasting development of emotion processing. Improvement in coding affective signals concur in time with structural and functional changes in brain areas involved in the emotional processing, such as the amygdala (Fecteau et al., 2005, 2007; Uematsu et al., 2012).

The facilitation or impoverishment effect of emotional information on performance in a non-related task in childhood is still controversial. For example, Kestenbaum and Nelson (1992) showed that although performance in a visual task was similar for 7-year-old children and adults, children's ERP associated with orienting processes differed from the adults' ones. Indeed, children showed enhanced amplitudes for angry faces compared to adults (Kestenbaum & Nelson, 1992). Thus, children seem to be more distracted by emotional information at a cortical level but they reach an advanced level in the performance. More recently, another study investigated the potential distracting effect of emotion on an identity-matching task. In this study, children between 4 and 15 years old had to match the identity of a target face with other two (different) faces, all expressing either emotional or neutral emotions with different intensities. Children's accuracy improved with age but the face intensity expression disrupted accuracy, indicating that more salient emotive stimuli distracted away from the task of identity-matching (Herba et al., 2006). Therefore, younger children seem to be more susceptible to highly relevant emotional stimuli than older children.

All in all, the developmental literature on the facilitation or distraction effect of emotion on attention is yet inconsistent and fragmentary, with even less information in the auditory modality.

1.5 The LC-NE system

As part of the attentional networks explained above (Corbetta & Shulman, 2002; Petersen & Posner, 2012) and its engagement in behaviorally relevant situations, the locus coeruleus (LC) plays a fundamental role in distraction and orienting of attention. The locus coeruleus is a small nucleus in the dorsal pons which project diffusely to the brainstem and vast areas of the cortex. It is the primary source of norepinephrine (NE) synthesizing neurons and plays a critical role in central behavioral and physiological processes resulting in facilitated processing of motivationally significant stimuli (Jones and Moore, 1977; Aston-Jones and Cohen, 2005; Joshi & Gold, 2020; Poe et al., 2020).

The rapid (phasic) response of the LC secretes norepinephrine in cortical and subcortical target regions, which are responsible for sensory and motor sensitivity (e.g., Corbetta & Shulman, 2002; Nieuwenhuis et al., 2005, 2011; Posner, 1990; Sara & Bouret, 2012; for review see Poe et al., 2020). This locus coeruleus-norepinephrine system (LC-NE) is related to many behavioral (regulation of waking/arousal) and cognitive processes including the prefrontal cortex, such as working memory, attention, learning, emotional amygdala-dependent memory and cognitive and behavioral responses to stress (Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Sara & Bouret, 2012; for review see Poe et al., 2020). The LC-NE activity hence stimulates the sympathetic system and with it sets off several physiological reactions, which can be measured for example through skin conductance responses, heart and respiration rate and pupil dilation response (Nikula, 1991; Xiefeng et al., 2019; Yang et al., 2007; Jauniaux et al., 2020; Bradley et al., 2008; Bradley & Lang, 2007;Wang et al., 2018, respectively). It is suggested that motivationally significant and new stimuli (for example emotional novel sounds) trigger norepinephrine release, which leads to behavioral readiness to respond to such stimuli (Aston-Jones & Cohen, 2005; Bradley et al., 2008; Joshi et al., 2016).

The Adaptive Gain Theory by Astone-Jones & Cohen (2005) describes a model of the LC-NE system in relation to arousal and behavior. LC neurons exhibit two activity modes, tonic and phasic. High tonic activity goes along with disengagement from the task or the surroundings, distractibility and unaroused state of the body. Tonic activity is moderate when the organism is engaged in a task and high when exploring an environment (Aston-Jones & Cohen, 2005). Phasic signals are related to target stimuli, task-related decision processes, high task-engagement and highly accurate behavior by analyzing costs and benefits associated with performance due to inputs from the cortical frontal areas and come along with moderate tonic mode and intensified arousal. Importantly in animals only, it has been demonstrated that effects and activity of neurons in the LC-NE system follow an inverted U-shape manner, such that facilitating effects are achieved when NE release is moderate and downgrade to modest when the release is initial or further increased (Poe, 2020; Aston-Jones & Cohen, 2005). This firing pattern resembles the classical Yerkes-Dodson relationship between arousal and performance (Teigen, 1994).

1.6 Co-registrations of LC, PDR and attention-related ERPs (P300, P3a)

Even though a relatively small amount of studies has made a simultaneous measurement of neural activity and pupil size, these studies demonstrated a functional relationship between LC and pupil size in both animals and humans.

But how can we infer actual brain activity from pupil size? Increasing number of studies are focusing principally on two components of pupil measurements: baseline pupil diameter (baseline PD), a relatively long-lasting dilation and pupil dilation response (PDR), a transient response to task-relevant but also unexpected, salient events. Baseline pupil size is measured during passive epochs or during the pre-task-related stimulus and is related to the tonic activity of the LC (Aston-Jones and Cohen, 2005). Transient PDR occurs after new, task-irrelevant, target-relevant or motivationally significant events and is related to the phasic activity of the LC (Aston-Jones & Cohen, 2005; Jepma & Nieuwenhuis, 2011; Krebs et al., 2018). Thus, baseline PD and pupil dilation can be used and interpreted as a marker of LC activity.

In some studies, single-cell recordings reveal a direct connection (relation) between LC cells and pupil changes in monkeys (Aston-Jones & Cohen, 2005; Joshi et al., 2016). Gilzenrat and colleagues (2010) discussed the role of pupil diameter as an index of LC activity in relation with task-evoked pupil dilations, baseline pupil size and behavioral performance in monkeys and human participants. Accordingly, Murphy et al. (2011) found the same relation in an oddball study in humans. In particular, performance decreased for lower and higher level of baseline pupil size, whereas optimal performance was obtained when baseline pupil size was at intermediate level (U-shape Yerkes-Dodson law). Moreover, in an fMRI experiment in humans, Murphy and colleagues (2014) observed a relationship between pupil diameter and BOLD activity in the LC region in response to targets in a two-stimulus oddball task.

The activity of the LC-NE system has been related to other methods used in the investigation of attention in adults. For example, Murphy and colleagues (2011) have collected evidence that LC activity is related to the event-related potential P300 (usually elicited by task-relevant stimuli and indicating evaluation processes of stimuli) while participants were performing an oddball task, thus P300 is thought to reflect activation of the LC-NE system, although the current evidence for this relationship is still indirect (Nieuwenhuis et al., 2005). Concerning the orienting and evaluation processes (in terms of the P3a component) and pupil dilation, Nieuwenhuis et al. (2011) discussed the possibility of communal processes involved in attention due to projections from a medullary pathway. Thus, P3a and pupil dilation might be influenced by the LC-NE system and share attention related processes, for example in the framework of auditory deviant and novelty information. However, whether the pupil dilation is sensitive to attention-related processes in the development, as shown in the ERP component P3a, is still an open question. Recently, Hoyer and colleagues (2021) have shown that attentional and motor components, among them arousal, follow a specific maturational trajectory during development. Additionally, an investigation into the link between the LC activity (reflected by the pupil dilation) and performance in children and adults in an auditory oddball paradigm has not been reported yet.

1.7 The LC-NE system and attention networks

The LC-NE system plays a fundamental role in many attention-related models. From the beginning, it has been related to Posner's attentional model. In particular, the *Alerting* network is modulated by the secretion of norepinephrine in the brain areas and involves frontal and parietal cortices. Not only, Corbetta and Shulman (2002) already stressed the importance of this subcortical area in the circuitry of the stimuli selection and evaluation. In addition to this, Bouret & Sara (2005) proposed that the LC-NE system acts more like a "reset" operator to its target structures, by interrupting the current networks and facilitating the activation of new ones to promote shifting of attention (Sara & Bouret 2012, for more discussion).

1.8 Research questions and hypotheses

Even if the development of attention is a very interesting and important research question, we still know little about it in the framework of auditory attention. Attentional control processes have been proposed to be the unifying construction underlying cognitive control in both children (Garon et al., 2008; Lehto et al., 2003) and adults (McCabe et al., 2010; Miyake et al., 2000). Moreover, investigating developmental trajectories of attention-related capacities would help improving the concept of learning environments in schools, where children may increase concentration, learning abilities, working performance or strategies to shield from distractors. Collecting knowledge about attention processes would improve the quality of life also in children with attentional disorders (Fisher et al., 2014; Godwin & Fisher, 2011). Thus, an exploration of attentional control and the influence of auditory task-irrelevant information on attention in the childhood appears to be a promising venue for a better understanding of early changes and maturations in the development of attention. This is particularly important for the investigation of sensitive age groups such as young children or atypically developing children (for example, children with attentional disorders such as attention deficit hyperactivity disorder). Further, classical neurophysiological research on attention control in younger children, toddler and infants tend to become more complex and difficult with decreasing age. EEG experiments conducted on very young participants require many trials to achieve a good amount of data to analyze. For that reason, a fruitful inspection of alternative methods, such as pupillometry, is on the agenda of this thesis in order to gain better understanding of the investigation of attention in these challenging age groups. From a broader perspective, research on attention development in the middle childhood (6 to 10 years old) has the potential to yield insight into how early attentional abilities lead to higher mental functioning in later years. Moreover, the influence of external factors, such as emotional information, on attention is still under discussion. The general purpose of this thesis is to explore the development of attention control and particularly the role of attentional control on children's performance when task-irrelevant novel and emotional information occur. Moreover, because EEG studies are time-consuming and difficult to apply on younger children and infants, an easier and faster method, such as pupillometry, would be of use for the developmental community. My work is aiming at closing a gap in the developmental research by investigating the effects of emotional information on involuntary auditory attention on a psychophysiological and behavioral level in an age group where research is still lacking: the middle childhood.

Therefore, I planned and carried out a series of experiments on this topic (for an overview see Table 1). In Study I, I investigated the influence of task-irrelevant novel and emotional information on attention in children aged 7 to 10 years old and adults by means of electroencephalography (EEG) and pupillometry (pupil dilation responses, PDR). The aim of this study was to examine if the developmental trajectory of attentional networks involved in orienting and evaluation processes to novel and emotional information is still maturing in middle childhood and if pupil dilation may be a marker of those networks. Enhanced ERPs amplitudes for novel compared to standard sounds (novelty effect) and for emotional novel compared to neutral novel sounds (emotion effect) were predicted. Because children's attentional processing is still immature, I expected to observe developmental differences in terms of larger ERPs amplitudes to novel and emotional information in children compared to adults. Moreover, I expected increased PDRs to novel sounds with larger amplitudes for children compared to adults and larger PDRs to emotional compared to neutral novel sounds. Whether the impact of emotion on the pupil was similar for children and adults was still an open question.

In Study II and III, I further investigated the effects of task-irrelevant novel and emotional information on performance in adults and younger children (6-8 years old) by means of reaction times (RTs) and pupil dilation responses (PDR). The aim of this study was to examine the relation between costs of orienting of attention and benefits coming from enhancement in the arousal level. That is, if distraction effects were related to enhanced arousal evoked by emotional information and if this relation is different from children to adults. Firstly, I hypothesized distraction effects to be larger in children compared to adults, as observed in previous studies using similar paradigms. Secondly, I expected reduced distraction effects in response to emotional novel sounds compared to neutral novel sounds in both children and adults, as previously observed in a study with adults. Because of inconsistency in the literature and of possibly different developmental maturation of the arousal system in children compared to adults, it remained unclear if this facilitation effect would have been larger in adults compared to children. Thirdly, I predicted a correlation between reduced distraction effects and increased pupil dilation in trials where emotional novel sounds were presented in both children and adults, because emotional sounds can enhance the arousal level reflected by the pupil dilation.

In Study IV, I developed an online version of the (at that time) planned Study II and III during the SARS-Covid pandemic in order to inspect potential differences and biases between laboratory and online experiments. Hypotheses on the behavioral responses were similar to Study II, however I aimed at investigating whether the distraction and facilitation effects were visible also under less controlled conditions and in an online version of the experiment. Therefore, I compared the online and the laboratory study.

In Study V, I explored the effects of many different deviant distractors on the pupil dilation in adults. The aim of this study was to examine whether pupil dilation might be sensitive to small changes in sound features as corresponding ERP components and therefore be used as a marker of auditory attention in future oddball studies with young children. Given the exploratory nature of this study, I just had few general hypotheses: I expected to observe larger pupil dilation responses to noise sounds and to higher pitch deviants compared to the standard sound, but no difference between lower pitch sounds and the standard sound (Liao, Kidani, et al., 2016; Liao, Yoneya, et al., 2016; Wetzel, Buttelmann, et al., 2016).

Furthermore, I collaborated in a tutorial paper on the usage of temporal principal component analysis (tPCA) in developmental research (Scharf et al., 2022). Commonly, ERP data suffer from spatially and temporally imprecise representation of the source activity in the brain, especially during brain maturation in children. Temporal PCA for ERP data aims to provide objective measures for statistical analyses reducing problems due to the enhanced noise level. For more details about this type of analysis, please see Study I.

Table 1: *Overview of the studies conducted in the present thesis.*

Study	Age group(s)	Paradigm	Methods	Aim/Questions	Published
I	32 7-10 yo children 32 adults	Auditory-visual oddball paradigm with emotional and neutral sounds, passive task	EEG Pupillometry	- Investigation of developmental differences in orienting and evaluation processes to unexpected task-irrelevant emotional information -Pupil dilation as an indirect marker of LC activity	yes*
II	57 adults	Auditory -visual oddball paradigm with emotional and neutral sounds, active task	Pupillometry Reaction times Temperament test	- Investigation of effects in distraction related to enhanced arousal evoked by emotional information - Do both effects reflect the same mechanisms?	Under review** (Preprint)
III	57 adults 42 6-8 yo children	Auditory -visual oddball paradigm with emotional and neutral sounds, active task	Pupillometry Reaction times	- Investigation of developmental effects in distraction related to enhanced arousal evoked by emotional information	In preparation
IV	66 adults	Online Auditory -visual oddball paradigm with emotional and neutral sounds, active task	Reaction times Temperament test	- Investigation of effects of distraction related to enhanced arousal evoked by emotional information - Inspection of potential differences in distraction and facilitation effects between laboratory and online experiments	no
V	65 adults	Auditory -visual oddball paradigm with frequency deviants, passive task	Pupillometry	- Investigation of effects of small changes in sound features on pupil dilation - Pupil dilation as a marker of attentional networks in future oddball studies	In preparation
Collaboration	32 7-10 yo children 32 adults	Auditory -visual oddball paradigm with emotional and neutral sounds, passive task	EEG Pupillometry	-Tutorial about how to use Principal Component Analysis on developmental data	yes***

* Bonmassar et al., 2020; **Bonmassar et al., (2021, August 11); ***Scharf et al., 2022

2. Study I: Which steps (early/late P3a, LDN) of involuntary attention will be influenced by auditory emotional novels in elementary school children? Which developmental differences can be observed between children and adults?

The impact of novelty and emotion on attention-related neuronal and pupil responses in children

Text with minor edits corresponds to Bonmassar, C., Widmann, A., & Wetzel, N. (2020). The impact of novelty and emotion on attention-related neuronal and pupil responses in children. *Developmental Cognitive Neuroscience*, *42*(August 2019), 100766. https://doi.org/10.1016/j.dcn.2020.100766. Corresponding author: Carolina Bonmassar. Figures and tables were renamed for the present thesis.

2.1 Introduction

Focused attention can be captured by an unexpected occurrence of new events even if they are not relevant for the task at hand. How attention control develops during childhood and which factors influence attention control, has not been fully researched. The present study aimed to investigate the neuronal basis of the underlying mechanisms for the orientation of attention and the evaluation of task-irrelevant events in middle childhood (7–10 years). Moreover, we focused on the impact of emotional information of novel sounds on attention processes in children. The analysis of emotion and novelty processing and their interaction is highly relevant to understand how children deal with new but unexpected emotional information. We applied a new approach and simultaneously registered EEG and pupil size in order to identify corresponding psychophysiological correlates of attention in the event-related potentials (ERPs) and in changes of the pupil diameter (Pupil Dilation Response; PDR). In children, pupillometry is easier to apply than neurophysiological or imaging techniques. Recent studies linked changes in pupil size to the activity of brain networks and their underlying cognitive functions (Eckstein et al., 2017). Therefore, our study is intended to provide a basis for future studies, focusing on the development of attention control, particularly with clinical and sensitive age groups. Knowledge about the development of attention processes can be used to improve learning environments and task structures, especially in schools (for an example, see (Fisher et al., 2014).

2.1.1 Processing of unexpected and task-irrelevant sounds reflected by ERPs

A number of studies argue that attentional orienting and the further processing of task-irrelevant information can impair performance (distraction effect, for review see Escera, Alho, Schröger, & Winkler, 2000). This has been studied experimentally using versions of the auditory oddball paradigm. Oddball paradigms include a sequence of repeated standard sounds and infrequently, randomly presented oddball sounds that differ in one or more features from standard sounds (Figure 2). On a behavioral level, oddball sounds frequently cause impaired performance in the task at hand in adults (for review see Friedman et al., 2001) and in children (for review see Wetzel & Schröger, 2014). In children, this distraction effect decreases throughout early (until 6 years) and middle childhood (7–10 years, Wetzel, Scharf, & Widmann, 2019). The further maturation of specific underlying neuronal mechanisms during middle and late childhood was described by neurophysiological and imaging studies (Olesen et al., 2007; Wetzel et al., 2006). This is in line with the maturational time course of the brain. It is assumed that distraction effects on a behavioral level are the sum of costs of the orienting of attention towards a new event and benefits of an increase of arousal, caused by the novel event (Masson & Bidet-Caulet, 2019; SanMiguel, Morgan, Klein, Linden, & Escera, 2010; Wetzel et al., 2012). In the EEG, novel oddball sounds evoke a sequence of components in event-related potentials (ERPs) in school age children and adults. In the present study we especially focused on a component of the P3 family occurring around 300ms after a novel sound onset. The two subcomponents of this P3 were labeled as early and late P3a (Escera et al., 1998; Yago et al., 2003) or as P3a and novelty P3 (Barry et al., 2016; Friedman et al., 2001; Masson & Bidet-Caulet, 2019). The P3a wave is assumed to index orienting of attention and enhanced evaluation of oddball stimuli (Alho et al., 1997; Escera et al., 1998; Polich, 2007). The P3a was observed in children and adults for fronto-central brain areas (for review see Wetzel & Schröger, 2014; Polich, 2007). The latency of the P3a decreases with age (Riggins & Scott, 2019) while age-related differences in amplitudes were inconsistently reported (e.g., Čeponiene et al., 2004; Gumenyuk et al., 2004). In addition, we analyzed two other attention-related ERP components: the P2 and the Late Discriminative Negativity (LDN). The P2 component, typically occurring around 200ms (Gajewski et al., 2018) originates mainly from the secondary auditory cortex (Bosnyak et al., 2004; Mahajan & McArthur, 2012) and spreads to fronto-central areas (Ponton et al., 2000). The P2 is associated with early classification processes of stimuli as target and with inhibition mechanisms in order to protect against interference (for review see Crowley & Colrain, 2004). P2 peak latency is not associated with age-related change from childhood to adulthood (for review see, Wunderlich et al., 2006), while age-related effects on amplitudes of the P2 remain inconsistent (Wunderlich et al., 2006). A late negative ERP component, the LDN, has a fronto-central scalp distribution and is elicited by unexpected deviant sounds in children (Čeponienė et al., 2004). Some authors discussed that LDN reflects reorienting of attention after distraction (Čeponiene et al., 2004; Shestakova et al., 2003). Latency and amplitude of the LDN considerably decrease with age (Cheour et al., 2001; Horváth et al., 2009; Putkinen et al., 2012) and there is only a scarce number of reports on the LDN in adults (Cheour et al., 2001).

2.1.2 Processing of emotional unexpected and task-irrelevant sounds reflected by ERPs

The processing of emotional information is very important for humans, even if emotion is task-irrelevant. Humans are sensitive to emotional information and unable to fully ignore affective stimuli (Pessoa, 2005; Vuilleumier et al., 2001; Vuilleumier, 2005). Infants already respond with increased arousal to emotional events within the first 15 months of postnatal life (Geangu et al., 2011; Wetzel, Buttelmann, et al., 2016). In the auditory modality, 7–12-year-old children showed an ERP pattern to emotional speech prosody, that was similar to adults in amplitude and latency but shifted in time (Lindström, Lepistö, Makkonen, & Kujala, 2012). Only a few studies focused on the processing of auditory emotional non-linguistic stimuli and the developmental trajectory has been either fragmentary or inconsistently described in the literature. A recent study observed improvements in the categorization of non-linguistic affective vocal expressions in children aged between 5 and 17 years (Grosbras, Ross, & Belin, 2018), indicating a long-lasting development of emotion processing. In contrast, few other studies reported matured emotional processing until the age of 5–8 years (visual modality, Leventon, Stevens, & Bauer, 2014; Solomon, DeCicco, & Dennis, 2012). We are not aware of auditory oddball studies using environmental emotional oddball sounds with children. There are a few studies with adults that observed increased P3a amplitudes in response to emotional compared to neutral stimuli (Pakarinen et al., 2014; Thierry & Roberts, 2007; Widmann et al., 2018) and increased P2 amplitudes (Masson & Bidet-Caulet, 2019).

2.1.3 Attention networks, the role of the locus coeruleus-norepinephrine system and pupil size

In the following section we introduce the relation between attention networks and the activity of the locus coeruleus-norepinephrine (LC-NE) system and corresponding psychophysiological markers (ERPs and PDR). Attention mechanisms during unexpected events can be described in the context of influential attention models. The neuroanatomical model of attention control by Corbetta and Shulman (2002) describes two separate brain networks involved in top-down selection processes (dorsal frontoparietal network) and in the detection of unattended and behaviorally relevant stimuli (ventral frontoparietal network). When a behavioral relevant distractor occurs, the ventral network interrupts and resets ongoing activity (Corbetta, Patel, & Shulman, 2008). It has been argued that this process is modulated by the LC-NE system which releases norepinephrine over cortical areas (Corbetta et al., 2008). The LC-NE system is also considered part of the visual attention model by Posner (2008), that includes an alerting, orienting, and executive attention network. These networks and their interactions develop considerably between the ages of 6 and 12 years (Pozuelos, Paz-Alonso, Castillo, Fuentes, & Rueda, 2014). Based on the model of orienting response by Sokolov (1963), Näätänen (1992) developed an auditory attention model. This model postulated that the orienting towards unexpected novel stimuli comprises costs of orienting attention and benefits of an increased arousal level (see also, Masson & Bidet-Caulet, 2019; SanMiguel et al., 2010; Wetzel et al., 2012). Increased arousal is related to the LC-NE system (Aston-Jones & Cohen, 2005) and can facilitate several sensory, motor and cognitive processes (e.g., Kahneman, 1973). Task-relevant or motivationally significant stimuli (e.g. novel stimuli) can evoke a phasic activation of the LC-NE system (for review see e.g., Sara & Bouret, 2012). Animal studies (for review see, Aston-Jones & Cohen, 2005; Sara & Bouret, 2012; for an experiment see, Joshi, Li, Kalwani, & Gold, 2016) and recently human studies (Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014) demonstrated that activity in the LC is reflected by phasic changes in pupil diameter. In a visual oddball study, Murphy and colleagues reported a covariation of pupil size with BOLD activity in the LC during the presentation of a visual oddball sequence. In the auditory modality, rare and unexpected sounds caused a pupil dilation (Friedman et al., 1973; Widmann et al., 2018).

Previous studies investigated the influence of the LC-NE system on the attention-related P3a and on pupil dilation (Murphy, Robertson, Balsters, & O'Connell, 2011; for review see, Nieuwenhuis, De Geus, & Aston-Jones, 2011). The authors discuss the hypothesis of communal processes involved in attention due to projections from a medullary pathway. That is, P3a and pupil dilation might be influenced by LC-NE system and share attention related processes, for example in the framework of novelty and emotional information.

Based upon the literature on immature attention control in children, we expected increased amplitudes of attention-related ERP components in response to novel sounds (relative to standard sounds) in children compared to adults (Čeponienė et al., 2004; Ruhnau, Wetzel, Widmann, & Schröger, 2010; Wetzel, 2015). Whether the pupil diameter is sensitive to these age-related changes in middle childhood was an open question as we were not aware of previous similar pupillary studies. Because of the significance of emotional events for humans, we hypothesized increased attentional-related brain activity (P3a, PDR) in response to emotional novel sounds compared to neutral novel sounds (Pakarinen et al., 2014; Thierry & Roberts, 2007; Widmann et al., 2018). Results in the literature were inconsistent and thus it is still an open question whether the impact of emotion on attention is similar for children and adults.

2.2 Materials and Methods:

2.2.1 Participants

65 participants took part in the experiment. One participant was excluded from further analysis because of very high impedance values (>50 kΩ). The data of 32 healthy children (M_{age} = 8;10 (years;months), range 7;4-10;3, 15 females, 3 left-handed) and 32 healthy adults (M_{age} = 26;6 years, range 18–36;4, 17 females, 3 left-handed) were used in the study. Participation was rewarded by a voucher for a local toy shop and a certificate (children, 7€/hour) or by money (adults, 7€/hour). All participants gave written consent (both children, parents and adults). Participants confirmed a normal or corrected-to-normal vision, no medication with effects on the nervous system, and no history of attention-related disorders. Handedness was measured with a shortened German version of the Oldfield Handedness Inventory (Oldfield, 1971). The project was approved by the local ethical committee.

2.2.2 Stimuli

Auditory stimuli. A total of 56 environmental sounds were collected from the database of a previous study (Max, Widmann, Kotz, Schröger, & Wetzel, 2015). This database consisted of a set of 210 auditory stimuli, collected from the International Affective Digitized Sounds study (IADS, Bradley & Laeng, 2007), by Hasting, Wassiliwizky, and Kotz (2010), and from other data bases as described by Max et al. (2015). In the study by Max and colleagues, the novel sounds had been rated on a 9-point scale for valence (1 = unpleasant — 5 = neutral — 9 = pleasant) and arousal (1 = calm — 9 = arousing).

In the present study, sounds were allocated to two categories: 28 high arousing negative sounds ($M_{valence}$ = 2.64; $M_{arousal}$ = 6.60, for example an ambulance siren or a crying baby) and 28 moderately arousing neutral sounds ($M_{valence}$ = 5.28; $M_{arousal}$ = 4.77, for example chinking coins or toasting glasses). An independent samples t-test was performed revealing that sound categories significantly differed in valence ($t(54) = -19.86$, $p < .001$) and arousal ($t(54) = 16.11$, $p < .001$). The complex standard sound was comprised of sinusoids with a fundamental frequency of 500 Hz including the second and third harmonic attenuated by -3 and -6 dB, respectively. Sounds had a duration of 500 ms including faded ends of 5 ms. They were presented at a loudness of 66.5 dB SPL (measured with PAA3 PHONIC Handheld audio analyzer, Phonic Corporation, Taipei, Taiwan). Loudness of sounds was equalized with root mean square normalization.

Visual stimuli. To draw attention away from sounds the same silent animated cartoon was presented to all participants. The cartoon dealt with the story of a sheep's adventures in a city. The cartoon was played continuously while the four sound blocks were presented. Thus, the cartoon was not repeated for every block and systematic effects of the video presentation on auditory processing were prevented. The video was displayed at the center of a screen with a size of 20 cm wide and 10.8 cm high (18.9° x 10.3° visual angle) on a grey background screen with a mean luminance of 2.9 cd/m2. The mean luminance of the movie was 53.1 cd/m2.

Apparatus and Software. The auditory stimuli were presented via loudspeakers (Bose Companion 2 series III Multimedia speaker system) located at the left and the right of the screen. The visual stimuli were presented on a 23,6 inch VIEWPixx/EEG display (VPixx Technologies Inc.) with a resolution of 1920 (H) x 1080 (V) and a refresh rate of 120 Hz. The distance from the participants eyes to the screen was approximately 60 cm. The experimental stimulation was presented via Psychtoolbox (Version 3.0.15, Kleiner, Brainard, Pelli, Ingling, Murray, & Broussard , 2007) using Octave (Linux, Version 4.0.0).

2.2.3 Procedure

Participants were instructed to focus on a silent video clip and to ignore the presented oddball sound sequence, including unpleasant emotional and neutral novel sounds. No further task was performed during the experiment. Participants sat on a recliner chair in an acoustically attenuated and electromagnetically shielded cabin. Illuminance in the cabin was held constant at a level of 61.1 lx (measured with MAVOLUX 5032B USB, GOSSEN Foto- and

Lichtmesstechnik GmbH, Nürnberg, Germany). Each of the four blocks started with a five-point eye-tracker calibration and validation procedure. A total of 280 sounds were presented per block with a randomized stimulus onset asynchrony (SOA, varying from 1800 to 2080 with 40 ms steps). In one block, 80% of the trials consisted of a standard sound (224) and 20% of a novel sound (56; Figure 2). Half of the novel sounds were emotional sounds (28) and half were neutral sounds (28). The sound sequence was pseudo-randomized and unique for each participant. This ensures that changes in brightness in the video clip do not systematically vary with sound types. Each novel was followed by at least two standard sounds. A total of 896 standard sounds and 224 novel sounds (112 emotional, 112 neutral) were presented during the session. Each novel was repeated 4 times in total (once per block). Each block lasted 9 minutes.

Figure 2: Sound sequence. Participants were instructed to ignore the oddball sound sequence and to focus on a silent video clip. Environmental sounds (EMO = emotional novel sounds; NEUTR = neutral novel sounds) were pseudo-randomly presented within a sequence of repeated standard sounds (STA). Example of novel sounds are illustrated in the trial structure (chinking coins, a crying baby, a siren, toasting glasses, etc.). A total of 56 different novel sounds were presented with a randomized stimulus-onset asynchrony of 1800-2080ms. Sounds were not relevant for the task (watching a video clip), but novel sounds were expected to capture attention.

2.2.4 EEG and Pupil Data recording

The electroencephalogram (EEG) was recorded at a sampling rate of 500 Hz from a 31 channel ActiChamp amplifier and a 31 active electrode Braincap (Brain Products GmbH, Gilching, Germany). The electrodes were placed according to the extended 10-20 system: Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, Oz, and at the left (M1) and right (M2) mastoids. Three electrodes recording the horizontal and vertical electrooculogram (EOG) were positioned to the left and right of the outer canthi of the eyes and below the left eye. The reference electrode was placed at the tip of the nose.

The pupil diameter of both eyes was recorded with an infrared EyeLink Portable Duo eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada). The eye tracking was set up in remote mode at a sampling rate of 500 Hz.

2.2.5 Data analyses

The first two standard trials per block and the two standard trials immediately following a deviant sound were removed from further analysis, because they could be affected by previous novel sound processing (Wetzel, 2015). Only corresponding identical trials from both ERP and pupil data were analyzed. That is, trials excluded from any, pupil or EEG data, were excluded from both types of analyses.

2.2.5.1 EEG data processing

EEG data analysis was implemented with MATLAB software and the EEGLAB toolbox (Delorme & Makeig, 2004). The signal was filtered offline with a 0.1 Hz high-pass filter (Hamming windowed sinc FIR filter, order = 8250, transition band width = 0.2 Hz) and a 40 Hz lowpass filter (Hamming windowed sinc FIR filter, order = 166, transition band width = 10 Hz, (Widmann et al., 2015; Widmann & Schröger, 2012). The data were segmented into epochs of 1 s duration including a 0.2 s pre-stimulus baseline. The raw data was filtered with a 1 Hz high-pass filter (Hamming windowed sinc FIR filter, order=8250, transition band width=0.2 Hz) and 40 Hz lowpass filter. Independent component analysis (ICA) was applied on the filtered (1 Hz) raw data. Data were segmented in epochs with the same duration as the 0.1–40 Hz filtered data but not baseline corrected (Groppe et al., 2009). As suggested by Winkler et al. (2015), the obtained demixing matrix was applied to the 0.1–40 Hz filtered data. ICA components were classified by the ICLabel EEGLAB plug-in for automatic independent component (IC) classification, manually selected and pruned (Pion-Tonachini et al., 2019). Component rejection was restricted to typical eye ICA components, i.e. blinks, horizontal and vertical pre-saccadic spike potential, horizontal and vertical movements of the corneo-retinal dipole and blink/eyelid induced artifacts. On average 4.7 components per subject were eliminated (16% of the total number of ICA components were rejected). Subsequently, trials with amplitude differences exceeding 150 µV were excluded from the analysis. Individual average ERPs were computed per participant and sound type. Grand-average waveforms were computed on the basis of individual averages (the number of included trials per condition and the mean of the ratio of excluded trials due to artifacts is described in the Supplementary Material, Table S 1).

2.2.5.2 Pupil data processing

Eye tracker pupil diameter digital counts were calibrated using the method suggested by Marchak and Steinhauer (2011) and converted to mm. Blinks and saccades were marked by the provided eye tracker event markers. Since partial blinks are not reported by the eye-tracker, an additional function was programmed, detecting those blinks from the smoothed velocity times series, i.e. pupil diameter changes exceeding 20 mm/s including a 50 ms pre-blink and a 100 ms post-blink interval were removed from further analysis (Merritt et al., 1994). Segmented data epochs of 2 s duration (including a 0.2 s pre-stimulus baseline) were baseline corrected by subtracting the mean amplitude of the baseline period from each epoch (Murphy et al., 2014; Widmann et al., 2018). Trials where at least one eye was closed or not recorded throughout the complete trial and data during blinks were excluded from averaging. Individual average PDRs were computed per participant and sound type from the mean of both eyes.

2.2.6 Statistical analysis

2.2.6.1 Principal Component Analyses (PCA)

Traditional ERP analyses suffer from two major, partly related problems: the relatively arbitrary definition of analysis time windows and the overlap of ERP components considerably biasing estimates of amplitude, latency, and location. We therefore applied a temporal PCA analysis (PCA, ERP PCA Toolkit MATLAB toolbox by Dien, 2010) to our data aiming (a) to identify the constituent components of the ERP and (b) provide dependent measures of these components for inferential testing to solve these problems (Dien, 2012). PCA belongs to the class of factor-analytic procedures using eigenvalue decomposition to extract linear combinations of variables (latent factors) accounting for patterns of covariance observed in the data, presumably due to ERP components (Dien & Frishkoff, 2005).

Temporal PCA results in a set of component loadings and a set of component scores. Component loadings reflect the strength of the association (correlation) of each variable (here time point) with each underlying factor and describe the time course of the components in temporal PCA. The component scores reflect the standardized weight with which each factor contributed to the observation, that is, combination of participant, condition, and electrode. Typically, components are sorted by the amount of variance they explain. Component loadings are frequently scaled by the standard deviation (SD) per variable (time point) to reflect real world units (here µV) and illustrate their relative amplitudes. Importantly, if the SD-scaled component loading vector (time course) is multiplied by the component score of an observation the result directly reflects the contribution of the component to the observed signal in µV units (see Dien, 1998, Appendix for a formal proof and Dien, 2012, for an accessible explanation). That is, the observed signal can be reconstructed as the sum of SD-scaled component loadings multiplied by component scores per observation.

PCA is particularly recommended for developmental populations reducing problems due to the enhanced noise level (Dien, 2012). In line with our study, recent studies on children used the temporal PCA (Kujawa et al., 2013; Speed et al., 2016). Other ERP-studies with adults report usage of temporal PCA (Foti et al., 2009; Kamp & Donchin, 2015; Widmann et al., 2018).

PCA was computed using Geomin rotation with $\varepsilon = 0.5$ (Scharf & Nestler, 2019), covariance relationship matrix and no weighting. The PCA analysis was conducted on the individual averages for all EEG channels (selection of electrodes or regions of interest for inferential analysis is a commonly applied procedure in temporal PCA, Hsu et al., 2014) and stimulus types (standard, emotional novel sound, neutral novel sound) separately for each group, because the component structure in the EEG differed between children and adults (for example the absence of a characteristic N1 component in children, see Wetzel et al., 2011). The number of components was determined using Horn's parallel test. A total of 13 components were extracted from the ERPs in the adult group and 16 components from the ERPs of the children group. We focused our analyses on four components of interest, P2, early and late P3a, and LDN, related to inhibition or (re-) orienting of attention based on previous literature (Čeponienė et al., 2004; Escera et al., 2000; Wunderlich et al., 2006). We identified the respective components based on the typical time course and topography in the children's and adults' PCA. For analysis the following electrodes were selected on the basis of the literature where available (Čeponienė et al., 2004; Escera et al., 2000; Ruhnau et al., 2010; Wunderlich et al., 2006) and on the component peak across conditions otherwise: Cz (P2), Cz (eP3a), Fz (lP3a) and F4 (LDN). For an overview on the peak latencies and electrodes of components as well as the explained variance of the extracted components, see Supporting Material (Table S 2).

We additionally analyzed component latencies as proposed in previous studies (Kiesel et al., 2008). We computed individual jack-knifing estimates for the component latencies separately for each group using an 80%-relative peak amplitude criterion (Kiesel et al., 2008). In both groups the PCA was recomputed from 32 data subsamples leaving one subject out in each run. In each run the component loading (scaled by SD) corresponding to the components of interest was identified and the latency of the time point when the amplitude reached 80% of the peak amplitude was measured. An 80%-relative peak amplitude criterion was chosen as relative latency estimates have been shown to be less noisy than peak latency estimates using the jack-knifing technique (for detailed discussion see Kiesel et al., 2008). Individual latencies were retrieved from the subsample scores as suggested by Smulders (Smulders, 2010; Equation 1) to account for the reduced variance in the estimates due to the jack-knifing technique (equivalent to the adjustment of t/F-values suggested by Kiesel et al., 2008, Equation 1; the retrieval of individual latencies allowed straight-forward computation of Bayesian t-tests). The mean of the individual latencies was compared between groups using independent (Bayesian) t-tests.

The PDR revealed a biphasic pattern. The PCA was computed with the same parameters as for the ERPs but not separated by group (as the decompositions for both groups were highly similar if computed separately; see also Wetzel et al., 2016). Two components were extracted. The early peak presumably reflects the inhibition of the parasympathetic system (iris sphincter muscle relaxation) and the later peak presumably reflects the activation of the sympathetic system (iris dilator muscle contraction, Widmann et al., 2018).

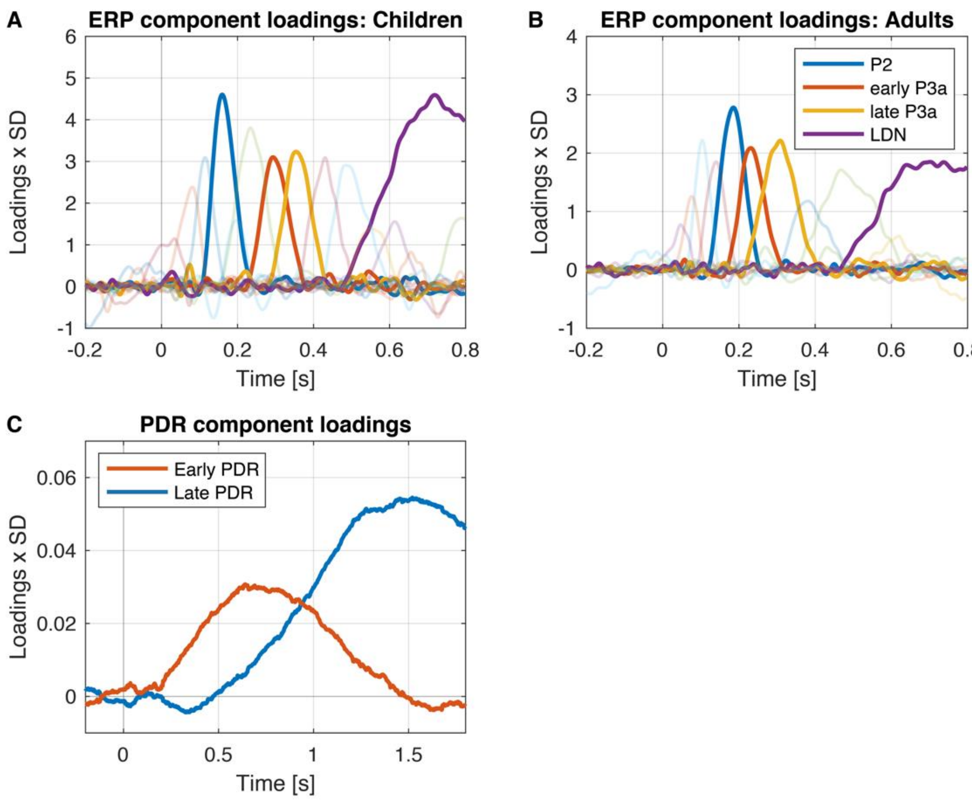

Figure 3: Scaled PCA component time courses (loadings * SD; µV) for ERPs (children Panel A, adults Panel B) and for PDR (both groups together, Panel C). Component loadings reflect the correlation of the variable (here time point) with the component (or factor). Component loadings do not reflect the

amplitudes of the components. The scaling of the component loadings by the standard deviation illustrates the relative contribution of each component to the observed signal. Panel A and B: The amplitudes differences in the scaled loadings between age groups reflect the differences in variability across subjects, electrodes, and conditions between groups. The components of interest for children and adults are highlighted.

