Infant and adult pupil dilation in response to unexpected sounds

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Abstract

Surprisingly occurring sounds outside the focus of attention can involuntarily capture attention. This study focuses on the impact of deviant sounds on the pupil size as a marker of auditory involuntary attention in infants. We presented an oddball paradigm including four types of deviant sounds within a sequence of repeated standard sounds to 14-month-old infants and to adults. Environmental and noise deviant sounds elicited a strong pupil dilation response (PDR) in both age groups. In contrast, moderate frequency deviants elicited a significant PDR in adults only. Moreover, a principal component analysis revealed two components underlying the PDR. Component scores differ, depending on deviant types, between age groups. Results indicate age effects of parasympathetic inhibition and sympathetic activation of the pupil size caused by deviant sounds with a high arousing potential. Results demonstrate that the PDR is a sensitive tool for the investigation of involuntary attention to sounds in preverbal children.

Keywords

pupil dilation, PDR, pupillometry, attention, distraction, novel, development, infants, children

Introduction

New, unexpected, and task-irrelevant sounds (deviants) occurring outside of the focus of attention can involuntarily capture attention and can impair performance of a task at hand (for review, see, Escera, Alho, Schröger, & Winkler, 2000; Parmentier, 2014; Wetzel & Schröger, 2014). The distraction of attention is associated with typical components in the event-related potentials (ERPs, for reviews see, Escera et al., 2000; Kushnerenko, Van den Bergh, & Winkler, 2013; Wetzel & Schröger, 2014). However, the measurement of ERPs requires the cooperation of participants and is subject to further restrictions as participants should not move their heads and bodies during test. This is posing a problem for the investigation of involuntary attention mechanisms particularly in the group of 1–5-year-old children. Indeed, this age group is underrepresented in the field of involuntary attention research. It has been shown that the pupil dilation response (PDR) is sensitive to the processing of unexpected stimuli in adults (Friedman, Hakerem, Sutton, & Fleiss, 1973; Qiyuan, Richer, Wagoner, & Beatty, 1985; Steinhauer & Hakerem, 1992). We hypothesize that the PDR can also be sensitive to the processing of unexpected deviants in preverbal children and that different types of deviants cause different PDR.

The mechanisms underlying distraction by task-irrelevant and unexpected sounds operate on several stages and have been described by a three-stage model of involuntary attention (e.g., Escera & Corral, 2007; Schröger, 1997; Wetzel & Schröger, 2014). The cognitive system establishes a predictive model of the acoustic environment and automatically compares the actual auditory input with the prediction (e.g., Schröger & Winkler, 2015; Winkler, Denham, & Nelken, 2009). At this point attention is initially focused on task-relevant stimuli (e.g., a child attends the blocks when building a block tower). If a violation of the prediction is detected (e.g., a sibling of the child suddenly switches on the TV) an error signal is generated calling for attention (first stage). At the second stage, attention is involuntarily directed to the novel sound (sound generated by the TV) even if this sound is not relevant for the task at hand. After evaluation of the novel sound the child might reorient attention back to the primary task and continue playing (third stage). The involuntary attention mechanisms on the different stages operate partly independent (Horvath, Winkler, & Bendixen, 2008; Wetzel, Widmann, & Schröger, 2009) and mature with a different developmental time course (Wetzel et al., 2009; Wetzel & Schröger, 2014). These involuntary attention mechanisms are functioning early in life. Brain responses associated with the detection of a prediction violation elicited by deviant sounds have been observed already in the human fetus (e.g., Draganova et al., 2005). The ability to detect changes in the environment and to orient attention to deviant sounds develops strongly within the

This project was supported by the German Research Foundation (DFG) project number WE5026/1-1. The authors would like to thank all participants and parents for participating in this study and T. Wohlfahrt and M. Kritsch for assistance in data acquisition.

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first year of life (for review, see, Kushnerenko et al., 2013). Processes of involuntary attention that might be associated with the three stages of the involuntary attention model introduced above can generally be observed already in 2–3-year-olds (Putkinen, Niinikuru, Lipsanen, Tervaniemi, & Huotilainen, 2012), even though these mechanisms strongly develop until adolescence (e.g., Gumenyuk, Korzyukov, Alho, Escera, & Näätänen, 2004; Maurer, Bucher, Brem, & Brandeis, 2003; Ruhnau et al., 2013; Wetzel, Widmann, Berti, & Schröger, 2006; Wetzel & Schröger, 2007a; Wetzel et al., 2009).