2.2.6.2 Frequentist and Bayesian analyses

Statistical analysis was conducted using the software JASP (Version 0.9.1; JASP Team, 2017). As the PCA on the ERPs had to be computed separately for children and adults it was not possible to directly compare component scores between groups. We therefore computed component time courses per component, participant, electrode location, and condition by multiplying the component loading by the SD and by the component score. The resulting time course reflects the portion of the recorded waveform accounted for by each component scaled to µV (see Dien, 1998, for a proof), that is, comparable between the separate children and adult group PCA decompositions. The statistical analyses were based on the mean amplitude of this time course in the time window around the peak (+/- 20ms) of every temporal component (in the component loadings). ERP difference amplitudes were obtained by subtracting the standard-related-ERP mean amplitude from the novel-related-ERP mean amplitude (Escera et al., 2000). For statistical tests of the difference amplitudes see Supplementary Material,Table S 3.

ERP difference amplitudes were analyzed using Frequentist and Bayesian repeated measures ANOVAs with the within subject factor emotion (emotional negative novel vs. neutral novel) and between subject factor group (children vs. adults). For the frequentist ANOVA an alpha-level of .05 was defined for all statistical tests and the η^2 effect size measure is reported.

Bayes factors (BF_{10} and BF_{Incl} or “Baws Factor”, Mathôt, 2017) were estimated using 50,000 Monte-Carlo sampling iterations and a scaling factor r = 0.5 for fixed effects (corresponding to the default “medium” effect size prior for fixed effects in the R Bayes-Factor package, Morey, 2015) and r = 1 for the participant random effect (default “nuisance” prior for random effects in the R Bayes-Factor package). Data were interpreted as moderate evidence in favor of the alternative (or null) hypothesis if BF_{10} was larger than 3 (or lower than 0.33), or strong evidence if BF_{10} was larger than 10 (lower than 0.1, Lee & Wagenmakers, 2013). BF_{10} between 0.33 and 3 are considered as weak evidence ("anecdotal evidence“ following Lee and Wagenmakers, 2013). Interaction of factors were analysed using follow up ANOVAs (if more than three factors included) and t-tests (if two factors included; two-sided).

The pupil data were analyzed using Frequentist and Bayesian repeated measures ANOVAs with the within subject factors emotion (emotional negative novel vs. neutral novel) and components (early component vs. late component) and between subject factor group (children vs. adults). The ANOVA was calculated directly on the PCA component scores (i.e., not re-scaled by SD and loadings as for the ERPs as we calculated the PCA on both groups together; see above).

2.3 Results

The analyses were based on the difference amplitudes (novel-related-ERP mean amplitude minus standard-related-ERP mean amplitude, Escera et al., 2000) of the components P2, early and late P3a and LDN observed in both groups. A N2 component was pronounced only in children and was not included in the analysis (Figure 3Figure 4,Figure 5 andFigure 6).

2.3.1 ERPs

Early P3a

Early P3a peak latency was 230 ms in adults and 294 ms in children. The 80%-relative peak latency of the early P3a components was significantly longer in children than in adults (275 vs. 211 ms; $t(62) = 3.592$, $p < .001$; $BF_{10} = 44.381$). Early P3a was maximal over the vertex (Cz electrode) in both groups. The analysis of early P3a showed a main effect of the factor emotion ($F(1,62) = 17.833$, $p <.001$, $\eta^2 =.215$), resulting from larger amplitudes in response to emotionally negative novel sounds, compared to neutral novel sounds. A main effect group ($F(1,62) = 10.95$, $p = .002$, $\eta^2 = .150$) results from larger amplitudes in children compared to adults. No interaction of the factors emotion x group was observed ($F(1,62) = 2.941$, $p = .091$, $\eta^2 = .036$). The Bayesian analysis provided strong evidence for the model including the main effects of emotion and group ($BF_{10} = 4411.044$). The data do not provide conclusive evidence for or against an interaction effect of the factors emotion and group ($BF_{Incl} = 0.858$).

Late P3a

Late P3a peak latency was 308 ms in adults and 354 ms in children. The 80%-relative peak latency of the late P3a components was significantly longer in children than in adults (333 vs. 277 ms; $t(62) = 4.037$, $p <.001$; $BF_{10} = 155.082$). Late P3a was maximal over fronto-central electrode sites in both groups. The analysis of late P3a showed a main effect of the factor emotion ($F(1,62) = 9.369$, $p = .003$, $\eta^2 = .131$) resulting from larger amplitudes in response to emotionally negative novel sounds compared to neutral novel sounds. A main effect group

(F(1,62) = 6.732, p = .012, η^2 = .098) results from larger amplitudes in children compared to adults. No interaction of the factors emotion x group was observed (F(1,62) = 0.173, p = .679, η^2 = .002). The Bayesian analysis provided strong evidence for the model, including the main effects of emotion and group (BF_{10} = 46.769). The data provide moderate evidence against an interaction effect of the factors emotion and group (BF_{Incl} = 0.282).

P2

P2 peak latency was 186 ms in adults and 160 ms in children. P2 80%-relative peak latency was not significantly different between children and adults (142 vs. 163 ms; t(62) = -0.656, p = .514; BF_{10} = 0.307). P2 was maximal over the vertex (Cz electrode) in both groups. The analysis of P2 showed a main effect of the factor emotion (F(1,62) = 31.583, p < .001, η^2 = .335) resulting from larger amplitudes in response to emotionally negative novel sounds, compared to neutral novel sounds in both age groups. A main effect group (F(1,62) = 45.85, p < .001, η^2 = .425) results from increased amplitudes in children, compared to adults. No interaction of the factors emotion x group was observed (F(1,62) = 0.664, p = .418, η^2 = .007). The Bayesian analysis provided strong evidence for the model including the main effects of emotion and group (BF_{10} = 3.964x1010). The data provide weak evidence against an interaction effect of the factors emotion and group (BF_{Incl} = 0.349).

LDN

LDN peak latency was 702 ms in adults and 718 ms in children. LDN 80%-relative peak latency was not significantly different between children and adults (643 vs. 607 ms; t(62) = 0.174, p = .863; BF_{10} = 0.259). LDN was maximal over right frontal electrode sites (F4 electrode) in both groups. A main effect group (F(1,62) = 9.030, p = .004, η^2 = .127) was observed showing larger amplitudes in children, compared to adults. The LDN was not affected by emotion (F(1,62) = 0.791, p = .377, η^2 = .013). No interaction of the factors emotion x group was observed (F(1,62) = .001, p = .971, η^2= .000). The Bayesian analysis provided strong evidence for the model including the main effect group (BF_{10} = 10.267). The data provide weak evidence against a main effect of the factor emotion (BF_{Incl} = 0.390) and moderate evidence against an interaction effect of the factors emotion x group (BF_{Incl} = 0.177).

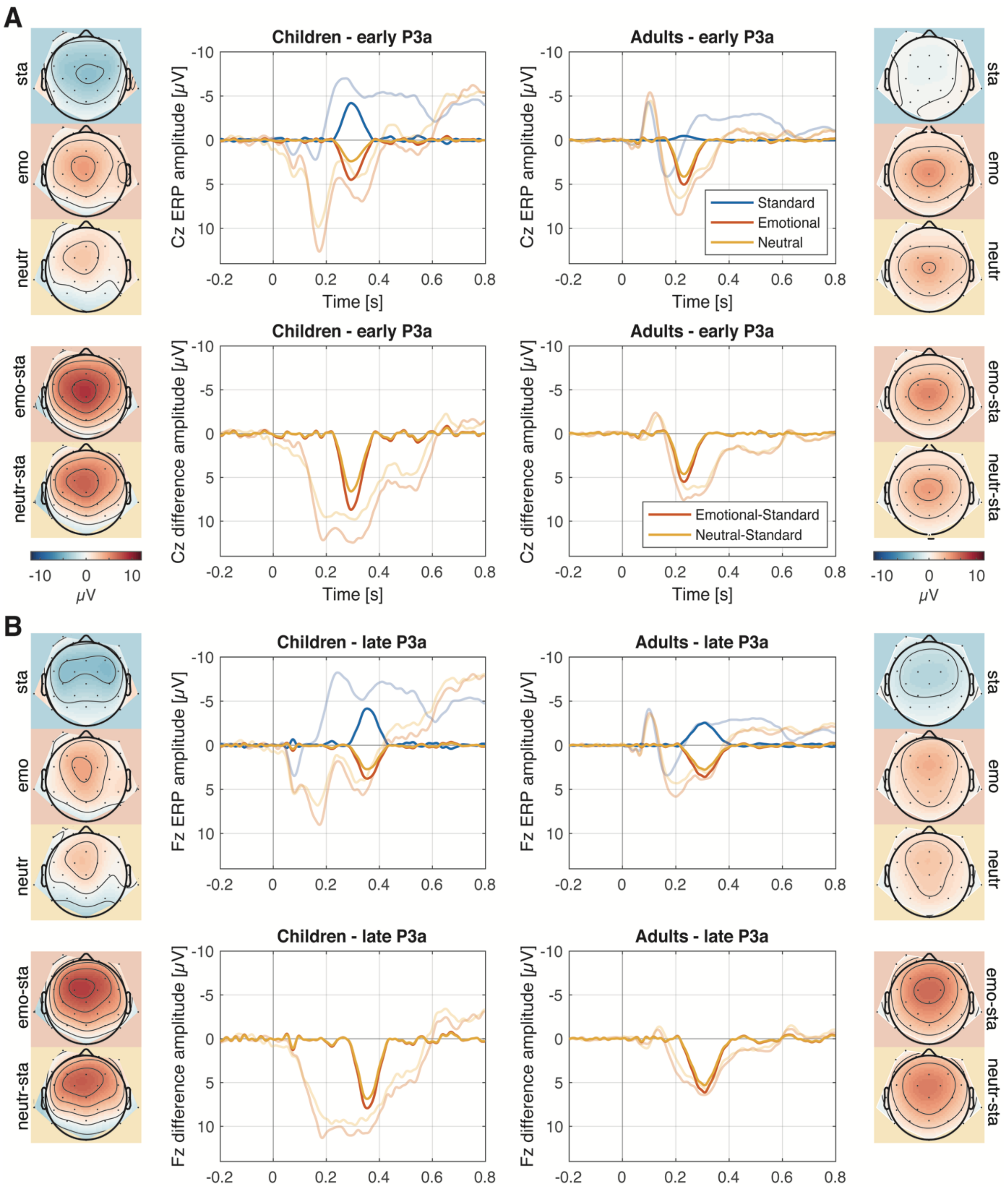

Figure 4: Panel A and B: PCA components (strong color) for the ERP components early P3a (A) and late P3a (B). The corresponding grand-averages at the specific electrode location are shown in transparent colors. The upper row of each Panel displays PCA components and ERPs evoked by standard sounds, emotional novel sounds, and neutral novel sounds. The lower row of each Panel displays the PCA components and ERPs of the difference waves of emotional novel minus standard and neutral novel minus standard. Topographies display the scalp distribution of the PCA components, on the left (children) and on the right (adults). Abbreviations at the side of the topographies indicate standard (sta), emotional (emo), neutral (neutr), and the difference waves emotional minus standard (emo-sta) and neutral minus standard (neutr-sta). Novel sounds evoked statistically significantly increased early and late P3a amplitudes in children than in adults. Emotional novel sounds statistically significantly evoked larger early and late P3a amplitudes than neutral novel sounds in both age groups.

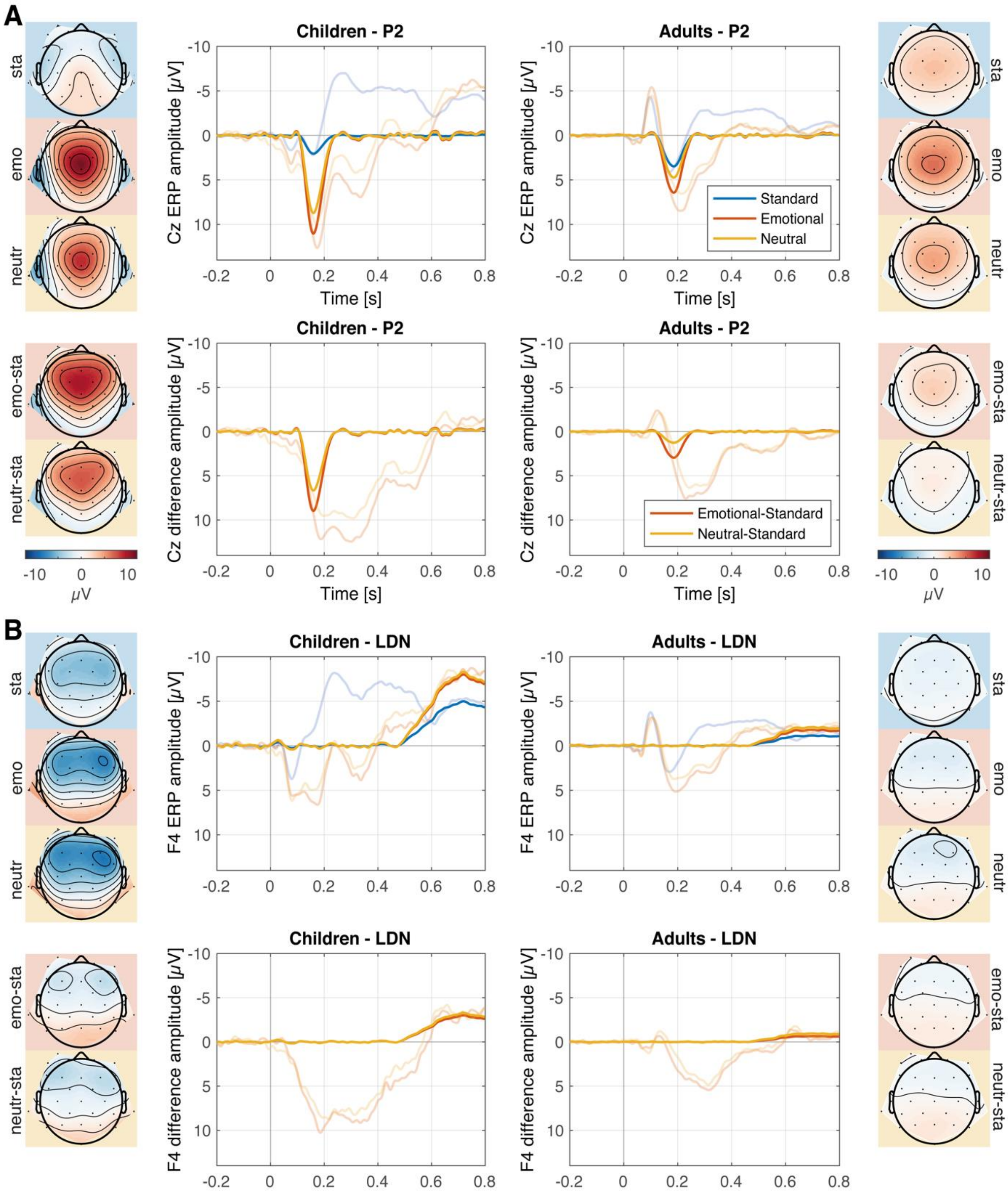

Figure 5: Panel A and B: PCA components (strong color) for the ERP components P2 (A) and LDN (B). The corresponding grand-averages at the specific electrode location are shown in transparent colors. The upper row of each Panel displays PCA components and ERPs evoked by standard sounds, emotional novel sounds, and neutral novel sounds. The lower row of each Panel displays the PCA components and ERPs of the difference waves of emotional novel minus standard and neutral novel minus standard. Topographies display the scalp distribution of the PCA components, on the left (children) and on the right (adults). Abbreviations at the side of the topographies indicate standard (sta), emotional (emo), neutral (neutr), and the difference waves emotional minus standard (diff-emo) and neutral minus standard (diff-neutr). Novel sounds evoked statistically significantly increased P2 amplitudes in children than in adults but not in the LDN. Emotional novel sounds statistically

significantly evoked larger P2 amplitudes than neutral novel sounds in both age groups but not in the LDN.

2.3.2 Pupil diameter

Pupil dilation response

The biphasic PDR to novel sounds was modulated by emotion and group (Figure 6). The early PDR peak latency was 640 ms while the late PDR peak latency was 1520 ms in both age groups. The analysis showed a main effect of the factor emotion ($F(1,62) = 15.454$, $p < .001$, $\eta^2 = .198$), resulting from larger pupil dilation in response to emotionally negative novel sounds, compared to neutral novel sounds. A main effect component ($F(1,62) = 1.789$, $p = .186$, $\eta^2 = .028$) was not observed. A main effect group ($F(1,62) = 7.036$, $p = .010$, $\eta^2 = .102$) results from larger pupil dilation in adults compared to children. No interaction of the factors emotion x group was observed ($F(1,62) = 0.470$, $p = .495$, $\eta^2 = .006$). A significant interaction of the factors emotion x component was observed ($F(1,62) = 11.651$, $p = .001$, $\eta^2 = .157$) resulting from larger pupil response for emotional novel sounds compared to neutral novel sound for the late ($t(62) = 5.798$, $p < .001$) but not for the early PDR component ($t(62) = 1.140$, $p = .259$). No interaction of the factors component x group was observed ($F(1,62) < 0.001$, $p = .997$, $\eta^2 < .001$).

The Bayesian analysis revealed strong evidence for the model including the main effects emotion, component, group, and the interaction of the factors emotion and component ($BF_{10} = 326.562$). The main effect component was not interpreted as the component scores are scaled differently and the factor was only included in the ANOVA to examine potential interaction effects. The data provide strong evidence for increased PDR amplitudes in response to emotional novel sounds, compared to neutral novel sounds on the late PDR component (Bayesian follow-up t-test emotional vs. neutral: $BF_{10} = 61242.266$) and moderate evidence against an effect of emotion on the early PDR component ($BF_{10} = 0.254$). The data provide moderate evidence against an interaction effect of emotion and group ($BF_{Incl} = 0.211$) and an interaction effect of component and group ($BF_{Incl} = 0.195$) and the three-way interaction of emotion, component and group ($BF_{Incl} = 0.378$).

Baseline mean pupil diameter

The observed baseline mean pupil diameter was 4.17 mm in the adult and 5.39 mm in the children group.

To separate growth-related differences in baseline pupil size from differences evoked by excitation, we estimated the expected baseline pupil diameter per participant, applying the implemented "Unified" model for light adapted pupil size (for details see Supplementary Material Part 1, (Wheatley & Spitschan, 2018). While the expected baseline pupil was similar in children and adults, analysis indicated a significant difference between the expected and the observed baseline pupil in the children group only (for details see Supplementary Material Part 1).

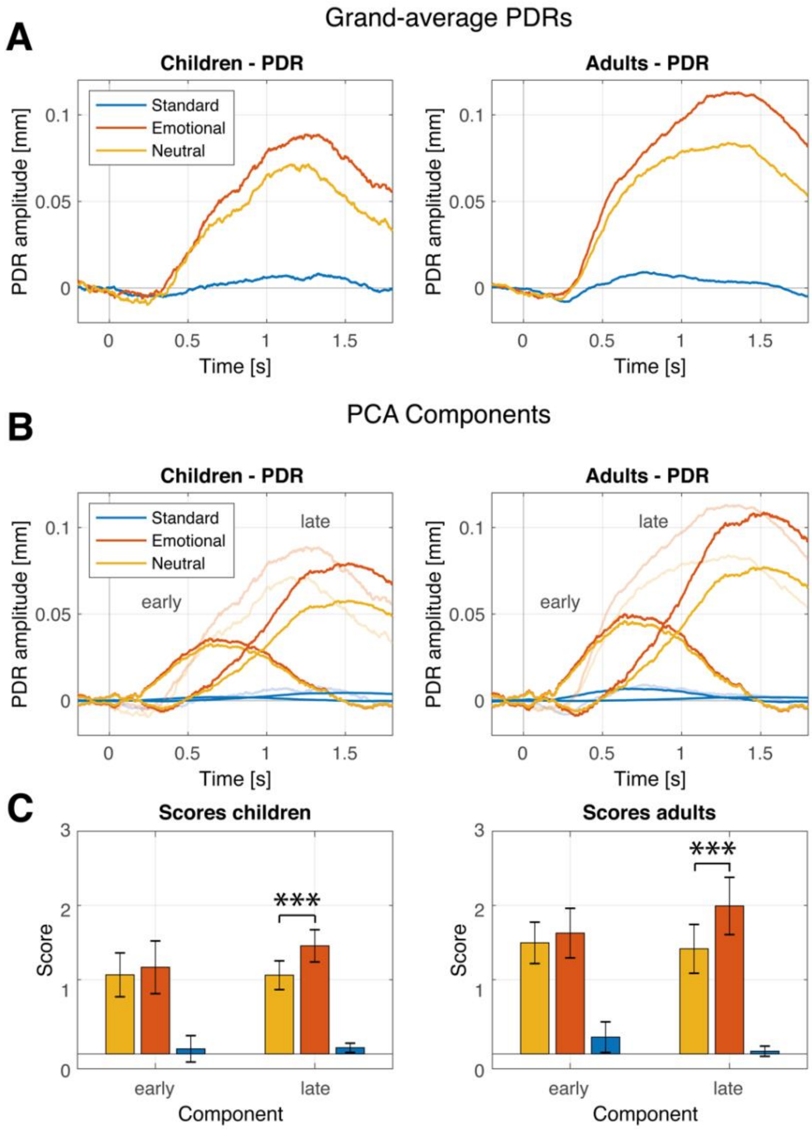

Figure 6: Panel A: Grand-average pupil dilation responses (PDRs) for emotional novel sounds, neutral novel sounds, and standard sounds for each age group. Novel sounds evoked statistically significantly increased PDRs compared to standard sounds in both groups. Panel B: Mean reconstructed component time courses (component loadings scaled by standard deviation (SD) and component scores per condition and age group; strong colors; mm) reflecting the portion of the recorded waveform accounted for by each component. The chronologically later component explains most variance and is discussed to reflect the activity of the sympathetic pathway of the autonomic nervous system. The earlier component is considered to reflect the activity of the parasympathetic pathway of the autonomic nervous system. The grand-average PDRs (transparent colors) were added for reasons of convenience and are identical to Panel A. Panel C displays mean PCA component scores (error bars

show the 95% confidence interval) that reflect the amplitudes for each sound type and group. Emotional novel sounds elicited statistically significantly increased amplitude for the late component only. Note. ***p <.001 (t-test).

2.4 Discussion

Task-irrelevant environmental novel sounds were presented in an oddball paradigm to 7–10-year-old children and adults while participants watched a silent video. Attention-related brain activity (EEG) and pupil dilation responses (PDR) were measured. Novel sounds per se and the emotional content of novel sounds caused increased amplitudes of attention-related ERPs (except for LDN in adults) and increased pupil diameter in both age groups (see Supplementary Material, Table S 3). Results indicate enhanced processing of novel sounds that increased further when novel sounds contained emotional information.

Novel sounds evoked a characteristic pattern of ERP components containing P2, early and late P3a, and LDN, that have been associated with attention. These components were observed in the ERP difference waves computed from novel-ERPs minus standard-ERPs, which demonstrate different processing of novel sounds in relation to standard sounds. As these components partly overlap with each other we performed a PCA to separate components (Supplementary Material, Table S 2). The PCA analysis revealed a structure of components that was not identical (for example an N2 component was pronounced in children only) but highly similar in children and adults. The temporal PCA could clearly classify and separate different components in time, therefore the selection of the components of interest for our study was fairly straightforward. This is a sustainable basis for comparing mechanisms associated to these components between age groups. In addition, two components in the pupil signal were extracted that were affected differently by the sounds' novelty and emotional information.

2.4.1 Age effects on enhanced attention in response to novelty and emotion

Unexpected novel sounds and their emotional content caused pronounced ERP and PDR responses. On EEG level, both early and late P3a were observed in children and adults. Latencies were increased for both P3a components by 64 ms (early) and 46 ms (late) in children compared to adults, indicating slower attention processes in children. Amplitudes of the early and late P3a (difference wave novel-minus-standard) were increased in children compared to adults. Following the interpretation that P3a reflects orienting and evaluation (Escera et al., 2000), our results indicate immaturity of these processes in the presence of novel sounds in middle childhood. This interpretation is in line with previous findings on the long-lasting developmental trajectory of attention control, observed on a neuronal and behavioral level in the auditory modality (Horváth et al., 2009; Huotilainen et al., 2008; Ruhnau et al., 2010; Wetzel, 2015).

Emotional, compared to neutral, novel sounds evoked increased amplitudes of both P3a components, indicating enhanced attentional processing of emotional novel sounds. Results are in line with recent studies with adults reporting increased P3a amplitudes in response to emotional compared to neutral stimuli (Pakarinen et al., 2014; Thierry & Roberts, 2007; Widmann et al., 2018, but see, Czigler et al., 2007, who did not find an emotion effect). The orienting of attention towards emotional novel sounds and their enhanced evaluation was comparable between age groups. This indicates an advanced level of maturation of the involved emotion-related neuronal mechanism. These results are in line with findings that reported an early development of emotional processing until middle childhood (Leventon et al., 2014; Solomon et al., 2012).

In addition, novel sounds evoked a large transient pupil dilation compared to standard sounds in both age groups. Such transient changes in pupil size in response to oddball stimuli are related to the activity of the LC-NE system (Murphy et al., 2014). It has been shown in a fMRI study with adults that the novelty of visual oddball stimuli increased the activity in the LC (Krebs, Park, Bombeke, & Boehler, 2018). The authors concluded that the noradrenergic system gives high priority to novel information. The significance of novelty for the LC-NE system was confirmed in a number of animal studies (Hervé-Minvielle & Sara, 1995; Larsen & Waters, 2018). The noradrenergic system is involved also in the processing of emotion (Berridge & Waterhouse, 2003; Nieuwenhuis et al., 2011; Ranganath & Rainer, 2003; Sara & Bouret, 2012). In line with these findings we observed increased PDR in response to emotional novel sounds. The sensitivity of the pupil to emotionally highly arousing pictures is long known (Hess & Polt, 1960) and was also observed in infants in response to the cry of a peer (Geangu et al., 2011; Wetzel, Schröger, & Widmann, 2016). Novel sounds in the present study evoked a biphasic waveform that was separated by the PCA in two components. Steinhauer and Hakerem (1992) hypothesized that the two components might reflect the activity of the parasympathetic and the sympathetic pathways of the autonomic nervous system. They assumed that the chronologically early component reflects the inhibition of the parasympathetically controlled sphincter muscle and that the later component controlled the activation of the sympathetically innervated dilator muscle. As these muscles operate antagonistically, both result in pupil dilation. This hypothesis has been recently experimentally tested and results supported the hypothesis (see also, Bradley et al., 2008; Wetzel et al., 2016; Widmann et al., 2018). Therefore, the observed two components can be interpreted as indicators of the parasympathetic and the sympathetic activity of the autonomic nervous system (ANS). The emotional content of novel sounds further increased pupil diameter, but only for the later component. These findings are in line with recent studies with adults in the auditory and visual modality (Bradley et al., 2008; Widmann et al., 2018) and indicate that emotional arousal is reflected by the activity of the sympathetic nervous system (SNS). As suggested by Nieuwenhuis et al. (2011) and Murphy et al. (2011), the observed concurrent activation of P3a and the sympathetic component of the PDR supports the hypothesis of shared processes involved in attention due to projections from a common medullary pathway (Murphy et al., 2011; for review see, Nieuwenhuis et al., 2011).

As PDR components did not differ between children and adults, this concurrent activation in response to emotionally arousing sounds is suggested to function on a similar level in both age groups. In a previous study with infants, age effects in the interaction of both pathways of the ANS in response to highly arousing novel sounds were reported, indicating ongoing development (Wetzel et al., 2016). Even if the experimental details differ between the study by Wetzel et al. (2016) and our study, the lack of age differences in response to emotional novel sounds assumes a maturation of the underlying mechanisms during early childhood that has reached an advanced level in middle childhood.

The mean phasic pupil dilation response was reduced in children compared to adults. These unexpectedly reduced PDR amplitudes are not in line with the increased amplitudes in novel-related ERPs in children. A potential explanation for the observed differences between children and adults might be provided by systematic differences in tonic arousal. Decreasing phasic responses are expected with increasing tonic arousal and LC activity (Aston-Jones & Cohen, 2005; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Kamp & Donchin, 2015). Additionally, higher tonic activity is reflected in larger baseline pupil diameters, limiting the dynamic range for pupil dilation (see e.g., Widmann et al., 2018, reporting larger PDRs in moderate compared to dark lighting conditions, note, in darkness the baseline pupil size is increased). We therefore tested for systematic differences in baseline pupil diameter between age groups. In fact, the observed baseline pupil diameter was considerably larger in children than in adults (by 29%) and also considerably larger than predicted by a model considering age, luminance, and field of view (Watson & Yellott, 2012). The pupil size changes with age, following a U-shape with a maximal peak around 15-20 years (MacLachlan & Howland, 2002; Wilhelm, 2011). The model predicts almost identical mean pupil diameters due to the visual stimulation for both age groups (see Supplementary Material Part 1). While the predicted baseline pupil size was very precise in adults, children's observed baseline was larger than predicted (by 28%). This indicates that the observed differences in the baseline pupil size resulted mainly not from physiological differences between age groups but from factors related to the experiment. For example, it is plausible that children were more excited by the video clip and the experimental situation. Another hypothesis might be that the children were more focused on the task compared to the adults. All hypotheses assume an increase in tonic arousal that is reflected in increased baseline pupil diameter and might affect the sound-evoked phasic PDR. As shown by Kamp et al. (2015) the negative effect of enhanced tonic arousal on phasic response amplitude is absent or much smaller for the P3 compared to pupil dilation. Further studies are needed to specify these relations in children.

2.4.2 Age effects on early and late processing of novelty and emotion

Early processing of novelty and emotion was related to the P2 component (Ponton et al., 2000). P2 amplitudes were increased in response to novel sounds compared to standard sounds indicating sensitivity of underlying processes for novelty. This novel-related increase was significantly larger in children than in adults indicating children's enhanced susceptibility to the novelty of sounds. Emotional novel sounds caused larger P2 amplitude than neutral novel sounds, demonstrating enhanced processing of the emotional information provided by novel sounds. This is consistent with previous literature focusing on adults. Increased amplitudes of P2, evoked by sounds with high valence ratings, were reported in adults (Masson & Bidet-Caulet, 2019). Similar to P3a results, the emotion effect did not differ between age groups. In line with previous studies, we observed no differences in latency between children and adults (for review see Wunderlich et al., 2006). The underlying mechanisms of the P2 are considered to provide the basis for subsequent cognitive processes. Some studies show that the P2 reflects stimulus classification processes (for review see Crowley & Colrain, 2004). Recently, Getzmann et al. (2018) interpreted larger P2 amplitudes in response to relevant, compared to irrelevant stimuli as classification of the target. Following this model, novel sounds and emotional novel sounds might be classified as highly significant, because they could require a behavioral response. This interpretation would be in line with studies reporting increased distraction effects on a behavioral level. Another hypothesis is that the P2 reflects inhibition processes (for review see Crowley & Colrain, 2004), that is, children less successfully inhibited the processing of task-irrelevant novel sounds or spent more resources on inhibition processes. Alho and colleagues (1987) observed, for example, an increased amplitude in the P2 component for non-target compared to target stimuli in an oddball paradigm. The authors interpreted this increase as increased effort in inhibition of non-target processing and protection against interference from irrelevant stimuli. Both hypotheses are in line with the long-lasting maturation of the prefrontal cortex, as this region is involved in novelty evaluation and inhibitory control (Case, 1992).

Late processing of novelty and emotion was associated with the Late discriminative negativity component (LDN, Čeponienė et al., 2004). In children, LDN amplitudes were increased in response to novel sounds compared to standard sounds, indicating sensitivity for novelty. This is in line with previous findings and indicate a long developmental trajectory of attentional reorienting processes (Pearson & Lane, 1991). LDN has been hypothesized to reflect the processing of complex deviant sounds and can be observed in oddball paradigms requiring to ignore the sound sequence (Čeponiene et al., 2004; Cheour et al., 2001; Choudhury et al., 2015; Linnavalli et al., 2018). Increased LDN amplitudes might reflect increased effort to reorient the attention to the task at hand. In a dichotic listening task with 8 and 11-year-old children and adults (participants listened with one ear to targets and were signaled to switch attention to the other ear), increasing ability to reorient attention with age was reported by Pearson & Lane (1991). Gumenyuk et al. (2001, 2004) observed increased late negativity (LN) in younger children (8 years old) in comparison to older children (13 years old). This was interpreted to indicate the degree of attention engaged by the distracting sounds. Moreover, the authors observed a linear correlation between the reaction time (RT) and the LN, i.e. RT prolongation was correlated with increased amplitudes in LN. This was interpreted as increased effort for younger children in reorienting their attention back to the task. The age difference might be due to more intensive and prolonged processing of novel sounds in middle childhood, while adults were able to rapidly inhibit the processing of irrelevant events.

2.5 Limitation

Although we expected novel sounds to evoke increased amplitudes of P3a and PDR, P3a amplitudes were increased in children relative to adults while PDR amplitudes were reduced. We discussed the different pupil dilation as a result of the increased baseline pupil size in children. Future research is required to systematically investigate the relation of baseline pupil size in experimental conditions to phasic pupil dilation in dependence on age.

The increased amplitudes in the P3a might also be considered a consequence of the immature skull density and thickness in childhood. However, it is likely to only have a minor influence across development in the age groups tested in our study. Frodl et al. (2001) combined event-related potentials and magnetic resonance imaging (MRI) in an auditory oddball paradigm in order to investigate the influence of skull and scalp thickness on the ERP component P300. The authors observed no relation between P3a amplitude and fronto-central skull thickness and scalp thickness. (Frodl et al., 2001). Maturational changes in EEG signals may be interpreted as a result of structural cortical modifications taking place in development. For example, gray matter volume decreases over childhood and adolescence and coincides with a reduction in the EEG power signal (Segalowitz et al., 2010). These maturational cortical modifications may be crucial when interpreting developmental changes in EEG activity.

2.6 Conclusion

Attention processes are modulated by the novelty and the emotional information of task-irrelevant sounds. Results of the present study indicate that involuntary attention in the presence of new events is still developing, while the emotional information is processed on an advanced level.

The use of pupillometry to investigate event-related attention mechanisms in children is a new and promising approach. We demonstrated that the phasic pupil dilation response reflects the processing of task-irrelevant novel sounds and their emotional content in children. The observed similar pattern of pupil dilation responses and well-known indicators of attention in the EEG allows conclusions on the neurophysiological and neuromodulatory interrelations of involved brain networks and their developmental pathways. Even if attention-related ERPs might be more sensitive to age-related changes in auditory attention processes, pupillometry can answer important questions on the development of attention, the activity of the ANS and the LC-NE system. This is particularly important for the investigation of sensitive age groups such as young children or atypically developing children. For example, it has been discussed that children diagnosed with ADHD suffer from instable or decreased brain arousal (Hegerl & Hensch, 2014), but that it might be normal for novel sound processing (Tegelbeckers et al., 2016; van Mourik et al., 2007). The present study provides the basis to investigate the interaction of these mechanisms using a method that is highly accepted by children.

3. Study II: How do costs of attention orienting and benefits in enhanced arousal evoked by task-irrelevant novel and emotional auditory stimulation influence performance in a task?

The impact of novelty and emotion on attention-related neuronal and pupil responses in children

Text with minor edits is under review in Cognition and corresponds to the preprint Bonmassar, C., Scharf, F., Widmann, A., & Wetzel, N. (2021, August 11). On the relationship of arousal and attentional distraction by emotional novel sounds. https://doi.org/10.31234/osf.io/vyqw8. Figures and tables were renamed for the present thesis.

3.1 Introduction

A sudden cry can capture our attention, impair performance in a task at hand and increase the level of arousal to prepare us for a fight or flight reaction. The orienting of attention and the increase in arousal are two aspects of the orienting response, reflecting costs of attention distraction and benefits of arousal increase (Näätänen, 1992; Sokolov, 1963). The present study investigates the direct relation of distraction costs and arousal benefits by the co-registration of performance and pupil size in a well-established distraction paradigm.

The involuntary capture of attention by unexpected stimuli occurring outside the current focus of attention enables the detection of potentially relevant events in the environment (e.g., a ringing smartphone). The involved orienting and evaluation mechanisms include capacity limited processes (Näätänen, 1992) that can result in impaired performance in a task (distraction effect, e.g., Escera et al., 1998; Schröger & Wolff, 1998). The underlying mechanisms have been described by a three-stage model of involuntary attention (e.g., Escera & Corral, 2007; Schröger, 1997). In the first stage a predictive model of the acoustic environment is created automatically. Unexpected sounds (e.g., new sounds) violate the prediction (Winkler et al., 2009; Winkler & Schröger, 2015; but see, May & Tiitinen, 2010). This can trigger an orienting of attention and further evaluation of the unexpected sound. If no adaptation of behavior is required, attention is reoriented to the task at hand. When applying an oddball paradigm including frequently repeated standard sounds and rare, randomly presented distractor or oddball sounds (also termed novel or deviant sounds), distractor sounds frequently cause prolonged reaction times (RTs) in a task not related to the sound sequence or to the deviant feature (auditory task, Berti et al., 2004; Horváth et al., 2008; Muller-Gass & Schröger, 2007; visual task, Escera et al., 1998; Parmentier et al., 2008).

Nonetheless, some studies reported reduced distraction effects or even improved performance when task-irrelevant emotional information was presented (Lindström & Bohlin, 2011; Lorenzino & Caudek, 2015; Max et al., 2015). These reduced distraction or facilitation effects have been thought to be caused by an increased level of arousal caused by the emotional content of the distractor event (Max et al., 2015). This explanation is in line with the models by Näätänen (1992) and Sokolov (1963) postulating that the orienting response includes costs of orienting and benefits of enhanced arousal (see also Hoyer et al., 2021). However, a direct relation between distraction effects and distractor-related changes on the level of arousal was not yet evidenced and will be investigated in the present study.

The level of arousal is primarily modulated by the activity of the locus coeruleus-norepinephrine (LC-NE) system (Aston-Jones & Cohen, 2005; Corbetta et al., 2008; Poe et al., 2020), whose activity results in facilitated processing of motivationally significant stimuli (Aston-Jones & Cohen, 2005; Joshi & Gold, 2020; Poe et al., 2020). The activity of the LC-NE system is reflected by changes in pupil size (Aston-Jones & Cohen, 2005; Joshi et al., 2016). Visual oddball stimuli evoke increased LC activity (Krebs et al., 2018) resulting in increases in pupil dilation (Murphy et al., 2014). Several studies confirmed that novel oddball sounds cause a transient dilation of the pupil (Bonmassar et al., 2020; Liao, Kidani, et al., 2016; Liao, Yoneya, et al., 2016; Wetzel, Buttelmann, et al., 2016; Widmann et al., 2018). The noradrenergic system is also involved in the processing of emotion (for review see Nieuwenhuis et al., 2011; Ranganath & Rainer, 2003; Sara & Bouret, 2012) and emotional events cause increased pupil diameter (Bradley et al., 2008, 2017; Hess & Polt, 1960). In recent oddball studies, emotionally negative novel sounds, that were interspersed in a sequence of repeated standard sounds, evoked stronger pupil dilation than emotionally neutral novel sounds (Bonmassar et al., 2020; Widmann et al., 2018). Additional evidence for emotional arousal being linked to an increase in pupil dilation is the simultaneous use of skin conductance responses and heart rate as a marker of emotional arousal. Recent studies observed a simultaneous increase in skin conductance responses and heart rate as well as pupil dilation responses to emotional stimuli (Bradley et al., 2008, 2017; Wang et al., 2018).

Thus, the pupil can be used as a marker of novel and emotional sound-related increase in arousal.

In sum, cumulative evidence supports a model postulating that distraction effects include costs of orienting and benefits of arousal. To test this hypothesis, we applied a well-established auditory-visual oddball paradigm, including emotional highly arousing and neutral moderately arousing environmental novel sounds while participants focused on a visual categorization task. We expected first task-irrelevant novel sounds to prolong RTs compared to standard sounds (distraction effect; Escera, 1998; Schröger & Wolff, 1998) and increase PDRs (Murphy et al., 2011; Widmann et al., 2018). Second, we expected reduced distraction effects in response to emotional novel sounds compared to neutral novel sounds (Max et al., 2015) but increased amplitudes of the PDRs to emotional vs. neutral novel sounds (Bonmassar et al., 2020). Third, we hypothesized a direct relationship between emotion-related distraction effects and emotion-related PDRs. Importantly, the relationship between RT and PDR needs to be analyzed at both within- and between-participant level to disentangle effects of the average PDR (e.g., participants with higher average PDR show smaller distraction effects) from effects at single trial level (e.g., smaller distraction effects occur in *trials* with larger PDR). This was achieved by means of applying adequate centering strategies in a linear mixed-effects models (for an example of different levels of analysis see LoTemplio et al., 2021). That is, we expected shorter RTs in trials with higher PDR for emotional but not for neutral novel sounds.

3.2 Method

3.2.1 Participants

61 participants took part in the experiment. Four participants were excluded for the following reasons: pupil data available from one eye only, reaction times deviating more than two standard deviations from the average (two participants) and an accidental double participation in the experiment. The data of 57 healthy adults (M_{age}=25 years, range 18-36, 31 females, 5 left-handed) were used in the study. Participation was rewarded by money (10€/hour). All participants gave written informed consent. Participants confirmed a normal or corrected-to-normal vision, normal hearing, no medication with effects on the nervous system, and no history of attention-related disorders. Handedness was measured with an abbreviated German version of the Oldfield Handedness Inventory (Oldfield, 1971). The project was approved by the local ethics committee.

3.2.2 Stimuli

Auditory stimuli. A total of 48 environmental novel sounds[1] were collected from the database of a previous study (Max et al., 2015). Max and colleagues selected a set of 210 auditory stimuli, collected from the International Affective Digitized Sounds study (IADS, Bradley & Lang, 2007), and from other data bases as described by Max et al. (2015).