The stimulus-related PDR was mainly investigated in the last century but is currently becoming more important as an indicator of cognitive effort and allocation of attention, particularly in research with young children because of its convenient applicability (Jackson & Sirois, 2009; Laeng, Sirois, & Gredebäck, 2012; Sebasti an-Gall es, 2013). The pupil is controlled by the autonomic nervous system via the parasympathetic and the sympathetic pathway. An important role for the autonomic nervous system plays the Locus Coeruleus (LC), a structure in the brainstem containing norepinephrine (NE)-synthesizing neurons. Current theories suggest that the LC-NE system mediates focused attention and task engagement (Aston-Jones & Cohen, 2005; Corbetta, Patel, & Shulman, 2008). It is suggested that behaviorally relevant stimuli trigger a high-frequency phasic activity of the LC and that the release of NE facilitates stimulus processing, that is, the LC-NE system acts as a temporal attention filter (Aston-Jones & Cohen, 2005). There is indeed a close relation between the activity of the LC and the changes in pupil size (Alnaes et al., 2014; Aston-Jones & Cohen, 2005; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014), supporting that the pupil size indexes attention-related brain activity.

The PDR was frequently used as an indicator of cognitive load, mental effort, or emotional arousal in adults (Beatty, 1982; Beatty & Lucero-Wagoner, 2000; Bradley, Miccoli, Escrig, & Lang, 2008; Hess & Polt, 1960; Kahneman, 1973; Partala & Surakka, 2003; Piquado, Isaacowitz, & Wingfield, 2010; Siegle, Steinhauer, & Thase, 2004; van der Meer et al., 2010; Zekveld & Kramer, 2014). Important for the present study is the finding that deviant sounds in terms of low stimulus probability elicited a stimulus-evoked phasic pupil response in adults (Murphy, Robertson, Balsters, & O'Connell, 2011; Murphy et al., 2014; Qiyuan et al., 1985; Steinhauer & Hakerem, 1992; Steinhauer & Zubin, 1982). Whether the deviant-related PDR is an index of the autonomic orienting response remains under discussion in the literature (Maher & Furedy, 1979; Nieuwenhuis, De Geus, & Aston-Jones, 2011; Steiner & Barry, 2011).

Whereas in adults the deviant-related PDR has been well investigated, not a single study can be found investigating pupil dilation in the context of novel or deviant sound processing in children. There are only a few studies (for review see, Karatekin, Marcus, & Couperus, 2007) that measured pupil dilation as an index of cognitive load or the recruitment of cognitive resources in school age children or as an index of the claim of cognitive resources in children aged 7–11 years (Boersma, Wilton, Barham, & Muir, 1970; Gardner, 1968; Karatekin, 2004; Karatekin et al., 2007). Pupil dilation was also measured in the context of the violation of infants' expectations (Jackson & Sirois, 2009; Sebastián-Gallés, 2013), and as an index of emotional or social processing in infants (Gardner, 1968; Geangu, Hauf, Bhardwaj, & Bentz, 2011; Gredebäck, Johnson, & von Hofsten, 2010; Hepach, Vaish, & Tomasello, 2012) and adolescents (Silk et al., 2009). Moreover, PDR measurement was used as a tool for the investigation of cognitive and emotional processing in clinical subgroups, for example in children and adolescents suffering from Major Depressive Disorder (Silk et al., 2007) or Autism Spectrum Disorder (Anderson, Colombo, & Jill Shaddy, 2006). In sum, the PDR has been observed in children as an index of several cognitive processes, so far. However, until now, there is no research applying PDR in the context of auditory involuntary attention research in children. For testing effects of different deviant types on involuntary attention we presented a version of an auditory oddball paradigm including one frequently presented sine wave standard sound (standard) and four types of rarely presented deviant sounds that differed from the standard sound.

The aim of the present study was to test whether deviant-related differences in PDR can be measured in infants and whether there are developmental changes. As both, the amount of physical information and the amount of semantic including emotional information of sounds are known to affect involuntary attention mechanisms in children (Wetzel et al., 2006; Wetzel, Widmann, & Schröger, 2011) or adults (Berti, Roeber, & Schröger, 2004; Max, Widmann, Kotz, Schröger, & Wetzel, 2015) we varied the deviant types along both dimensions: The physical information content differed in spectral bandwidth and the contrast to the standard sound between a simple sine wave *frequency deviant* (spectrally sparse and low contrast to standard; predominantly used in auditory involuntary attention research), two environmental sounds (intermediate spectral complexity and contrast to standard), and *pink noise* (maximal spectral bandwidth and contrast to standards). The two artificial sounds provided no semantic information (besides that they are both deviants). The two environmental sounds, the *cry of a baby* and a *phone ring*, provided semantic information. That is, they either did or did not provide emotional content. Thus, the two environmental sounds differed in their arousing potential—the cry of a peer being more arousing than a phone ring—and presumably affect involuntary attention mechanisms differently in children and adults. We were aware that semantic versus physical information are confound in this design. In order to be able to measure deviant-related PDR in infants we tried to maximize the stimulus contrasts.