In the present study, sounds were allocated to three categories: 24 highly arousing emotionally negative sounds (for example an ambulance siren), 24 moderately arousing neutral sounds (for example toasting glasses), and 3 moderately arousing neutral sounds used as standard sounds (for example a musical instrument). Descriptive statistic and independent samples *t*-test are reported in Table 2 and Table 3. Sounds had a duration of 500 ms including faded ends of 5 ms. They were presented at a loudness of 54.5 dB SPL (measured with PAA3 PHONIC Handheld audio analyzer, Phonic Corporation, Taipei, Taiwan). Loudness of sounds was equalized with root mean square normalization.

Visual stimuli. Three different target categories were presented in separate blocks: (a) princesses vs. knights (Figure 7), (b) cats vs. hens, (c) butterflies vs. fish. For each target figure two versions were presented (slightly differing in shape, color and direction). All versions of the target figures were presented with equal probability (e.g. 25% princess with a pink dress, 25% princess with a blue dress, 25% knights with gray armor, 25% knight with blue armor) in a pseudorandomized order. For each target category a different scene was used as a background. Princesses and knights were presented in front of a palace (left side) and a fortress (right side), cats and hens were presented in front of a basket (left side) and a hen-roost (right side), and butterflies and fishes were presented with a flowering shrub (left side) and a pond (right side). The background landscapes' pictures were displayed at the center of a screen with a size of 960 x 720 px, 267 x 200 mm, (24.3° x 18.3° visual angle from a viewing distance of 620 mm). Picture mean luminance without targets or feedback was 51.2 cd/m^2 on a grey background screen with a mean luminance of 2.9 cd/m^2 (princess/knights 50.3 cd/m^2, cat/hen 55.1 cd/m^2, butterfly/fish 48.2 cd/m^2). The different versions of the targets and background scenes were presented to apply exactly the same paradigm to children in a future study (not reported here).

Apparatus and Software. The auditory stimuli were presented via loudspeakers (Bose Companion 2 series III Multimedia speaker system) located at the left and the right of the

[1] All sounds used in the present study were environmental sounds. In the following we will omit the specification "environmental" and we will term the sounds as "standard", "emotional novel" and "neutral novel" in order to improve readability.

screen. The visual stimuli were presented on a VIEWPixx/EEG display (VPixx Technologies Inc.) with a resolution of 1920 x 1080 (23,6-inch diagonal display size) and a refresh rate of 120 Hz. Responses to the target were given pressing a button on a response box (RTbox) located in the front of the screen (Li et al., 2010). The experimental stimulation was presented via Psychtoolbox (Version 3.0.15, Kleiner et al., 2007) using Octave (Linux, Version 4.0.0).

Table 2: *Descriptive statistics of the categories of sounds used in the experiment.*

Sound		**Valence**		**Arousal**	
	Number	**Mean**	**SD**	**Mean**	**SD**
Standard	3	5.66	0.21	4.43	0.40
Emotional	24	2.59	0.57	6.68	0.45
Neutral	24	5.21	0.46	4.81	0.37

Note. Sounds had been rated on a 9-point scale for valence (1 = unpleasant — 5 = neutral — 9 = pleasant) and arousal (1 = calm — 9 = arousing).

Table 3: *Independent t-tests of the categories of sounds used in the experiment.*

Condition	**Valence**					**Arousal**				
	t	***df***	***p***	***d***	BF_{10}	***t***	***df***	***p***	***d***	BF_{10}
emotional vs. neutral	−17.36	46	**< .001**	-5.012	2.845×10^{18}	15.56	46	**< .001**	4.493	4.358×10^{16}
emotional vs. standard	−9.003	25	**< .001**	-5.513	1.747×10^{6}	8.103	25	**< .001**	4.962	282390.711
neutral vs. standard	−1.666	25	.108	-1.020	1.098	1.631	25	.115	0.999	1.061

Note. Statistically significant results are marked in bold.

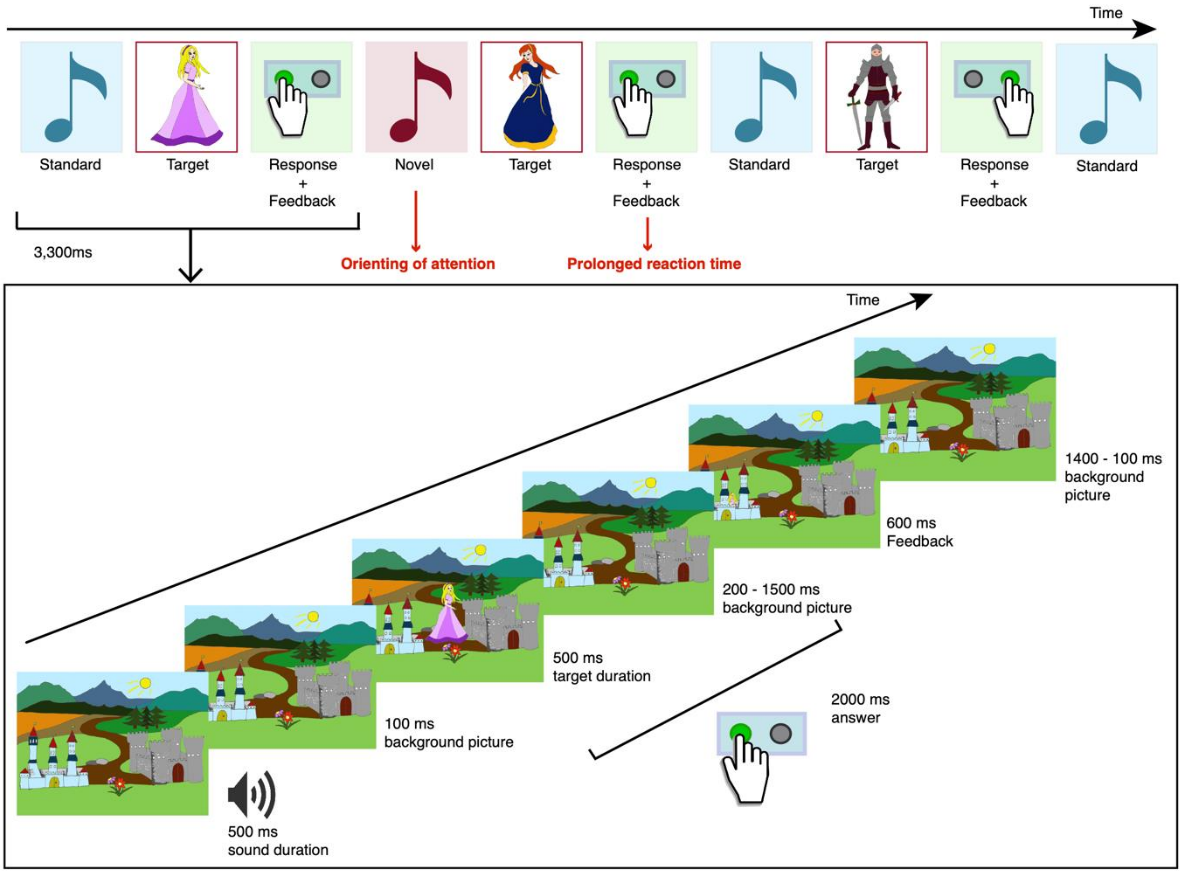

Figure 7: Trial structure. In every trial, a sound was presented for 500 ms, followed by the target (e.g. princess) that was presented 100ms after sound offset. The target was presented for 500 ms. Participants were instructed to press the left button when a princess appeared and the right button when a knight appeared. The response time window was 2,000 ms after target onset. Correct responses within the response time window were directly followed by a feedback. The visual background was presented during the entire trial.

3.2.3 Procedure

The experiment was conducted in an acoustically attenuated and electromagnetically shielded cabin. Illuminance of the cabin was held constant at a level of 48.9 lx (measured with MAVOLUX 5032B USB, GOSSEN Foto- and Lichtmesstechnik GmbH, Nürnberg, Germany). Participants sat in front of a screen, having their right and left index finger on the RTbox buttons. Each experimental block started with a five-point eye-tracker calibration and validation procedure.

Task and Feedback. Participants were instructed to press the left button when a princess (or cat or butterfly) appeared on the screen and the right button when a knight (or hen or fish) appeared (see Figure 7). They were asked to respond to the target stimuli as fast and correctly as possible and to ignore the sounds. Correct responses were followed by feedback, that is, the target moved towards the left or right side. For example, the princess moved to the palace on the left side and the knight moved to the fortress on the right side (Figure 7). The feedback motion consisted of two images with a duration of 150 and 450 ms.

Trial and block structure. Each sound was presented with a fixed stimulus onset asynchrony (SOA) of 3300 ms (Figure 7). 100 ms after sound offset, each sound was followed by a visual target. The target was presented for 500 ms. After target onset, participants had a 2 s time window to respond. The feedback was presented with a duration of 600 ms directly after the response, but not earlier than 200 ms after target offset. A total of six blocks were presented, each consisting of 40 trials. Two blocks included princesses and knights as target figure, two blocks of cats and hens and two blocks of butterflies and fish. The order of blocks containing different scenes were balanced across participants. Blocks containing the same scene were always presented one after another. Each block lasted about 2 minutes.

Sound sequence. The sound sequence included standard sounds (80%), emotional (10%) and neutral (10%) novel sounds. These probabilities of sound type presentation were equal over each block. That is, each of the six blocks included 32 standard sounds, 4 emotional novel sounds and 4 neutral novel sounds. In total, 192 standard sounds, 24 emotional novel sounds and 24 neutral novel sounds were presented. The sound sequence was unique for each participant. This ensured that potential changes in brightness were *not* systematically related to the occurrence of different sound types. For each scene (princesses vs. knights, cats vs. hens, butterflies vs. fish) a different standard sound was presented. This prevented potential effects of specific stimulus features of a single standard sound on performance. The assignment of standard sounds to the scene was counter-balanced across participants. The sound sequence was pseudo-randomized so that each novel was preceded by at least two standard sounds. Each novel was presented only once in total.

Training blocks. To familiarize participants with each of the three different scenes in the experimental block, three short training blocks including 8 trials each (6 standard sounds, 1 emotional and 1 neutral novel sounds) were performed. Sounds presented in the training blocks were not presented in the experimental blocks. If more than 50% of the trials was answered incorrectly, the training was repeated. Because the experiment was designed to be suitable for children, all participants of the present study understood the task promptly and no repetition was needed.

3.2.4 Data Analysis

The first two standard trials per block are required for the formation of a predictive model of the upcoming stimuli (Bendixen et al., 2007). Because the two standard trials immediately following an oddball sound can be affected by previous distractor sound processing (Wetzel, 2015), these were removed from all analyses. Only corresponding identical trials from the behavioral and pupil data, including a correct response, were used for analysis. Trials with incorrect or missing responses were excluded from pupil data analysis and trials with missing pupil data or blinks which could not be interpolated (see below) were also excluded from RT analysis.

3.2.5 Pupil data processing

The pupil diameter of both eyes was recorded with an infrared EyeLink Portable Duo eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada). The eye tracking was set up in remote mode at a sampling rate of 500 Hz.

The eye-tracker automatically reports the number of pixels below a specific threshold as belonging to the pupil (in case area is recorded or in case diameter is recorded, as here, a transformation of area to diameter by: (256 * √ (area in pixel ÷ Π)). By maintaining constant distance between the participant and the eye-tracker, the number of pixels actually reflects a meaningful and valid physical unit which can be converted to other meaningful units by simple linear transformations (e.g., mm; as described in several publications, for example Hayes & Petrov, 2016; Klingner et al., 2008). We converted the eye tracker pupil diameter digital counts to mm as suggested by Steinhauer and colleagues (2022). Pupil size analysis was implemented with MATLAB software. Eye saccade and blink information were provided by the eye tracker. Partial blinks were detected during post-processing from the smoothed velocity times series by an additional custom function, i.e., pupil diameter changes exceeding 20 mm/s including a 50 ms pre-blink and a 100 ms post-blink interval (Merritt et al., 1994). We applied Kret et al.'s (2019) dynamic offset algorithm to average data from both eyes. Isolated data segments between blinks or missing data shorter than 10 ms were considered as missing data. Subsequently, segments with blinks or missing data shorter than 1 s were interpolated with linear interpolation, longer segments were removed from the continuous data. Data were segmented in epochs of 2 s of duration (including a -0.2 to 0 s pre-stimulus interval), baseline corrected by subtracting the mean amplitude of the baseline period (-0.2 to 0.2 s) from each epoch. Typically, the pupil is not able to contract or dilate any earlier than 200 ms after stimulus onset (Mathôt et al., 2018). Thus, baseline correction was extended to range from -0.2 to 0.2 s, which allows for a wider span of baseline activity. The mean PDRs were computed in a time window around the peak between 1.3 and 1.5 s for each trial and each participant. In addition, for each trial, the average pupil size in the baseline period was computed.

3.2.6 Behavioral data (reaction times, RTs)

Incorrect responses, responses faster than 100 ms after target onset and missing responses (or responses given later than 2 s after target onset) were excluded from RT and pupil analysis. Participants deviating more than 2 standard deviations from the average reaction times were excluded from the analysis.

3.2.7 Statistical analysis

Analysis of Condition Effects

A paired samples t-test and Bayesian paired samples t-test were performed to compare PDR amplitudes in response to standard sounds, emotional novel and neutral novel sounds in the selected analysis mean amplitude time window (1.3-1.5 s). The same analysis was performed for the RTs in trials including standard sounds, emotional novel, and neutral novel sounds. All t-tests and Bayesian t-tests were performed using the R packages stats (v4.0.3, R Core Team, 2019) and BayesFactor (v0.9.12-4.2, Morey et al., 2011; Morey & Rouder, 2011; Rouder et al., 2009).

Analysis of Statistical Associations

We analyzed the relationship between RT and PDR both at trial and participant level with Linear mixed effect models (LMMs) to account for the dependencies between trials within participants. Trials were treated as primary unit of investigation (level 1) nested within participants (level 2). All models were estimated with the Maximum Likelihood method using the R packages lme4 (v1.1-27, Bates et al., 2015), and lmerTest (v3.1-3, Kuznetsova et al., 2017). As measures of goodness-of-fit model, we computed marginal and conditional R^2 (Nakagawa & Schielzeth, 2013), that is, the proportion of the total variability explained by the fixed effects and by all fixed and random effects together, respectively. Please note that relatively low values for R^2 are not uncommon due to the considerable variability of RTs between trials. Degrees of freedom for statistical tests were approximated using Satterthwaite's approximation. Bayes Factors were approximated from differences in the Bayesian Information Criterion, that is, $BF_{01} = exp\left(\frac{BIC_0 - BIC_1}{2}\right)$ (Raftery, 1995). Specifically, we followed the logic of a "Type III" analysis of variance and computed the

Bayes Factors from the comparison of the full model versus the full model excluding the respective effect.

We explored a range of conceivable models in which *RT* was modeled as a function of the various candidate predictors. To systemize the search for the best model, we applied a best subset selection and selected the best-fitting model using the Bayesian information criterion (BIC; Burnham & Anderson, 2004; Schwarz, 1978, Table 4). The set of candidate predictors contained various predictors at trial- and participant-level. Following from the experimental design, we always included Novelty (Standard vs. Distractor) and Emotionality (Neutral novel sound vs. Emotional novel sound) of the presented sounds as predictors. We applied a contrast coding such that the coefficient of Novelty (0 for standard, 1 for novels *irrespective* of the emotional content) is an estimate of the predicted difference in RT between standards and neutral novels whereas the coefficient of Emotionality (0 for standard sounds and neutral novels, 1 for emotional novels) reflects the predicted difference in RT between emotional and neutral novels. We included a random intercept (i.e., varying average RT) and a random slope for the predictor Novelty across participants (i.e., varying distraction effects). A random slope for Emotionality was not supported by the data and resulted in a singular fit[2].

We considered several potential relationships between pupil diameter and RTs: Both pupil diameter within the baseline period (baseline PD) and during the pupil dilation response (PDR) were used as potential predictors (LoTemplio et al., 2021; Murphy et al., 2011). The baseline PD was included in the selection process of the best model only to improve the model estimates (Alday, 2019) by controlling for potential confounding due to differences in baseline PD. This approach is comparable to an ANCOVA approach where covariates are included – although they are not of substantive interest – to control for confounding. We did not interpret the resulting baseline effects as this would have gone beyond the scope of the manuscript (however, for possible interpretation see Supplementary material Study II).

We considered that baseline PD and PDR can vary from trial to trial but there may also be systematic differences between participants and both these sources of variation could affect response times differentially. To give an intuition why this can happen: When the raw PDR

[2] Initially, we intended to use the predictor Condition (Standard vs. Emotional novel sound vs. Neutral novel sound). However, a random slope of Condition results in 2 separate random slopes for the differences between emotional novels vs. standards and neutral novels vs. standards, respectively. Both for RT and PDR as dependent variable, this resulted in a singular model due to the high correlation of these random slopes – indicating that a single random slope across both novel types was more appropriate. Re-parameterization into the separate predictors Novelty and Emotionality enabled a model with a common random slope (i.e., individual distraction effects) across both types of novel sounds.

takes a “large” value (e.g., relative to the grand mean) it remains unclear what “large” exactly implies, because large values could be due to the respective participant generally showing large PDRs or due to the specific trial showing a large PDR. If the raw baseline PD or PDR values were used as predictors, the trial and participant level effects of these predictors would be confounded and uninterpretable.

An established way to disentangle trial level from participant level variance is to create two variables: a trial level variable which is centered around the mean *within* participants and a participant level variable which represents the mean of each participant centered around the grand mean of all participants (Enders & Tofighi, 2007). The former variable represents the effect of fast fluctuations on trial level (e.g., do participants respond faster in trials with a larger PDR *relative* to the participant’s individual average?). The later variable represents the effect of interindividual differences which are stable over the course of the experimental session (e.g., do participants with a generally larger PDR have larger behavioral distraction effects?). Both baseline PD and PDR were treated this way to separate the two sources of variation. We refer to the trial-level variables by the index “trial” (e.g., PDR_{trial}) and to the participant-level variables by the index “participant” (e.g., $PDR_{participant}$).

The least complex model under consideration contained Novelty, Emotionality, PDR_{trial} and $Baseline_{trial}$ as simple effects. The most complex model could include Novelty, Emotionality, linear, and quadratic effects of PDR and baseline PDR both at trial level and participant[3] level as well as their interactions with Novelty and Emotionality. Between these models, all possible alternative models were considered in the model space with two restrictions: (1) Any model containing a quadratic effect or interaction should also include the respective lower order (“simple”) effect. (2) Any interaction including either Novelty or Emotionality should always be accompanied by an interaction with the respective other predictor because potential differences between the sound types are of genuine substantive interest to our study. All model effects specified based on the BIC selection are listed in Table 4. Except for a moderate skewness (2.29) in the level-1 residuals due to very slow responses in some single trials, all model assumptions were respected. We decided to keep these rare trials in the dataset because their removal would not have changed the results in any meaningful way given the large number of trials available for the model (7554)[4].

[3] Theoretically, the participant-level PDR/Baseline could be computed from the average across all sound types or separately for each sound Type. The correlations between the values from these approaches were very high (all rs > .80) and the choice between these methods did therefore not change the results in any meaningful way. For the sake of comprehensibility, we only report the results when averaging PDR/Baseline across all sound types.

[44] We investigated the potential impact of the misspecified level-1-residual distribution by comparing our model with normal level-1 distribution with a model with an exgaussian distribution which can account for the

considerable skewness of RTs at trial-level using brms (Bürkner, 2017, 2018; Carpenter et al., 2016) which utilizes a Bayesian estimation algorithm. The exgaussian model fit the data substantially better, but this did not affect any substantive conclusion, because none of the parameters changed its sign or effect size fundamentally.

Table 4: *Overview of the 10 best BIC-selected models.*

BIC model selection

	1st best Model	2nd best Model	3rd best Model	4th best Model	5th best Model	6th best Model	7th best Model	8th best Model	9th best Model	10th best Model
Intercept	X	X	X	X	X	X	X	X	X	X
$\text{Baseline}_{\text{trial}}$	X	X	X	X	X	X	X	X	X	X
$(\text{Baseline}_{\text{trial}})^2$	X		X	X	X	X	X	X	X	X
$\text{Baseline}_{\text{participant}}$										X
$(\text{Baseline}_{\text{Particioant}})^2$							X			
Novelty	X	X	X	X	X	X	X	X	X	X
Emotionality	X	X	X	X	X	X	X	X	X	X
$\text{PDR}_{\text{trial}}$	X	X	X	X	X	X	X	X	X	X
$\text{PDR}_{\text{participant}}$	X	X		X	X	X	X	X	X	X
$\text{Baseline}_{\text{trial}} \times$ Novelty	X	X		X	X	X	X	X	X	X
$\text{Baseline}_{\text{trial}} \times$ Emotionality										
$\text{Baseline}_{\text{participant}} \times$ Novelty										
$\text{Baseline}_{\text{participant}} \times$ Emotionality										
Novelty $\times (\text{Baseline}_{\text{trial}})^2$									X	
Novelty $\times (\text{Baseline}_{\text{Particioant}})^2$										
Novelty $\times \text{PDR}_{\text{trial}}$				X						
Novelty $\times \text{PDR}_{\text{participant}}$								X		
Emotionality $\times (\text{Baseline}_{\text{trial}})^2$					X					
Emotionality $\times (\text{Baseline}_{\text{Particioant}})^2$										
Emotionality $\times \text{PDR}_{\text{trial}}$						X				
Emotionality $\times \text{PDR}_{\text{participant}}$										
Df	12.00	11.00	11.00	13.00	13.00	13.00	13.00	13.00	13.00	13.00
loglik	-43851.65	-43858.42	-43858.55	-43849.99	-43850.11	-43850.19	-43850.34	-43850.69	-43851.20	-43851.25
BIC	87810.46	87815.06	87815.33	87816.08	87816.30	87816.46	87816.76	87817.47	87818.48	87818.59
delta		4.61	4.87	5.62	5.84	6.00	6.31	7.01	8.02	8.13
weight	0.62	0.06	0.05	0.04	0.03	0.03	0.03	0.02	0.01	0.01

Note. The parameters or predictors that are included in the model are marked with a “X”.

Table 5: *Coefficients for the mixed-effects model.*

RT-PDR-model

Dependent variable	Predictor/Fixed effect	Estimate	SE	df	t-value	P	BF	Results‘ description
Reaction times	Intercept	406.040	5.144	57.683	78.941	**<0.001**	–	mean (predicted) standard PDRs
	Novelty	22.859	2.963	109.884	7.714	**<0.001**	**$8.7 \cdot 10^7$**	novel RTs minus standard RTs
	Emotionality	-10.947	3.077	7444.833	-3.558	**<0.001**	**6.4**	emotional RTs minus neutral RTs
	$Baseline_{trial}$	-2.954	4.140	7465.697	-0.713	0.475	1	
	$Baseline_{trial}$ × Novelty	35.670	8.335	7468.218	4.280	**<0.001**	**107.9**	*fastest* RTs to novel sounds when the baseline is *smaller* than average
	$Baseline_{trial}$ × Emotionality	9.101	10.525	7492.214	0.865	0.387	0.02	
	$(Baseline_{trial})^2$	17.239	4.609	7500.540	3.740	**<0.001**	**12.4**	*fastest* RTs when the baseline is *at average* within each participant
	PDR_{trial}	12.506	5.000	7477.175	2.501	**0.013**	**2.6**	at a trial level, *slower* RTs for trials with *larger* PDRs
	$PDR_{participant}$	-189.637	47.221	57.174	-4.016	**<0.001**	**11.3**	participants with *generally larger* PDRs showed *faster* RTs
	Random effects	**Variance**	**SD**	**Corr**				
Participant	Intercept	1424.1	37.74					
	Novelty	153.4	12.39	0.37				
Residuals		6261.0	79.13					

Note. Statistically significant results are marked in bold.
RT = reaction time; SE= standard error; df = degree of freedom; SD = standard deviation; Corr = correlation; PDR = pupil dilation response; BF = Bayes Factor.

3.3 Results

PDR

Tests of the three a-priori hypotheses were conducted using Bonferroni adjusted alpha levels of .016 per test (.05/3). The analysis of the pupil dilation responses in the time window selected showed an effect of novel sounds (emotional vs. standard sounds: $t(56)= 11.2$, $p <.001$, $BF_{10}= 1.01 \times 10^{13}$; neutral vs. standard sounds: $t(56)= 7.90$, $p <.001$, $BF_{10}= 9.04 \times 10^{7}$, see Figure 8 and Figure 9, Panel B), resulting from larger amplitudes for novel sounds compared to standard sounds. An effect of emotional sounds (emotional vs. neutral sounds: $t(56)= 5.86$, $p <.001$, $BF_{10}= 5.77 \times 10^{4}$) resulted from larger amplitudes for emotional novel sounds compared to neutral novel sounds.

RTs

Tests of the three a-priori hypotheses were conducted using Bonferroni adjusted alpha levels of .016 per test (.05/3). The analysis of the reaction times showed an effect of novel sounds (emotional vs. standard sounds: $t(56)= 4.79$, $p <.001$, $BF_{10}= 1.5 \times 10^{3}$; neutral vs. standard sounds: $t(56)= 7.58$, $p <.001$, $BF_{10}= 2.8 \times 10^{7}$, see Figure 9, Panel A), resulting from slower reaction times for novel sounds compared to standard sounds. An effect of emotional sounds (emotional vs. neutral sounds: $t(56)= -3.92$, $p <.001$, $BF_{10}= 98.24$) resulted from faster reaction times for emotional novel sounds compared to neutral novel sounds.

RT-PDR-model

The best-fitting BIC-selected model contained the predictors Novelty, Emotionality, $\text{Baseline}_{\text{trial}}$[5], $\text{Baseline}_{\text{trial}}$ × Novelty, $\text{Baseline}_{\text{trial}}$ × Emotionality[5], $(\text{Baseline}_{\text{trial}})^2$, $\text{PDR}_{\text{trial}}$ and $\text{PDR}_{\text{participant}}$. The effects of the predictors Novelty and Emotionality showed that participants responded significantly slower to novel than to standard sounds but significantly faster to emotional novels compared to neutral novel sounds (Figure 9, Panel A; Table 5, Novelty and Emotionality effects) – resembling the results of the confirmatory analyses above. In addition, we found dissociable relationships between PDR and RT at trial and participant level. At trial level, slower RTs were predicted for trials with larger PDR (Figure 10, Panel A; Table 5, effect $\text{PDR}_{\text{trial}}$), but participants with generally larger PDRs tended to respond *faster* (Figure 10, Panel B; Table 5, effect $\text{PDR}_{\text{participant}}$). The model also revealed effects of the baseline PD on RTs and distraction effects that are described in detail in the Supplement material Study II.

[5] These terms were added manually following the substantive restrictions outlined above. This change did not affect size or hypothesis test of any other effect in the model.

With respect to our research questions, the existence of an interaction of pupil dilation and behavioral distraction effects (either at trial or participant level) was of major interest. Therefore, we computed additional Bayes Factors comparing the BIC-selected model with models in which we added such interactions. At trial level, there was strong evidence against the inclusion of the terms PDR_{trial} × Novelty and PDR_{trial} × Emotionality into the BIC-model (BF = 0.002). At participant level, there was strong evidence against the inclusion of the terms $PDR_{participant}$ × Novelty and $PDR_{participant}$ × Emotionality (BF = 0.006). That is, the model did not support an interaction of these factors neither on the trial level nor on the participants level.

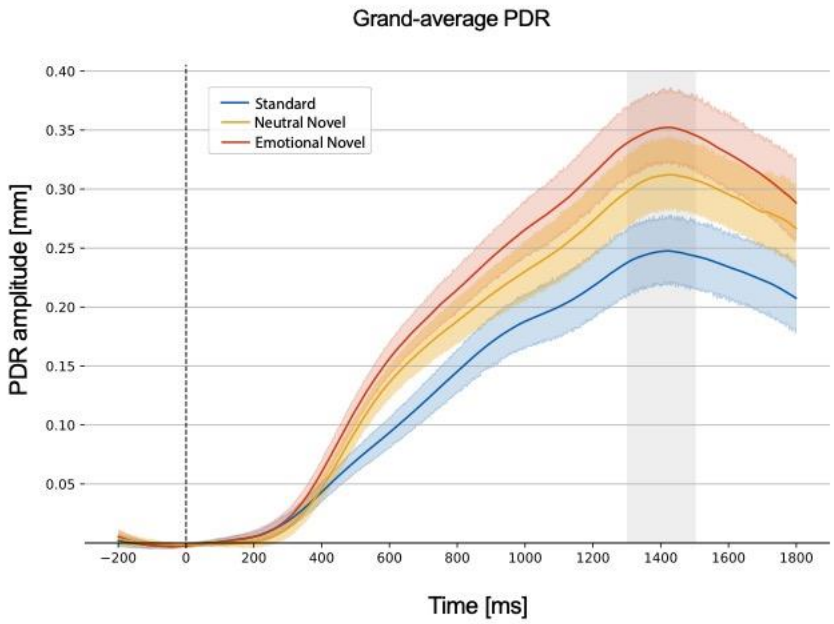

Figure 8: Grand-average pupil dilation responses (PDRs) for emotional novel sounds, neutral novel sounds, and standard sounds. Sound onset is at time point zero. Shading indicates the 95% confidence interval. The gray window indicates the time window used for analysis. Novel sounds evoked statistically significantly increased PDRs compared to standard sounds. Emotional novel sounds evoked statistically significantly increased PDRs compared to neutral novel sounds.

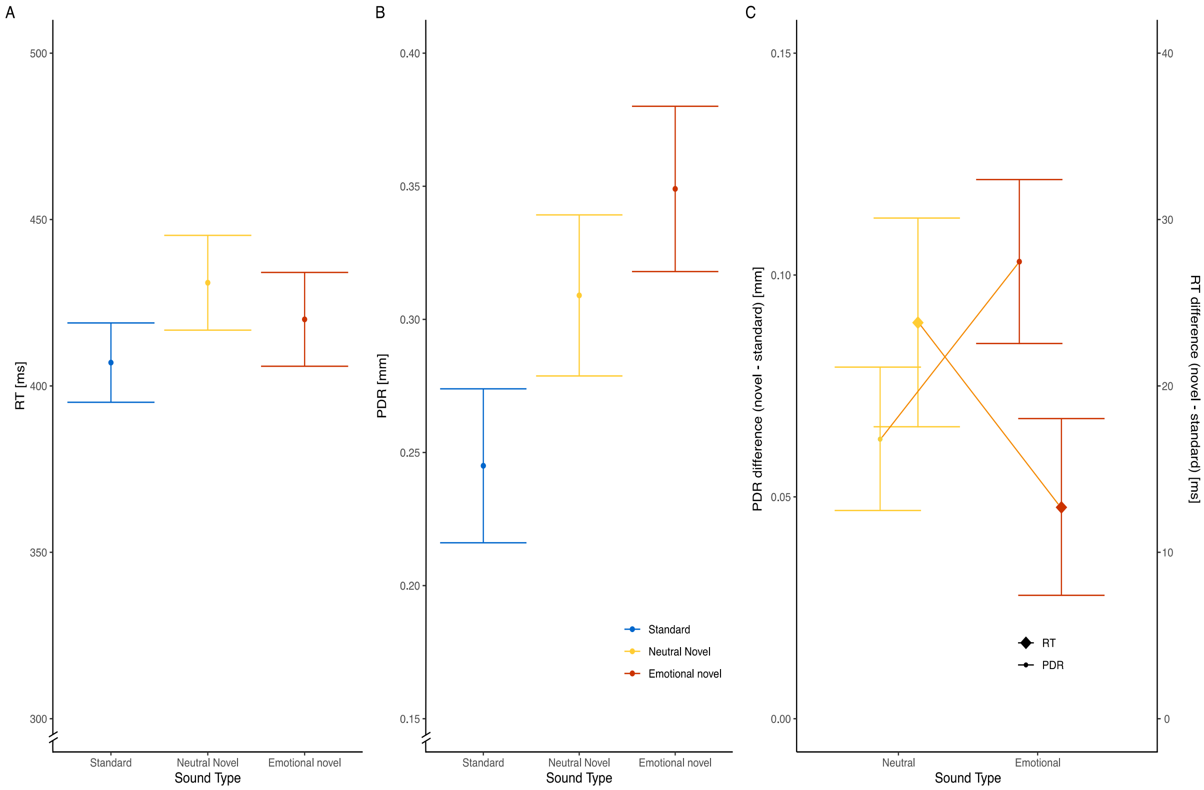

Figure 9: Panel A: Mean reaction time (RT) for standard, neutral novel and emotional novel sounds. Novel sounds evoked increased RTs compared to standard sounds, demonstrating a distraction effect. Emotional novel sounds caused reduced RTs compared to neutral novel sounds, indicating a facilitation effect. Panel B: Mean pupil dilation response for standard, neutral novel and emotional novel sounds. Novel sounds evoked larger PDRs compared to standard sounds. Emotional novel sounds evoked larger PDR compared to neutral novel sounds, indicating an increase in arousal. Panel C: Mean distraction effects (RT novel minus RT standard sound) and pupil dilation differences between PDR to novel and standard sound. This plot displays the hypothesized relationship between faster reaction times and larger pupil dilations to emotional novel sounds. This relation has been disconfirmed by the multilevel analysis. The plots show 95% confidence interval.

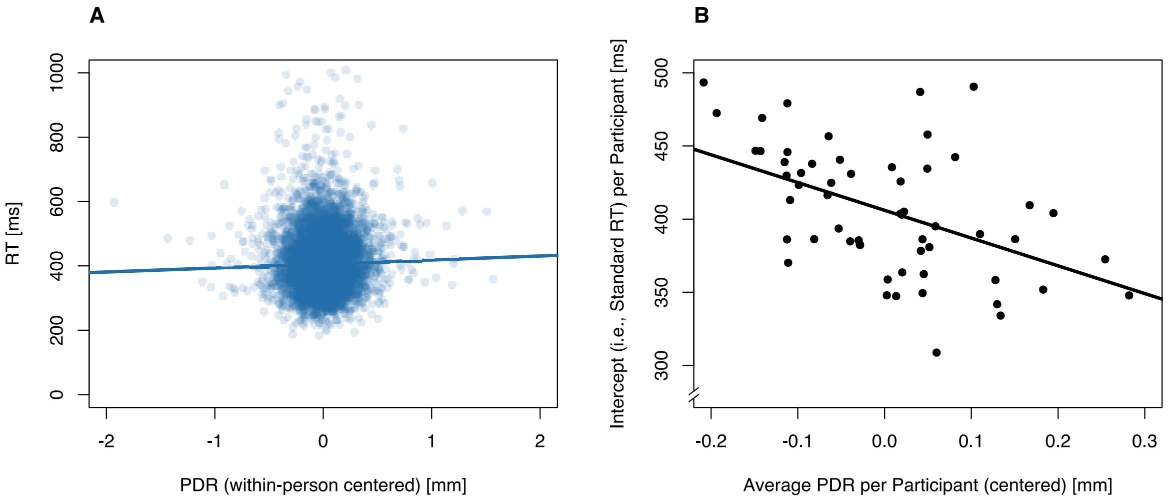

Figure 10: Panel A: The relationship between performance (reaction times, RT) and pupil dilation response (PDR) at trial level. Larger pupil dilations in a trial were associated with slower reaction times. Panel B: The relationship between performance (standard reaction times, RT) and pupil dilation response (PDR) at participant level. Participants with larger pupil dilations showed faster average response times.

3.4 Discussion

This study investigated the direct relations of emotion-related distraction effects on performance in a primary task and increased levels of arousal evoked by processing of such emotional distractor sounds. Novel sounds, compared to standard sounds, prolonged RTs in a visual categorization task and evoked a transient dilation of the pupil. On the behavioral level, distraction effects were reduced in response to emotional compared to neutral novel sounds while the pupil dilated even more in response to emotional novel sounds vs. neutral novel sounds. However, mixed-model effects could not provide any evidence for a correlation between performance and transient changes in pupil diameter that was specific to a sound's novelty or emotional content. This result was confirmed by Bayes Factors.

Novel sounds impaired performance in a subsequent categorization task compared to standard sounds. This result is consistent with current models of distraction of attention (Corbetta & Shulman, 2002; Escera & Corral, 2007; Näätänen, 1992; Posner, 1980, 2016; Sokolov, 1963). New, salient, and task-irrelevant events can involuntarily capture attention and can impair performance. This distraction effect (difference between RTs to distractor and RTs to standard sounds) has been observed in the auditory, visual, and tactile modality (Akatsuka et al., 2007; Escera, 1998; Schröger & Wolff, 1998) and has been replicated many times (Berti & Schröger, 2001, 2004; Hoyer et al., 2021; Parmentier, 2014; Wetzel et al., 2019). Task-irrelevant emotional novel sounds significantly decreased distraction effects compared to neutral novel sounds. Our results indicate that task-irrelevant emotional stimuli facilitated processing and improved behavioral performance in a subsequent task (Lindström & Bohlin, 2011; Lorenzino & Caudek, 2015; Max et al., 2015; Phelps et al., 2006; Zeelenberg & Bocanegra, 2010). Emotional stimuli innately achieve prioritized processing due to their high motivational relevance (Mather et al., 2016; Schupp et al., 2003). However, previous studies also observed that emotional information can capture higher attentional resources than less salient stimuli resulting in impaired performance (for example, Kanske, 2012; Most et al., 2005; Pereira et al., 2006; Pessoa, 2008; for a review on visual emotional stimuli, see Bradley et al., 2012). Opposite results on modulations of emotional information on performance and attentional capacities may be explained due to differences between experimental designs, sensory stimulus presentation, task relevance and task assignment. For example, stimuli presented in the same modality interfere more with each other than stimuli presented in different modalities (e.g., Duncan et al., 1997; Schupp et al., 2008; Soto-Faraco & Spence, 2002). Thus, emotional distraction effects may be reduced by presenting the task-irrelevant emotional stimulus in a different modality compared to the target (reduced response times De Houwer et al., 2002; Jiang et al., 2007; Scott et al., 2009; improved identification of visual targets Brosch et al., 2007, 2008; Zeelenberg & Bocanegra, 2010).

On a psychophysiological level, we observed a larger transient pupil dilation response (PDR) to novel sounds compared to standard sounds. This finding is in line with our hypothesis and with previous studies (Gilzenrat et al., 2010; Marois et al., 2020; Murphy et al., 2011) and has been discussed to reflect a transient increase in arousal (Joshi et al., 2016; Joshi & Gold, 2020; Krebs et al., 2018; Murphy et al., 2014; for a review see, Eckstein et al., 2017; Poe et al., 2020; Zekveld et al., 2018). Moreover, larger pupil dilation was observed in response to emotional novel sounds compared to neutral novel sounds (as e.g., Bonmassar et al., 2020; Partala & Surakka, 2003; Widmann et al., 2018). A dilation of the pupil is likely to be modulated by the increased activity of LC-NE system (Poe et al., 2020). The bias in favor of salient, emotional, and high-priority information is modulated by the norepinephrine release of the locus coeruleus (Joshi & Gold, 2020; Mather et al., 2016; Poe et al., 2020). Thus, our study could replicate effects of unexpected, task-irrelevant, and emotionally arousing sounds on both performance and pupil size from previous studies.

Even though emotional novel sounds evoked larger PDRs and reduced distraction effects separately, the applied multilevel model did not support a correlation between both effects neither on the trial nor on the participant level. The lack of a correlation was confirmed by the computation of Bayes Factors, which showed that the data provide strong evidence against such interactions. That is, emotional novel sounds evoking larger PDRs did not show systematically larger behavioral facilitation effects and participants showing larger average PDRs in response to emotional distractor sounds did not show correspondingly larger behavioral facilitation effects. Based on these results, we suggest that the emotion-related facilitation effect on the behavioral level and the increase in arousal reflected by the PDR do not reflect the operation of identical processes. They are presumably caused by at least partly independent mechanisms. This does not exclude common precursor processes. It can be speculated that one of the involved processes does not show proportional behavior, for example due to all-or-nothing effects or ceiling or floor effects. Taken together, we propose that our behavioral and psychophysiological results indicate the operation of possibly related, but not identical mechanisms contributing to emotion-related decreased effects of distraction.

Even though we did not find an emotion-specific correlation between reduced distraction effects and increased PDR, our exploratory analysis showed two opposite relationships between RTs and PDRs at the trial and the participant level, independent of the sound type presented. On a participant level, participants with larger mean PDR, responded faster to target stimuli. Behaviorally relevant stimuli can dilate the pupil (e.g., Beatty, 1982; Murphy et al., 2014). The negative correlation could indicate that participants with increased PDR have continuously and more effectively used the sounds as a temporal cue for both the occurrence and the timing of the upcoming target (Hackley, 2009; Hackley & Valle-Inclán, 2003) and effectively prepared for the onset of the to-be-categorized stimulus (Volosin et al., 2016; Wetzel et al., 2013). This can result in faster responses compared to participants who were less engaged in the task. Strauch and colleagues suggested that pupil dilation might be interpreted as a readout of all three attentional subsystems, alerting, orienting and executive attention as suggested by Petersen & Posner (2012). Following this suggestion, the negative correlation at participant level could also reflect higher-level attentional factors related to the executive functions: Participants with larger PDR employed more attentional resources because they were more engaged in performing the task. In both cases, the negative correlation between RTs and PDRs might reflect participant-level aspects of task engagement (see e.g. also Hopstaken et al., 2015).