Based on the literature review we postulate several hypotheses. First, we expect that rarely presented deviant sounds elicit a PDR in adults as well as in 14-month-old children. This hypothesis is based on studies reporting basic but functional involuntary attention mechanisms in preverbal children (for review see, Kushnerenko et al., 2013). Second, we expect differential changes in PDR in response to different types of deviant sounds (noise, baby cry, phone ring, frequency deviant) since those differ in the amount of physical and semantic including emotional information content. Since increased physical information content of deviant sounds caused stronger brain responses associated with involuntary attention in adults (Berti et al., 2004), in primary school age children (Wetzel et al., 2006) and caused strong brain responses for spectral broadband deviants relative to frequency deviants in neonates (Kushnerenko et al., 2007), we expect the largest PDR in response to noise deviants, the second largest in response to the environmental sounds because of their lower amount of physical information (baby cry and phone ring) and the lowest in response to the frequency deviant in both age groups. Furthermore, we expected differences with respect to the semantic information. Emotional information (in our study provided by the baby cry) is known to increase pupil size in adults (Bradley et al., 2008; Partala & Surakka, 2003) and infants (Geangu et al., 2011). Therefore, we expect increased effects of deviant's emotional content on the pupil. Since children's involuntary attention mechanisms are suggested to be more susceptible against highly significant distractor sounds relative to less significant distractor sounds (Wetzel, 2015), we third hypothesize that the emotional information content of the baby cry affect the deviant-related PDR more in children than in adults.

Methods

Participants

Thirty-three healthy children (13.2–15.9 month; mean age 14.3 month; 20 girls) and 31 healthy adults (22.4–33.9 years; mean 25.0 years; 24 females) participated in the study. Five additional children were tested but excluded from further analysis as less than three deviant trials were remaining in one or more sound categories after artifact rejection. Participation was rewarded by certificate and a toy (children) or by money or credit points (adults). Adults and parents representing children gave written informed consent. All participants or parents (in case of children) reported normal hearing and normal or corrected-to-normal vision.

Stimulus Material and Procedure

Stimuli. The sounds[1] of a cry of a baby and of a phone ring were collected from a commercial CD (1,111 Geräusche, Döbeler Cooperation, Hamburg, Germany). The pink noise sound was created using Matlab. The frequency deviant sound was a harmonic tone of 750 Hz fundamental frequency and the standard sound was of 500 Hz. Both sounds were constructed from the three lowest partials, with the second and third partials having a lower intensity than the first one by –3 and –6 dB, respectively. Sounds had a duration of 800 ms, including 10 ms faded ends. Sounds were RMS matched and presented with an intensity of 60 dB sound pressure level. Sounds were presented pseudo-randomly. Each deviant sound was preceded by at least two standard sounds. Deviant sounds were presented mixed in the same block (Fig. 1) with an overall probability of 25 %. Each deviant sound type was presented eight times. Stimuli were presented with a variable stimulus-onset asynchrony of 1,800–2,400 ms (equiprobably 1,800 ms, 2,000 ms, 2,200 ms, or 2,400 ms). During sound presentation participants watched a silent video. The video clip showed a female actor who played with toys and virtually interacted with the participants.

Apparatus. The video clip was presented at a TV screen (37" Panasonic TX-L37S20E) in 4:3 format (61.3 cm wide and 46 cm high). The distance between the TV and participants' eyes was approximately 100 cm and the angle of vision was 34° horizontal, 26° vertical and 42° diagonal. As the video format did not fill the complete screen black bars were visible on the left and the right. The auditory stimuli were presented using Matlab. Sounds were presented via loudspeakers located to the left and right of the screen. Pupil dilation was recorded by an infrared EyeLink 1000 (SR Research Ltd, Osgoode, ON, Canada) remote eye-tracker (250 Hz, sampling in 4 ms intervals). The distance between the eye-tracker and participants' eyes was approximately 60 cm. We tracked the left eye (one child required the change from the left to the right eye during the session). The light intensity in the dimly lit lab was identical for all participants (approximately 400 cd/m^2).