At the trial level we observed a positive correlation between RTs and PDRs, that is, in trials with slower reaction times we observed larger PDRs in the same trial irrespective of sound type (as previously reported by Murphy et al., 2011). Again, following the suggestion by Strauch et al. (2022), this positive correlation could reflect intermediate-level factors related to alerting and orienting of attention (Petersen & Posner, 2012): at a trial level, pupil dilation indicates orienting and distraction of attention in response to stimuli occurring in the surrounding. Interestingly, as we did not observe an interaction effect of trial-level PDR and novelty, the relation slower RT-larger PDR apparently might also hold for standard trials. We suggest that attentional orienting and enhanced stimulus processing observable in distracting novel trial at larger scales might also occur in standard trials at smaller scales, for example in relation to increased phasic NE release, potentially due to attentional orienting toward sound stimulation and spontaneous fluctuations of the LC activity (Jepma & Nieuwenhuis, 2011), resulting in enhanced processing of the current sound (and vice versa; Aston-Jones & Cohen, 2005) also in standard trials. The enhanced processing of the task-irrelevant standard and novel sounds can impair subsequent target stimulus-related processes, resulting in increased RT at trial-level.

Since PDR and RT on a trial level consider deviations relative to the participants' individual averages whereas participant level RT and PDR consider deviations of the participants individual averages from the grand average, these correlations represent differentiable sources of variance and the relationships can point in different directions (Enders & Tofighi, 2007; see also LoTemplio et al., 2021 for the relation of P3b and RT in an oddball task). More generally, the trial-to-trial fluctuation of activity could reflect brain processes specific to that stimulus-driven behavior, whereas a difference between participants could reflect a general individual response bias to incoming stimuli. Our results demonstrate that the centering strategies, common in multilevel models, can also be applied effectively to disentangle enduring and transient effects in experimental settings.

3.5 Conclusion

Our findings indicate that task-irrelevant and unexpected novel sounds impair performance in a categorization task and distraction effects are reduced in response to emotional compared to neutral novel sounds. Transient changes in pupil size are larger in response to novel sounds compared to standard sounds and this increase is larger for emotional than for neutral novel sounds. Our frequentist and Bayesian results disconfirm our hypothesis of a direct relation between reduced distraction effects on the behavioral level and increased arousal reflected by larger PDR to emotional novel sounds. We suggest that both performance and pupil diameter reflect partly distinct processes. The locus coeruleus may embody a common antecedent for both effects, spreading norepinephrine to cortical areas involved in attention control and control of the pupil. In addition, the observed emotion-unspecific correlations between performance (RT) and levels of arousal (PDR), that differ on the trial and the participants level, provide new insights into the underlying mechanisms of potential fluctuation of the LC-NE system, aspects of individual task engagement and their effects on performance.

4. Study III: How do costs of attention orienting and benefits in enhanced arousal evoked by task-irrelevant novel and emotional auditory stimulation influence performance in a task? Which age differences can be observed between children and adults?

4.1 Introduction

The ability to focus on a primary task and be aware of the surrounding represents a balance between voluntary and involuntary attention. Involuntary attention can often drive to distraction, so attention can be captured by irrelevant information. In particular, when distractor sounds convey motivationally significant or emotional information, a competition takes place between costs of orienting of attention toward the event and benefits in the increase of arousal level due to the processing of such events (Max et al., 2015). I investigated the impact of distractor's emotional content on reaction times in adults (Study II) and I will examine this aspect in children aged 6 to 8 years old in the present study.

At a cortical level, voluntary and involuntary attention has been located to two partially overlapping dorsal and ventral fronto-parietal networks (Corbetta & Shulman, 2002). These two networks seem to interact with the prefrontal cortex (Corbetta & Shulman, 2002; Elshafei et al., 2018). In the development, the maturation of the prefrontal cortex is protracted at least until young adulthood (Fuster, 2002; Giedd et al., 1999; Gogtay et al., 2004; Sowell et al., 2004). The ability to shield oneself from irrelevant information increases with age during childhood (Ridderinkhof & Van der Stelt, 2000) and is supported by studies reporting increased sensibility to distracting sounds in younger children compared to older children or in children compared to adults (Gumenyuk et al., 2001, 2004; Lane & Pearson, 1982; Wetzel et al., 2006; Wetzel & Schröger, 2007a; for review, see Klatte et al., 2013). Distraction of attention by unexpected sounds has been described in a three-stage model of involuntary attention in adults (Escera & Corral, 2007; Schröger, 1997). Following this model, when novel sounds occur less resources are available to perform the task and this results in impaired performance (i.e. prolonged reaction times, Escera et al., 2000). The interference of unexpected and task-irrelevant sounds may be reflected by prolonged reaction times (RTs) after such sounds (Escera et al., 1998; Schröger & Wolff, 1998). Only a handful of studies showed increased distraction effects with increasing age (Gumenyuk et al., 2004; Volkmer et al., 2022; Wetzel et al., 2006, 2019; Wetzel, Schröger, et al., 2016; Wetzel & Schröger, 2007a). But older children (9- to 10-year-old) did not show such larger distraction effect compared with adults (Parmentier et al., 2020; Ruhnau et al., 2010, 2013; Wetzel, 2015). However, several factors of the experimental designs may have contributed to the divergence of the results: For example, features of the sounds (novelty, frequency deviants), sensory modality and demands of the task.

Concerning the decrease in distraction effects, recent data from two studies showed that older children can adapt to distractor events (novel sounds) considerably faster than younger children (Volkmer et al., 2022; Wetzel et al., 2021). In these studies, children aged 6 to 10 years old showed initial strong distraction effects which declined throughout the experimental session to the level of adults. The authors discussed the results as a sign of qualitative changes of attention control in middle childhood. However, whether a similar pattern of reduction of attention can be observed when children are exposed to emotional novel sounds (therefore arousal) and if this is different in children compared to adults has not being researched yet.

Thus, previous findings propose that attentional control in the framework of task-irrelevant novel sounds develops until 10 years of age and that distraction effects may decrease throughout the experimental session.

Nevertheless, some studies on adults have demonstrated that task-irrelevant emotional information may reduce distraction effects or even facilitate performance (Lindström & Bohlin, 2011; Lorenzino & Caudek, 2015; Max et al., 2015). As discussed above, these effects may be related to an increased level of arousal caused by the emotional content of the distractor event (Max et al., 2015) and fit the hypothesis of both costs of orienting and benefits of enhanced arousal in the orienting response (Näätänen, 1992; Sokolov, 1963; see also Hoyer et al., 2021). However, distraction effects and distractor-related changes on the level of arousal seem to be at least partly independent (see Study II). Behavioral and physiological studies have provided evidence that infants are able to discriminate between happy, sad, angry and fearful facial expressions (for example, Grossmann, 2013; Kotsoni et al., 2001) and already respond with increased arousal to emotional events within the first 15 months of postnatal life (Geangu et al., 2011; Wetzel, Buttelmann, et al., 2016). However, evidence about emotional influence on performance remains sporadic in school aged children and conclusions are made even more difficult due to differences in experimental setup, stimuli and modality presentation. On one side, few other studies reported matured emotional

processing until the age of 5–8 years (visual modality, Leventon et al., 2014; Solomon et al., 2012). For example, Leventon and colleagues (2014) showed that children as young as 5 years rate positive and negative stimuli as emotional, and show increased electrophysiological (ERP) and physiological responses (heart rate) to these stimuli, similarly to adults. On the other hand, Grosbras and colleagues (2018) showed that the ability to identify emotion from short affective bursts in a forced-choice task, improves slowly but significantly with age, reaching adults' level around the age of 15 (school aged children between 5 and 17), indicating a long-lasting development of emotion processing. In my previous study (Study I) I observed that emotional information oriented the attention (cost) in a similar way to adults. However, the behavioral effects of such emotional sounds in children are yet to be investigated. In fact, the orienting of attention seems to be similar on a cortical level in children and adults but the benefits evoked by the arousal level may be not. One explanation may be that the LC-NE system may not be yet matured in middle childhood (Pozuelos et al., 2014), and so the interactions between the LC and the fronto-parietal attentional networks (Hoyer et al., 2021; Mather et al., 2016). To the best of our knowledge, no study has investigated the relation between distraction effects and distractor-related changes on the level of arousal in children aged 6 to 8 years old.
Therefore, cumulative evidence, mainly on adults' experiments, supports a model proposing that distraction effects include costs of orienting and benefits of arousal. However, the contribution of these cost and benefit factors to behavioral distraction might be different in children compared to adults.

As shown in Study II, the pupil dilation displays the activity of the LC-NE system, which facilitates the processing of motivationally significant stimuli, such as emotional information (Aston-Jones & Cohen, 2005; Corbetta et al., 2008; Joshi & Gold, 2020; Poe et al., 2020; Krebs et al., 2018; Murphy et al., 2014). This effect has been observed and replicated many times using novel oddball sounds (Bonmassar et al., 2020; Liao, Kidani, et al., 2016; Liao, Yoneya, et al., 2016; Wetzel, Buttelmann, et al., 2016; Widmann et al., 2018). The noradrenergic system is also involved in the processing of emotion (for review see Nieuwenhuis et al., 2011; Ranganath & Rainer, 2003; Sara & Bouret, 2012) and emotional stimuli enlarge pupil diameter (Bradley et al., 2008; Hess & Polt, 1960). Recent oddball studies showed that emotionally negative novel sounds evoke increased pupil dilation than emotionally neutral novel sounds in children (Bonmassar et al., 2020) and adults (Widmann et al., 2018). Moreover, transient pupil dilation activity has been linked to emotional arousal by other physiological methods, such as skin conductance responses and heart rate (Bradley et al., 2008, 2017; Wang et al., 2018). Therefore, the pupil can be used as a marker of novel and emotional sound-related increase in arousal.

Taking all the above-mentioned previous findings, a systematical in-depth analysis on the effects of novelty and the emotional content of distracting sounds on children's attention and behavioral performance is still missing and will be addressed in the present study. Closing this gap, I tested (1) the impact of distractor's emotional content on distraction effects (DE) in children compared to adults (emotion drives to facilitation?); (2) the hypothesis of a relationship between distraction effects and distractor-related changes on the level of arousal a different in children (6-8 years old) compared to adults (for developmental trajectory of arousal see Hoyer, 2021; analysis with linear mixed models as in Study II) and (3) whether 6 to 8 years old children show effects of learning on distraction by emotional novel sounds by means of a block analysis (future analysis with linear mixed models as in Volkmers 2022).

4.2 Method

4.2.1 Participants

The data of 57 adult participants from Study II were used. For the child group, 52 participants took part in the experiment. Ten participants were excluded for the following reasons: bad pupil data quality (five participants), reaction times deviating more than two standard deviations from the average (five participants). The data of 42 healthy children (M_{age}=7;7 (years;months), range 6-8, 26 females, 3 left-handed) were used in the study. Participation was rewarded by a gift voucher and a certificate (children) or by money (adults, 10€/hour). All participants gave written informed consent (both children, parents and adults). Participants confirmed a normal or corrected-to-normal vision, normal hearing, no medication with effects on the nervous system, and no history of attention-related disorders. Handedness was measured with an abbreviated German version of the Oldfield Handedness Inventory (Oldfield, 1971). The project was approved by the local ethics committee.

4.2.2 Stimuli, procedure, data analysis, pupil data processing and behavioral data (reaction times, RTs)

All these paragraphs were identical to Study II, therefore not reported here. Please see Study II paragraph 3.2.2-3.2.6.

4.2.3 Statistical analysis

Analysis of Condition Effects

A paired samples t-test and Bayesian paired samples t-test were performed to compare PDR amplitudes in response to standard sounds, emotional novel and neutral novel sounds in the selected analysis mean amplitude time window (1.5-1.7 s) in children and in the time window (1.3-1.5 s) in adults. The same analysis was performed for the RTs in trials including standard sounds, emotional novel, and neutral novel sounds. All t-tests and Bayesian t-tests were performed using the R packages stats (v4.0.3, R Core Team, 2019) and BayesFactor (v0.9.12-4.2, Morey et al., 2011; Morey & Rouder, 2011; Rouder et al., 2009). Distraction effects (novel minus standard sounds) were analyzed using frequentist and Bayesian repeated measures ANOVAs with the within-subject factor condition (emotion vs. neutral) and between-subject factor group (children vs. adults). Novel minus standard amplitudes of the pupil dilation responses were analyzed using frequentist and Bayesian repeated measures ANOVAs with the within-subject factor condition (emotional novel vs. neutral novel) and between-subject factor group (children vs. adults). An alpha level of 0.05 was defined for all statistical tests and the η^2 effect size measure is reported. Bayes factors (BF_{10}, Mathôt, 2017) were estimated using 50,000 Monte-Carlo sampling iterations and a scaling factor r = 0.5 for fixed effects (corresponding to the default "medium" effect size prior for fixed effects in the R Bayes-Factor package, Morey et al., 2022 and r = 1 for the participant random effect (default "nuisance" prior for random effects in the R Bayes-Factor package).

4.3 Results

Table 6: *Mean and standard deviation of the child and the adult group (Study II)*

	Children		Adults	
Condition	**Mean (ms)**	**sd**	**Mean (ms)**	**sd**
Standard	575	86.3	407	44.9
Emotional novel	622	72.4	420	53.1
Neutral novel	639	87.4	431	53.7

Table 7: *T-tests novel vs. standard sound in the RTs and PDR (time window 1.5-1.7 s) in the child group*

RTs	**t**	**df**	**p**	**BF_{10}**
Emotional novel vs standard	4.87 (4.79)	41 (56)	**<.001 (<.001)**	1.2×10^3 (1.5×10^3)
Neutral novel vs standard	5.9 (7.58)	41 (56)	**<.001 (<.001)**	2.7×10^4 (2.8×10^7)
Emotional novel vs neutral novel	-2.67 (-3.92)	41 (56)	**<.001 (<.001)**	3.71 (98.24)
PDR				
Emotional novel vs standard	4.23 (11.2)	41 (56)	**<.001 (<.001)**	1.90×10^2 (1.01×10^{13})
Neutral novel vs standard	2.47 (7.90)	41 (56)	=.054 **(<.001)**	2.44 (9.04×10^7)
Emotional novel vs neutral novel	3.13 (5.86)	41 (56)	**=.01 (<.001)**	1.07×10^1 (5.77×10^4)

Note. Tests of the three a-priori hypotheses were conducted using Bonferroni adjusted alpha levels of .016 per test (.05/3). Significant results are marked in bold. Adults t-tests (t), p-values (p), degree of freedom (df) and Bayes Factory (BF_{10}) are reported in brackets.

Comparison distraction effects children vs. adults. The ANOVA with the between-subject factors group and within-subject factor condition evidenced a main effect of the factor group (F(1,97)= 15, p <.001, η^2 = .06), resulting from larger distraction effects in children compared to adults (t(151.31)= 3.5, p<.001; BF_{10}= 1.6 $\times 10^2$, Figure 11). A main effect of the factor condition (F(1.18,144.42)= 62.3, p <.001, η^2 = .26), resulting from larger distraction effects in neutral novel sounds vs. emotional novel (t(98)= 4.3, p<.001; BF_{10}= 3.7 $\times 10^2$, Table 6). An interaction of the factors group x condition was observed (F(1.18,144.42)= 11.01, p <.001, η^2 = .06), resulting from larger emotion effects in children compared to adults (post-hoc t-test comparison: emotion vs. neutral in children t(41)= -2.66, p =.011, BF_{10}= 3.71 and in adults t(56)= -3.92, p <.001, BF_{10}= 98.23; facilitation effect in children = 17 ms vs adults = 11 ms). The Bayesian analysis provided strong evidence for the model including the main effects of condition and group and their interaction ($BF_{10} = 2.7 \times 10^{18}$).

Comparison pupil dilations children vs. adults. The ANOVA with the between-subject factors group and within-subject factor condition evidenced a main effect of the factor group (F(1,97)= 7.85, p <.01, η^2 = .005), resulting from smaller pupil dilations in children compared to adults (see Table 7, Figure 12). A main effect of the factor condition (F(1.43,139.1)= 20, p <.001, η^2 = .08), resulting from larger pupil dilations in emotional novel sounds vs. neutral novel (t(98)= 6.27, p<.001; BF_{10}= 1.15 $\times 10^6$). An interaction of the factors group x condition was not observed (F(1.43,139.6)= 3.35, p =.054, η^2 = .01). The Bayesian analysis provided strong evidence for the model including the main effects of condition and group without the interaction (BF_{10} = 3.06 × 10^5).

Comparison mean baseline pupil diameter children vs. adults. The mean baseline pupil diameter was 5 mm in the children and 3.6 mm in the adult group. The mean baseline pupil diameter was significantly different in children compared to adults ($t(87.5)$= -5.12, p<.001; BF_{10}= 1.8 ×10^3), resulting from larger baseline pupil diameter in children compared to adults.

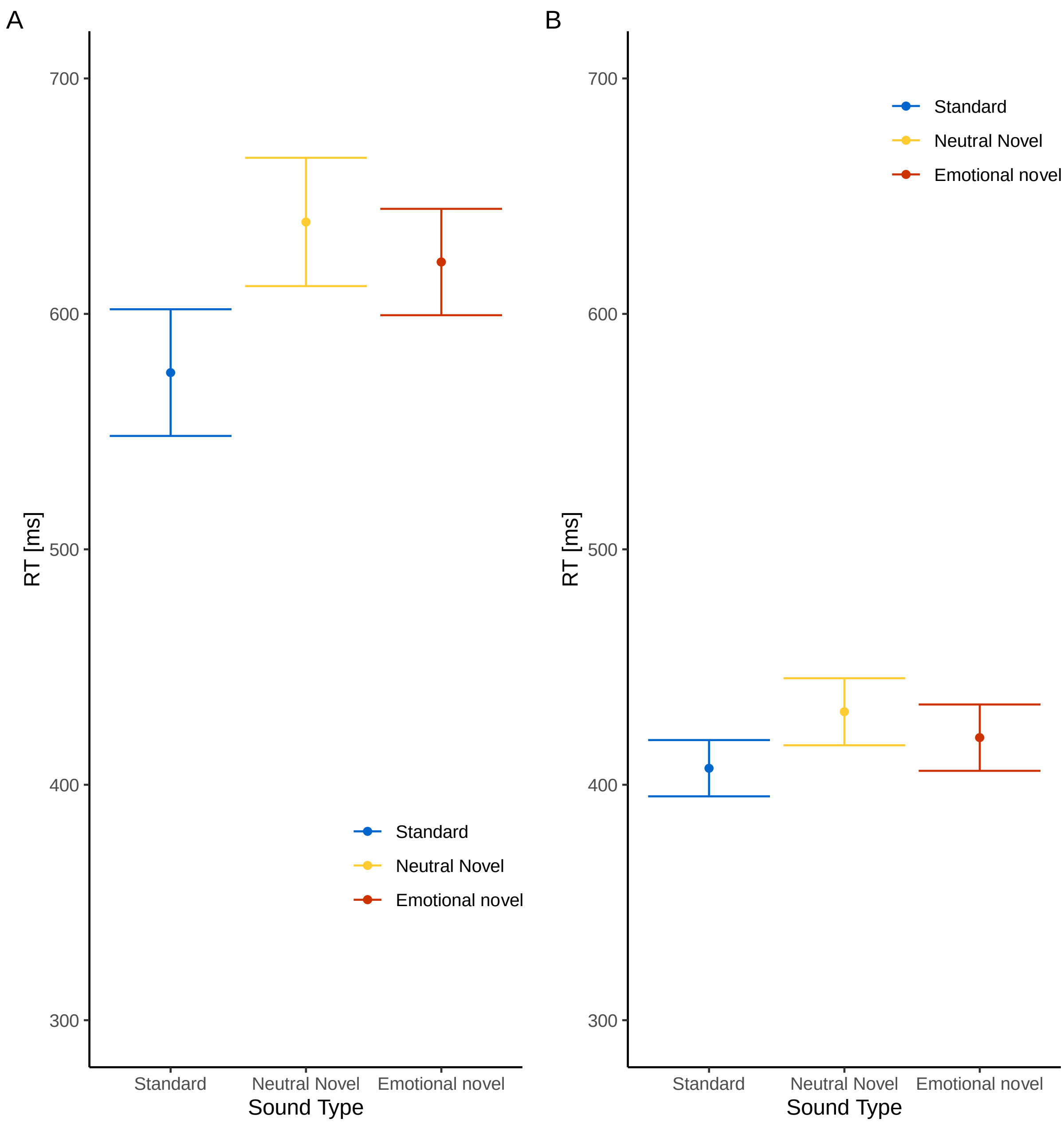

Figure 11: mean reaction times (RTs) for standard, neutral novel and emotional novel sounds in the child group (Panel A) and the adult group (Panel B). Novel sounds evoked increased RTs compared to standard sounds, demonstrating a distraction effect. Emotional novel sounds caused reduced RTs

compared to neutral novel sounds, indicating a facilitation effect. The plots show RTs with 95% confidence interval.

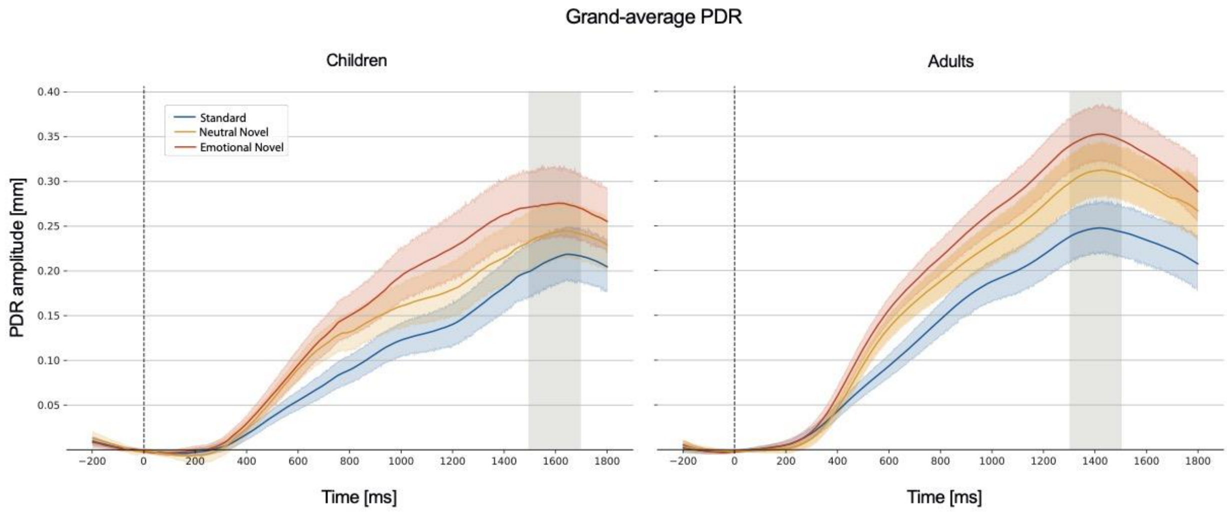

Figure 12: Pupil dilation response for standard, neutral novel and emotional novel sounds in children and adults. Novel sounds evoked larger PDRs compared to standard sounds (except for a lack of difference between neutral novel and standard sounds in children). Emotional novel sounds evoked larger PDR compared to neutral novel sounds, indicating an increase in arousal. Sound onset is at time point zero. The plots show PDRs with 95% confidence interval.

4.4 Discussion

The present study investigated the effect of emotional content of distractor sounds on performance and pupil dilation in children and adults. We applied an auditory-visual oddball paradigm, including emotionally highly arousing and neutral moderately arousing environmental novel sounds while children and adults focused on a visual categorization task. Novel sounds, compared to standard sounds, prolonged reaction times and evoked a transient pupil dilation in both children and adults (except for the PDR to novel sounds in children, which did not differ from the PDR to standard sounds). Reaction times were reduced after emotional compared to neutral novel sounds and the pupil was more dilated after emotional compared to neutral novel sounds in both groups. Children showed larger distraction effects and larger facilitation effects compared to adults. Because of the Covid-19 pandemic, only preliminary data are reported in this study, thus the relationship between faster RTs and increased pupil dilation for emotional novel sounds and the block analysis by means of mixed-model analysis were not analyzed (but will be considered when the children data collection will be completed).

Larger distraction effects in children compared to adults

Answering our first research question, responses to targets preceded by task-irrelevant novel sounds were prolonged compared to responses to targets preceded by standard sounds in both groups. The distraction effect was larger in children compared to adults. This results are in line with previous studies indicating that distraction of attention decreases with age (e.g., Hoyer et al., 2021; Wetzel et al., 2006, 2019, 2021). For example, younger children (6 years old) seem to improve attention control abilities compared to older children (9- to 10 – years old; Wetzel et al., 2019) and children are generally more distracted by task-irrelevant novel sounds than adults and show larger distraction effects (Wetzel et al., 2021). The present results are consistent with the maturational trajectory of the neuronal mechanisms underlying behavioral distraction. In fact, orienting and evaluation processes, associated with the ERP components P3a or novelty P3 (Escera et al., 2000; Polich, 2007), develop throughout childhood (Wetzel et al., 2006) and differ in children compared to adults (Bonmassar et al., 2020). Additionally, the observed age difference in distraction effects may be explained by the extended developmental course of executive functions until adolescence (Diamond, 2002). For example, children may own immature inhibitory abilities to shield themselves from task-irrelevant information.

Larger facilitation effects in children compared to adults

In the present study, task-irrelevant emotional novel sounds improved performance compared to neutral novel sounds in both children and adults. This finding is in line with previous adult studies in the auditory (Max et al., 2015) and visual modality (Lindström & Bohlin, 2011; Lorenzino & Caudek, 2015; Phelps et al., 2006; Zeelenberg & Bocanegra, 2010). In fact, emotional novel sounds are motivationally significant as they can signal crucial changes in the surrounding that might require behavioral responses and are processed with priority (Mather et al., 2016; Schupp et al., 2003). Nonetheless, the reduced distraction effect may originate from the different modality presentation of the target and the emotional stimulus as mentioned in Study II. Stimuli presented in the same modality may conflict with each other more than stimuli presented in different modalities (e.g., Duncan et al., 1997; Schupp et al., 2008).

Most interesting, in contrast to adults, this reduced distraction effect was larger in children, that is, responses to visual targets were speeded when the preceding sound was emotional novel. Within the theoretical framework of previous studies on adults (SanMiguel, Morgan, et al., 2010), I hypothesize that the alerting potential of emotional novel sounds may be larger in children than in adults (at least in the present paradigm and with this sample size). That is, the alerting aspect of emotional novel sounds exceeds the distracting aspect only in children. However, because the present finding is new in the literature and the presented analyses are only preliminary, this conclusion may be taken with caution. The decreased distraction effect may be the result of a smaller sample size and still larger variability in the children.

Pupil dilation responses to novelty and emotion

In the present study, transient pupil dilation responses (PDRs) were increased for novel sounds compared to standard sounds in adults and in children only the pupil dilation to the emotional novel sounds differed from the pupil dilation to the standard sounds (Table 7). That is, the pupil dilation response to the neutral novel sounds was similar to the one to the standard sounds. This finding may be explained due to the relatively small sample size and therefore the small amount of trials available for analysis in the children group (BF_{10}= 2.44). Previous studies on children and infants showed indeed a larger pupil dilation to neutral novel sounds compared to standard sounds (Bonmassar et al., 2020; Wetzel, Buttelmann, et al., 2016). Moreover, both groups showed larger pupil dilations in response to emotional novel sounds compared to neutral novel sounds (as e.g., Bonmassar et al., 2020; Wetzel 2016; Partala & Surakka, 2003; Widmann et al., 2018). Compared to a previous study from Wetzel and colleagues (2016), I could demonstrate that the emotion effect observed was not only a consequence of the physical characteristics and frequency spectrum of the emotional novel sounds. In fact, the relatively large number and the physical variability of emotional novel sounds used in the present study may have balanced these differences with each other and therefore have played a minimal role on the effect observed in the pupil. Moreover, the present results are coherent with my first study (Study I), also when the standard sound is environmental and not just a pure tone. A final new aspect of the present study is the presence of the emotional effect also in the context of fixed SOAs (stimulus-onset asynchrony), which may have served as a temporal cue for both the occurrence and the timing of the upcoming target also in children aged 6 to 8 years old (e.g., Hackley, 2009; Hackley & Valle-Inclán, 2003).

No statistical age difference was found in pupil dilations to emotional compared to neutral novel sounds, indicating that the underlying mechanisms of emotional processing and the maturation of the arousal level evoked by emotional novel sounds seem to be matured in middle childhood. This result is consistent with previous finding on a cortical level (Bonmassar et al., 2020, Study I) revealing an early development of emotional processing until middle childhood (Leventon et al., 2014; Solomon et al., 2012).

Baseline influences on the transient PDR

Transient pupil dilation responses were reduced in children compared to adults. This result is indeed similar to previous studies (for example Bonmassar et al., 2020, Study I). Similarly to the discussion of Study I, a potential explanation might find confirmation in systematic differences in tonic arousal between groups. Increasing tonic arousal and LC activity are expected with decreasing phasic responses (Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Kamp & Donchin, 2015). Moreover, higher tonic activity limits the range of the pupil dilation and is reflected by larger baseline pupil diameters (see e.g., Gilzenrat et al., 2010). To control for these differences, I tested for differences in baseline pupil diameter between age groups. The observed mean baseline pupil diameter was considerably larger in children than in adults (children = 5 mm; adults = 3.6 mm). As discussed in Study I (Bonmassar et al., 2020), the observed differences in the baseline pupil size may result from factors related to the experiment and the experimental situation. For example, children might have been more excited about the experiment and the categorization task compared to the adults or children might have been more focused on the task than adults. All possible explanations suppose higher tonic arousal that is displayed in larger baseline diameter and may reduce the transient sound-evoked phasic PDR (but see our analysis using the model by Watson & Yellott, 2012 and discussion in Study I). Additionally, the pupil diameter undergoes changes in the development, following a U-shape with a maximal peak around 15–20 years (MacLachlan & Howland, 2002; Wilhelm, 2011). However, further studies are needed to specify these relations in children.

Thus, my study could shed light on the effects of unexpected, task-irrelevant, and emotionally arousing sounds on both performance and pupil size in children aged 6 to 8 years old and replicate previous adults' findings.

Lastly, due to the Covid-19 pandemic I was not able to collect all the participants that were necessary for this study. However, as mentioned before I will finish to collect the data (N= 60) and analyze the hypothesized relation between the reduced distraction effect and the faster reaction times when emotional novel sounds are presented (as in Study II) and investigate the possible learning effect that children may show throughout the experimental session.

In sum, the preliminary results of the present study demonstrate that the attention control in the context of task-irrelevant novel sounds undergoes a long-term maturation during middle childhood, whereas the alerting potential of emotional novel sounds may be larger in children than in adults. However, the investigation of a relationship between decreased distraction effects and increased pupil dilation for emotional novel sounds in children compared to adults will be the next step as soon as the data collection will be completed. I am planning to analyze other important developmental aspects, such as short-term learning abilities on attention control throughout the experimental session (as for example in Wetzel et al., 2021).

5. Study IV: How do costs of attention orienting and benefits in enhanced arousal due to task-irrelevant novel and emotional auditory stimulation influence performance in a task? Are these effects visible also in an online study?

5.1 Introduction

The COVID-19 pandemic that began in 2020 has forced the research world to move from daily in person to online verbal communication and psychophysiological experiments were no exception. My working group and I had to pause our research and decide whether to move it online. Although many researchers have been trying to conduct studies remotely (mostly visual experiments or surveys), sufficient examination of the validity of "more complex" auditive online research is absent to date. To close this gap, I developed an online version of Study II to see if I could find any difference between the laboratory-experiment and its online version in the behavioral distraction effect driven by novel sounds and the facilitation effect driven by emotional novel sounds. As mentioned in the introduction of Study II, the distraction effect indicates slower reaction times after novel sounds compared to standard sounds (RTs after novel minus RTs after standard sounds), whereas the facilitation effect by emotional novel sound indicates faster RTs after emotional novel compared to neutral novel sounds (RTs after emotional novel minus RTs after neutral novel sounds). I aimed at investigating whether distraction and facilitation effects are valid even if the contextual setting is different and more likely represents a naturalistic, ecological and variable situation (as in an online experiment). Thus, the main research questions and hypotheses remained the same as the previous experiment, with the only difference that we could not apply a pupil dilation measurement. In the following I will just report additional or changed feature mainly in the setup, procedure and analysis. If not mentioned, everything was hold constant as in the version performed in the laboratory.

As pointed out by other recent studies, for example Finley et al, (2021), pro-and-con arguments have to be taken into consideration before planning an online study. Except for survey studies, online experimental studies tend to be fairly complex. This is most of the time desirable and unavoidable, because these experimental tasks aim at mimicking the complexity of real-life tasks. Indeed, one of the most convincing advantage of online experiments is the higher ecological validity compared to lab-based tasks (e.g., Dandurand et al., 2008). Unlike laboratory experiments, online research can accelerate recruiting time and data collection by reducing the many months to few weeks. This is particularly true for developmental studies and/or studies with clinical groups (for example, children with attentional disorders as ADHD). In fact, online studies are easier to schedule and run than in-lab studies because they don't require anyone to travel or coordinate schedules between participant and experimenter (so called "unmoderated" studies). The participant can decide when to take part in the study. Especially for rating stimuli or setting up a short pilot study that would take weeks in the lab, online experiments may accelerate actual experimental sessions (Lourenco & Tasimi, 2020; Sheskin et al., 2020). Thus, there is ample reason to continue conducting developmental research online even after the COVID-19 pandemic has passed. Moreover, unlike laboratory experiments, in which participants tend to be limited to residents around universities and labs (e.g., Henrich et al., 2010), in online studies researchers can recruit heterogeneous sample by expanding geographical borders. This aspect is critical also for developmental research: In-lab studies often recruit children from the families that close to the lab itself and that can plan the experiment session in the family schedule and that have expressed interest in participating in research. This way, the demographics of in-lab studies depends heavily on the lab's location and the willingness of the families. In more infrequent cases, experimenters are able to move part of the lab tools to other locations (for example in classrooms or kinder gardens). However, a number of concerns have to be taken in consideration when using online platforms: If the online experiment is planned to be "moderated" by the experimenter, it might be difficult to create a rapport between the experimenter and the participants. If the online experiment is planned to be "unmoderated", a particular set up has to be carefully designed (involving programming in JavaScript or even full web development). In unmoderated experiments, researchers have less control over the experimental environment (potential distractors occurring during the session) and are not able to give instructions or correct anything the participant does, unless the participant reports issues at the end of the experimental session. In these cases, additional work has to be invested to guarantee completion as intended. Other challenges may bring to poor data quality (due to technical differences between computers, software, keyboards, etc…), difficulties in the data acquisition (lack of attendance) and stimulus presentation (e.g. Chetverikov & Upravitelev, 2016). At last, some problems may arise from in-person to online research in terms of participant engagement (Dandurand et al., 2008) and response honesty (Shapiro et al., 2013).

Crucially though, certain tasks and forms of research, such as physiological experiments, will not or will be hard to be converted to an online and/or independent format. However, the benefits of online research may overcome or at least soften such disadvantages if data validity can be assured. Thus, it is imperative to accumulate data from online studies to determine its suitability for use in future research and in particular for developmental and clinical groups, which are typically hard to recruit.

To my knowledge, no previous study has proposed an online behavioral task on task-irrelevant emotional information during the COVID-19 epidemic lockdown. The occurring of sudden and unexpected stimuli outside the current focus of attention can indicate potentially relevant events in the environment (e.g., a crying child) and can capture attention. The involved orienting and evaluation mechanisms towards the sudden stimulus may drive to capacity limited processes (Näätänen, 1992) that can result in impaired performance in a task (distraction effect, e.g., Escera et al., 1998; Schröger & Wolff, 1998). However, some studies reported reduced distraction effects or even improved performance when task-irrelevant emotional information was presented (Lindström & Bohlin, 2011a; Lorenzino & Caudek, 2015; Max et al., 2015). This reduction of distraction or facilitation effect are discussed to be generated by an increased level of arousal caused by the emotional content of the distractor event (Max et al., 2015). This explanation is consistent with the models by Näätänen (1992) and Sokolov (1963) assuming an inclusion of costs of orienting and benefits of enhanced arousal in the orienting response (see also Hoyer et al., 2021). Therefore, I designed an auditory-visual oddball paradigm, containing emotional and neutral environmental novel sounds embedded in a sequence of repeated standard sounds while participants focused on a primary visual categorization task. Firstly, I expected slower reaction times to visual targets after novel sounds compared to standard sounds (distraction effect; Escera et al., 1998; Schröger & Wolff, 1998). Secondly, I hypothesized reduced distraction effects after emotional novel sounds compared to neutral novel sounds (facilitation effect, Max et al., 2015). Because distraction and facilitation effects have been reported and replicated many times and are discussed to be fairly strong, I was expecting similar results between online and lab-experimental session.

5.2 Methods

5.2.1 Participants

The data of 57 adult participants from Study II were used. A total of 109 participants expressed their willingness to participate in the online experiment. Of this large pool, 91 participants took part in the experiment. Twenty participants had problems with the completion of the experiment because of technical problems (e.g., audio stimuli not there, audio stopping before the end of the task, and/or self-reported audio or video issues). One participant was excluded because reaction times deviated more than two standard deviations from the average. Six other participants were excluded because they have not completed a temperament test not reported in this chapter. The data of 64 healthy adults (M_{age}=25.42 years, range 35:19, 39 females) were used in the study. Participation was volunteer and rewarded by money (10 €). All participants gave written electronical informed consent. They were free to withdraw from the study at any time by closing the browser, and were naïve to the rationale of the study. The project was approved by the local ethical committee.

5.2.2 Stimuli

Auditory stimuli. I used the same sounds as in Study II, see paragraph 3.2.2.

Visual stimuli. I used the same visual stimuli and task as in Study II, see page paragraph 3.2.2. The background landscapes' pictures were displayed at the center of a screen with a slightly variable size depending on the size of the screen used by the participants.

Apparatus and Software. The auditory stimuli were presented either via computer loudspeakers, or external loudspeakers located at the left and the right of the screen or headphones (not wireless). The entire study was scripted with the free software OpenSesame (Sebastiaan Mathôt et al., 2012). It was published on the Internet through the free software JATOS (version 3.5.4, https://ncdstudien.lin-magdeburg.de/jatos; (Lange et al., 2015) and run on a web server hosted by the institute Leibniz Institute for Neurobiology. I used the OSWeb Open Source Version 1.3.8.0 and its interaction with the free software JATOS was experimental and still under development.

5.2.3 Procedure

First, the invitation emails were sent with the information about the experiment and declaration of consent. After consent, the experiment link and with it, a paper or virtual version of the temperament test were mailed. Participants were asked to perform the experiment in a quiet room and to avoid external distractions during the entire session. After having started the experiment, participants were asked to set loudness at a comfortable level as if a person was talking to them in a normal conversation around 1 meter far away from themselves. Participants were asked to run the experiment only on laptops and personal computers (thus, no smartphones or tablets). Participants' recruitment was performed via participants' databases and social medias. The link for the experiment was personal and valid just for being used once, i.e. participants were allowed to do the experiment just once.

Task and Feedback. Same as in Study II, see paragraph 3.2.3.

Sound sequence. Same as in Study II, see paragraph 3.2.3.

Training blocks. Same as in Study II, see paragraph 3.2.3.

5.2.4 Data Analyses

The first two standard trials per block account for the formation of a predictive model of the upcoming stimuli (Bendixen et al., 2007). Whereas the two standard trials immediately following a novel sound could be affected by previous novel sound processing (Wetzel, 2015). Both were removed from all analyses. Incorrect responses, responses faster than 100 ms after target onset and missing responses (or responses given later than 2 s after target onset) were excluded from RT. Participants deviating more than 2 standard deviations from the average reaction times were excluded from the analysis.

5.2.5 Statistical analysis

Frequentist and Bayes analyses

Paired samples t-tests and Bayesian paired samples t-tests were performed to compare RTs in trials including standard sounds, emotional novel, and neutral novel sounds in the online study separately. Reaction times to standard and novel sounds were analyzed using frequentist and Bayesian repeated measures ANOVAs with the within-subject factor condition (standard vs emotional novel vs. neutral novel) and between-subject factor group (online vs. laboratory). Greenhouse–Geisser corrections were applied when appropriate. An alpha level of 0.05 was defined for all statistical tests and the η^2 effect size measure is reported.

All statistical tests were performed using the R packages stats (v4.0.3, R Core Team, 2019) and BayesFactor (v0.9.12-4.2, Morey et al., 2011; Morey & Rouder, 2011; Rouder et al., 2009). Bayes factors (BF_{10}, Mathôt, 2017) were estimated using 50,000 Monte-Carlo sampling iterations and a scaling factor r = 0.5 for fixed effects (corresponding to the default "medium" effect size prior for fixed effects in the R Bayes-Factor package, (Morey et al., 2022) and r = 1 for the participant random effect (default "nuisance" prior for random effects in the R Bayes-Factor package).

5.3 Results

Reaction times

Online experiment. Tests of the three a priori hypotheses were conducted using Bonferroni adjusted alpha levels of .016 per test (.05/3). The analysis of the reaction time responses showed a significant effect of novelty (emotional novel sounds vs. standard sounds: $t(63)$= 5.60, p= <.001, BF_{10}= 2.93×10^4; neutral novel sounds vs. standard sounds: $t(63)$= 5.16, p= <.001, BF_{10}=6.22×10^3, Figure 13 and Table 8), resulting from larger distraction effects for emotional and neutral novel sounds compared to standard sounds. No effect of emotion was found (emotional vs. neutral novel sounds: $t(63)$= -1.04, p= 0.30, BF_{10}= 0.23), indicating no decreased distraction effects after emotional novel sounds.

Comparison online and laboratory experiment. The analysis of reaction times between online and laboratory experiment evidenced a main effect of the factor group ($F(1,119)$= 104.78, p= <.001, η^2 = .45, Figure 13), resulting from slower reaction times in the online group compared to the laboratory group (online vs. laboratory: $t(343.32)$= 17.431, p <.001, BF_{10}= 6.57). A main effect of the factor condition ($F(1.84,219)$= 48.03, p <.001, η^2 = .02), resulting from slower reaction times in novel compared to standard sounds (emotional novel sounds vs. standard sounds: $t(120)$= 7.3, p= <.001, BF_{10}= 2.49×10^8; neutral novel sounds vs. standard sounds: $t(120)$= 8.47, p= <.001, BF_{10}= 9.75×10^{10}) and from faster reaction times in emotional compared to neutral sounds (emotional novel vs. neutral novel sounds: $t(120)$= -3.12, p= <.01, BF_{10}= 9.95). No interaction of the factors group x condition was observed ($F(1.84,219)$= 1.37, p= .0.25, η^2 = .001). The Bayesian analysis provided strong evidence for the model including the main effects of condition and group (BF_{10} = 9.54×10^{44}).

Table 8: *Descriptive statistic: mean reaction times (rt) in milliseconds (ms) and standard deviations (SD) for standard, emotional and neutral novel sounds, hits and error rates for the online and the laboratory experiment.*

	Online experiment		**Laboratory experiment**	
Sound type	**rt (ms)**	**SD**	**rt (ms)**	**SD**
Standard	520	63.7	407	44.9
Emotional novel	539	71.4	420	53.1
Neutral novel	542	81.6	431	53.7
	hits (%)	**error (%)**	**hits (%)**	**error (%)**
Standard	96	4	97.3	2.7
Emotional novel	96	4	97.6	2.4
Neutral novel	96.3	3.7	98.3	1.7

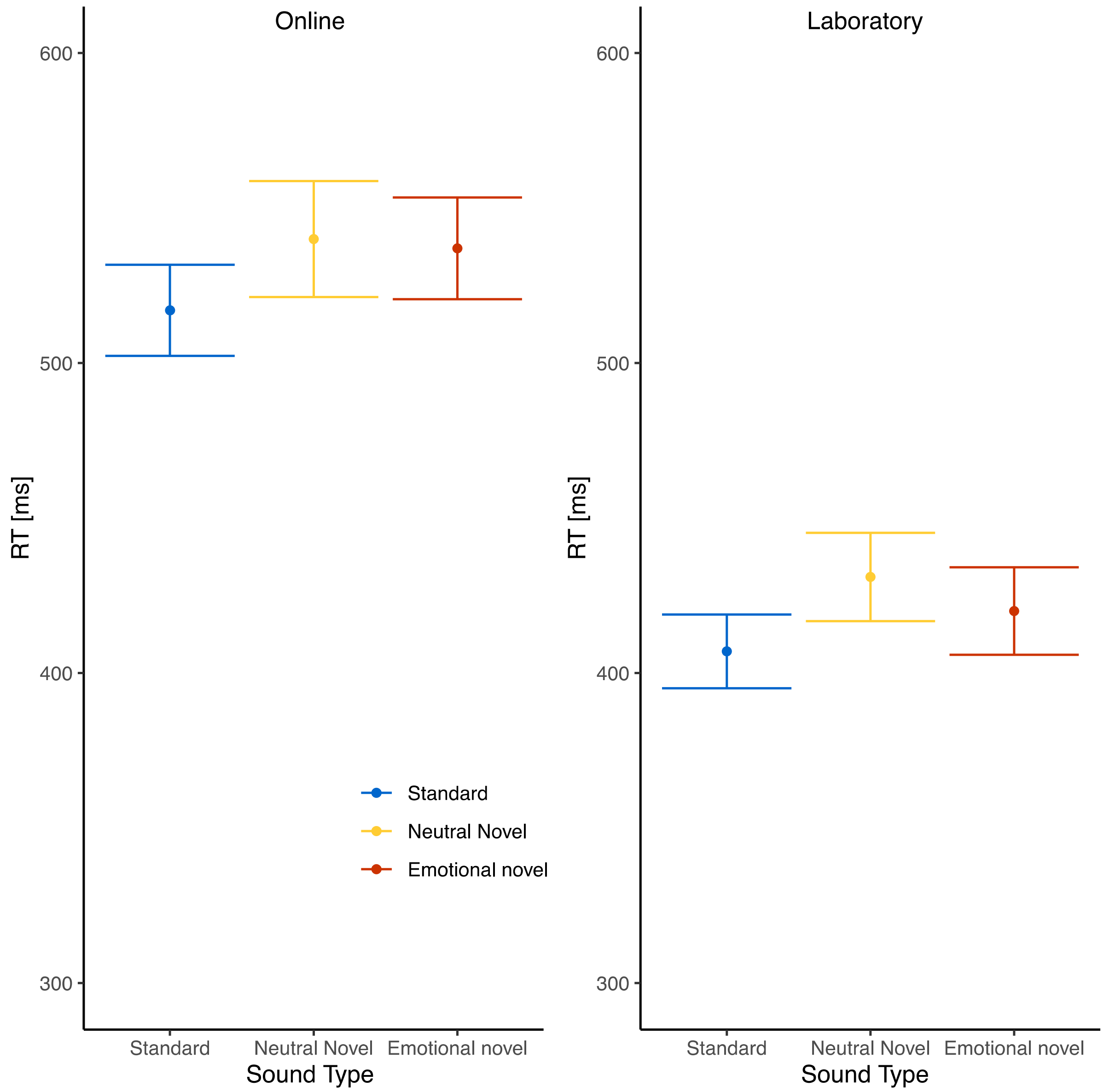

Figure 13: Mean reaction time (RT) in milliseconds for standard, neutral novel and emotional novel sounds in the online and lab-based experiment. Novel sounds evoked prolonged RTs compared to standard sounds, indicating a distraction effect in both experiments. Emotional novel sounds did not evoke faster RTs compared to neutral novel sounds in the online experiment, indicating absence of facilitation effect.

5.4 Discussion

The present online study aimed at replicating and comparing the main behavioral distraction and facilitation effects of Study II (under review in Cognition). It was an attempt to gain more information about the validity of online studies for prospectively developmental research during the COVID pandemic and beyond. By investigating the effectivity of this paradigm on online studies, researchers would have access to greater sample sizes with less resources and effort, especially when examining critical samples such as young children or clinical groups. In the present online study, novel sounds prolonged reaction times in a visual categorization task. Differently from the laboratory study, the distraction effect was not reduced in response to emotional compared to neutral novel sounds. Moreover, reaction times were significantly increased in the online study compared to the laboratory study.

Novel sounds impaired performance in a following categorization task compared to standard sounds. As demonstrated by current models on distraction of attention (Corbetta & Shulman, 2002; Escera & Corral, 2007; Näätänen, 1992; Posner, 1980, 2016; Sokolov, 1963), new, task-irrelevant and salient events, can involuntarily capture attention and can result in impaired performance. This distraction effect (difference between distractor and standard sound RTs) has been already observed in the auditory modality (Escera et al., 1998; Schröger & Wolff, 1998) and has been replicated many times in lab-experimental setups (Berti & Schröger, 2001, 2004; Parmentier, 2014; Wetzel et al., 2019). For the first time distraction effects to task-irrelevant novel sounds could be measured in an online study, showing the validity and solidity of such distraction effects and of such paradigms in more ecological and variable environments. Because experimental online tasks have to be planned in advance and cannot be controlled remotely, technical problems may occur more often than in in-lab experiments. Differences in hardware, software, and response modality are the most common (Chetverikov & Upravitelev, 2016), followed by differences in browsers, operating systems, and hardware (Bridges et al., 2020; Garaizar et al., 2014) and finally delays in the display of the stimuli and in the recording of the reaction times with a lag of 80-100 ms (Anwyl-Irvine et al., 2020; Bridges et al., 2020). A discussion of such timing issues is out of the scope of the present study, however, a very well documented report regarding the constraints of online behavioral tasks have been reported by Anwyl-Irvine et al. (2020). Nevertheless, distraction effects to task-irrelevant novel sounds seem to be consistent even in an online experiment. Accordingly, results show longer reaction times in the online compared to the in-lab study (slightly more than 100 ms, Table 8), whose delay was slightly higher than expected (110 ms of delay vs 80 ms from the literature, see Anwyl-Irvine et al., 2020). Despite this, results of the online study differ from the lab-based study in size of the distraction effect and variability (larger SDs, Table 8). Distraction effects between emotional novel and standard sounds were larger in the online study compared to the lab-based study (19 ms vs 13 ms), whereas the distraction effects between neutral novel and standard sounds were almost equal (22 ms vs. 24 ms). However, the variability in the online study was larger than in the lab-based experiment (differences between SDs 21.6 ms on average). Such variability may rely on the nature of online studies itself. As mentioned above, uncontrolled variables may have enhanced variability in the recording of reaction times.

Even though previous literature and our previous experiment demonstrated that emotional novel sounds can evoke speeded reaction times (Max et al., 2015; in the visual modality Lindström & Bohlin, 2011; Öhman et al., 2001; Phelps et al., 2006), no facilitation effect has been highlighted in this study. Overall, emotional novel sounds have a high potential to capture attention. This has been shown, for example, by studies focusing on the event-related component P3a in the EEG, which has been discussed to reflect orienting of attention (Alho et al., 1997; Escera, 1998; Pakarinen et al., 2014; Polich, 2007, Bonmassar et al., 2020; Thierry & Roberts, 2007; Widmann et al., 2018) . Moreover, emotional information is processed with priority (Mather et al., 2016) and therefore benefits from enhanced and faster processing (by means of phasic LC activity, see similar discussion in Study II). However, the interpretation of these results must be cautiously made. The decreased distraction effect by emotional novel sounds might be less solid and less stable than the distraction effect by novel sounds, and therefore not occurring in more variable data sets. Structural difficulties of online experiments may have misled the results: For example, the environmental conditions in which participants performed the task, external noises or visual events which appeared during the experiment or just some uncontrolled technical delays in the sounds' presentation.

This experiment indicates that online studies collecting behavioral responses might be carefully considered in the future as a valuable solution. This preliminary study might offer a new perspective on the applicability of an online experiment focused on the effect of task-irrelevant novel sounds on involuntary attention. Despite the above-mentioned limitations, online tasks might be used in future attention-related experiments to recruit many participants, and most importantly children and patients, in a relatively short amount of time. In particular, it might be very useful in the investigation of distraction effects, because these seem to be more stable than facilitation effects driven by emotional content.

Generally, the online assessment and monitoring of the psychological, cognitive and emotional functioning may be necessary, especially in the case of possible long-term maintenances of social restriction measurements. Notably, more research needs to be made in order to assess the reliability of online studies in general. Although my attempt is just an initial approach which was driven by an external critical and sudden situation, the topic of online research might be very relevant to data collection from particular populations, for example children or clinical groups, which are hard to recruit for testing in a laboratory environment.

6. Study V: Can the distractor-dependent PDR be a marker for the attentional mechanisms in a context of pitch deviants and environmental sounds?

6.1 Introduction

Distractor sounds can evoke an orienting of attention, impair performance in an ongoing task and increase the level of arousal for a fight or flight reaction. The orienting of attention and the increase in arousal are two aspects of the orienting response reflecting costs of attention distraction and benefits of arousal increase (Näätänen, 1992; Sokolov, 1963). The present study aimed to investigate the physiological basis (Pupil Dilation Response; PDR) of the underlying mechanisms for the orienting of attention toward deviant sounds differing in multiple auditory and location features. In children, pupillometry is easier to apply than neurophysiological or imaging techniques. Recent research highlighted important links between changes in pupil size and the activity of brain networks and their underlying cognitive functions (Eckstein et al., 2017a). Therefore, this study is intended to provide a basis for future studies, aiming at simplifying developmental research of attention control, particularly with clinical and sensitive age groups.

Processing of unexpected and task-irrelevant deviants reflected by PDRs

The unexpected presentation of a sound that deviates from the recent auditory past can induce attention orienting, therefore drawing the focus of attention away from the ongoing task (distraction effect, for review see (Escera et al., 2000; Schröger, 1997). This has been studied experimentally using versions of the auditory oddball paradigm. Oddball paradigms include a sequence of repeated standard sounds and infrequently, randomly presented oddball sounds that differ in one or more features from standard sounds (Figure 2). Attention orienting toward a deviant sound can be demonstrated either behaviorally by the disruption of an unrelated focal task (e.g., Hughes et al., 2007; Parmentier et al., 2008; Vachon et al., 2017), or physiologically by enhancement of attention-related components in the brain named event related potentials (ERP; e.g., Escera et al., 1998; Näätänen et al., 2001; Schröger & Wolff, 1998; Sokolov, 1963). A current model of attention, the three-stage model (Winkler et al., 2009; Winkler & Schröger, 2015), explains the orienting response as a consequence of the violation of sound predictions built up in the brain. Violations of predictions may signal potential important changes in the environment and are therefore processed with priority (Corbetta et al., 2008; Dayan & Yu, 2006; Sara & Bouret, 2012). Such violations may be represented by simple pitch deviants occurring in the environment. Attentional brain sensibility to pitch deviations is commonly investigated through EEG studies. Typical event-related components occurring in auditory oddball experiments reflect the attentional mechanisms underlying change detection (N1), sensory and memory-based deviance-detection process (MMN), orienting and evaluation processes of those deviant sounds (P3a) and reorienting processes (RON; for example, Berti & Schröger, 2001; Horváth, Roeber, et al., 2008; Näätänen et al., 2007; Näätänen & Picton, 1987; but also Horváth, Winkler, et al., 2008). Many studies relied on these physiological responses to explore distraction and orienting of attention, but recent studies have associated changes in pupil size with the orienting response as well (Nieuwenhuis et al., 2001). Pupil dilation can easily be evoked by presenting a rare unexpected stimulus (Marois et al., 2018; Murphy et al., 2014; Zekveld et al., 2018), a salient stimulus (defined as something noticeable compared with its surroundings or defined by novelty and uniqueness, deviating from the background, Liao et al., 2016), or by changes in the statistical distribution of the stimuli (Bala et al., 2020; Zhao et al., 2019). Salient auditory or visual stimuli can evoke pupil dilation also in animals (Montes-Lourido et al., 2021; Wang & Munoz, 2014; for review see, Aston-Jones & Cohen, 2005; Sara & Bouret, 2012; for an experiment see, Joshi et al., 2016; Selezneva et al., 2021) and humans (Bradley et al., 2012; Murphy et al., 2011, 2014).

Few studies tried to investigate if and how the pupil reacts when different types of deviant sounds are presented. In particular, Liao and colleagues examined in two experiments (1) whether the pupillary dilation can be used as a physiological index of auditory salience (Liao, Kidani, et al., 2016), (2) whether the mechanisms behind pupil response reflect novelty and/or stimulus salience or any temporary change per se (Liao, Yoneya, et al., 2016). In the first study oddballs were both artificial (1000 Hz, white noise) and environmental sounds. By letting participants rate the saliency of those sounds, the authors discover a very close relation between saliency and loudness. Interestingly, the authors showed that PDR is sensitive to salience (“easy to be noticed”) and that PDR indicates the individual’s subjective perception of loudness. In the second study oddballs (2000 Hz pure tone, burst of white noise) were presented against standard repeated pure tone (1000 Hz), while participants were performing a visual task. The authors showed that PDR is sensitive to novelty and suggest that the underlying mechanism may be the same violation detector that is related to attention orienting in the ERPs (component P3a). Nonetheless, in both experiments noise oddballs elicited stronger PDRs compared to tone oddballs. One explanation may rely on the large physical difference (e.g. spectrum, broadband) between the noise and the tone oddball from the standard tone. According to this, Wetzel and colleagues (2016) evidenced a different dilation of the pupil to pure tones and bursts of pink noise between children and adults. The pupil increased dilation to pitch deviants (750 Hz) in the adult group only, not in infants. Indeed, the authors explained that a pure tone deviant might not be as attention catching as a burst of noise for infants, probably because of its physical information or high arousing information. Other pupil studies focused on the investigation of the magnitude of size discrepancy between deviant and standard sounds (Boswijk et al., 2020; Marois et al., 2018; Montes-Lourido et al., 2021). For example, Marois et al. (2018), found larger PDR amplitudes in response to larger standard-deviant deviations in terms of pitch sounds.

All in all, pupil dilation responses may be used, alternatively to ERPs, as a marker of orienting response in auditory oddball paradigms in the context of deviant sounds differing in multiple auditory and location features.

PDR and LC-NE system

New, task-irrelevant distractor sounds evoke a biphasic waveform in the pupil dilation that has been hypothesized to reflect the activity of the parasympathetic and the sympathetic pathways of the autonomic nervous system (Steinhauer & Hakerem, 1992). Steinhauer & Hakerem assumed that the chronologically early component reflected the inhibition of the parasympathetically controlled sphincter muscle and that the later component controlled the activation of the sympathetically innervated dilator muscle. As these muscles operate antagonistically, both result in pupil dilation. This hypothesis has been recently experimentally tested (Carolina Bonmassar et al., 2020; Bradley et al., 2008; Wetzel, Schröger, et al., 2016; Widmann et al., 2018). Thus, sensory change detections and potentially relevant reactions associated with the orienting response activate the autonomic nervous system (ANS) and dilate the pupil. This enhanced activity of the ANS arise from the activation of the LC-NE system, which produces a rapid (phasic) reaction of the locus coeruleus and a consequent secretion of norepinephrine in several target regions responsible for sensory and motor sensitivity (for example, Aston-Jones & Cohen, 2005; Corbetta et al., 2008; Kahneman, 1975; Nieuwenhuis et al., 2005, 2011; Poe et al., 2020; Sara & Bouret, 2012). The role of the neuromodulator norepinephrine is critical in updating processes which drive to behavioral responses caused by the relevant event (Bouret & Sara, 2005; Sara & Bouret, 2012). The activity of the LC-NE system seems to be reflected by changes in pupil size (Aston-Jones & Cohen, 2005; Joshi et al., 2016). In fact, visual novel oddball stimuli evoked increased LC activity (Krebs et al., 2018) and pupil dilation (Murphy et al., 2014).

Despite growing interest and due to differences in experimental conditions, type of stimuli and participants (human vs animals), it remains unclear whether the pupil is a suitable marker of attention in the context of deviant sounds differing in multiple auditory and location features. Therefore, I designed an auditory-visual oddball paradigm, containing pitch and location oddball sounds which were previously used in EEG studies. Frequency, location, loudness and burst of noise deviant sounds were embedded in a sequence of repeated standard sounds while participants focused on a primary passive visual task. Based on results of previous studies with PDR (Liao, Kidani, et al., 2016; Liao, Yoneya, et al., 2016; Marois et al., 2018; Wetzel, Schröger, et al., 2016), I hypothesize that amplitudes of the PDR will be significantly larger for those deviants which largely differ from the standard sound in its frequency (750 Hz, 1000 Hz), broadband (i.e., pink noise) and loudness. Because of small physical differences between the small-deviance (525 Hz; Marois et al., 2018; Wetzel et al., 2006) and the low-loudness deviant sounds with the standard sound, I expect to observe no difference. Moreover, it remained an open question if pupil dilation was sensitive to different location sources.

6.2 Methods

6.2.1 Participants

A total of 65 participants took part in the experiment. The data of 65 healthy adults (M_{age}=25.8 years, range 34-18, 35 females, 3 left-handed) were used in the study. Participation was rewarded by money (7€/hour). All participants gave written consent. Participants confirmed a normal or corrected-to-normal vision, no medication with effects on the nervous system, and no history of hearing disorders. Handedness was measured with a shortened German version of the Oldfield Handedness Inventory (Oldfield, 1971). The project was approved by the local ethical committee.

6.2.2 Stimuli

Auditory stimuli. A total of 7 deviant and one standard sound were produced with MATLAB. Three frequency deviants (525 Hz, 750 Hz, 1000 Hz), two loudness deviants (low-loudness (58 dB), high-loudness (69.7 dB), modelled with (Moore & Glasberg, 2004), a pink noise and a location deviant sound (right or left). The complex standard sound was comprised of sinusoids with a fundamental frequency of 500 Hz including the second and third harmonic attenuated by -3 and -6 dB, respectively. Sounds had a duration of 800ms including faded ends of 10ms. They were presented at a loudness of 59.8 dB SPL (measured with PAA3 PHONIC Handheld audio analyzer, Phonic Corporation, Taipei, Taiwan). Loudness of sounds was equalized with root mean square normalization. All sounds were presented from one of the two loudspeakers (for example, right), except for the location deviant which was presented from the other loudspeaker (for example, left). The sound presentation was alternated every 70-trial-block, that is the first 70 trials sounds were presented from the right loudspeaker except for the location deviant (left), from trial 71 sounds were presented from the left loudspeaker except for the location deviant (right) and so on.

Visual stimuli. To draw attention away from sounds the same sequence of silent animated cartoons were presented to the subjects. The cartoons dealt with the story of a mole experiencing adventures. The video was displayed at the center of a screen with a size of 19 cm wide and 15,5 cm high on a grey background screen with a mean luminance of 5.11 cd/m2.

Apparatus and Software. The auditory stimuli were presented via loudspeakers (Bose Companion 2 serie III Multimedia speaker system) located at the left and the right of the screen. The visual stimuli were presented at VIEWPixx/EEG Display (VPixx Technologies Inc.) Resolution 1920(H)x1080(V)-23,6-inch display size (diagonal), refresh rate 120Hz. The distance from the participants' eyes to the screen was approximately 60 cm. The experimental stimulation was presented via Psychtoolbox (Version 3.0.15, Kleiner et al., 2007) using Octave (Linux, Version 4.0.0).

6.2.3 Procedure

Participants were instructed to focus on a silent video clip and to ignore the presented oddball sound sequence including frequency deviants (525 Hz, 750 Hz, 1000 Hz), loudness deviants (low-loudness, high-loudness), pink noise and a location deviant sounds (right or left). The task was to focus and watch a silent videoclip showing the adventures of a mole. Participants sat on a recliner chair in an acoustically attenuated and electromagnetically shielded cabin. Illuminance of the cabin was held constant at a level of 61.1lx (measured with MAVOLUX 5032B USB, GOSSEN Foto- and Lichtmesstechnik GmbH, Nürnberg, Germany). The block started with a five-point eye-tracker calibration and validation procedure. A total of 350 sounds were presented in one block with a randomized stimulus onset asynchrony (SOA, varying from 1800 to 2400 with 200 ms steps). If a break was needed, the experiment could have been paused every 70 trials. In the block, 80% of the trials consisted of a standard sound (280) and 20% of a deviant sound (70). The sound sequence was pseudo-randomized and unique for each participant, balancing out any systematical variation between the brightness in the video clip and the sound types. The sounds were randomized in the 70-trial-blocks (for the eventual breaks) so that each deviant was repeated two times but the same deviant was not repeated two times consecutively. Each deviant was followed by at least two standard sounds. Each deviant was repeated 10 times in total. The experiment lasted 12 minutes excluding breaks.

6.2.4 Data Analysis

The first two standard trials per block are required for the formation of a predictive model of the upcoming stimuli (Bendixen et al., 2007). Whereas the two standard trials immediately following a novel sound could be affected by previous novel sound processing (Wetzel, 2015). Both were removed from the analyses.

Pupil Data recording

The pupil diameter of both eyes was recorded with an infrared EyeLink Portable Duo eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada). The eye tracking was set up in remote mode at a sampling rate of 500 Hz.

Pupil size analysis was implemented with MATLAB software. As suggested by Marchak and Steinhauer (2011), the eye tracker pupil diameter digital counts were converted to mm. Eye saccade and blink information were provided by the eye tracker. Partial blinks were detected during post-processing from the smoothed velocity times series by an additional custom function, i.e., pupil diameter changes exceeding 20 mm/s including a 50 ms pre-blink and a 100 ms post-blink interval (Merritt et al., 1994). We applied Kret et al.'s (2019) dynamic offset algorithm to average data from both eyes. Isolated data segments between blinks or missing data shorter than 10 ms were considered missing data. Subsequently, segments with blinks or missing data shorter than 1 s were interpolated with linear interpolation, longer segments were removed from the continuous data. Data were segmented in epochs of 2 s of duration (including a -0.2 to 0 s pre-stimulus baseline) were baseline corrected by subtracting the mean amplitude of the baseline period (-0.2 to 0.2 s) from each epoch. The mean PDRs were computed in the time windows around the peaks between 0.5-0.9 and 1.2-1.6 s on the grand averages, representing the two components of the pupil dilation (Steinhauer & Hakerem, 1992).

6.2.5 Statistical analysis

Frequentist and Bayesian analyses

PDR different amplitudes (deviant minus standard sound) were analyzed using frequentist and Bayesian repeated measures ANOVAs with the within-subject factor condition (525 Hz, 750 Hz, 1000 Hz, low-loudness, high-loudness, burst of pink noise and location deviant) and time window (early 0.5-0.9 s vs. late 1.2-1.6 s). For the frequentist Greenhouse-Geisser corrected ANOVA an alpha-level of .05 was defined for all statistical tests and the η2 effect size measure is reported. In case of statistically significant interactions further analyses for within-subject factors were computed by Bonferroni corrected t-test. Statistical analysis was conducted using the R package stats (v4.0.3). All frequentist and Bayesian analysis were performed using the R packages stats (v4.0.3, R Core Team, 2019) and BayesFactor (v0.9.12-4.2, Morey et al., 2011; Morey & Rouder, 2011; Rouder et al., 2009). Bayes factors (BF_{10}, Mathôt, 2017) were estimated using 50,000 Monte-Carlo sampling iterations and a scaling factor r = 0.5 for fixed effects (corresponding to the default “medium” effect size prior for fixed effects in the R Bayes-Factor package, Morey et al., 2022) and r = 1 for the participant random effect (default “nuisance” prior for random effects in the R Bayes-Factor package).

6.3 Results

ANOVA

The analyses of the deviant sounds in the early and late time window revealed a main effect of condition ($F(5.12, 327.73) = 19.88$, $p < .001$, η2 = .16, Figure 14, Table 9Table 10), resulting from different amplitudes of the pupil dilation response to the different deviant sounds. In particular the larger amplitude was evoked by the pink noise, followed by the 1000 Hz, the 750 Hz, high-loudness and location deviant. For the remaining deviants, the difference-amplitudes of the pupil dilation (deviant minus standard) were not significantly larger. An interaction effect of the factor condition and time window ($F(5.2, 332.72) = 6.77$, $p < .001$, η2 = .01), resulting from differential difference-amplitudes of the pupil dilation (deviant minus standard) in the two time windows. No main effect time window was shown ($F(1,64) = 1.01$, p =0.32, η2 = .00). The Bayesian analysis provided a strong evidence for the model including the main effect condition (BF_{10}= 1.47 x 10^{28}), therefore the frequentist interaction should be cautiously interpreted.

Pairwise t-tests with Bonferroni correction

The analysis of the post hoc pairwise t-tests evidenced differences between time windows in the high-loudness (t(64)= -2.26, p= .03) and in the pink noise (t(64)= -4.43, p < .001), resulting from larger pupil dilations in the late compared to the early time window. The low-loudness evoked larger pupil dilations in the early compared to the late time window (t(64)= 2.11, p= .04). For the other deviants, no difference was highlighted between time windows.

Table 9: *T-tests deviant vs. standard sound in the early time window (500-900 ms)*

Condition	**t**	**df**	**p**	**BF_{10}**
525 Hz vs standard	0.70	64	0.35	0.17
750 Hz vs standard	3.80	64	**<.001**	69.31
1000 Hz vs standard	4. 25	64	**<.001**	2.92×10^2
Low-loudness Hz vs standard	0.52	64	0.60	0.15
High-loudness vs standard	2	64	**0.05**	0.87
Pink noise vs standard	12.20	64	**<.001**	1.24×10^{15}
location vs standard	3.51	64	**<.001**	31.15

Table 10: *T-tests deviant vs. standard sound in the late time window (1200-1600 ms)*

Condition	**t**	**df**	**p**	**BF_{10}**
525 Hz vs standard	0.12	64	0.90	0.14
750 Hz vs standard	2.83	64	**<.05**	5.18
1000 Hz vs standard	4.22	64	**<.05**	2.7×10^2
Low-loudness Hz vs standard	-1.04	64	0.30	0.23
High-loudness vs standard	2.60	64	**0.01**	2.95
Pink noise vs standard	11.60	64	**<.001**	2.58×10^{14}
location vs standard	1.74	64	0.08	0.57

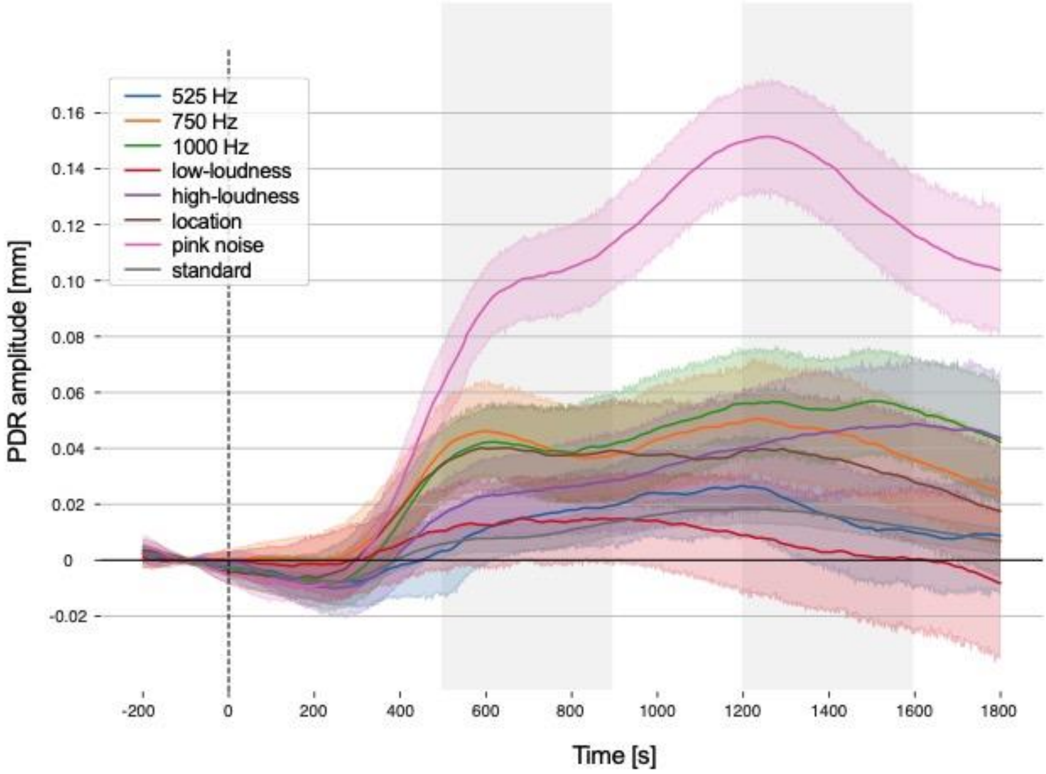

Figure 14: Grand-average pupil dilation responses (PDRs) for the deviant sounds and standard sounds. Sound onset is at time point zero. Shading indicates the 95% confidence interval. The gray window indicates the time window used for analysis. The pink noise, followed by the 1000 Hz, the 750 Hz evoked larger pupil amplitudes, whereas 525 Hz, low-loudness did not evoke larger pupil dilations. Controversial findings are observed for the location deviant, the high-loudness and the low-loudness deviant.

6.4 Discussion

For the first time the present oddball study showed the impact of different artificial unexpected and task-irrelevant deviant sounds on the pupil dilation response in adults watching a silent video. First, the 1000 Hz, the 750 Hz frequency deviants and the pink noise caused increased amplitudes of attention-related PDRs compared to standard sounds in both time windows. The lower frequency and the low-loudness deviant did not evoke larger pupil dilations in any of the time windows. Controversial findings are discussed for the location deviant, the high-loudness and the low-loudness deviant. The pupil responses in two time windows showed that the high-loudness deviant and the pink noise evoked larger PDRs in the late time window, whereas the low-loudness deviant evoked PDRs were larger in the early time window. However, the latter results should be interpreted cautiously, inasmuch the Bayes analysis did not supported it. The purpose of the present study was to investigate the physiological basis (Pupil Dilation Response; PDR) of the underlying mechanisms for the orienting of attention toward deviant sounds differing in multiple auditory and location features. Additional knowledge is indeed needed to establish a solid background demonstrating that pupil dilation can be used as a marker of attention.

Overall previous results indicate that PDR is not only sensitive to the acoustic change, but also to the content of the change (Bonmassar et al., 2020; Wetzel, Buttelmann, et al., 2016; Widmann et al., 2018) and physical features (e.g. spectrum, broadband; Liao, Yoneya, et al., 2016; Wetzel, Schröger, et al., 2016). They suggest that the PDR can be used as a physiological index of the orienting reflex to the detection of a deviant, novel and salient auditory event and comprises costs of orienting of attention and benefits of arousal enhancement (Nieuwenhuis et al., 2011). The present study extended our understanding of the pupil responses to auditory deviance. According to previous literature, the PDRs to the deviant stimuli were stronger for the noise burst and the higher frequency oddballs (1000 Hz, 750 Hz) than to the standard tone (500 Hz; Liao, Kidani, et al., 2016; Marois et al., 2018; Wetzel, Schröger, et al., 2016). One explanation may be that deviants providing a large difference of physical information from the standard sound enhance the level of arousal via the autonomic nervous system (Bonmassar et al., 2020; Liao, Kidani, et al., 2016; Liao, Yoneya, et al., 2016; Steinhauer & Hakerem, 1992; Widmann et al., 2018). In particular, the more the deviant sound is dissimilar to the standard tone, the more dilates the pupil. Several studies confirmed that novel oddball sounds evoke a transient dilation of the pupil (Bonmassar et al., 2020; Liao, Kidani, et al., 2016; Liao, Yoneya, et al., 2016; Wetzel, Schröger, et al., 2016; Widmann et al., 2018). These findings are coherent with previous EEG studies observing typical ERPs to change discrimination and evaluation of the changed or new sound in the auditory stimulation. In these studies, brain activity to deviants showed the components MMN, P3a and RON, which are believed to represent different stages in the processing of deviant sounds (the three stage model of attention, Berti & Schröger, 2001). Additional evidence is reported in distraction effects to deviating sounds or sound features which are not relevant for the task at hand (for example, Bendixen et al., 2007; Roeber et al., 2003). Because the elicitation of these brain components and distraction effects to deviancy is assumed to provide evidence for attentional shift, the similar pupil behavior to these stimuli may also be interpreted as attentional switch toward deviancy. The pupil did not react to the small frequency deviant (525 Hz) as it was very similar to the standard sound. This result is similar to a previous physiological result on the EEG (Wetzel et al., 2006). In this study, the authors did not find a P3a component to a small deviant when adults had to ignore the sounds and focus the attention on a videoclip. In these terms, results suggest that adults were able to ignore sounds as instructed and additionally, to shield themselves from any auditory distraction presented when this was very similar to the standard sound. Similarly, participants may have been able to protect themselves from auditory distractions, which were similar to the standard sound. In the same way, the low-loudness deviant did not evoke a larger pupil response compared to the standard sound, presumably because such stimulus did not represent potential behavioral relevance and therefore, was easy to ignore. Our findings of the pupillary dilation responses to the high-loudness deviant were inconsistent. Even if the frequentist analysis supported an enhanced dilation of the pupil to the deviant in both time windows, the Bayes analysis did not show enough evidence to support this hypothesis. Previous studies showed that pupillary dilation may be affected by the loudness of deviant oddballs. As previously demonstrated by Liao et al. (2016) and Boswijk et al. (2020), loudness can specifically elicit larger pupil sizes, even within different sound types (environmental sounds and spoken sentences, respectively). Usually salient or more motivationally significant stimuli tend to catch the attention and therefore evoke a pupillary response (Liao, Yoneya, et al., 2016), due to enhanced arousal level (Bonmassar et al., 2020; Murphy et al., 2011; Widmann et al., 2018). Loudness-induced PDR has been showed in early studies as well, for example Nunnally et al., (1967) illustrated increased pupil responses to increasingly louder tones in the first half of a sound sequence with a peak dilation for the loudest sound. In the second half of the sequence instead, pupil dilations to tones with the same loudness presented in the first half of the sequence were smaller in size. Further research is needed to understand if pupil dilation is sensitive to changes in loudness features of auditory stimuli.

On the exploratory side of this study, our location deviant evoked a greater PDR compared to the standard sound in the early time window only. However, this larger pupil dilation was not significantly larger than the amplitude in the late time window, making this result hard to interpret. I am not aware of previous studies analyzing such feature in the pupil dilation in humans, so I can report a very speculative deduction from my work. Classically, location deviants are believed to be effective in evoking involuntary shifts of attention in oddball paradigms (for example, Paavilainen et al., 1989; Winkler et al., 1998; Roeber et al., 2003). Previous EEG studies already demonstrated that auditory distraction can be initiated by task-irrelevant deviations in location of sounds by reporting enhanced amplitudes in MMR/MMN (for example, Näätänen et al., 2004; Pakarinen et al., 2007; Roeber et al., 2003). In my study, one could speculate that the pupil may be sensitive to changes in the source presentation at an early stage of dilation, possibly indicating the activation of the parasympathetic nervous system, which usually drives to constriction of the pupil over time (Steinhauer & Hackerem, 1992). However, given the inconsistent nature of this result, interpretations should be made carefully. Definitely, more research is needed to shed light on this feature.

Three deviant sounds showed a significant difference in their difference-amplitude (novel minus standard) between time windows. The following results should be cautiously interpreted because the Bayesian analysis did not support the model with the interaction condition and time window as best model. First, the pink noise evoked a pupil response that was significantly larger in the late time window, possibly indicating the activation of the sympathetic nervous system (Bonmassar et al., 2020; Steinhauer & Hakerem, 1992; Widmann et al., 2018). Spectral acoustic characteristics of the deviants seem to influence the dilation of the pupil as well. For example, the pink noise may activate a wider range of frequency channels at a certain level of auditory processing compared to the channels activated already by the standard sound. Whereas the frequency deviants activate a smaller number of spectral auditory channels, which do not strongly differ in number from the ones activated by the standard tone. An enhanced PDR may be influenced also by the number of newly activated channels. These results are in line with the findings of Liao and colleagues (Liao, Kidani, et al., 2016), who demonstrated that a burst of white noise is perceived louder than a 1000Hz pure tone when the sound pressure level is hold constant and causes a larger PDR. At last, the greater dilation for the pink noise may find its explanation on a property of the superior colliculus (SC) which is involved in pupillary responses (Netser et al., 2010; Wang et al., 2012) and responds more robustly to broadband than to narrowband stimuli (King & Carlile, 1994; Wise & Irvine, 1983). Based on the SC responses on different acoustic spectra, it may be reasonable to suppose that different stimulations of the superior colliculus would result in different pupillary responses. Second, the amplitude of the high-loudness deviant evoked PDR was significantly larger in the late time window, possibly indicating the activation of the sympathetic nervous system (Steinhauer & Hackerem, 1992; Widmann et al., 2018, Bonmassar et al., 2020). As mentioned above, previous pupillary studies (Liao et al., 2016; Boswijk et al., 2020) demonstrated pupil's sensitivity to loudness. This may be explained because louder sounds are usually more salient or more motivationally significant and are able to enhance the arousal level (Widmann et al., 2018; Bonmassar et al., 2020; Murphy et al., 2011). The arousal level is indeed controlled by the sympathetic nervous system and therefore reflected by the later component of the pupil dilation. Third, even though the low-loudness deviant did not evoke a larger amplitude neither in the early nor in the late time window compared to the standard sound, its amplitude resulted to be larger in the early time window compared to the late one. This pattern of dilation may possibly indicate the activation of the parasympathetic nervous system, which usually drives to constriction of the pupil over time (Steinhauer & Hackerem, 1992; Widmann et al., 2018, Bonmassar et al., 2020).

In conclusion, unexpected and task-irrelevant noise, higher frequency deviant (500 and 250 Hz deviation) and increased loudness sounds elicit a significant PDR in adults that has previously been linked to attention-related brain activity (e.g., Murphy et al., 2014). In contrast, lower frequency and lower loudness did not evoke such a response in adults. These differences may reflect different activations of the LC-NE system. Somehow questionable remains the lack of dilation in the late time window of the location deviant. All in all, my study provides new insights in the processing of attention catching stimuli through pupillometry. Pupillometry showed similar responses to deviancy as more commonly used event-related brain components such as MMN and P3a. Because pupillometry is discussed to share common processes with the component P3a (see Study I), it may be used as marker of attention in oddball paradigms. More research is definitely needed to investigate potential similar pattern of activation (1) between attention-related ERPs and PDR (MMN, P3a, RON); (2) between adults and infants or children (as for example in Wetzel, Buttelmann, et al., 2016) and (3) between typically developed children and children with attentional disorder (for example ADHD patients). The usage of pupillometry opens new perspectives for the investigation of attention mechanisms commonly studied with other methodologies, for example EEG, and enables research in particularly challenging groups such as infants. Testing this new method on adults and then on children will bring developmental research a step further in the investigation of attention development and attentional disorders. Because pupillometry's setup is very fast and easily, it may become a valuable substitute of well-known methodologies which investigate auditory distraction of attention, involuntary attention or error predictions.