[1]Examples of sounds can be found online: http://home.uni-leipzig.de/biocog/wetzel/standard.wav; http://home.uni-leipzig.de/biocog/wetzel/pitch_deviant.wav; http://home.uni-leipzig.de/biocog/wetzel/pink_noise.wav; http://home.uni-leipzig.de/biocog/wetzel/baby_cry.wav; http://home.uni-leipzig.de/biocog/wetzel/phone_ring.wav

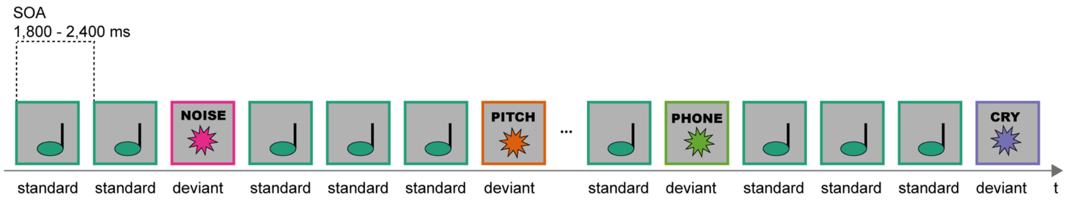

Fig. 1. Deviant sounds (pink noise, cry of a baby, phone ring, frequency deviant) were pseudo-randomly and rarely presented within a sequence of repeated simple standard sounds. Participants watched a silent video clip during the sound presentation.

Procedure. After the children arrived in the lab, they played with the experimenter in a playing room for familiarization while an assistant explained the study to the parent. The assistant did not mention any hypotheses of the study. Parents were asked to sit still and to say nothing during the experimental session but were asked to smile whenever infants interacted with them. During play the experimenter put a small target sticker, required as a landmark for the eye-tracker, on children's forehead. After entering the lab children were seated on parent's lap in front of the TV screen and the eye-tracker. Then a three-point eye tracker calibration procedure using rotating toys was performed. The experimenter manually started the sound stimulation after the video clip was started. The sound sequence was presented within one block but the experimenter had to continue the presentation manually by button press after each 32 sounds. The sequence of sounds was randomized individually for each participant. The stimulation without breaks lasted 4 min 29 s. During the presentation, the experimenter left the room. Adult participants performed the same procedure like children except playing at the beginning of the session. As one's own phone ring affects distractor processing differently from those of other phone rings (Roye, Jacobsen, & Schröger, 2007) we asked adult participants whether the presented phone ring was identical with their own phone ring. All subjects negated this question.

Data Analysis

Eye tracker pupil diameter digital counts were calibrated using the method suggested by Marchak and Steinhauer (2011) and converted to mm. Data were filtered with a 5-point moving average filter (–3 dB cutoff = 22 Hz, Marchak & Steinhauer, 2011). Data regions with diameter changes exceeding 5 mm/s within a 5-point moving window were marked as artifacts (Merritt, Keegan, & Mercer, 1994). Pupil diameter values smaller than 1 mm or larger than 8 mm were marked as artifacts. Data regions including less than five consecutive samples between two regions marked as artifacts were also marked as artifacts. Data in regions marked as artifacts up to 1 s duration were interpolated using linear interpolation (Merritt et al., 1994; Marchak & Steinhauer, 2011). Longer artifact regions were discarded. Data were epoched into segments of 2 s duration including a .2 s pre-stimulus baseline. The first two (standard) sounds per block and each (standard) sound immediately following a deviant sound were removed from further analyzes since post-deviant effects on the subsequent standard have been reported (e.g., Wetzel, 2015). Moreover, this procedure avoids the contamination of standard responses by late PDRs to deviants. Data were baseline corrected and averaged per sound type. A time window of .5 s duration was centered on the peaks of the averaged dilation responses (1.172 s for both groups). Steinhauer & Hakerem (1992) described a biphasic response that they associated with the summation of two (parasympathetic and sympathetic) PDRs. A similar biphasic response was observed in our data (Fig. 2). Therefore, we additionally performed a temporal principal component analysis (PCA) in order to separate main factors underlying the biphasic response with the ERP PCA Toolkit MATLAB toolbox by Dien (2010). PCA was computed using Promax rotation ($\kappa = 3$) with a covariance relationship matrix and Kaiser weighting. Two components were retained explaining more than 95 % of the variance (Figs. 2 and 3).

Statistical Analysis

Mean amplitudes of changes of the PDR were tested in a mixed-model analyses of variance (ANOVA) including the within-subject factor *sound type* (standard, frequency deviant, noise, cry of a baby, phone ring) and the between-subject factor *group* (infants, adults). Scores of the two components resulting from the PCA were additionally analyzed by an ANOVA including the within-subject factors *sound type* × *component* (component 1, component 2) and the between-subject factor *group*.

An alpha-level of .05 was defined for all statistical tests. Statistically significant results were reported including the partial η_P^2 effect size measure. Greenhouse-Geisser corrections of degrees of freedom were applied when appropriate. Follow up t-tests were run for statistically significant interactions and were Bonferroni-corrected if necessary.

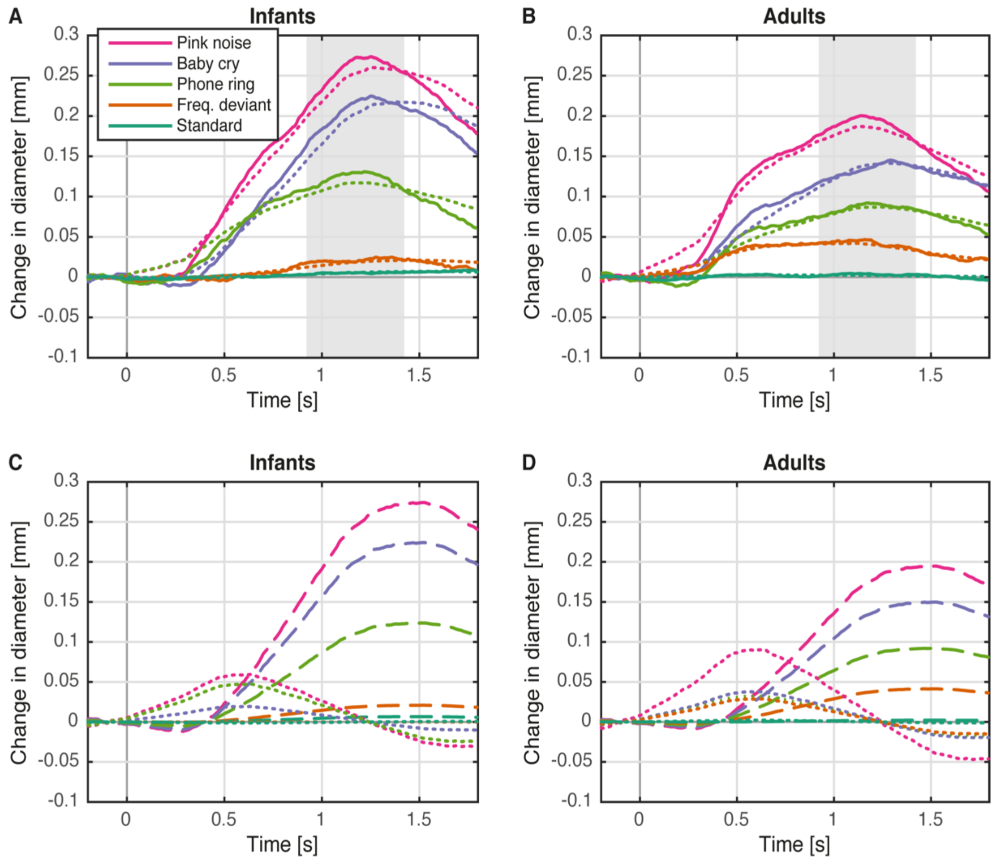

Fig. 2. Panels A and B: Changes in pupil dilation observed in response to all sound types in infants and adults (solid lines) and corresponding PDRs reconstructed from the PCA (i.e., the sum of both component responses shown in Panel C and D; dotted lines). The comparison of observed and reconstructed responses demonstrates that the data pattern can be validly reduced to only two principal component time courses. The gray patches indicate the time window used for the statistical analysis. Panels C and D: PDRs to all sound types plotted separately for component 1 (dashed line; presumably reflecting sympathetic activation) and component 2 (dotted lines; presumably reflecting parasympathetic inhibition).