7. General discussion and conclusions

In the present dissertation, I have addressed key developmental aspects of the orienting of auditory attention to emotional and neutral task-irrelevant novel sounds and discussed its relation with costs and benefits related to the performance in a task. Moreover, I conducted a fruitful inspection of alternative methods (i.e., pupillometry) to currently used ones (i.e., EEG) to gain better understanding of attention-related processes in children and potentially clinical groups (for example infants, children with attention or phobic disorders). Overall, results showed that children aged 8 to 10 years old are more sensitive to the occurrence of novel sounds but are able to process emotional novel sounds at an advanced level both on a behavioral and cortical level. Furthermore, the pupil can be used as an alternative method in attentional developmental research.

In the following I will summarize the results I collected in the single studies and then discuss the subsumption of these results in the attentional three-stage model of distraction of attention (Escera et al., 1998; Schröger et al., 2000) as well as give an impression of future perspectives.

7.1 Answering our research questions

I. Which steps (early/late P3a, LDN) of involuntary attention will be influenced by auditory emotional novels in elementary school children? Which developmental differences can be observed between children and adults?

In Study I, I examined how orienting and evaluation of attention develop in middle childhood and if pupil dilation responses can be used as a marker of attention. The first study served as a baseline for the following studies in this thesis on both children and adults. I demonstrated that children between the age of 7 and 10 years showed immature mechanisms involved in auditory involuntary attention in the presence of new events. Emotional versus neutral novel sounds evoked increased responses in the ERPs and in the PDR in both age groups. This showed the increased impact of emotional novel sounds on attention mechanisms and the lack of age differences indicated an advanced level of emotional information processing in children. I showed that the phasic pupil dilation response reflects the arousal level evoked by the processing of task-irrelevant novel sounds and their emotional content also in elementary school children. The similar pattern of responses in the pupil dilation and in the well-known ERP indicators of attentional orienting supports the hypotheses of neuro-physiological interrelations of involved brain networks and their developmental pathway was illustrated in this experiment. Even if attention-related ERPs might be temporally more precise and more sensitive to age-related changes in auditory attention processes, pupillometry seems to be a suitable and more manageable method to investigate orienting of attention and systems related to it such as the arousal level, the activity of the autonomic nervous system (ANS) and the LC-NE system in young children.

II. How do costs of attention orienting and benefits in enhanced arousal evoked by task-irrelevant novel and emotional auditory stimulation influence performance in a task? Which age differences can be observed between children and adults?

In Study II and III, I examined costs of orienting of attention toward a distracting event and benefits of arousal enhancement evoked by the processing of such event. In particular, I hypothesized a relationship between faster RTs and larger PDRs in trials where emotional information was presented. For the first time, I demonstrated that highly arousing emotional novel sounds were able to reduce distraction effects and that this effect was larger in children aged between 6 and 8 years compared to adults. I replicated results of Study I, showing that pupil dilation can be used as an indicator of arousal in response to emotional and neutral unexpected and task-irrelevant novel sounds even in children. However, preliminary data showed no difference between PDR to neutral novel sounds and standard sounds in children (possibly due to lack of power). A direct relationship between larger PDRs (i.e., more arousal) and an acceleration of reaction times in the emotional trials was not confirmed by the data collected on adults (will be analyzed in children when the data collection will be completed). This might indicate that both performance and pupil diameter reflect partially distinct processes. The locus coeruleus may embody a common antecedent for both effects, spreading norepinephrine to cortical areas involved in attention control and control of the pupil.

III. How do costs of attention orienting and benefits in enhanced arousal due to task-irrelevant novel and emotional auditory stimulation influence performance in a task? Are these effects visible also in an online study?

In Study IV, I extended the current literature on the topic of costs of orienting of attention toward a distracting event and benefits of arousal enhancement evoked by the processing of such event in an online study. Even in uncontrolled but more ecological environments, distraction effects seem to be very stable. However, the reduced distraction effects due to emotional novel sounds seem to be cancelled out. I discussed several reasons (see paragraph 5), for example, the higher variability in response times or delays in the sound presentation may have neutralized the beneficial effect of higher arousal by emotional novel sounds in the population tested. However, online studies seem to be a suitable method for investigating distraction effects. Thus, the online application of tasks may help collecting data more quickly in crucial age or clinical groups (children and patients).

IV. Can the distractor-dependent PDR be a marker for the attentional mechanisms in a context of pitch deviants and environmental sounds?

In Study V, I investigated whether pupil responses reflected the same mechanisms, that have been investigated in common EEG studies on auditory attention (e.g., MMN). A better understanding of the sensitivity of the pupil toward deviant stimuli would help its usage in critical groups, for example in infants. All in all, unexpected and task-irrelevant noise, moderate to strong frequency deviants from the standard sound and high-loudness sounds elicited significant PDRs in adults. In contrast, small frequency deviants from the standard sound, low-loudness and location deviants did not evoke such responses in adults. These differences may derive from variable activation of the LC-NE system due to more or less motivationally significant deviants. That is, high significant deviants may be classified as more relevant and therefore increase the pupil dilation, whereas less significant deviants may be classified less relevant resulting in less pupil dilation. Even though more research is needed, the usage of pupillometry opens new perspectives for the investigation of attention mechanisms which are commonly investigated with EEG. Of particular relevance would be the study of attention related paradigm in developmental research by means of pupillometry.

7.2 Integration of results within current neurophysiological models of attention in adults and in children

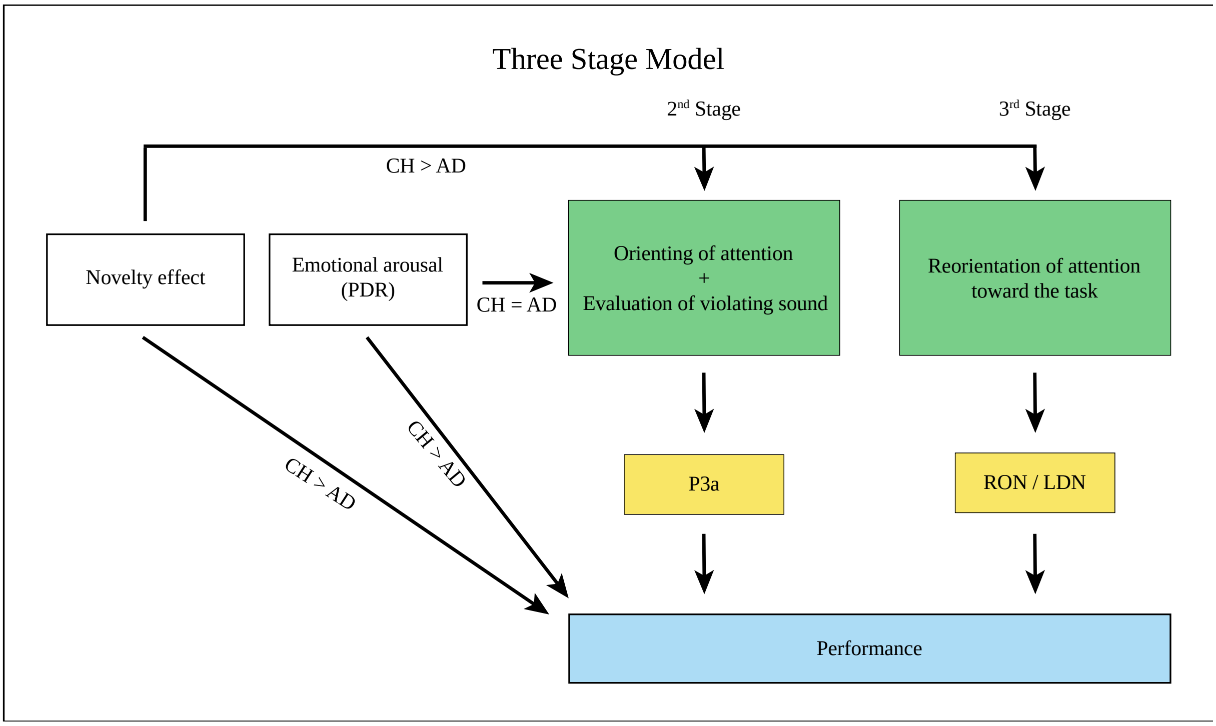

Figure 15: Overview of the updated three-stage model of attention (original model Escera et al., 1998, 2000; Horváth et al., 2008; Schröger et al., 2000; for a developmental review Wetzel & Schröger, 2014). In my Studies I investigated different steps of this attentional model by means of EEG and pupillometry, with a particular focus on the 2nd and 3rd stage. Novelty seems to influence orienting, evaluation and reorienting processes in children (CH) more than adults(AD), whereas emotional information seems to influence orienting and evaluation processes only and it is similar in children and adults on a cortical level but different in the performance.

In the present thesis, new key aspects emerged from the investigation of distraction of attention by novel and emotional novel sounds in the development: 1) Children in middle childhood have immature neurophysiological pattern of orienting and distraction of attention to novel sounds compared to adults; 2) children process emotional novel sounds similarly to adults on a cortical level; 3) enhanced arousal levels drive to decreased distraction effects in a behavioral task in children and adults; 4) the pupil dilation reflects at least partly the same attention-related pattern of activity as more commonly used ERP brain components (for example P3a) in the framework of involuntary auditory attention in both children and adults.

7.2.1 Development of attention in middle childhood

In daily situations that are rich in distracting information (such as classrooms), distractibility by unexpected and task-irrelevant sounds can be a consequence of a reduced ability to voluntarily focus on relevant information or to inhibit distractors (costs of orienting). Attention and inhibitory control skills are part of the core of executive functions and cognitive control (for review see Diamond, 2013; Troller-Renfree et al., 2020; Braver, 2012). Executive functions and cognitive control are especially important in novel situations which require a flexible adaptation of behavior due to new changes in the environment (Huizinga et al., 2006). Unexpected, task-irrelevant and novel sounds can induce distraction (i.e., the reactive shift of attention and resources toward a salient event) and are followed, if possible, by a reorienting of attention toward the task at hand, resulting in behavioral costs as described by the three-stage model of attention (Bidet-Caulet et al., 2015; Escera et al., 1998, 2000; Näätänen, 1992; Schröger et al., 2000). At a cortical level, the results of Study I showed a sequence of brain components which are typically observed in adults in paradigms of attentional distraction. However, results highlighted that children aged between 7 and 10 years showed a similar but still immature pattern of response compared to adults. In fact, the underlying mechanisms of orienting of attention and attention control are discussed to mature until adulthood (Čeponiene et al., 2001, 2004; Troller-Renfree et al., 2020) and have been tied to the maturation of the brain in the prefrontal and frontal cortex (location of the executive functions; e.g., Fuster, 2002; Rueda et al., 2004; for a review see Diamond, 2002; Garon et al., 2008). As highlighted above in the introduction section, frontal cortical areas represent core structures of the *orienting* and *alerting* network (Posner, 1990) and are involved in the neuroanatomical attentional network from Corbetta and Shulman (2002). All the steps of distraction of attention analyzed in Study I indicated immaturity of these processes in the presence of novel sounds in middle childhood: The early classification of relevant stimuli (P2, Getzmann et al., 2018), the orienting and evaluation processes (P3a, Escera et al., 2000) and the reorienting toward the task (LDN, Čeponiene, 2004). That is, larger attention-related ERP amplitudes to unexpected novel sounds implied that children aged between 7 and 10 years were more susceptible to task-irrelevant novel sounds.

To understand whether these cortical differences were displayed also in the performance of a task, I conducted Study II and III. Behaviorally, children are more distractible than adults (for example, Wetzel, 2015; Wetzel et al., 2019). In line with the literature, new, salient and task-irrelevant novel sounds prolonged reaction times in both groups, but significantly greater in children compared to adults. In children, distraction effects are discussed to decrease throughout early (until 6 years) and middle childhood (7–10 years, Pearson & Lane, 1991; Wetzel et al., 2019) and to follow the maturation of the frontal brain areas detectable? as typical ERP components of attention (Fuster, 2002). As illustrated for example by Pozuelos (2014) for the visual modality, a clear developmental improvement in orienting and reallocation capacities occurs in children between 6 and 12 years of age. In particular, younger children showed larger orienting of attention, slower responses and less accuracy when having to reorient attention to the location of the target compared to older children.

Taken together, my physiological and behavioral results agree in indicating immature attentional mechanisms to novelty in children aged 6 to 10 years old compared to adults. Thus, costs of attentional orienting have been observed both at the level of the brain (larger P3a and LDN amplitudes) and in the performance (larger distraction effects). Therefore, I suggest a revised version of the three-stage model of distraction of attention by introducing the larger effect of novelty on the orienting and evaluation and the reorienting processes in children compared to adults (see Figure 15).

7.2.2 Emotional processing

With this paragraph I discuss the main new aspect I wanted to investigate in this thesis: the effect of emotion, and therefore arousal, on attentional mechanisms in children.

Brain responses in children highlighted that emotional, compared to neutral novel sounds evoked increased amplitudes of attention-related ERP components (early classification of relevant stimuli (P2), the orienting and evaluation processes (early and late P3a) but not reorienting processes LDN (Study I)), indicating an advanced level of maturation of the involved emotion-related neuronal mechanism similar to adults. Until now, such emotion-related responses had been observed in adults only and were not investigated in middle childhood (Getzmann et al., 2018; Masson & Bidet-Caulet, 2019; Pakarinen et al., 2014; Thierry & Roberts, 2007; Widmann et al., 2018).

To examine whether this cortical similarity was displayed also in the performance of a task, I conducted Study II and III. The interplay between costs and benefits underlying the distraction of attention has been poorly documented in children until now. Results of Study II and III showed reduced distraction effects after task-irrelevant emotional novel sounds in adults and for the first-time in children between 6 and 8 years of age. However, children showed a larger facilitation effect compared to adults. I hypothesized that the alerting aspect of emotional novel sounds may exceed the distracting aspect only in children. Nevertheless, the latter finding may be interpreted with caution because the presented analyses are only preliminary and results may change after the data collection will be completed. Thus, emotional processing seems to reach maturation at a relatively early stage in life and being at an advanced level in middle childhood already. From an evolutionary aspect, this is not surprising: emotional stimuli are indeed able to signal a general importance of a situation, irrespective of their relevance for the current task. Humans and animals must be able to adapt behavior and transfer attention across sensory modalities in potentially dangerous situations (Tartar et al., 2012; for a review Koelewijn et al., 2010). Emotional information triggers activity in the sympathetic nervous system evoking higher arousal, which in turn facilitates processing of motivationally relevant stimuli, motor and behavioral responses (Aston-Jones & Cohen, 2005; Kahneman, 1973). The burst of arousal triggered by relevant sounds may be mediated by the LC-NE system, and it may result in a transient and nonspecific state of readiness to respond to any upcoming stimulus (Aston-Jones & Cohen, 2005; Corbetta et al., 2008). In line with this idea, improved processing and performance could also appear after task-irrelevant emotional stimuli. For example, in adults visual perception seems to be enhanced when fearful relative to neutral faces precedes visual targets (Phelps et al., 2006). Moreover, Max and colleagues (2015) observed reduced distraction effects in an unrelated visual task after emotional novel sounds. Even though developmental literature in the framework of emotional information and involuntary attention is scarce and patchy, few studies already suggested that emotional processing may be fully developed in middle childhood (e.g., Leventon et al., 2014; Solomon et al., 2012; for review see Dickey et al., 2021;).

Considering all my results, emotional information seems to affect early classification processes of relevant stimuli (ERP component P2) and the orienting and evaluation processes of such emotional events (ERP component P3a) similarly in children and adults. On the contrary reorienting processes do not seem to be influenced by the emotional features of the stimuli. Despite the costs of orienting of attention toward the relevant stimulus, parallel beneficial mechanisms driven by the enhancement of arousal may reduce the initial distraction effects in middle childhood as well as in adulthood. This arousal modulation contributes to the processing and responses in the ongoing task, especially in children. Therefore, I suggest a revised version of the three-stage model of distraction of attention by introducing the larger effect of emotional arousal (indicated by the PDR) on the orienting and evaluation processes and in the performance of an ongoing task in children compared to adults (see Figure 15). Future studies may take into consideration that these two aspects (costs and benefits) may be the result of possibly related, but not identical mechanisms that have a common precursor, the locus coeruleus. To better understand the mechanisms behind the costs and benefits given by emotional information, a co-registration of attentional orienting (P3a) and distraction effects (RTs) in children would be the key to solve this relationship.

7.2.3 Pupil responses to task-irrelevant stimuli

In Study I, II, III, and V, I showed that pupil dilation can be used as a methodological tool in the investigation of attentional orienting not only in the framework of emotional and neutral novel sounds but also in the framework of deviant distractors. By means of principal component analysis (Study I) I could separate the activity of the sympathetic and parasympathetic pathways of the autonomic nervous system (ANS). As hypothesized by Steinhauer & Hackerem (1992), I could highlight two peaks in the dilation of the pupil. For the first time, I showed that the chronologically later peak was specifically modulated by the emotional content of novel sounds, possibly indicating the activity of the sympathetic pathway of the ANS not only in adults but also in children. Therefore, the enhanced dilation of the pupil had a striking resemblance in the conditions that evoked the P3a component in the ERPs (Study I). Both measures were preferentially sensitive to novelty and motivationally significant stimuli (e.g. emotion) that are potentially important for survival or goal-directed behavior (for a detailed review see Nieuwenhuis et al., 2011). Novel results of Study II and III showed that even in active paradigms, where the motor response may interfere in the pupil dilation (McCloy et al., 2016; Moresi et al., 2008; Simpson, 1969), pupillometry is a valid method to use in the framework of novelty and emotion. On the exploratory but nonetheless innovative side of this thesis, Study V, I demonstrated that the pupil dilation may be sensitive to differences in frequency, loudness and broadband features of the deviant sounds. These results expand the possibilities to investigate and set up experiments with infants and younger children in the context of small deviant stimuli. However, further research has to be conducted to collect more evidence which may drive to firmer conclusions. All the various dilations of the pupil to novel, emotional novel and deviant sounds may derive from variable activation of the LC-NE system due to more or less significant characteristics of the sounds. That is, more significant deviants may increase activity in the LC-NE system and therefore increase the pupil dilation, whereas less significant deviants may not or less increase the LC-NE activity resulting in less pupil dilation. Previous evidence and my results agree on the view that PDR is indirectly modulated by the activity of the LC (Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Joshi et al., 2016; Joshi & Gold, 2020; Liao, Kidani, et al., 2016; Liao, Yoneya, et al., 2016; Murphy et al., 2011, 2014) . Even though cumulative evidence regarding PDR conveying important information of the LC activity and the level of arousal has been collected, a direct link between cortical and subcortical activity and the pupil dilation has still to be demonstrated in humans (in animals it has been already proved Gilzenrat et al., 2010; Joshi et al., 2016).

Taken together, my results provide support to the abovementioned models of attention (Corbetta & Shulman, 2002; Posner, 1990) claiming that the locus coeruleus plays an important role in the selective attention and in the ability to maintain and increase readiness of preparation for an upcoming stimulus (*Alerting* Posner, 1990; Corbetta & Shulman, 2002, 2008).

All in all, I could demonstrate that the pupil reacts to novel and emotional information in children as well as to different deviant sounds in adults. The pupil showed the effects of emotional information by displaying the activity of the sympathetic system in its temporally later dilation. Pupillometry seems to represent a fruitful methodological tool for the investigation of attentional orienting and enhancement of arousal even in children. Future projects may then think of employing pupil dilation as a marker of attention because of the advantages that come with it (less trials needed, easy to mount and apply) even with infants and young age groups.

7.2.4 Updating the 3-stage model of attention

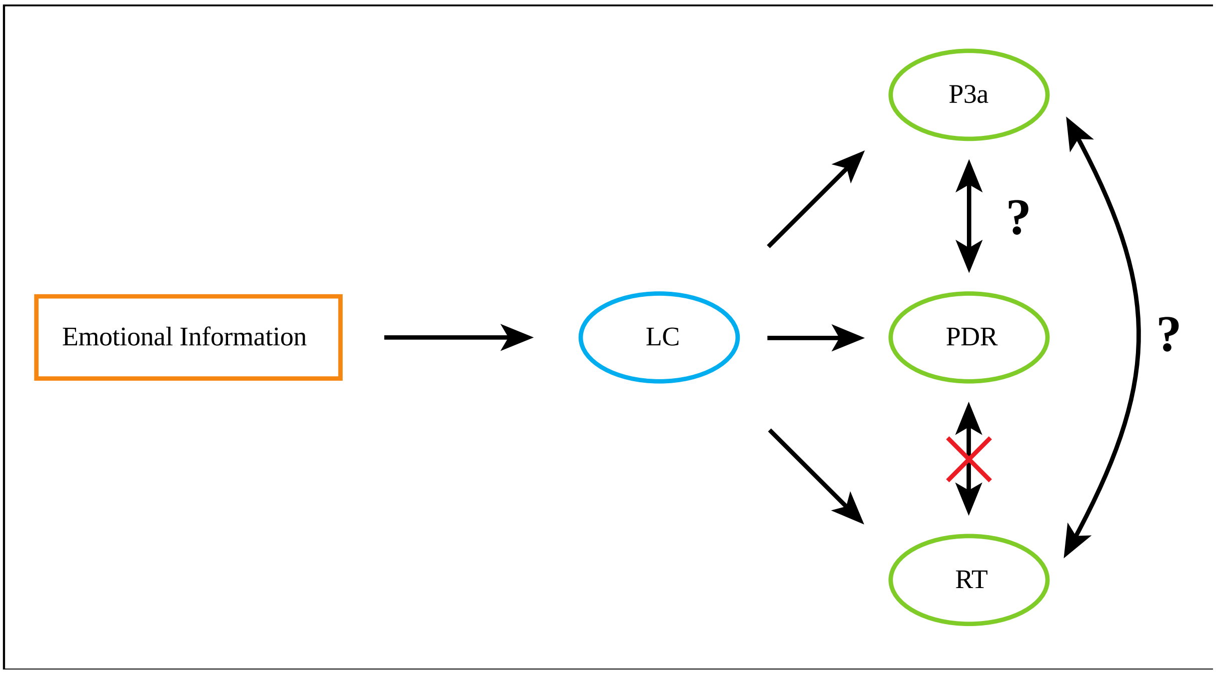

Figure 16: Overview of the effect of emotional information on the LC activity and the influence of LC activity on the three measures used in the present studies. A direct relationship between PDR and RT was not observed in Study II. RT-P3a and PDR-P3a relationships (marked with '?') are still discussed in the literature.

With my findings I suggest an updated version of the 3-stage model of attention by adding the effects of emotional information, and therefore arousal, on orienting and distraction of attention and the differences of those mechanisms in children compared to adults (Figure 15 Figure 16).

As demonstrated above, children owned immature orienting/evaluation and reorienting mechanisms when novel information occurred. This was evident in both the larger P3a amplitudes and larger distraction effects in children compared to adults. The arousal level evoked by emotional information had an impact on orienting/evaluation processes but not on reorienting mechanisms and facilitated the performance in a task. A difference was observed between children and adults; therefore, children already reached an advanced level in handling the emotional content of stimuli and may benefit from it even more than adults.

My work was aimed at examining the role of arousal (evoked by emotional information) on the P3a component and the performance in a task and whether these two measures differed between children and adults. Emotional information seems to influence the activity of the LC, which in turn has an effect on P3a, PDR and RTs. Therefore, the LC is not responsible for the orienting or facilitation process itself, but instead, it acts to optimize information processing by modulating the level of arousal. The role of the LC-NE system has been extensively explained in the adaptive gain theory of Aston-Jones and Cohen (2005). This theory states that task engagement is modulated by tonic LC activity in a manner that mirrors the classic Yerkes–Dodson arousal curve. However, associations between the P3 component, the pupil dilation and behavioral performance have been already discussed for example in the LC-P3 hypothesis by Nieuwenhuis (2005) and by Murphy et al. (2011). The potential relationship derives from a co-activation of the LC-NE system as a common antecedent for the P3 component of the event-related potential and the behavioral response. Even though those measures exhibit similar or concomitant outcomes to relevant stimuli, the direct psychophysiological and neurophysiological relationship has not been found yet and awaits new empirical tests. To start with, my data did not provide evidence for a relationship between the mechanisms behind the enhanced arousal shown by the pupil and the decreased distraction effects, indicating at least partly independent processes. Yet, future co-registrations of the P3a component of the ERP (indicating attentional orienting), the pupil dilation (indicating arousal) and the reaction times (indicating facilitation) may shed light on the interrelationships (if any) between those measures in the presence of motivationally relevant stimuli. Whether these relationships would differ between children and adults will be a key question.

7.3 General conclusions

This doctoral thesis explored the effects of emotional novel sounds on involuntary auditory attention in the development, both at the neural and at the behavioral levels. To my knowledge, the set of experiments that constitutes this work is the first to provide systematical evidence for effects of emotional distractors in middle childhood in the auditory modality. The lack of a systematical investigation of these attentional models in the development and the variety of different tasks, paradigms and presentation's modality of previous studies made it difficult to drive general, consistent and solid conclusions on the developmental trajectory of attention control. I demonstrated that orienting and reorienting attentional processes are still maturing in middle childhood. However, in the presence of motivationally relevant (e.g., emotional) information performance may benefit from the enhanced arousal evoked by such stimuli and reach adult level in middle childhood. This further knowledge adds new insights about the developmental trajectory of distraction of attention and may help improving the concept of learning environments and classrooms in which children can concentrate and focus resources on the relevant material and build up strategies to shield from distractors. Not only typically developing children but also children with attentional disorders may take advantage of new protective strategies in their learning journey at school and at home (Fisher et al., 2014; Godwin & Fisher, 2011) Moreover, I demonstrated that pupillometry may be employed as a marker of attention in critical age groups (e.g., infants) where other more commonly used measures, for example EEG, may be unrealistic.

Thus, with this dissertation I was able to add a developmental and neurophysiological perspective to the current models of orienting and distraction of attention.

7.4 Future perspectives

Investigating physiological and behavioral developmental aspects of auditory involuntary attention opens new horizons into the study of the developmental trajectory of cognition and attention control. I believe that future studies should make use of pupillometry as an additional method to investigate auditory attentional processes at different stages in the development. In order to better proof the hypothesis that the acquisition of data through pupillometry is an effective tool, I began to provide evidence that even the indirect measurement of brain activity is a reliable result of the underlying attentional processes in both children and adults. Future studies should then strive to add more evidence about the direct correlation between cortical areas (such as the attention-related components of attention P300 and P3a), the LC activity and the pupil dilation in humans. For example, introducing trial level analyses with multilevel models could help us understanding possible relationships between cortical activity (P3a) and pupil dilation responses (as in Study II). Another way could be the usage of fMRI studies, even though locating the LC might be very challenging because of its small size. Up to now, just few studies examined relations between these measurements (Murphy et al., 2011; Nieuwenhuis et al., 2005, 2011) and an unequivocal conclusion has not been reached yet. For this reason, a combination of multiple methods may open new horizons in attentional research.

Last but not least, the ultimate goal of studies examining distraction and orienting of attention by novel and emotional novel sounds should always be the prevention and remediation of developmental attention disorders. The development of attention control in children is highly important because it supports learning and school-related acquisition of abilities at early stages. Adding knowledge to how typically developed children control their attention will open new windows on the atypical development as well and will help setting up prevention campaigns for learning spaces and classrooms at school. Even training programs may be developed for the improvement of attention control and protection from distractors. As this fascinating field of research is still growing, more studies are required to better characterize the strengths, limitations and the mechanisms underlying brain development in the context of novel and emotional information and the application of new methods in the development, such as pupillometry.

8. Supplementary material

8.1 Study I:

Table S 1: *Descriptive statistics (mean, SD, min, max) for the number of trials included in the individual ERP and the PDR averages per condition separately for children and adults (Panel A). The mean of the ratio of trials excluded due artifacts in the ERP data (voltage differences exceeding 150 µV per trial at any channel), artifacts in the pupil data (one or both eyes closed throughout the entire trial), or both within the same trial per condition (Panel B). Any trials excluded from analysis due to other reasons (first two standards per block, first two standards following a novel sound) are not included into the total number of trials used for the computation of the ratio of included/excluded trials. Note that trials with artifacts at either measure, ERP or pupil (or both) are excluded from all analyses. That is, the analyses of ERP and pupil data are based on corresponding trials. The ratio of the number of included trials to the number of total number of trials was significantly higher in adults than in children ($F(1,62) = 36.672$, $p < .001$, $BF_{Incl} = 37585$) and not significantly different between conditions ($F(2,124) = 0.978$, $p = .372$, $\varepsilon = .902$, $BF_{Incl} = 0.116$). The Bayesian ANOVA preferred the model including the group main effect only ($BF_{10} = 37698$).*

	Adults				**Children**			
A Number of included trials:								
	Mean (% total)	**SD**	**Min**	**Max**	**Mean (% total)**	**SD**	**Min**	**Max**
Standard	421.2 (95.6 %)	36.1	300	446	342.3 (77.7 %)	79.6	76	437
Emotional	106.8 (96.0 %)	7.8	78	112	84.8 (76.1 %)	21.3	15	111
Neutral	107.0 (96.2 %)	8.5	77	112	85.4 (76.7 %)	20.8	16	111
B Mean of the ratio of excluded trials due to artifacts:								
		ERP	**Pupil**	**Both**		**ERP**	**Pupil**	**Both**
Standard		3.2 %	1.1 %	0.1 %		13.6 %	7.6 %	1.0 %
Emotional		2.8 %	1.0 %	0.1 %		15.1 %	7.4 %	1.3 %
Neutral		2.6 %	1.2 %	0.0 %		14.1 %	8.0 %	1.2 %

Table S 2: *Overview over the PCA components used for analysis (PCA temporal factor, first column). The chronological order of the factors reflects the proportion of explained variance (fifth column). For each component the corresponding latency (second column) and electrode (third column) is displayed. Corresponding ERP components to the PCA components are displayed in the fourth column.*

	PCA temporal factor	Latency	Electrode	ERP Component	% variance explained
Children	1	718 ms	F4	LDN	45.1 %
	3	160 ms	Cz	P2	5.3 %
	5	354 ms	Fz	late P3a	2.7 %
	6	294 ms	Cz	early P3a	2.1 %
Adults	1	702 ms	F4	LDN	42.7 %
	2	186 ms	Cz	P2	24.6 %
	4	308 ms	Fz	late P3a	6.1 %
	5	230 ms	Cz	early P3a	3.1 %

Table S 3: *Frequentist and Bayesian paired t-test of the difference between emotional novel sound ERP and standard sound ERP (emo vs. sta) and neutral novel sound ERP and standard sound ERP (neutr vs. sta) for the ERP components P2, early P3a, late P3a, and LDN. All differences are statistically significant from zero (except for adult LDN emo vs. sta). Data were interpreted as moderate evidence in favor of the alternative (or null) hypothesis if BF_{10} was larger than 3 (or lower than 0.33), or strong evidence if BF_{10} was larger than 10 (lower than 0.1, Lee & Wagenmakers, 2013). BF_{10} between 0.33 and 3 are considered as weak evidence ("anecdotal evidence" following Lee and* Wagenmakers, *2013).*

		Children				**Adults**			
Component	**Condition**	***t***	***p***	***d***	BF_{10}	***t***	***p***	***d***	BF_{10}
P2	emo vs. sta	14.01	< .001	2.476	1.086×10^{12}	4.377	< .001	0.774	206.356
	neutr vs. sta	10.79	< .001	1.908	1.724×10^{9}	2.046	= .049	0.362	1.180
Early P3a	emo vs. sta	11.08	< .001	1.959	3.232×10^{9}	10.19	< .001	1.802	4.577×10^{8}
	neutr vs. sta	10.11	< .001	1.787	3.820×10^{8}	11.23	< .001	1.985	4.403×10^{9}
Late P3a	emo vs. sta	13.71	< .001	2.423	6.230×10^{11}	12.90	< .001	2.280	1.320×10^{11}
	neutr vs. sta	13.05	< .001	2.307	1.774×10^{11}	11.33	< .001	2.003	5.482×10^{9}
LDN	emo vs. sta	−3.494	= .001	−0.618	23.35	−1.926	= .063	−0.340	0.968
	neutr vs. sta	−4.679	< .001	−0.827	449.84	−3.329	= .002	−0.588	15.888

Part 1. Baseline mean pupil diameter and the "Unified" model

The observed baseline mean pupil diameter was 4.17 mm in the adult and 5.39 mm in the children group. We calculated the expected baseline pupil diameter per participant applying the "Unified" model for light adapted pupil size as suggested by Watson and Yellot (2012) and extended this to ages below 20 years (see, Watson & Yellott, 2012, Appendix 1) as implemented by Wheatley and Spitschan (Wheatley & Spitschan, 2018). As parameters we used the age of the participant in years, the movie's mean luminance (53.1 cd/m^2) and visual angle (18.9°), and binocular viewing. The predicted pupil diameter was 4.24 mm for the adult and 4.22 mm for the children.

We compared the observed and the predicted baseline mean pupil diameter in an ANOVA with the factors, prediction error (observed vs. predicted) and group. It showed a significant interaction effect of prediction error and group ($F(1,62) = 53.7$, $p < .001$, $\eta^2 = .341$; and two spurious main effects prediction error and group). The corresponding Bayesian analysis also favored the model including both main effects and the interaction ($BF_{10} = 1.683\times10^{17}$). The observed baseline mean pupil diameter was not significantly different from the predicted pupil diameter in the adult group ($t(31) = -0.543$, $p = .591$, $d = -0.096$; $BF_{10} = 0.216$), but significantly larger than predicted in the children group ($t(31) = 11.41$, $p < .001$, $d = 2.017$; $BF_{10} = 6.520\times10^9$).

Moreover, we tested the pupil baseline between conditions and groups. The ANOVA including the factors condition (standard vs. emotional novel sound vs. neutral novel sound) and group showed a significant main effect of group ($F(1,62) = 48.12$, $p < .001$, $\eta^2 = .437$). The corresponding Bayesian analysis favored the model including the main effect group ($BF_{10} = 248884.022$). The data provide moderate evidence against a difference in baseline pupil diameter between conditions ($BF_{Incl} = 0.164$) and against an interaction effect of conditions and group ($BF_{Incl} = 0.233$).

8.2 Study II:

In this section of the Supplementary Material, we report an additional discussion on the influence of baseline pupil diameter on changes in pupil size and behavioral responses in the unrelated task performed by the participants in this study.

With respect to the baseline PD, we found a substantial quadratic relationship with RT for trial level baseline PD, the positive coefficient (Table 5, effect $(\text{Baseline}_{\text{trial}})^2$) indicated a U-shaped relationship. That is, the fastest RTs were predicted for values around the average baseline within each participant and both lower and higher baseline PDs predicted slower RTs (Figure S 1, Panel A). Moreover, trial level baseline PD interacted with the predictor Novelty (Table 5, effect Baseline$_{trial}$ × Novelty), indicating a left shift of the point of optimal performance for novel sounds compared to standard sounds, that is, the fastest responses to novel sounds were observed when the baseline PD was smaller than the average (Figure S 1, Panel B). Thus, the baseline PD on the trial level had an impact on the observed distraction effect, a smaller than average baseline PD is accompanied by reduced RT in response to novel sounds and increased RT in response to standard sounds, resulting in reduced distraction effects. A larger than average baseline PD is accompanied by larger RTs to novel trials compared to standard trials resulting in increased distraction effects. There was no significant difference between neutral and emotional novels with respect to this shift indicating that the point of optimal performance was shifted by a similar amount for neutral and emotional novels (Table 5; effect Baseline$_{trial}$ × Emotionality). In addition, the size of the quadratic effect (i.e., the "width" of the U-shape) did not depend on stimulus type.

To provide further evidence for the latter finding, we split the data into four subsets based around the quartiles of the predictor baseline PD. We computed the average RTs for standard, neutral and emotional novels for each subset separately (Table S 4). These conditional averages showed the same pattern depicted by the mixed model in Figure S 1, Panel B. That is, for lower values of baseline PD, the distraction effects were smaller (e.g., about 3 ms and 11 ms difference to standards for emotional and neutral novels, respectively in Q1 vs. 30 ms and 47 ms in Q4). For higher values of baseline PD, the distraction effects increased. We conclude that the quadratic relationship captured a pattern which is observable in the data and that the dependence of distraction effects on baseline PD is not simply an artifact of the quadratic model.

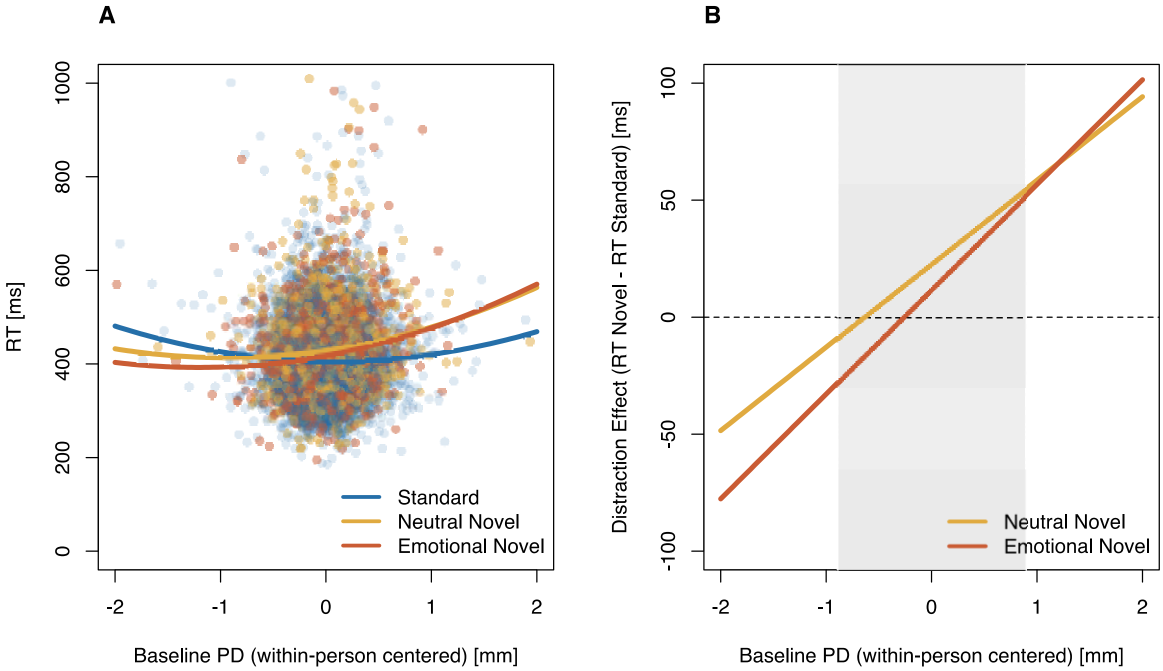

Figure S 1: Panel A: The U-shaped relationship between performance (reaction times, RT) and baseline pupil diameter (PD) for all sound types. Trials marked by an intermediate pupil diameter (PD = 0) are accompanied with best performance. That is, the fastest RTs were achieved for values around the average baseline within each participant and both lower and higher Baseline PDs were accompanied by increased RTs. However, the point of optimal performance was shifted toward smaller baseline pupil diameters for novel compared to standard sounds. Panel B: The quadratic model in Panel A has important implications for the relationship between distraction effects (RT novel – RT standard) and baseline pupil diameter (PD) for novel sounds. This panel shows the differences between the novel curves and the standard curve in Panel A, demonstrating larger baseline PD implied larger distraction effects and smaller RT differences between neutral and emotional novels. However, when the baseline PD was lower than average, benefits of arousal level compensated the costs of orienting and distraction effects were reduced. In contrast, a larger than average baseline PD was accompanied by increased distraction effects.

Table S 4: *Quartiles of the baseline pupil dilation (PD, mean reaction times (RTs) and standard deviation (SD) to the different sound types around the baseline pupil dilation (PD) quartiles.*

Subsets of RT data around the baseline PD quartiles

Q1	**Condition**	**Mean (ms)**	**SD**
Standard sounds		413.807	88.479
Emotional novel sounds		416.557	80.238
Neutral novel sounds		424.824	86.353
Q2			
Standard sounds		404.464	85.350
Emotional novel sounds		407.374	77.265
Neutral novel sounds		422.848	93.982
Q3			
Standard sounds		400.186	85.639
Emotional novel sounds		414.365	92.607
Neutral novel sounds		427.920	103.784
Q4			
Standard sounds		411.537	89.210
Emotional novel sounds		441.056	103.926
Neutral novel sounds		448.720	140.434

Note. This table shows the data split into four subsets based around the quartiles of the Baseline PD. The computed average RTs for standard, neutral and emotional novels for each subset separately are shown in the Mean column. These conditional averages show smaller distraction effects and large difference in distraction effects between emotional and neutral novels for lower values of baseline PD. For higher values of baseline PD, the distraction effects increase and the difference between emotional and neutral novels decreases.

Supplement discussion

In addition to the sound-related changes in pupil size, we observed a relation between the pre-sound baseline pupil diameter and PDR as well as RTs. Our findings showed that larger pre-stimulus baseline pupil diameter was followed by smaller stimulus-related PDRs. This is consistent with previous studies analyzing the activity of PDRs in animals (Gilzenrat et al., 2010; Joshi et al., 2016) and humans (Kamp & Donchin, 2015; Murphy et al., 2011).