Results

PDR

The ANOVA with the factors sound type and group revealed a main effect of the factor sound type ($F(4,248) = 79.02$, $p < .001$, $\eta_p^2 = .560$, $\varepsilon = .874$). Deviant sounds elicited a PDR but standard sounds did not elicit a PDR (t-test against zero: standard: mean = .0061 mm, $t(63) = 1.824$, $p = .073$; noise: mean = .2254 mm, $t(63) = 14.112$, $p < .001$; baby cry: mean = .1746 mm, $t(63) = 11.651$, $p < .001$; phone ring: mean = .1080 mm, $t(63) = 8.199$, $p < .001$, frequency deviant: mean = .0306 mm, $t(63) = 3.408$, $p = .001$; see Fig. 2). Furthermore, a main effect of the factor group was observed ($F(1,62) = 5.445$, $p = .023$, $\eta_p^2 = .081$), indicating an increased PDR in infants compared to adults. The interaction of the factors sound type and group was statistically significant ($F(4,248) = 4.057$, $p = .005$, $\eta_p^2 = .061$, $\varepsilon = .874$). Bonferroni-corrected t-tests revealed PDR in trials including noise, the cry of a baby, and phone ring compared to standard sounds in both age groups (infants: noise: ($t(32) = -10.323$, $p < .001$; cry of a baby: $t(32) = -9.020$, $p < .001$; phone ring: $t(32) = -7.090$, $p < .001$; adults: noise: ($t(30) = -9.869$, $p < .001$; cry of a baby: $t(30) = -8.746$, $p < .001$; phone ring: $t(30) = -3.987$, $p < .001$). Importantly, adults, but not infants, showed a PDR in trials including a frequency deviant (adults: $t(30) = -3.024$, $p = .005$; infants: ($t(32) = -0.975$, $p = .337$).

Two Components of the PDR

The ANOVA including the scores of the PCA (sound type × component × group) revealed a main effect of sound type ($F(4,248) = 56.982$, $p < .001$, $\eta_p^2 = .479$, $\varepsilon = .787$) and a main effect of component ($F(1,62) = 17.157$, $p < .001$, $\eta_p^2 = .217$). Statistically significant interactions of the factors sound type × component ($F(4,248) = 9.021$, $p < .001$, $\eta_p^2 = .127$, $\varepsilon = .781$) and component × group ($F(1,62) = 10.693$, $p = .002$, $\eta_p^2 = .147$) were observed. Importantly, the interaction of the factors sound type × component × group revealed statistical significance ($F(4,248) = 3.679$, $p = .012$, $\eta_p^2 = .056$, $\varepsilon = .781$). The follow-up