Increased baseline pupil size is shown to be related to task disengagement and higher explorative behavior reflecting high levels of tonic LC activity, whereas reduced baseline pupil size is linked to drowsiness, reflecting very low levels of tonic LC activity (Joshi & Gold, 2020). Commitment and optimal task performance are obtained with moderate baseline pupil size (tonic LC activity) and prominent phasic LC activity (Aston-Jones & Cohen, 2005). In accordance to this model and the evidence of a U-shape relationship between baseline pupil size and task performance of a previous oddball study (Murphy et al., 2011), our exploratory analysis also highlighted a U-shape relationship between baseline pupil size and RTs for all sound types being similar to the classical Yerkes-Dodson relationship between arousal and performance (Teigen, 1994). On the trial level, participants with extremely high or low baseline pupil size (relative to their own baseline pupil average) showed greatly increased reaction times. In line with the U-shape relationship, when the baseline was average, participants were able to perform at optimal level, showing the fastest reaction times. This effect was similar for all sound types presented (standard, emotional, novel, and neutral novel sounds, see Figure S 1, Panel A). However, the point of optimal performance was shifted toward smaller baseline pupil diameters for novel compared to standard sounds. This implied that distraction effects became larger when the baseline pupil size was above average (e.g., +1 on the x-axis in Figure S 1, Panel B), indicating reduced benefits of novel-related arousal increase. When the baseline pupil size was below average (e.g., -1 on the x-axis in Figure S 1, Panel B), benefits of novel-related arousal level compensated for the costs of orienting of attention and distraction effects became smaller. Thus, the baseline PD on the trial level can predict RTs as well as distraction effects. This indicates a specific interplay between costs of attentional orienting and benefits of arousal level when unexpected novel sounds are processed during a primary task. The baseline pupil size is likely to reflect tonic LC activity (Joshi & Gold, 2020) and therefore cognitive status such as task-engagement or drowsiness (Gilzenrat et al., 2010), therefore the baseline pupil size might be considered as a factor predicting distraction effects[6].

[6] Although this is an interesting finding, it must be acknowledged that it was extracted from an exploratory model search. Above all, this means, that replications of these findings are necessary to establish their generalizability. In addition, the size of the effect must be put into perspective, because the observed relationship was small relative to the *trial level* variability. It might nevertheless reveal valuable insights into the underlying processes and inform further theory development, because many average-level effects are small when compared to the trial level variability. Nevertheless, it remains challenging to predict single-trial RTs indicating that trial level RTs are influenced by (possibly many) other factors. For instance, this residual variability might reflect the contribution of varying motivation in performing the experiment, a general mental state, fluctuations in arousal

and focused attention, individual interpretations of the sounds due to previous experiences and relative cognitive load.

References

Akatsuka, K., Wasaka, T., Nakata, H., Kida, T., Hoshiyama, M., Tamura, Y., & Kakigi, R. (2007). Objective examination for two-point stimulation using a somatosensory oddball paradigm: An MEG study. *Clinical Neurophysiology*, *118*(2), 403–411. https://doi.org/https://doi.org/10.1016/j.clinph.2006.09.030

Alday, P. M. (2019). How much baseline correction do we need in ERP research? Extended GLM model can replace baseline correction while lifting its limits. *Psychophysiology*, *56*(12), e13451. https://doi.org/https://doi.org/10.1111/psyp.13451

Alho, K., Sainio, K., Sajaniemi, N., Reinikainen, K., & Näätänen, R. (1990). Event-related brain potential of human newborns to pitch change of an acoustic stimulus. *Electroencephalography and Clinical Neurophysiology/ Evoked Potentials*, *77*(2), 151–155. https://doi.org/10.1016/0168-5597(90)90031-8

Alho, Kimmo, Escera, C., Díaz, R., Yago, E., & Serra, J. M. (1997). Effects of involuntary auditory attention on visual task performance and brain activity. *NeuroReport*, *8*(15). https://journals.lww.com/neuroreport/Fulltext/1997/10200/Effects_of_involuntary_auditory_attention_on.10.aspx

Alho, Kimmo, Töttölä, K., Reinikainen, K., Sams, M., & Näätänen, R. (1987). Brain mechanism of selective listening reflected by event-related potentials. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *68*(6), 458–470. https://doi.org/https://doi.org/10.1016/0168-5597(87)90057-8

Anderson, L., & Shimamura, A. P. (2005). Influences of Emotion on Context Memory while Viewing Film Clips. *The American Journal of Psychology*, *118*(3), 323–337. http://www.jstor.org/stable/30039069

Anwyl-Irvine, A. L., Dalmaijer, E., Hodges, N., & Evershed, J. (2020). Online Timing Accuracy and Precision: A comparison of platforms, browsers, and participant's devices. *PsyArXiv*, doi:10.31234/osf.io/jfeca.

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience*, *28*, 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Aston-Jones, G., Rajkowski, J., & Cohen, J. B. T.-P. in B. R. (2000). Locus coeruleus and regulation of behavioral flexibility and attention. In *Cognition, emotion and autonomic responses: The integrative role of the prefrontal cortex and limbic structures* (Vol. 126, pp. 165–182). Elsevier. https://doi.org/https://doi.org/10.1016/S0079-6123(00)26013-5

Bala, A. D. S., Whitchurch, E. A., & Takahashi, T. T. (2020). Human Auditory Detection and Discrimination Measured with the Pupil Dilation Response. *JARO - Journal of the Association for Research in Otolaryngology*, *21*(1), 43–59. https://doi.org/10.1007/s10162-019-00739-x

Barry, R. J., Steiner, G. Z., & De Blasio, F. M. (2016). Reinstating the Novelty P3. *Scientific Reports*, *6*, 1–13. https://doi.org/10.1038/srep31200

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. In *Psychological Bulletin* (Vol. 91, Issue 2, pp. 276–292). American Psychological Association. https://doi.org/10.1037/0033-2909.91.2.276

Bendixen, A., Roeber, U., & Schröger, E. (2007). Regularity extraction and application in dynamic auditory stimulus sequences. *Journal of Cognitive Neuroscience*, *19*(10), 1664–1677. https://doi.org/10.1162/jocn.2007.19.10.1664

Berridge, C. W., & Waterhouse, B. D. (2003). The locus coeruleus-noradrenergic system: Modulation of behavioral state and state-dependent cognitive processes. *Brain Research*

Reviews, *42*(1), 33–84. https://doi.org/10.1016/S0165-0173(03)00143-7
Berti, S., Roeber, U., & Schröger, E. (2004). Bottom-Up Influences on Working Memory: Behavioral and Electrophysiological Distraction Varies with Distractor Strength. *Experimental Psychology*, *51*(4), 249–257. https://doi.org/10.1027/1618-3169.51.4.249
Berti, S., & Schröger, E. (2001). A comparison of auditory and visual distraction effects: behavioral and event-related indices. *Cognitive Brain Research*, *10*(3), 265–273. https://doi.org/https://doi.org/10.1016/S0926-6410(00)00044-6
Berti, S., & Schröger, E. (2004). Distraction effects in vision: Behavioral and event-related potential indices. *NeuroReport*, *15*(4), 665–669. https://doi.org/10.1097/00001756-200403220-00018
Bidet-Caulet, A., Bottemanne, L., Fonteneau, C., Giard, M. H., & Bertrand, O. (2015). Brain Dynamics of Distractibility: Interaction Between Top-Down and Bottom-Up Mechanisms of Auditory Attention. *Brain Topography*, *28*(3), 423–436. https://doi.org/10.1007/s10548-014-0354-x
Bonmassar, C, Scharf, F., Widmann, A., & Wetzel, N. (2021, August 11). *On the relationship of arousal and attentional distraction by emotional novel sounds.* https://doi.org/https://doi.org/10.31234/osf.io/vyqw8
Bonmassar, Carolina, Widmann, A., & Wetzel, N. (2020). The impact of novelty and emotion on attention-related neuronal and pupil responses in children. *Developmental Cognitive Neuroscience*, *42*(August 2019), 100766. https://doi.org/10.1016/j.dcn.2020.100766
Booth, J. R., Burman, D. D., Meyer, J. R., Lei, Z., Trommer, B. L., Davenport, N. D., Li, W., Parrish, T. B., Gitelman, D. R., & Mesulam, M. M. (2003). Neural development of selective attention and response inhibition. *NeuroImage*, *20*(2), 737–751. https://doi.org/https://doi.org/10.1016/S1053-8119(03)00404-X
Bosnyak, D. J., Eaton, R. A., & Roberts, L. E. (2004). Distributed auditory cortical representations are modified when non-musicians are trained at pitch discrimination with 40 Hz amplitude modulated tones. *Cerebral Cortex*, *14*(10), 1088–1099. https://doi.org/10.1093/cercor/bhh068
Boswijk, V., Loerts, H., & Hilton, N. H. (2020). Salience is in the eye of the beholder: Increased pupil size reflects acoustically salient variables. *Ampersand*, *7*(September 2019). https://doi.org/10.1016/j.amper.2020.100061
Bouret, S., & Sara, S. J. (2005). Network reset: A simplified overarching theory of locus coeruleus noradrenaline function. *Trends in Neurosciences*, *28*(11), 574–582. https://doi.org/10.1016/j.tins.2005.09.002
Bradley, M. M., Keil, A., & Lang, P. J. (2012). Orienting and emotional perception: Facilitation, attenuation, and interference. *Frontiers in Psychology*, *3*(NOV), 1–6. https://doi.org/10.3389/fpsyg.2012.00493
Bradley, M. M., & Lang, P. J. (2007). The International Affective Digitized Sounds (; IADS-2): Affective ratings of sounds and instruction manual. *University of Florida, Gainesville, FL, Tech. Rep. B-3*.
Bradley, M. M., Miccoli, L., Escrig, M. A., & Lang, P. J. (2008). The pupil as a measure of emotional arousal and autonomic activation. *Psychophysiology*, *45*(4), 602–607. https://doi.org/10.1111/j.1469-8986.2008.00654.x
Bradley, M. M., Sapigao, R. G., & Lang, P. J. (2017). Sympathetic ANS modulation of pupil diameter in emotional scene perception: Effects of hedonic content, brightness, and contrast. *Psychophysiology*, *54*(10), 1419–1435. https://doi.org/10.1111/psyp.12890
Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms framework. *Trends in Cognitive Sciences*, *16*(2), 106–113. https://doi.org/10.1016/j.tics.2011.12.010
Bridges, D., Pitiot, A., MacAskill, M. R., & Peirce, J. W. (2020). The timing mega-study: Comparing a range of experiment generators, both lab-based and online. *PeerJ*, *8*, 1–29. https://doi.org/10.7717/peerj.9414

Brinkman, M. J. R., & Stauder, J. E. A. (2008). The development of passive auditory novelty processing. *International Journal of Psychophysiology*, *70*(1), 33–39. https://doi.org/10.1016/j.ijpsycho.2008.04.005
Brosch, T., Grandjean, D., Sander, D., & Scherer, K. R. (2008). Behold the voice of wrath: Cross-modal modulation of visual attention by anger prosody. *Cognition*, *106*(3), 1497–1503. https://doi.org/10.1016/j.cognition.2007.05.011
Brosch, T., Sander, D., & Scherer, K. R. (2007). That baby caught my eye... attention capture by infant faces. *Emotion*, *7 3*, 685–689.
Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, *33*(2), 301–311. https://doi.org/10.1016/S0896-6273(01)00583-9
Bürkner, P. C. (2017). brms: An R package for Bayesian multilevel models using Stan. *Journal of Statistical Software*, *80*(1). https://doi.org/10.18637/jss.v080.i01
Bürkner, P. C. (2018). Advanced Bayesian multilevel modeling with the R package brms. *R Journal*, *10*(1), 395–411. https://doi.org/10.32614/rj-2018-017
Burnham, K. P., & Anderson, D. R. (2004). Multimodel inference: Understanding AIC and BIC in model selection. *Sociological Methods and Research*, *33*(2), 261–304. https://doi.org/10.1177/0049124104268644
Carpenter, B., Gelman, A., Hoffman, M., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M. A., Li, P., & Riddell, A. (2016). Journal of Statistical Software Stan : A Probabilistic Programming Language. *Journal of Statistical Software*, *VV*(Ii).
Case, R. (1992). The role of the frontal lobes in the regulation of cognitive development. *Brain and Cognition*, *20*(1), 51–73. https://doi.org/10.1016/0278-2626(92)90061-P
Casey, B. J., Giedd, J. N., & Thomas, K. M. (2000). Structural and functional brain development and its relation to cognitive development. *Biological Psychology*, *54*(1–3), 241–257. https://doi.org/10.1016/S0301-0511(00)00058-2
Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., Giedd, J. N., Castellanos, F. X., Haxby, J. V, Noll, D. C., Cohen, J. D., Forman, S. D., Dahl, R. E., & Rapoport, J. L. (1997). A Developmental Functional MRI Study of Prefrontal Activation during Performance of a Go-No-Go Task. *Journal of Cognitive Neuroscience*, *9*(6), 835–847. https://doi.org/10.1162/jocn.1997.9.6.835
Čeponiene, R., Lepistö, T., Alku, P., Aro, H., & Näätänen, R. (2003). Event-related potential indices of auditory vowel processing in 3-year-old children. *Clinical Neurophysiology*, *114*(4), 652–661. https://doi.org/10.1016/S1388-2457(02)00436-4
Čeponiene, R., Lepistö, T., Soininen, M., Aronen, E., Alku, P., & Näätänen, R. (2004). Event-related potentials associated with sound discrimination versus novelty detection in children. *Psychophysiology*, *41*(1), 130–141. https://doi.org/10.1111/j.1469-8986.2003.00138.x
Čeponiene, R., Shestakova, A., Balan, P., Alku, P., Yiaguchi, K., & Näätanen, R. (2001). Children’s auditory event-related potentials index sound complexity and “speechness.” *International Journal of Neuroscience*, *109*(3–4), 245–260. https://doi.org/10.3109/00207450108986536
Cheour, M., Korpilahti, P., Martynova, O., & Lang, A. H. (2001). Mismatch negativity and late discriminative negativity in investigating speech perception and learning in children and infants. *Audiology and Neuro-Otology*, *6*(1), 2–11. https://doi.org/10.1159/000046804
Chetverikov, A., & Upravitelev, P. (2016). Online versus offline: The Web as a medium for response time data collection. *Behavior Research Methods*, *48*(3), 1086–1099. https://doi.org/10.3758/s13428-015-0632-x
Choudhury, N. A., Parascando, J. A., & Benasich, A. A. (2015). Effects of presentation rate and attention on auditory discrimination: A comparison of long-latency auditory evoked

potentials in school-aged children and adults. *PLoS ONE*, *10*(9). https://doi.org/10.1371/journal.pone.0138160
Corbetta, M., Kincade, J. M., Ollinger, J. M., McAvoy, M. P., & Shulman, G. L. (2000). Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature Neuroscience*, *3*(5), 521. https://doi.org/10.1038/74905
Corbetta, M., Patel, G., & Shulman, G. L. (2008). The Reorienting System of the Human Brain: From Environment to Theory of Mind. *Neuron*, *58*(3), 306–324. https://doi.org/10.1016/j.neuron.2008.04.017
Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 201–215. https://doi.org/10.1038/nrn755
Crowley, K. E., & Colrain, I. M. (2004). A review of the evidence for P2 being an independent component process: Age, sleep and modality. *Clinical Neurophysiology*, *115*(4), 732–744. https://doi.org/10.1016/j.clinph.2003.11.021
Czigler, I., Cox, T. J., Gyimesi, K., & Horváth, J. (2007). Event-related potential study to aversive auditory stimuli. *Neuroscience Letters*, *420*(3), 251–256. https://doi.org/https://doi.org/10.1016/j.neulet.2007.05.007
Dandurand, F., Shultz, T. R., & Onishi, K. H. (2008). Comparing online and lab methods in a problem-solving experiment. *Behavior Research Methods*, *40*(2), 428–434. https://doi.org/10.3758/BRM.40.2.428
Dayan, P., & Yu, A. J. (2006). Phasic norepinephrine: A neural interrupt signal for unexpected events. *Network: Computation in Neural Systems*, *17*(4), 335–350. https://doi.org/10.1080/09548980601004024
De Houwer, J., Hermans, D., Rothermund, K., & Wentura, D. (2002). Affective priming of semantic categorisation responses. *Cognition and Emotion*, *16*(5), 643–666. https://doi.org/10.1080/02699930143000419
Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009
Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood. In *Principles of frontal lobe function* (pp. 466 – 503).
Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750
Dickey, L., Politte-Corn, M., & Kujawa, A. (2021). Development of emotion processing and regulation: Insights from event-related potentials and implications for internalizing disorders. *International Journal of Psychophysiology*, *170*, 121–132. https://doi.org/https://doi.org/10.1016/j.ijpsycho.2021.10.003
Dien, J. (2010). The ERP PCA Toolkit: An open source program for advanced statistical analysis of event-related potential data. *Journal of Neuroscience Methods*, *187*(1), 138–145. https://doi.org/https://doi.org/10.1016/j.jneumeth.2009.12.009
Dien, J. (2012). Applying Principal Components Analysis to Event-Related Potentials: A Tutorial. *Developmental Neuropsychology*, *37*(6), 497–517. https://doi.org/10.1080/87565641.2012.697503
Dien, J., & Frishkoff, G. A. (2005). Principal components analysis of event-related potential datasets. *Event-Related Potentials: A Methods Handbook*, 189–208.
Dondi, M., Simion, F., & Caltran, G. (1999). Can newborns discriminate between their own cry and the cry of another newborn infant? *Developmental Psychology*, *35*(2), 418–426. https://doi.org/10.1037/0012-1649.35.2.418
Draganova, R., Eswaran, H., Murphy, P., Huotilainen, M., Lowery, C., & Preissl, H. (2005). Sound frequency change detection in fetuses and newborns, a magnetoencephalographic study. *NeuroImage*, *28*(2), 354–361. https://doi.org/10.1016/j.neuroimage.2005.06.011

Duncan, J., Martens, S., & Ward, R. (1997). Restricted attentional capacity within but not between sensory modalities. *Nature*, *387*(6635), 808–810. https://doi.org/10.1038/42947
Eckstein, M. K., Guerra-Carrillo, B., Miller Singley, A. T., & Bunge, S. A. (2017). Beyond eye gaze: What else can eyetracking reveal about cognition and cognitive development? In *Developmental Cognitive Neuroscience*. https://doi.org/10.1016/j.dcn.2016.11.001
Elshafei, H. A., Bouet, R., Bertrand, O., & Bidet-Caulet, A. (2018). Two sides of the same coin: Distinct sub-bands in the α rhythm reflect facilitation and suppression mechanisms during auditory anticipatory attention. *ENeuro*, *5*(4). https://doi.org/10.1523/ENEURO.0141-18.2018
Enders, C. K., & Tofighi, D. (2007). Centering predictor variables in cross-sectional multilevel models: a new look at an old issue. *Psychological Methods*, *12*(2), 121–138. https://doi.org/10.1037/1082-989X.12.2.121
Escera, C. (1998). *Neural Mechanisms of Involuntary Attention*. 590–604.
Escera, C., Alho, K., Schröger, E., & Winkler, I. (2000). Involuntary Attention and Distractibility as Evaluated with Event-Related Brain Potentials. *Audiol Neurootol*, *5*, 151–166.
Escera, C., Alho, K., Winkler, I., & Näätänen, R. (1998). Neural Mechanisms of Involuntary Attention to Acoustic Novelty and Change. *Journal of Cognitive Neuroscience*, *10*(5), 590–604. https://doi.org/10.1162/089892998562997
Escera, C., & Corral, M. J. (2007). Role of mismatch negativity and novelty-P3 in involuntary auditory attention. *Journal of Psychophysiology*, *21*(3–4), 251–264. https://doi.org/10.1027/0269-8803.21.34.251
Farrant, K., & Uddin, L. Q. (2015). Asymmetric development of dorsal and ventral attention networks in the human brain. *Developmental Cognitive Neuroscience*, *12*, 165–174. https://doi.org/10.1016/j.dcn.2015.02.001
Fecteau, S., Armony, J. L., Joanette, Y., & Belin, P. (2005). Sensitivity to voice in human prefrontal cortex. *Journal of Neurophysiology*, *94*(3), 2251–2254. https://doi.org/10.1152/jn.00329.2005
Fecteau, S., Belin, P., Joanette, Y., & Armony, J. L. (2007). Amygdala responses to nonlinguistic emotional vocalizations. *NeuroImage*, *36*(2), 480–487. https://doi.org/https://doi.org/10.1016/j.neuroimage.2007.02.043
Fellman, V., & Huotilainen, M. (2006). Cortical auditory event-related potentials in newborn infants. *Seminars in Fetal and Neonatal Medicine*, *11*(6), 452–458. https://doi.org/10.1016/j.siny.2006.07.004
Finley, A. J., & Penningroth, S. L. (2021). Online versus In-lab: Pros and Cons of an Online Prospective Memory Experiment Anna. *Advances in Psychology Research*, *113*, 135–162.
Fisher, A. V, Godwin, K. E., & Seltman, H. (2014). Visual Environment, Attention Allocation, and Learning in Young Children: When Too Much of a Good Thing May Be Bad. *Psychological Science*, *25*(7), 1362–1370. https://doi.org/10.1177/0956797614533801
Fiske, A., & Holmboe, K. (2019). Neural substrates of early executive function development. *Developmental Review*, *52*(December 2018), 42–62. https://doi.org/10.1016/j.dr.2019.100866
Foti, D., Hajcak, G., & Dien, J. (2009). Differentiating neural responses to emotional pictures: Evidence from temporal-spatial PCA. *Psychophysiology*, *46*(3), 521–530. https://doi.org/https://doi.org/10.1111/j.1469-8986.2009.00796.x
Friedman, D., Cycowicz, Y. M., & Gaeta, H. (2001). The novelty P3: An event-related brain potential (ERP) sign of the brain's evaluation of novelty. *Neuroscience and Biobehavioral Reviews*, *25*(4), 355–373. https://doi.org/10.1016/S0149-7634(01)00019-7
Friedman, D., Hakerem, G., Sutton, S., & Fleiss, J. L. (1973). Effect of stimulus uncertainty

on the pupillary dilation response and the vertex evoked potential. *Electroencephalography and Clinical Neurophysiology*, *34*(5), 475–484. https://doi.org/10.1016/0013-4694(73)90065-5

Friedman, N. P., & Miyake, A. (2017). Unity and diversity of executive functions: Individual differences as a window on cognitive structure. *Cortex*, *86*, 186–204. https://doi.org/10.1016/j.cortex.2016.04.023

Frodl, T., Meisenzahl, E. M., Müller, D., Leinsinger, G., Juckel, G., Hahn, K., Möller, H.-J., & Hegerl, U. (2001). The effect of the skull on event-related P300. *Clinical Neurophysiology*, *112*(9), 1773–1776. https://doi.org/https://doi.org/10.1016/S1388-2457(01)00587-9

Frühholz, S., Trost, W., & Kotz, S. A. (2016). The sound of emotions-Towards a unifying neural network perspective of affective sound processing. *Neuroscience and Biobehavioral Reviews*, *68*, 1–15. https://doi.org/10.1016/j.neubiorev.2016.05.002

Fuchigami, T., Okubo, O., Fujita, Y., Okuni, M., Okuni, M., Noguchi, Y., & Yamada, T. (1993). Auditory event-related potentials and reaction time in children evaluation of cognitive development. *Developmental Medicine & Child Neurology*, *35*(3), 230–237. https://doi.org/https://doi.org/10.1111/j.1469-8749.1993.tb11627.x

Fuster, J. M. (2002). 2002 - Fuster - J Neurocytol Frontal lobe & cognitive development. *Journal of Neurocytology*, *385*(2002), 373–385. https://doi.org/10.1023/A:1024190429920

Gajewski, P. D., Ferdinand, N. K., Kray, J., & Falkenstein, M. (2018). Understanding sources of adult age differences in task switching: Evidence from behavioral and ERP studies. *Neuroscience and Biobehavioral Reviews*, *92*(June), 255–275. https://doi.org/10.1016/j.neubiorev.2018.05.029

Garaizar, P., Vadillo, M. A., López-De-Ipiña, D., & Matute, H. (2014). Measuring software timing errors in the presentation of visual stimuli in cognitive neuroscience experiments. *PLoS ONE*, *9*(1). https://doi.org/10.1371/journal.pone.0085108

Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: A review using an integrative framework. In *Psychological Bulletin* (Vol. 134, Issue 1, pp. 31–60). American Psychological Association. https://doi.org/10.1037/0033-2909.134.1.31

Geangu, E., Hauf, P., Bhardwaj, R., & Bentz, W. (2011). Infant pupil diameter changes in response to others' positive and negative emotions. *PLoS ONE*, *6*(11). https://doi.org/10.1371/journal.pone.0027132

Getzmann, S., Wascher, E., & Schneider, D. (2018). The role of inhibition for working memory processes: ERP evidence from a short-term storage task. *Psychophysiology*, *55*(5), 1–9. https://doi.org/10.1111/psyp.13026

Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., & Zijdenbos, A. (1999). Brain development during childhood and adolescence: a longitudinal MRI study Jay. *Neuropsychol, Dev*.

Gilzenrat, M. S., Nieuwenhuis, S., Jepma, M., & Cohen, J. D. (2010). Pupil diameter tracks changes in control state predicted by the adaptive gain theory of locus coeruleus function. *Cogn Affect Behav Neurosci*, *10*(2), 252–269. https://doi.org/10.3758/CABN.10.2.252.Pupil

Godwin, K. E., & Fisher, A. V. (2011). Allocation of attention in classroom environments: consequences for learning. *Proceedings of the 33rd Annual Conference of the Cognitive Science Society*, 2806–2811. http://csjarchive.cogsci.rpi.edu/proceedings/2011/papers/0643/paper0643.pdf

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., Nugent, T. F., Herman, D. H., Clasen, L. S., Toga, A. W., Rapoport, J. L., & Thompson, P. M. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences of the United States of*

America, *101*(21), 8174–8179. https://doi.org/10.1073/pnas.0402680101
Groppe, D. M., Makeig, S., & Kutas, M. (2009). Identifying reliable independent components via split-half comparisons. *NeuroImage*, *45*(4), 1199–1211. https://doi.org/10.1016/j.neuroimage.2008.12.038
Grosbras, M. H., Ross, P. D., & Belin, P. (2018). Categorical emotion recognition from voice improves during childhood and adolescence. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-32868-3
Grossmann, T. (2013). *The Early Development of Processing Emotions in Face and Voice* (pp. 95–116). https://doi.org/10.1007/978-1-4614-3585-3_5
Gumenyuk, V., Korzyukov, O., Alho, K., Escera, C., & Näätanen, R. (2004). Effects of auditory distraction on electrophysiological brain activity and performance in children aged 8-13 years. *Psychophysiology*, *41*(1), 30–36. https://doi.org/10.1111/1469-8986.00123
Gumenyuk, V., Korzyukov, O., Alho, K., Escera, C., Schröger, E., Ilmoniemi, R. J., & Näätänen, R. (2001). Brain activity index of distractibility in normal school-age children. *Neuroscience Letters*, *314*(3), 147–150. https://doi.org/https://doi.org/10.1016/S0304-3940(01)02308-4
Hackley, S. A. (2009). The speeding of voluntary reaction by a warning signal: Presidential Address, 2006. *Psychophysiology*, *46*(2), 225–233. https://doi.org/10.1111/j.1469-8986.2008.00716.x
Hackley, S. A., & Valle-Inclán, F. (2003). Which stages of processing are speeded by a warning signal? *Biological Psychology*, *64*(1), 27–45. https://doi.org/https://doi.org/10.1016/S0301-0511(03)00101-7
Háden, G. P., Stefanics, G., Vestergaard, M. D., Denham, S. L., Sziller, I., & Winkler, I. (2009). Timbre-independent extraction of pitch in newborn infants. *Psychophysiology*, *46*(1), 69–74. https://doi.org/10.1111/j.1469-8986.2008.00749.x
Hämäläinen, J. A., Leppänen, P. H. T., Guttorm, T. K., & Lyytinen, H. (2008). Event-related potentials to pitch and rise time change in children with reading disabilities and typically reading children. *Clinical Neurophysiology*, *119*(1), 100–115. https://doi.org/10.1016/j.clinph.2007.09.064
Hasting, A., Wassiliwizky, E., & Kotz, S. A. (2010). Erfahrung übertrifft Emotion: Differentielle Effekte von Vertrautheit und Valenz im ereigniskorrelierten Potential auf Umweltgeräusche im Novelty-Oddball Paradigma [Experience beats Emotion: Differential effects of familiarity and valence on the event-rel. *36. Tagung" Psychologie Und Gehirn"*.
Hayes, T. R., & Petrov, A. A. (2016). Mapping and correcting the influence of gaze position on pupil size measurements. *Behavior Research Methods*, *48*(2), 510–527. https://doi.org/10.3758/s13428-015-0588-x
Hegerl, U., & Hensch, T. (2014). The vigilance regulation model of affective disorders and ADHD. *Neuroscience and Biobehavioral Reviews*, *44*, 45–57. https://doi.org/10.1016/j.neubiorev.2012.10.008
Henrich, J., Heine, S. J., & Norenzayan, A. (2010). The weirdest people in the world? *Behavioral and Brain Sciences*, *33*(2–3), 61–83. https://doi.org/DOI: 10.1017/S0140525X0999152X
Herba, C. M., Landau, S., Russell, T., Ecker, C., & Phillips, M. L. (2006). The development of emotion-processing in children: Effects of age, emotion, and intensity. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *47*(11), 1098–1106. https://doi.org/10.1111/j.1469-7610.2006.01652.x
Hervé-Minvielle, A., & Sara, S. J. (1995). Rapid habituation of auditory responses of locus coeruleus cells in anaesthetized and awake rats. *NeuroReport*, *6*(10). https://journals.lww.com/neuroreport/Fulltext/1995/07100/Rapid_habituation_of_auditor

y_responses_of_locus.1.aspx
Hess, E. H., & Polt, J. M. (1960). Pupil Size as Related to Interest Value of Visual Stimuli. *Science*, *132*(3423), 349 LP – 350. https://doi.org/10.1126/science.132.3423.349
Hopstaken, J. F., van der Linden, D., Bakker, A. B., & Kompier, M. A. J. (2015). The window of my eyes: Task disengagement and mental fatigue covary with pupil dynamics. *Biological Psychology*, *110*, 100–106. https://doi.org/10.1016/j.biopsycho.2015.06.013
Horváth, J. (2014). Sensory ERP effects in auditory distraction: Did we miss the main event? *Psychological Research*, *78*(3), 339–348. https://doi.org/10.1007/s00426-013-0507-7
Horváth, J., Czigler, I., Birkás, E., Winkler, I., & Gervai, J. (2009). Age-related differences in distraction and reorientation in an auditory task. *Neurobiology of Aging*, *30*(7), 1157–1172. https://doi.org/https://doi.org/10.1016/j.neurobiolaging.2007.10.003
Horváth, J., Czigler, I., Jacobsen, T., Maess, B., Schröger, E., & Winkler, I. (2008). MMN or no MMN: No magnitude of deviance effect on the MMN amplitude. *Psychophysiology*, *45*(1), 60–69. https://doi.org/https://doi.org/10.1111/j.1469-8986.2007.00599.x
Horváth, J., Roeber, U., Bendixen, A., & Schröger, E. (2008). Specific or general? The nature of attention set changes triggered by distracting auditory events. *Brain Research*, *1229*, 193–203. https://doi.org/https://doi.org/10.1016/j.brainres.2008.06.096
Horváth, J., Winkler, I., & Bendixen, A. (2008). Do N1/MMN, P3a, and RON form a strongly coupled chain reflecting the three stages of auditory distraction? *Biological Psychology*, *79*(2), 139–147. https://doi.org/10.1016/j.biopsycho.2008.04.001
Hoyer, R. S., Elshafei, H., Hemmerlin, J., Bouet, R., & Bidet-Caulet, A. (2021). Why Are Children So Distractible? Development of Attention and Motor Control From Childhood to Adulthood. *Child Development*, *00*(0), 1–22. https://doi.org/10.1111/cdev.13561
Hsu, Y. F., Hämäläinen, J. A., & Waszak, F. (2014). Both attention and prediction are necessary for adaptive neuronal tuning in sensory processing. *Frontiers in Human Neuroscience*, *8*(MAR), 1–9. https://doi.org/10.3389/fnhum.2014.00152
Hughes, R. W., Vachon, F., & Jones, D. M. (2007). Disruption of Short-Term Memory by Changing and Deviant Sounds: Support for a Duplex-Mechanism Account of Auditory Distraction. *Journal of Experimental Psychology: Learning Memory and Cognition*, *33*(6), 1050–1061. https://doi.org/10.1037/0278-7393.33.6.1050
Huizinga, M., Dolan, C. V., & van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia*, *44*(11), 2017–2036. https://doi.org/10.1016/j.neuropsychologia.2006.01.010
Huotilainen, M., Shestakova, A., & Hukki, J. (2008). Using magnetoencephalography in assessing auditory skills in infants and children. *International Journal of Psychophysiology*, *68*(2), 123–129. https://doi.org/10.1016/j.ijpsycho.2007.12.007
Huttenlocher, P. R. (1979). Accepted July 13th, 1978. *Brain Research*, *163*(2), 195–205. http://linkinghub.elsevier.com/retrieve/pii/0006899379903494
Jauniaux, J., Tessier, M. H., Regueiro, S., Chouchou, F., Fortin-Côté, A., & Jackson, P. L. (2020). Emotion regulation of others' positive and negative emotions is related to distinct patterns of heart rate variability and situational empathy. *PLoS ONE*, *15*(12 December 2020), 1–25. https://doi.org/10.1371/journal.pone.0244427
Jepma, M., & Nieuwenhuis, S. (2011). Pupil Diameter Predicts Changes in the Exploration–Exploitation Trade-off: Evidence for the Adaptive Gain Theory. *Journal of Cognitive Neuroscience*, *23*(7), 1587–1596. https://doi.org/10.1162/jocn.2010.21548
Jiang, Y., Vagnini, V., Clark, J., & Zhang, Q. (2007). Reduced sensitivity of older adults to affective mismatches. *TheScientificWorldJournal*, *7*(February), 641–648. https://doi.org/10.1100/tsw.2007.115
Joshi, S., & Gold, J. I. (2020). Pupil size as a window on neural substrates of cognition. *Trends in Cognitive Sciences*, *24*(6), 466–480. https://doi.org/10.1016/j.tics.2020.03.005

Joshi, S., Li, Y., Kalwani, R. M., & Gold, J. I. (2016). Relationships between Pupil Diameter and Neuronal Activity in the Locus Coeruleus, Colliculi, and Cingulate Cortex. *Neuron*, *89*(1), 221–234. https://doi.org/10.1016/j.neuron.2015.11.028

Jurado, M. B., & Rosselli, M. (2007). The elusive nature of executive functions: A review of our current understanding. *Neuropsychology Review*, *17*(3), 213–233. https://doi.org/10.1007/s11065-007-9040-z

Kahneman, D. (1973). Attention and Effort. In *The American Journal of Psychology* (Vol. 88, Issue 2). https://doi.org/10.2307/1421603

Kamp, S. M., & Donchin, E. (2015). ERP and pupil responses to deviance in an oddball paradigm. *Psychophysiology*, *52*(4), 460–471. https://doi.org/10.1111/psyp.12378

Kanske, P. (2012). On the influence of emotion on conflict processing. *Frontiers in Integrative Neuroscience*, *6*(JULY 2012), 2010–2013. https://doi.org/10.3389/fnint.2012.00042

Kestenbaum, R., & Nelson, C. A. (1992). Neural and behavioral correlates of emotion recognition in children and adults. *Journal of Experimental Child Psychology*, *54*(1), 1–18. https://doi.org/10.1016/0022-0965(92)90014-W

Kiesel, A., Miller, J., Jolicœur, P., & Brisson, B. (2008). Measurement of ERP latency differences: A comparison of single-participant and jackknife-based scoring methods. *Psychophysiology*, *45*(2), 250–274. https://doi.org/https://doi.org/10.1111/j.1469-8986.2007.00618.x

King, A. J., & Carlile, S. (1994). Responses of neurons in the ferret superior colliculus to the spatial location of tonal stimuli. *Hearing Research*, *81*(1), 137–149. https://doi.org/https://doi.org/10.1016/0378-5955(94)90161-9

Klatte, M., Bergström, K., & Lachmann, T. (2013). Does noise affect learning? A short review on noise effects on cognitive performance in children. *Frontiers in Psychology*, *4*(August), 1–6. https://doi.org/10.3389/fpsyg.2013.00578

Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in psychtoolbox-3? *Perception (ECVP Abstract Supplement) 14*.

Klingner, J., Kumar, R., & Hanrahan, P. (2008). Measuring the Task-Evoked Pupillary Response with a Remote Eye Tracker. *Proceedings of the 2008 Symposium on Eye Tracking Research & Applications*, 69–72. https://doi.org/10.1145/1344471.1344489

Koelewijn, T., Bronkhorst, A., & Theeuwes, J. (2010). Attention and the multiple stages of multisensory integration: A review of audiovisual studies. *Acta Psychologica*, *134*(3), 372–384. https://doi.org/10.1016/j.actpsy.2010.03.010

Kotsoni, E., de Haan, M., & Johnson, M. H. (2001). Categorical Perception of Facial Expressions by 7-Month-Old Infants. *Perception*, *30*(9), 1115–1125. https://doi.org/10.1068/p3155

Krebs, R. M., Park, H. R. P., Bombeke, K., & Boehler, C. N. (2018). Modulation of locus coeruleus activity by novel oddball stimuli. *Brain Imaging and Behavior*, *12*(2), 577–584. https://doi.org/10.1007/s11682-017-9700-4

Kret, M. E., & Sjak-Shie, E. E. (2019). Preprocessing pupil size data: Guidelines and code. *Behavior Research Methods*. https://doi.org/10.3758/s13428-018-1075-y

Kujawa, A., Weinberg, A., Hajcak, G., & Klein, D. N. (2013). Differentiating event-related potential components sensitive to emotion in middle childhood: Evidence from temporal–spatial PCA. *Developmental Psychobiology*, *55*(5), 539–550. https://doi.org/https://doi.org/10.1002/dev.21058

Kushnerenko, E., Winkler, I., Horváth, J., Näätänen, R., Pavlov, I., Fellman, V., & Huotilainen, M. (2007). Processing acoustic change and novelty in newborn infants. *European Journal of Neuroscience*, *26*(1), 265–274. https://doi.org/10.1111/j.1460-9568.2007.05628.x

Kushnerenko, E. V., Van den Bergh, B. R. H., & Winkler, I. (2013). Separating acoustic deviance from novelty during the first year of life: A review of event-related potential evidence. *Frontiers in Psychology*, *4*(SEP), 1–16. https://doi.org/10.3389/fpsyg.2013.00595

Kuznetsova, A., Brockhoff, P., & Christensen, R. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, *82*, 1–26.

Lane, D. M., & Pearson, D. A. (1982). The Development of Selective Attention. *Merrill-Palmer Quarterly*, *28*(3), 317–337. http://www.jstor.org/stable/23086119

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (1997). Motivated attention: Affect, activation, and action. In *Attention and orienting: Sensory and motivational processes.* (pp. 97–135). Lawrence Erlbaum Associates Publishers.

Lange, K., Kühn, S., & Filevich, E. (2015). "Just another tool for online studies" (JATOS): An easy solution for setup and management of web servers supporting online studies. *PLoS ONE*, *10*(6), 1–14. https://doi.org/10.1371/journal.pone.0130834

Larsen, R. S., & Waters, J. (2018). Neuromodulatory correlates of pupil dilation. *Frontiers in Neural Circuits*, *12*(March), 1–9. https://doi.org/10.3389/fncir.2018.00021

Lee, M. D., & Wagenmakers, E.-J. (2013). *Bayesian Cognitive Modeling: A Practical Course.* Cambridge University Press.

Lehto, J. E., Juujärvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology*, *21*(1), 59–80. https://doi.org/10.1348/026151003321164627

Leventon, J. S., Stevens, J. S., & Bauer, P. J. (2014). Development in the neurophysiology of emotion processing and memory in school-age children. *Developmental Cognitive Neuroscience*, *10*, 21–33. https://doi.org/10.1016/j.dcn.2014.07.007

Li, X., Liang, Z., Kleiner, M., & Lu, Z.-L. (2010). RTbox: A device for highly accurate response time measurements. *Behavior Research Methods*, *42*(1), 212–225. https://doi.org/10.3758/BRM.42.1.212

Liao, H. I., Kidani, S., Yoneya, M., Kashino, M., & Furukawa, S. (2016). Correspondences among pupillary dilation response, subjective salience of sounds, and loudness. *Psychonomic Bulletin and Review*, *23*(2), 412–425. https://doi.org/10.3758/s13423-015-0898-0

Liao, H. I., Yoneya, M., Kidani, S., Kashino, M., & Furukawa, S. (2016). Human pupillary dilation response to deviant auditory stimuli: Effects of stimulus properties and voluntary attention. *Frontiers in Neuroscience*, *10*(FEB). https://doi.org/10.3389/fnins.2016.00043

Lindström, B. R., & Bohlin, G. (2011). Emotion processing facilitates working memory performance. *Cognition and Emotion*, *25*(7), 1196–1204. https://doi.org/10.1080/02699931.2010.527703

Linnavalli, T., Putkinen, V., Huotilainen, M., & Tervaniemi, M. (2018). Maturation of speech-sound erps in 5⇓6-year-old children: A longitudinal study. *Frontiers in Neuroscience*, *12*(NOV), 1–12. https://doi.org/10.3389/fnins.2018.00814

Lorenzino, M., & Caudek, C. (2015). Task-irrelevant emotion facilitates face discrimination learning. *Vision Research*, *108*, 56–66. https://doi.org/10.1016/j.visres.2015.01.007

LoTemplio, S., Silcox, J., Federmeier, K. D., & Payne, B. R. (2021). Inter- and intra-individual coupling between pupillary, electrophysiological, and behavioral responses in a visual oddball task. *Psychophysiology*, *58*(4), 1–14. https://doi.org/10.1111/psyp.13758

Lourenco, S. F., & Tasimi, A. (2020). No Participant Left Behind: Conducting Science During COVID-19. *Trends in Cognitive Sciences*, *24*(8), 583–584. https://doi.org/10.1016/j.tics.2020.05.003

Lu, Y., Jaquess, K. J., Hatfield, B. D., Zhou, C., & Li, H. (2017). Valence and arousal of emotional stimuli impact cognitive-motor performance in an oddball task. *Biological Psychology*, *125*, 105–114. https://doi.org/10.1016/j.biopsycho.2017.02.010

Luna, B., Padmanabhan, A., & O’Hearn, K. (2010). What has fMRI told us about the Development of Cognitive Control through Adolescence? *Brain and Cognition*, *72*(1), 101–113. https://doi.org/10.1016/j.bandc.2009.08.005
MacLachlan, C., & Howland, H. C. (2002). Normal values and standard deviations for pupil diameter and interpupillary distance in subjects aged 1 month to 19 years. *Ophthalmic and Physiological Optics*, *22*(3), 175–182. https://doi.org/10.1046/j.1475-1313.2002.00023.x
Mahajan, Y., & McArthur, G. (2012). Maturation of auditory event-related potentials across adolescence. *Hearing Research*, *294*(1–2), 82–94. https://doi.org/10.1016/j.heares.2012.10.005
Mahajan, Y., & McArthur, G. (2015). Maturation of mismatch negativity and P3a response across adolescence. *Neuroscience Letters*, *587*, 102–106. https://doi.org/10.1016/j.neulet.2014.12.041
Marchak, F. M., & Steinhauer, S. R. (2011). *Fundamentals of pupillary measures and eye tracking. Paper Presented at the 2011 Annual Meeting of the Society for Psychophysiolocal Research.*
Marois, A., Labonté, K., Parent, M., & Vachon, F. (2018). Eyes have ears: Indexing the orienting response to sound using pupillometry. *International Journal of Psychophysiology*, *123*(March 2017), 152–162. https://doi.org/10.1016/j.ijpsycho.2017.09.016
Marois, A., Pozzi, A., & Vachon, F. (2020). Assessing the Role of Stimulus Novelty in the Elicitation of the Pupillary Dilation Response to Irrelevant Sound. *Auditory Perception & Cognition*, *00*(00), 1–17. https://doi.org/10.1080/25742442.2020.1820290
Masson, R., & Bidet-Caulet, A. (2019). Fronto-central P3a to distracting sounds: An index of their arousing properties. *NeuroImage*, *185*(September 2018), 164–180. https://doi.org/10.1016/j.neuroimage.2018.10.041
Mather, M., Clewett, D., Sakaki, M., & Harley, C. W. (2016). Norepinephrine ignites local hotspots of neuronal excitation: How arousal amplifies selectivity in perception and memory. *Behavioral and Brain Sciences*, *39*. https://doi.org/10.1017/S0140525X15000667
Mathôt, S. (2017). Bayes like a Baws: Interpreting Bayesian repeated measures in JASP. *Cognitive Science and More. Retrieved from: Https://Www. Cogsci. Nl/Blog/Interpreting-Bayesian-Repeated-Measures-in-Jasp*.
Mathôt, Sebastiaan, Fabius, J., Van Heusden, E., & Van der Stigchel, S. (2018). Safe and sensible preprocessing and baseline correction of pupil-size data. *Behavior Research Methods*, *50*(1), 94–106. https://doi.org/10.3758/s13428-017-1007-2
Mathôt, Sebastiaan, Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7
Max, C., Widmann, A., Kotz, S. A., Schröger, E., & Wetzel, N. (2015). Distraction by emotional sounds: Disentangling arousal benefits and orienting costs. *Emotion*, *15*(4), 428–437. https://doi.org/10.1037/a0039041
May, P. J. C., & Tiitinen, H. (2010). Mismatch negativity (MMN), the deviance-elicited auditory deflection, explained. *Psychophysiology*, *47*(1), 66–122. https://doi.org/10.1111/j.1469-8986.2009.00856.x
McCabe, D. P., Roediger, H. L., McDaniel, M. A., Balota, D. A., & Hambrick, D. Z. (2010). The relationship between working memory capacity and executive functioning: Evidence for a common executive attention construct. *Neuropsychology*, *24*(2), 222–243. https://doi.org/10.1037/a0017619
McCloy, D. R., Larson, E. D., Lau, B., & Lee, A. K. C. (2016). Temporal alignment of pupillary response with stimulus events via deconvolution. *The Journal of the Acoustical*

Society of America, *139*(3), EL57–EL62. https://doi.org/10.1121/1.4943787
Merritt, S. L., Keegan, A. P., & Mercer, P. W. (1994). Artifact Management in Pupillometry. *Nursing Research*, *43*(1). https://journals.lww.com/nursingresearchonline/Fulltext/1994/01000/Artifact_Management_in_Pupillometry.12.aspx
Miyake, A., Emerson, M. J., & Friedman, N. P. (2000). Assessment of executive functions in clinical settings: Problems and recommendations. *Semin Speech Lang*, *21*(02). https://doi.org/10.1055/s-2000-7563
Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science*, *21*(1), 8–14. https://doi.org/10.1177/0963721411429458
Montes-Lourido, P., Kar, M., Kumbam, I., & Sadagopan, S. (2021). Pupillometry as a reliable metric of auditory detection and discrimination across diverse stimulus paradigms in animal models. *Scientific Reports*, *11*(1), 1–15. https://doi.org/10.1038/s41598-021-82340-y
Moore, B. C. J., & Glasberg, B. R. (2004). A revised model of loudness perception applied to cochlear hearing loss. *Hearing Research*, *188*(1–2), 70–88. https://doi.org/10.1016/S0378-5955(03)00347-2
Moresi, S., Adam, J. J., Rijcken, J., Van Gerven, P. W. M., Kuipers, H., & Jolles, J. (2008). Pupil dilation in response preparation. *International Journal of Psychophysiology*, *67*(2), 124–130. https://doi.org/10.1016/j.ijpsycho.2007.10.011
Morey, R. ., Rouder, J. N., Jamil, T., Urbanek, S., Forner, K., & Ly, A. (2022). *Package ' BayesFactor .'* https://richarddmorey.github.io/BayesFactor/
Morey, R. D., & Rouder, J. N. (2011). Bayes factor approaches for testing interval null hypotheses. In *Psychological Methods* (Vol. 16, Issue 4, pp. 406–419). American Psychological Association. https://doi.org/10.1037/a0024377
Morey, R. D., Rouder, J. N., Pratte, M. S., & Speckman, P. L. (2011). Using MCMC chain outputs to efficiently estimate Bayes factors. *Journal of Mathematical Psychology*, *55*, 368–378.
Morr, M. L., Shafer, V. L., Kreuzer, J. A., & Kurtzberg, D. (2002). Maturation of Mismatch Negativity in Typically Developing Infants and Preschool Children. *Ear and Hearing*, *23*(2). https://journals.lww.com/ear-hearing/Fulltext/2002/04000/Maturation_of_Mismatch_Negativity_in_Typically.5.aspx
Most, S. B., Chun, M. M., Widders, D. M., Haven, N., & Zald, D. H. (2005). *Attentional rubbernecking: Cognitive control and personality in emotion-induced blindness*. *12*(4), 654–661.
Mueller, V., Brehmer, Y., von Oertzen, T., Li, S. C., & Lindenberger, U. (2008). Electrophysiological correlates of selective attention: A lifespan comparison. *BMC Neuroscience*, *9*, 1–21. https://doi.org/10.1186/1471-2202-9-18
Muller-Gass, A., & Schröger, E. (2007). Perceptual and cognitive task difficulty has differential effects on auditory distraction. *Brain Research*, *1136*, 169–177. https://doi.org/https://doi.org/10.1016/j.brainres.2006.12.020
Murphy, P. R., O'Connell, R. G., O'Sullivan, M., Robertson, I. H., & Balsters, J. H. (2014). Pupil diameter covaries with BOLD activity in human locus coeruleus. *Human Brain Mapping*, *35*(8), 4140–4154. https://doi.org/10.1002/hbm.22466
Murphy, P. R., Robertson, I. H., Balsters, J. H., & O'connell, R. G. (2011). Pupillometry and P3 index the locus coeruleus-noradrenergic arousal function in humans. *Psychophysiology*, *48*(11), 1532–1543. https://doi.org/10.1111/j.1469-8986.2011.01226.x
Näätänen, R., Paavilainen, P., Rinne, T., & Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: A review. *Clinical Neurophysiology*,

118(12), 2544–2590. https://doi.org/10.1016/j.clinph.2007.04.026
Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral and Brain Sciences*, *13*(2), 201–233. https://doi.org/DOI: 10.1017/S0140525X00078407
Näätänen, R. (1992). *Attention and Brain Function*.
Näätänen, R., Pakarinen, S., Rinne, T., & Takegata, R. (2004). The mismatch negativity (MMN): Towards the optimal paradigm. *Clinical Neurophysiology*, *115*(1), 140–144. https://doi.org/10.1016/j.clinph.2003.04.001
Näätänen, R., & Picton, T. (1987). The N1 Wave of the Human Electric and Magnetic Response to Sound: A Review and an Analysis of the Component Structure. *Psychophysiology*, *24*(4), 375–425. https://doi.org/https://doi.org/10.1111/j.1469-8986.1987.tb00311.x
Näätänen, R., Tervaniemi, M., Sussman, E., Paavilainen, P., & Winkler, I. (2001). 'Primitive intelligence' in the auditory cortex. *Trends in Neurosciences*, *24*(5). https://doi.org/10.1016/S0166-2236(00)01790-2
Nagy, Z., Westerberg, H., & Klingberg, T. (2004). Maturation of White Matter is Associated with the Development of Cognitive Functions during Childhood. *Journal of Cognitive Neuroscience*, *16*(7), 1227–1233. https://doi.org/10.1162/0898929041920441
Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution*, *4*(2), 133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x
Netser, S., Ohayon, S., & Gutfreund, Y. (2010). Multiple manifestations of microstimulation in the optic tectum: Eye movements, pupil dilations, and sensory priming. *Journal of Neurophysiology*, *104*(1), 108–118. https://doi.org/10.1152/jn.01142.2009
Nieuwenhuis, S., Aston-Jones, G., & Cohen, J. D. (2005). Decision making, the P3, and the locus coeruleus-norepinephrine system. *Psychological Bulletin*, *131*(4), 510–532. https://doi.org/10.1037/0033-2909.131.4.510
Nieuwenhuis, S., De Geus, E. J., & Aston-Jones, G. (2011). The anatomical and functional relationship between the P3 and autonomic components of the orienting response. *Psychophysiology*, *48*(2), 162–175. https://doi.org/10.1111/j.1469-8986.2010.01057.x
Nieuwenhuis, S., Ridderinkhof, K. R., Bloom, J., Band, G. P. H., & Kok, A. (2001). Error-related brain potentials are differentially related to awareness of response errors: Evidence from an antisaccade task. *Psychophysiology*, *38*(5), 752–760. https://doi.org/DOI: 10.1111/1469-8986.3850752
Nikula, R. (1991). Psychological Correlates of Nonspecific Skin Conductance Responses. *Psychophysiology*, *28*(1), 86–90. https://doi.org/10.1111/j.1469-8986.1991.tb03392.x
Norman, D. A., & Shallice, T. (1986). *Attention to Action BT - Consciousness and Self-Regulation: Advances in Research and Theory Volume 4* (R. J. Davidson, G. E. Schwartz, & D. Shapiro (eds.); pp. 1–18). Springer US. https://doi.org/10.1007/978-1-4757-0629-1_1
Nunnally, J. C., Knott, P. D., Duchnowski, A., & Parker, R. (1967). Pupillary response as a general measure of activation. *Perception & Psychophysics*, *2*(4), 149–155. https://doi.org/10.3758/BF03210310
Öhman, A., Flykt, A., & Esteves, F. (2001). Emotion drives attention: Detecting the snake in the grass. *Journal of Experimental Psychology: General*, *130*(1), 466–478. https://doi.org/10.1037/0096-3445.130.3.466
Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113. https://doi.org/https://doi.org/10.1016/0028-3932(71)90067-4
Olesen, P. J., Macoveanu, J., Tegnér, J., & Klingberg, T. (2007). Brain activity related to working memory and distraction in children and adults. *Cerebral Cortex*, *17*(5), 1047–

1054. https://doi.org/10.1093/cercor/bhl014
Paavilainen, P., Karlsson, M.-L., Reinikainen, K., & Näätänen, R. (1989). Mismatch negativity to change in spatial location of an auditory stimulus. *Electroencephalography and Clinical Neurophysiology*, *73*(2), 129–141. https://doi.org/https://doi.org/10.1016/0013-4694(89)90192-2
Pakarinen, S., Sokka, L., Leinikka, M., Henelius, A., Korpela, J., & Huotilainen, M. (2014). Fast determination of MMN and P3a responses to linguistically and emotionally relevant changes in pseudoword stimuli. *Neuroscience Letters*, *577*, 28–33. https://doi.org/https://doi.org/10.1016/j.neulet.2014.06.004
Pakarinen, S., Takegata, R., Rinne, T., Huotilainen, M., & Näätänen, R. (2007). Measurement of extensive auditory discrimination profiles using the mismatch negativity (MMN) of the auditory event-related potential (ERP). *Clinical Neurophysiology*, *118*(1), 177–185. https://doi.org/10.1016/j.clinph.2006.09.001
Parmentier, F. B. R. (2014). The cognitive determinants of behavioral distraction by deviant auditory stimuli: A review. *Psychological Research*, *78*(3), 321–338. https://doi.org/10.1007/s00426-013-0534-4
Parmentier, F. B. R., Elford, G., Escera, C., Andrés, P., & San Miguel, I. (2008). The cognitive locus of distraction by acoustic novelty in the cross-modal oddball task. *Cognition*, *106*(1), 408–432. https://doi.org/10.1016/j.cognition.2007.03.008
Parmentier, F. B. R., Fraga, I., Leiva, A., & Ferré, P. (2020). Distraction by deviant sounds: disgusting and neutral words capture attention to the same extent. *Psychological Research*, *84*(7), 1801–1814. https://doi.org/10.1007/s00426-019-01192-4
Partala, T., & Surakka, V. (2003). Pupil size variation as an indication of affective processing. *International Journal of Human Computer Studies*, *59*(1–2), 185–198. https://doi.org/10.1016/S1071-5819(03)00017-X
Paulsen, D. J., Hallquist, M. N., Geier, C. F., & Luna, B. (2015). Effects of incentives, age, and behavior on brain activation during inhibitory control: A longitudinal fMRI study. *Developmental Cognitive Neuroscience*, *11*, 105–115. https://doi.org/https://doi.org/10.1016/j.dcn.2014.09.003
Pearson, D. A., & Lane, D. M. (1991). Auditory attention switching: A developmental study. *Journal of Experimental Child Psychology*, *51*(2), 320–334. https://doi.org/10.1016/0022-0965(91)90039-U
Pereira, M. G., Volchan, E., de Souza, G. G. L., Oliveira, L., Campagnoli, R. R., Pinheiro, W. M., & Pessoa, L. (2006). Sustained and transient modulation of performance induced by emotional picture viewing. *Emotion*, *6*(4), 622–634.
Pessoa, L. (2005). To what extent are emotional visual stimuli processed without attention and awareness? *Current Opinion in Neurobiology*, *15*(2), 188–196. https://doi.org/10.1016/j.conb.2005.03.002
Pessoa, L. (2008). *On the relationship between emotion and cognition*. *9*(2). www.nature.com/reviews/neuro
Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience, 35,* 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525
Phelps, E. A., Ling, S., & Carrasco, M. (2006). Emotion facilitates perception and potentiates the perceptual benefits of attention. *Psychological Science*, *17*(4), 292–299. https://doi.org/10.1111/j.1467-9280.2006.01701.x
Pion-Tonachini, L., Kreutz-Delgado, K., & Makeig, S. (2019). ICLabel: An automated electroencephalographic independent component classifier, dataset, and website. *NeuroImage, 198,* 181–197. https://doi.org/https://doi.org/10.1016/j.neuroimage.2019.05.026
Poe, G. R., Foote, S., Eschenko, O., Johansen, J. P., Bouret, S., Aston-Jones, G., Harley, C.

W., Manahan-Vaughan, D., Weinshenker, D., Valentino, R., Berridge, C., Chandler, D. J., Waterhouse, B., & Sara, S. J. (2020). Locus coeruleus: a new look at the blue spot. *Nature Reviews Neuroscience, 21*(11), 644–659. https://doi.org/10.1038/s41583-020-0360-9

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019

Ponton, C. W., Eggermont, J. J., Kwong, B., & Don, M. (2000). Maturation of human central auditory system activity: Evidence from multi-channel evoked potentials. *Clinical Neurophysiology*, *111*(2), 220–236. https://doi.org/10.1016/S1388-2457(99)00236-9

Posner, M. I. (2011). *Cognitive Neuroscience of Attention*. Guilford Press.

Posner, M. I. (1980). Orienting of Attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Posner, M. I. (1990). Hierarchical distributed networks in the neuropsychology of selective attention. In *Cognitive neuropsychology and neurolinguistics: Advances in models of cognitive function and impairment.* (pp. 187–210). Lawrence Erlbaum Associates, Inc.

Posner, M. I. (2008). Measuring alertness. *Annals of the New York Academy of Sciences*, *1129*, 193–199. https://doi.org/10.1196/annals.1417.011

Posner, M. I. (2016). Orienting of Attention: Then and Now. *Quarterly Journal of Experimental Psychology*, *69*(10), 1864–1875. https://doi.org/10.1080/17470218.2014.937446

Pozuelos, J. P., Paz-Alonso, P. M., Castillo, A., Fuentes, L. J., & Rueda, M. R. (2014). Development of attention networks and their interactions in childhood. *Developmental Psychology*, *50*(10), 2405–2415. https://doi.org/10.1037/a0037469

Putkinen, V., Niinikuru, R., Lipsanen, J., Tervaniemi, M., & Huotilainen, M. (2012). Fast measurement of auditory event-related potential profiles in 2-3-year-olds. *Developmental Neuropsychology*, *37*(1), 51–75. https://doi.org/10.1080/87565641.2011.615873

R Core, T. (2019). *R: a language and environment for statistical computing. R Foundation for Statistical Computing, Austria*.

Raftery, A. E. (1995). Bayesian Model Selection in Social Research. *Sociological Methodology*, *25*, 111–163. https://doi.org/10.2307/271063

Ranganath, C., & Rainer, G. (2003). Cognitive neuroscience: Neural mechanisms for detecting and remembering novel events. *Nature Reviews Neuroscience*, *4*(3), 193–202. https://doi.org/10.1038/nrn1052

Raz, A., & Buhle, J. (2006). Typologies of attentional networks. *Nature Reviews Neuroscience*, *7*(5), 367–379. https://doi.org/10.1038/nrn1903

Ridderinkhof, K. R., & Van der Stelt, O. (2000). Attention and selection in the growing child: Views derived from developmental psychophysiology. *Biological Psychology*, *54*(1–3), 55–106. https://doi.org/10.1016/S0301-0511(00)00053-3

Riggins, T., & Scott, L. S. (2019). P300 development from infancy to adolescence. *Psychophysiology*, *57*(7), 1–30. https://doi.org/10.1111/psyp.13346

Roeber, U., Widmann, A., & Schröger, E. (2003). Auditory distraction by duration and location deviants: a behavioral and event-related potential study. *Cognitive Brain Research*, *17*(2), 347–357. https://doi.org/https://doi.org/10.1016/S0926-6410(03)00136-8

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. J. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin \& Review*, *16*, 225–237.

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., & Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia*, *42*(8), 1029–1040. https://doi.org/10.1016/j.neuropsychologia.2003.12.012

Ruff, H. A., & Rothbart, M. K. (1996). *Attention in early development: Themes and variations* (Oxford University Press (ed.)).
Ruhnau, P., Herrmann, B., Maess, B., Brauer, J., Friederici, A. D., & Schröger, E. (2013). Processing of complex distracting sounds in school-aged children and adults: Evidence from EEG and MEG data. *Frontiers in Psychology*, *4*(OCT), 1–15. https://doi.org/10.3389/fpsyg.2013.00717
Ruhnau, P., Wetzel, N., Widmann, A., & Schröger, E. (2010). The modulation of auditory novelty processing by working memory load in school age children and adults: A combined behavioral and event-related potential study. *BMC Neuroscience*, *11*, 1–14. https://doi.org/10.1186/1471-2202-11-126
SanMiguel, I., Linden, D., & Escera, C. (2010). Attention capture by novel sounds: Distraction versus facilitation. *European Journal of Cognitive Psychology*, *22*(4), 481–515. https://doi.org/10.1080/09541440902930994
SanMiguel, I., Morgan, H. M., Klein, C., Linden, D., & Escera, C. (2010). On the functional significance of Novelty-P3: Facilitation by unexpected novel sounds. *Biological Psychology*, *83*(2), 143–152. https://doi.org/10.1016/j.biopsycho.2009.11.012
Sara, S. J., & Bouret, S. (2012). Orienting and Reorienting: The Locus Coeruleus Mediates Cognition through Arousal. *Neuron*, *76*(1), 130–141. https://doi.org/10.1016/j.neuron.2012.09.011
Scharf, F., & Nestler, S. (2019). A comparison of simple structure rotation criteria in temporal exploratory factor analysis for event-related potential data. *Methodology*, *15*(1), 43–60. https://doi.org/10.1027/1614-2241/A000175
Scharf, F., Widmann, A., Bonmassar, C., & Wetzel, N. (2022). A tutorial on the use of temporal principal component analysis in developmental ERP research – Opportunities and challenges. *Developmental Cognitive Neuroscience*, *54*(January), 101072. https://doi.org/10.1016/j.dcn.2022.101072
Schröger, E. (1997). On the detection of auditory deviations: A pre-attentive activation model. *Psychophysiology*, *34*(3), 245–257. https://doi.org/https://doi.org/10.1111/j.1469-8986.1997.tb02395.x
Schröger, E. (1998). Measurement and interpretation of the mismatch negativity. *Behavior Research Methods, Instruments, and Computers*, *30*(1), 131–145. https://doi.org/10.3758/BF03209423
Schröger, E., Giard, M. H., & Wolff, C. (2000). Auditory distraction: Event-related potential and behavioral indices. *Clinical Neurophysiology*, *111*(8), 1450–1460. https://doi.org/10.1016/S1388-2457(00)00337-0
Schröger, E., & Wolff, C. (1996). Mismatch response of the human brain to changes in sound location. *NeuroReport*, *7*(18). https://journals.lww.com/neuroreport/Fulltext/1996/11250/Mismatch_response_of_the_human_brain_to_changes_in.41.aspx
Schröger, E., & Wolff, C. (1998). Attentional orienting and reorienting is indicated by human event-related brain potentials. *Cognitive Brain Research*, *7*(1), 71–87. https://doi.org/10.1016/S0926-6410(98)00013-5
Schupp, H. T., Junghöfer, M., Weike, A. I., & Hamm, A. O. (2003). Attention and emotion: An ERP analysis of facilitated emotional stimulus processing. *NeuroReport*, *14*(8), 1107–1110. https://doi.org/10.1097/00001756-200306110-00002
Schupp, H. T., Stockburger, J., Bublatzky, F., Junghöfer, M., Weike, A. I., & Hamm, A. O. (2008). The selective processing of emotional visual stimuli while detecting auditory targets: An ERP analysis. *Brain Research*, *1230*, 168–176. https://doi.org/https://doi.org/10.1016/j.brainres.2008.07.024
Schwarz, G. (1978). Estimating the Dimension of a Model. *The Annals of Statistics*, *6*(2), 461–464. https://doi.org/10.1214/aos/1176344136

Scott, G. G., O'Donnell, P. J., Leuthold, H., & Sereno, S. C. (2009). Early emotion word processing: Evidence from event-related potentials. *Biological Psychology*, *80*(1), 95–104. https://doi.org/10.1016/j.biopsycho.2008.03.010

Segalowitz, S. J., Santesso, D. L., & Jetha, M. K. (2010). Electrophysiological changes during adolescence: A review. *Brain and Cognition*, *72*(1), 86–100. https://doi.org/https://doi.org/10.1016/j.bandc.2009.10.003

Selezneva, E., Brosch, M., Rathi, S., Vighneshvel, T., & Wetzel, N. (2021). Comparison of Pupil Dilation Responses to Unexpected Sounds in Monkeys and Humans. *Frontiers in Psychology*, *12*(December), 1–11. https://doi.org/10.3389/fpsyg.2021.754604

Shapiro, D. N., Chandler, J., & Mueller, P. A. (2013). Using mechanical turk to study clinical populations. *Clinical Psychological Science*, *1*(2), 213–220. https://doi.org/10.1177/2167702612469015

Sheskin, M., Scott, K., Mills, C. M., Bergelson, E., Bonawitz, E., Spelke, E. S., Fei-Fei, L., Keil, F. C., Gweon, H., Tenenbaum, J. B., Jara-Ettinger, J., Adolph, K. E., Rhodes, M., Frank, M. C., Mehr, S. A., & Schulz, L. (2020). Online Developmental Science to Foster Innovation, Access, and Impact. *Trends in Cognitive Sciences*, *24*(9), 675–678. https://doi.org/10.1016/j.tics.2020.06.004

Shestakova, A., Huotilainen, M., Čeponiene, R., & Cheour, M. (2003). Event-related potentials associated with second language learning in children. *Clinical Neurophysiology*, *114*(8), 1507–1512. https://doi.org/10.1016/S1388-2457(03)00134-2

Simpson, H. M. (1969). Effects of a Task-Relevant Response on Pupil Size. *Psychophysiology*, *6*(2), 115–121. https://doi.org/10.1111/j.1469-8986.1969.tb02890.x

Skau, S., Helenius, O., Sundberg, K., & Bunketorp-k, L. (2022). *Trends in Neuroscience and Education Proactive cognitive control , mathematical cognition and functional activity in the frontal and parietal cortex in primary school children : An fNIRS study*. *28*. https://doi.org/10.1016/j.tine.2022.100180

Smulders, F. T. Y. (2010). Simplifying jackknifing of ERPs and getting more out of it: Retrieving estimates of participants' latencies. *Psychophysiology*, *47*(2), 387–392. https://doi.org/https://doi.org/10.1111/j.1469-8986.2009.00934.x

Sokolov, E. N. (1963). Higher Nervous Functions: The Orienting Reflex. *Annual Review of Physiology*, *25*(1), 545–580. https://doi.org/10.1146/annurev.ph.25.030163.002553

Sokolov, E. N. (1963). *Perception and the Conditioned Reflex*. Elsevier.

Solomon, B., Decicco, J. M., & Dennis, T. A. (2012). Emotional picture processing in children: An ERP study. *Developmental Cognitive Neuroscience*, *2*(1), 110–119. https://doi.org/10.1016/j.dcn.2011.04.002

Soto-Faraco, S., & Spence, C. (2002). Modality-specific auditory and visual temporal processing deficits. *The Quarterly Journal of Experimental Psychology Section A*, *55*(1), 23–40. https://doi.org/10.1080/02724980143000136

Sowell, E. R., Peterson, B. S., Thompson, P. M., Welcome, S. E., Henkenius, A. L., & Toga, A. W. (2003). Mapping cortical change across the human life span. *Nature Neuroscience*, *6*(3), 309–315. https://doi.org/10.1038/nn1008

Sowell, E. R., Thompson, P. M., Leonard, C. M., Welcome, S. E., Kan, E., & Toga, A. W. (2004). Longitudinal mapping of cortical thickness and brain growth in normal children. *Journal of Neuroscience*, *24*(38), 8223–8231. https://doi.org/10.1523/JNEUROSCI.1798-04.2004

Speed, B. C., Nelson, B. D., Auerbach, R. P., Klein, D. N., & Hajcak, G. (2016). Depression risk and electrocortical reactivity during self-referential emotional processing in 8 to 14 year-old girls. In *Journal of Abnormal Psychology* (Vol. 125, Issue 5, pp. 607–619). American Psychological Association. https://doi.org/10.1037/abn0000173

Steinhauer, S. R., Bradley, M. M., Siegle, G. J., Roecklein, K. A., & Dix, A. (2022). Publication guidelines and recommendations for pupillary measurement in

psychophysiological studies. *Psychophysiology*, *59*(4), 1–36. https://doi.org/10.1111/psyp.14035
Steinhauer, S. R., & Hakerem, G. (1992). The Pupillary Response in Cognitive Psychophysiology and Schizophrenia. *Annals of the New York Academy of Sciences*, *658*(1), 182–204. https://doi.org/10.1111/j.1749-6632.1992.tb22845.x
Strauch, C., Wang, C.-A., Einhäuser, W., Van der Stigchel, S., & Naber, M. (2022). Pupillometry as an integrated readout of distinct attentional networks. *Trends in Neurosciences*, 1–13. https://doi.org/10.1016/j.tins.2022.05.003
Tartar, J. L., de Almeida, K., McIntosh, R. C., Rosselli, M., & Nash, A. J. (2012). Emotionally negative pictures increase attention to a subsequent auditory stimulus. *International Journal of Psychophysiology*, *83*(1), 36–44. https://doi.org/10.1016/j.ijpsycho.2011.09.020
Tegelbeckers, J., Schares, L., Lederer, A., Bonath, B., Flechtner, H. H., & Krauel, K. (2016). Task-irrelevant novel sounds improve attentional performance in children with and without ADHD. *Frontiers in Psychology*, *6*(JAN), 1–9. https://doi.org/10.3389/fpsyg.2015.01970
Teigen, K. H. (1994). Yerkes-Dodson: A Law for all Seasons. *Theory & Psychology*, *4*(4), 525–547. https://doi.org/10.1177/0959354394044004
Thierry, G., & Roberts, M. V. (2007). Event-related potential study of attention capture by affective sounds. *NeuroReport*, *18*(3). https://journals.lww.com/neuroreport/Fulltext/2007/02120/Event_related_potential_study_of_attention_capture.10.aspx
Tiitinen, H., May, P., Reinikainen, K., & Näätänen, R. (1994). Attentive novelty detection in humans is governed by pre-attentive sensory memory. *Nature*, *372*(6501), 90–92. https://doi.org/10.1038/372090a0
Troller-Renfree, S. V., Buzzell, G. A., & Fox, N. A. (2020). Changes in working memory influence the transition from reactive to proactive cognitive control during childhood. *Developmental Science*, *23*(6), 1–9. https://doi.org/10.1111/desc.12959
Uematsu, A., Matsui, M., Tanaka, C., Takahashi, T., Noguchi, K., Suzuki, M., & Nishijo, H. (2012). Developmental Trajectories of Amygdala and Hippocampus from Infancy to Early Adulthood in Healthy Individuals. *PLOS ONE*, *7*(10), e46970. https://doi.org/10.1371/journal.pone.0046970
Vachon, F., Labonté, K., & Marsh, J. E. (2017). Attentional capture by deviant sounds: A noncontingent form of auditory distraction? *Journal of Experimental Psychology: Learning Memory and Cognition*, *43*(4), 622–634. https://doi.org/10.1037/xlm0000330
van Mourik, R., Oosterlaan, J., Heslenfeld, D. J., Konig, C. E., & Sergeant, J. A. (2007). When distraction is not distracting: A behavioral and ERP study on distraction in ADHD. *Clinical Neurophysiology*, *118*(8), 1855–1865. https://doi.org/10.1016/j.clinph.2007.05.007
Volkmer, S., Wetzel, N., Widmann, A., & Scharf, F. (2022). Attentional control in middle childhood is highly dynamic—Strong initial distraction is followed by advanced attention control. *Developmental Science*, *April*, 1–18. https://doi.org/10.1111/desc.13275
Volosin, M., Grimm, S., & Horváth, J. (2016). Exploiting temporal predictability: Event-related potential correlates of task-supportive temporal cue processing in auditory distraction. *Brain Research*, *1639*, 120–131. https://doi.org/10.1016/j.brainres.2016.02.044
Vuilleumier, P, A., J. L., Driver, J., & Dolan, R. J. (2001). Effects of attention and emotion on face processing in the human brain. *Neuron*, *30*, 829–841.
Vuilleumier, P. (2005). How brains beware: Neural mechanisms of emotional attention. *Trends in Cognitive Sciences*, *9*(12), 585–594. https://doi.org/10.1016/j.tics.2005.10.011

Wang, C.-A., & Munoz, D. P. (2014). Modulation of stimulus contrast on the human pupil orienting response. *European Journal of Neuroscience, 40*(5), 2822–2832. https://doi.org/https://doi.org/10.1111/ejn.12641

Wang, C. A., Baird, T., Huang, J., Coutinho, J. D., Brien, D. C., & Munoz, D. P. (2018). Arousal Effects on Pupil Size, Heart Rate, and Skin Conductance in an Emotional Face Task. *Frontiers in Neurology*, *9*(December), 1–13. https://doi.org/10.3389/fneur.2018.01029

Wang, C. A., Boehnke, S. E., White, B. J., & Munoz, D. P. (2012). Microstimulation of the monkey superior colliculus induces pupil dilation without evoking saccades. *Journal of Neuroscience*, *32*(11), 3629–3636. https://doi.org/10.1523/JNEUROSCI.5512-11.2012

Watson, A. B., & Yellott, J. I. (2012). A unified formula for light-adapted pupil size. *Journal of Vision*, *12*(10), 1–16. https://doi.org/10.1167/12.10.12

Wetzel, N. (2015). Effects of the short-term learned significance of task-irrelevant sounds on involuntary attention in children and adults. *International Journal of Psychophysiology*, *98*(1), 17–26. https://doi.org/https://doi.org/10.1016/j.ijpsycho.2015.06.003

Wetzel, N., Buttelmann, D., Schieler, A., & Widmann, A. (2016). Infant and adult pupil dilation in response to unexpected sounds. *Developmental Psychobiology*, *58*(3), 382–392. https://doi.org/10.1002/dev.21377

Wetzel, N., Scharf, F., & Widmann, A. (2019). Can't Ignore—Distraction by Task-Irrelevant Sounds in Early and Middle Childhood. *Child Development*, *90*(6), e819–e830. https://doi.org/10.1111/cdev.13109

Wetzel, N., & Schröger, E. (2007a). Cognitive control of involuntary attention and distraction in children and adolescents. *Brain Research*, *1155*(1), 134–146. https://doi.org/10.1016/j.brainres.2007.04.022

Wetzel, N., & Schröger, E. (2007b). Modulation of involuntary attention by the duration of novel and pitch deviant sounds in children and adolescents. *Biological Psychology*, *75*(1), 24–31. https://doi.org/10.1016/j.biopsycho.2006.10.006

Wetzel, N., & Schröger, E. (2014). On the development of auditory distraction: A review. *PsyCh Journal*, *3*(1), 72–91. https://doi.org/10.1002/pchj.49

Wetzel, N., Schröger, E., & Widmann, A. (2013). The dissociation between the P3a event-related potential and behavioral distraction. *Psychophysiology*, *50*(9), 920–930. https://doi.org/10.1111/psyp.12072

Wetzel, N., Schröger, E., & Widmann, A. (2016). Distraction by novel and pitch-deviant sounds in children. *Frontiers in Psychology*, *7*(DEC), 1–12. https://doi.org/10.3389/fpsyg.2016.01949

Wetzel, N., Widmann, A., Berti, S., & Schröger, E. (2006). The development of involuntary and voluntary attention from childhood to adulthood: A combined behavioral and event-related potential study. *Clinical Neurophysiology*, *117*(10), 2191–2203. https://doi.org/10.1016/j.clinph.2006.06.717

Wetzel, N., Widmann, A., & Scharf, F. (2021). Distraction of attention by novel sounds in children declines fast. *Scientific Reports*, *11*(1), 1–13. https://doi.org/10.1038/s41598-021-83528-y

Wetzel, N., Widmann, A., & Schröger, E. (2011). Processing of novel identifiability and duration in children and adults. *Biological Psychology*, *86*(1), 39–49. https://doi.org/10.1016/j.biopsycho.2010.10.005

Wetzel, N., Widmann, A., & Schröger, E. (2012). Distraction and facilitation-two faces of the same coin? *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 664–674. https://doi.org/10.1037/a0025856

Wheatley, W., & Spitschan, M. (2018). *Watson & Yellott's (2012) Unified Formula for Light-Adapted Pupil Size*.

Widmann, A., & Schröger, E. (2012). Filter effects and filter artifacts in the analysis of

electrophysiological data. *Frontiers in Psychology*, *3*(JUL), 1–5. https://doi.org/10.3389/fpsyg.2012.00233
Widmann, A., Schröger, E., & Maess, B. (2015). Digital filter design for electrophysiological data - a practical approach. *Journal of Neuroscience Methods*, *250*, 34–46. https://doi.org/10.1016/j.jneumeth.2014.08.002
Widmann, A., Schröger, E., & Wetzel, N. (2018). Emotion lies in the eye of the listener: Emotional arousal to novel sounds is reflected in the sympathetic contribution to the pupil dilation response and the P3. *Biological Psychology*, *133*(January 2017), 10–17. https://doi.org/10.1016/j.biopsycho.2018.01.010
Wilhelm, H. (2011). Disorders of the pupil. In *Handbook of Clinical Neurology* (1st ed., Vol. 102). Elsevier B.V. https://doi.org/10.1016/B978-0-444-52903-9.00022-4
Winkler, I, Debener, S., Müller, K., & Tangermann, M. (2015). On the influence of high-pass filtering on ICA-based artifact reduction in EEG-ERP. *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 4101–4105. https://doi.org/10.1109/EMBC.2015.7319296
Winkler, I. (2007). *Interpreting theMismatch Negativity*. *21*(1992), 147–163. https://doi.org/10.1027/0269-8803.21.3.147
Winkler, I., Denham, S. L., & Nelken, I. (2009). Modeling the auditory scene: predictive regularity representations and perceptual objects. *Trends in Cognitive Sciences*, *13*(12), 532–540. https://doi.org/https://doi.org/10.1016/j.tics.2009.09.003
Winkler, I., & Schröger, E. (2015). Auditory perceptual objects as generative models: Setting the stage for communication by sound. *Brain and Language*, *148*, 1–22. https://doi.org/10.1016/j.bandl.2015.05.003
Winkler, I., Tervaniemi, M., Schröger, E., Wolff, C., & Näätänen, R. (1998). Preattentive processing of auditory spatial information in humans. *Neuroscience Letters*, *242*(1), 49–52. https://doi.org/10.1016/S0304-3940(98)00022-6
Wise, L. Z., & Irvine, D. R. F. (1983). Auditory response properties of neurons in deep layers of cat superior colliculus. *Journal of Neurophysiology*, *49*(3), 674–685. https://doi.org/10.1152/jn.1983.49.3.674
Wunderlich, J. L., Cone-Wesson, B. K., & Shepherd, R. (2006). Maturation of the cortical auditory evoked potential in infants and young children. *Hearing Research*, *212*(1–2), 185–202. https://doi.org/10.1016/j.heares.2005.11.010
Xiefeng, C., Wang, Y., Dai, S., Zhao, P., & Liu, Q. (2019). Heart sound signals can be used for emotion recognition. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-42826-2
Yago, E., Escera, C., Alho, K., Giard, M. H., & Serra-Grabulosa, J. M. (2003). Spatiotemporal dynamics of the auditory novelty-P3 event-related brain potential. *Cognitive Brain Research*, *16*(3), 383–390. https://doi.org/10.1016/S0926-6410(03)00052-1
Yang, T. T., Simmons, A. N., Matthews, S. C., Tapert, S. F., Bischoff-Grethe, A., Frank, G. K. W., Arce, E., & Paulus, M. P. (2007). Increased amygdala activation is related to heart rate during emotion processing in adolescent subjects. *Neuroscience Letters*, *428*(2–3), 109–114. https://doi.org/10.1016/j.neulet.2007.09.039
Zeelenberg, R., & Bocanegra, B. R. (2010). Auditory emotional cues enhance visual perception. *Cognition*, *115*(1), 202–206. https://doi.org/10.1016/j.cognition.2009.12.004
Zeelenberg, R., Wagenmakers, E.-J., & Rotteveel, M. (2006). The Impact of Emotion on Perception: Bias or Enhanced Processing? *Psychological Science*, *17*(4), 287–291. https://doi.org/10.1111/j.1467-9280.2006.01700.x
Zekveld, A. A., Koelewijn, T., & Kramer, S. E. (2018). The Pupil Dilation Response to Auditory Stimuli: Current State of Knowledge. *Trends in Hearing*, *22*, 1–25. https://doi.org/10.1177/2331216518777174

Zelazo, P. D., Carlson, S. M., & Kesek, A. (2008). The development of executive function in childhood. In *Handbook of developmental cognitive neuroscience, 2nd ed.* (pp. 553–574). MIT Press.

Zhao, S., Chait, M., Dick, F., Dayan, P., Furukawa, S., & Liao, H. I. (2019). Pupil-linked phasic arousal evoked by violation but not emergence of regularity within rapid sound sequences. *Nature Communications*, *10*(1), 1–16. https://doi.org/10.1038/s41467-019-12048-1