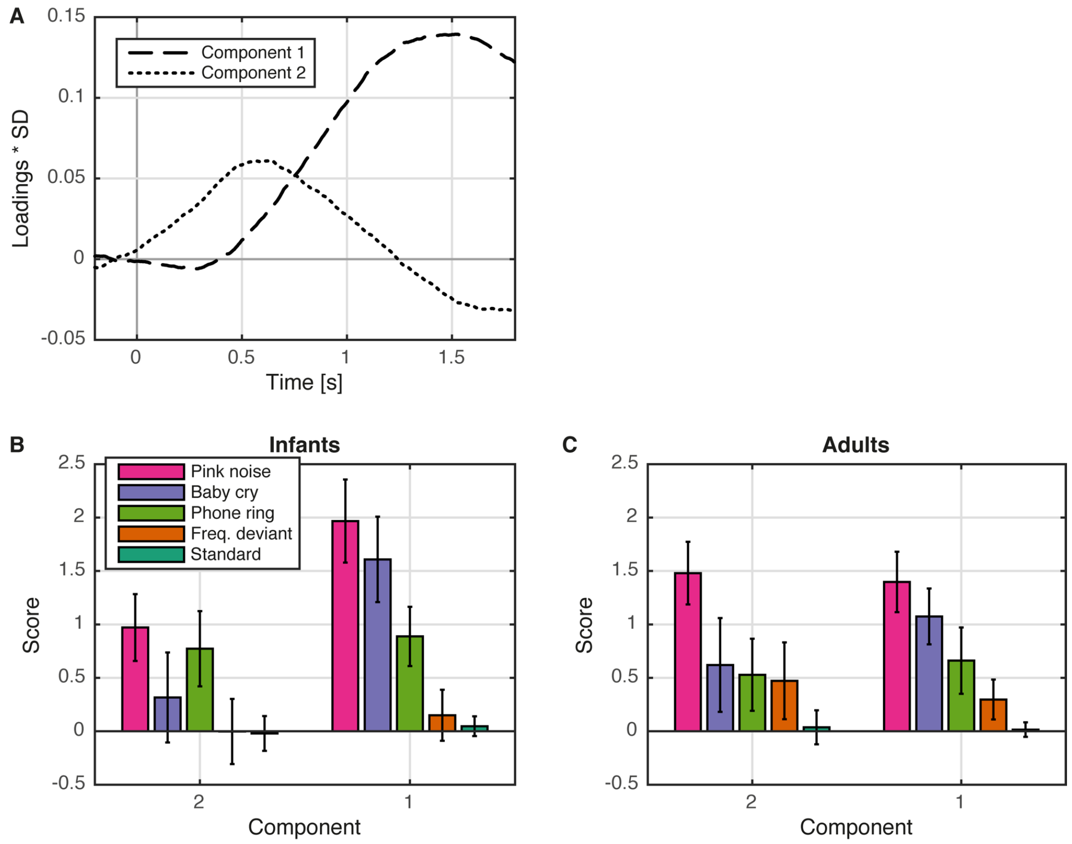

Fig. 3. Results of the principal component analysis (PCA). Component loadings (time courses) scaled by the standard deviation are shown in Panel A. The component scores are shown in Panel B and C separately for infants and adults. The error bars indicate the 95% confidence intervals. No significant PDR was observed in response to standards in infants and adults. Furthermore, no significant PDR was observed in infants in response to the frequency deviant for both components and in response to the baby cry for component 2. Please note that the peak of component 2 precedes the peak of component 1 in time. We have consequently ordered the component scores by the temporal order or the component peaks for improved accessibility.

tests revealed a significant interaction of the factors component × sound type ($F(4,128) = 10.707$, $p < .001$, $\eta_P^2 = .251$, $\varepsilon = .774$ in children but not in adults ($F(4,120) = 1.979$, $p = .102$, $\eta_P^2 = .062$, $\varepsilon = .685$). In children Bonferroni-corrected t-tests revealed increased scores for pink noise and baby cry in component 1 (late peak) compared to component 2 (early peak; noise: $t(32) = -3.964$, $p < .001$; sound of a baby cry: ($t(32) = –5.494$, $p < .001$; see Fig. 3). The scores of standard sound, frequency deviant, and phone ring did not significantly differ between components (standard sound: $t(32) = –0.93$, $p = .359$; frequency deviant: $t(32) = –.741$, $p = .464$; phone ring: $t(32) = –.855$, $p = .399$).

In sum, unexpected and task-irrelevant noise and environmental sounds caused a significant PDR in infants and adults. In contrast, moderate frequency deviants elicited a significant PDR in adults only. In infants, but not in adults, noise and the sound of a baby cry caused component scores that increased from an early component to a late component.

Discussion

The present oddball study tested for the first time the impact of environmental and artificial unexpected and task-irrelevant deviant sounds on the pupil dilation response in preverbal infants while watching a silent video. Different deviant types (pink noise and two environmental sounds) elicited significant PDRs of different amplitude in infants and adults. Simple frequency deviants elicited a significant PDR only in adults but not in infants. A principal component analysis revealed two components that have been linked to aspects of parasympathetic inhibition and sympathetic excitation of the pupil dilation and differ between infants and adults. In response to pink noise and baby cry deviants the sympathetic excitation component was enhanced compared to parasympathetic inhibition component in infants but not in adults.

Different deviant types elicited different PDR that differed between age groups

Results revealed that deviant sounds, which strongly differ physically from standard sounds, elicited a prominent PDR in infants. Moreover, different types of deviant sounds elicited a differential PDR in both infants and adults. The largest PDR was elicited by pink noise sounds, the second largest by the sound of a crying baby followed by the sound of a phone (see next section for detailed discussion). The frequency deviant elicited the smallest response in pupil dilation. Interestingly, we observed age differences in pupil dilation elicited by frequency deviant sounds. There were statistically significant deviant-related changes in the PDR relative to standards in adults only but not in infants. This is surprising since infants' brains are able to respond to 750 Hz frequency deviation relative to 500 Hz standard sounds (e.g., Kushnerenko et al., 2007). However, the change in frequency is probably not as attention catching in 14-month-olds as it is in adults. Support for this assumption comes from a recent oddball study in which 2–3-year-old children were presented with different deviant types (e.g., frequency deviants, duration deviants, environmental novels etc., Putkinen et al., 2012). Their results support the less attention catching nature of frequency deviants compared to environmental sounds in young children. Putkinen et al. (2012) reported that environmental sounds only elicited robust brain responses on individual level in the time window of the ERP components P3a and Late Discriminative Negativity (LDN), which are associated with the orienting of attention and evaluation. The age-dependent different distractive potential of different sound types is an interesting result taking into account that in the literature, focusing on involuntary attention, frequency deviants as well as novel environmental sounds were used as distractor sounds. This might contribute to the partly inconsistent results in the respective literature (for an overview see, Wetzel & Schröger, 2014).

Different components of the deviant sound-related PDR that differed between age groups

We observed a biphasic PDR resembling those observed by Steinhauer and Hakerem (1992). Steinhauer & Hakerem (1992) suggested a model postulating that the PDR is a summation of an early peak that reflects the parasympathetic inhibition of the ringshaped sphincter pupillae muscle and a later peak reflecting the sympathetic excitation of the radial dilator muscle. Both pathways might be modulated by the contribution of different cognitive processes (Steinhauer & Hakerem, 1992). The performed PCA identified two components underlying the biphasic waveform of the PDR. Thus, our results perfectly match the hypothesis by Steinhauer and Hakerem (1992). Importantly, we observed age effects of the increase of the scores across components (i.e., with time) in dependence on the sound type. Infants' PDR elicited by the noise sound and the cry of a baby significantly increased in the later component compared to the earlier component. Such a strong increase was not observed for any of the other sounds and was not observed in adults at all. Based on the model of Steinhauer and Hakerem (1992) results might be interpreted as a strong increase of sympathetic activation of the dilator pupillae (that dilates the pupil when activated) in response to noise and cry of a baby relative to the preceding parasympathetic inhibition. Noise and the cry of a peer have a high arousing potential that might be attention catching. Arousal can be boosted by noise because of the wide frequency spectrum of noise or by the semantic (emotional) information of a cry of a peer (Dondi, Simion, & Caltran, 1999). Results suggest that deviant sounds, providing a large amount of physical information or high arousing emotional information, affect the PDR via the autonomic nervous system. Our results could indicate that infants are more sensitive than adults to deviant sounds with a high arousing potential.

Our findings and conclusions are in line with pupil dilation literature as well as with ERP literature in the context of involuntary attention. It has been shown in ERP studies that neonates and infants are particularly sensitive to an increased amount of physical information of deviants (Kushnerenko et al., 2007; Muenssinger et al., 2013). Also involuntary attention mechanisms of primary-school age children were more affected by sounds that strongly differ from standard sounds relative to those that deviated little from standard sounds (Wetzel et al., 2006). Negative emotions reflected by an image and the sound of a crying peer evoked sustained pupil dilation within the first year of life (Geangu et al., 2011). This is in line with adult studies reporting that the pupil response during the viewing of affective pictures reflects emotional arousal that have been associated with increased sympathetic activity (Bradley et al., 2008). Also auditory high arousing emotional stimuli affected pupil size in adults (Partala & Surakka, 2003). Moreover, effects of high arousing emotional sounds on distraction of attention have been observed in adults (Max et al., 2015).

Our study has some limitations. A clear separation of the physical and the semantic including emotional information content of deviant sounds is required in further studies. We cannot completely exclude the possibility that the observed PDRs depended solely on the frequency spectrum of sounds or on their physical contrast to standard sounds. However, the sound of a baby cry and of a phone ring have a comparable spectral bandwidth and complexity and deviate to a rather similar extent from the standard sound but elicited clearly different PDRs in children. The cry-related PDR increased with time and the scores of the principal component associated with sympathetic activation are significantly higher than those of the principal component associated with parasympathetic inhibition. Importantly, this was not observed for the PDR evoked by the phone ring indicating that other factors than the physical contrast to the standard sound or the frequency spectrum affect the deviant-related PDR in infants. Such a factor could be the arousal that might in turn be boosted by the emotional information of the baby cry.

Moreover, we cannot conclude from our data whether the observed age effect was caused by physiological or cognitive differences in the parasympathetic and the sympathetic pathways between infants and adults. Such a differentiation could be possible under different light conditions as the parasympathetic mechanism operates differently in light or darkness (see, Steinhauer & Hakerem, 1992). We think a potential separation of the parasympathetic and sympathetic innervations of the pupil and the determination and separation of the modulating cognitive processes are a promising issue for further studies.

In conclusion, unexpected and task-irrelevant noise and environmental sounds elicit a significant PDR in infants and adults that has previously been linked to attention-related brain activity (e.g., Murphy et al., 2014). In contrast, moderate frequency deviants evoke such a response in adults only. Moreover, we extracted two principal components underlying the observed biphasic PDR. These components have been associated with different autonomic innervation that is modulated differently by high arousing deviant sounds in children and adults. This provides new insights in the processing of attention catching stimuli. Our study demonstrates that the PDR is a promising, economic, and sensitive tool for the investigation of involuntary attention mechanisms in preverbal children. Note that each deviant sound was presented eight times only and the whole experiment lasted approximately 4 min without long lasting technical preparation or any discomfort for the child. Thus, this tool opens new perspectives for the investigation of attention mechanisms particularly in young children and might close the gap in involuntary attention research with 1–5-year-old children.

Research Highlights

- Unexpected environmental and noise sounds elicited a large pupil dilation response in infants and adults.
- Frequency deviants elicited a significant pupil dilation response in adults only.
- Age effects of the parasympathetic inhibition and the sympathetic activation of the pupil size caused by deviant sounds with a high arousing potential were observed.

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