Fronto-central P3a to distracting sounds: an index of their arousing properties

Rémy Masson[1†], Aurélie Bidet-Caulet[1]

[1] Brain Dynamics and Cognition Team, Lyon Neuroscience Research Center (CRNL), INSERM UMRS 1028, CNRS UMR 5292, Université Claude Bernard Lyon 1, Université de Lyon, F-69000, Lyon, France

[†] Correponding author. E-mail adress: remy.masson@ens-lyon.fr

Abstract

The P3a is an event-related potential comprising an early fronto-central phase and a late fronto-parietal phase. It is observed after novel events and has classically been considered to reflect the attention processing of distracting stimuli. However, novel sounds can lead to behavioral facilitation as much as behavioral distraction. This illustrates the duality of the orienting response which includes both an attentional and an arousal component. Using a paradigm with visual or auditory targets to detect and irrelevant unexpected distracting sounds to ignore, we showed that the facilitation effect by distracting sounds is independent of the target modality and endures more than 1500 ms. These results confirm that the behavioral facilitation observed after distracting sounds is related to an increase in unspecific phasic arousal on top of the attention capture. Moreover, the amplitude of the early phase of the P3a to distracting sounds positively correlated with subjective arousal ratings, contrary to other event-related potentials. We propose that the fronto-central early phase of the P3a would index the arousing properties of distracting sounds and would be linked to the arousal component of the orienting response. Finally, we discuss the relevance of the P3a as a marker of distraction.

Keywords: Auditory attention, P3a, EEG, arousal, distraction, novelty

1. Introduction

Attentional processes enable us to selectively attend stimuli which are relevant to our goals, and to filter out irrelevant stimuli, to increase task-efficiency. However, unexpected salient stimuli tend to attract our attention away from the task at hand: this is commonly referred as distraction or involuntary attention. This distraction effect is usually transient and we are able to focus back on the task, unless the sound was evaluated as significant.

Auditory distraction has been mostly investigated using audio-visual oddball paradigms during which task-irrelevant standard or rare novel sounds precede visual targets to be discriminated (Escera et al., 2003, 2000, 1998; Schröger and Wolff, 1998). These studies have shown that novel sounds, compared to standard sounds lead to prolonged reaction times or decreased hit rates to visual (Andrés et al., 2006; Berti et al., 2004; Escera et al., 1998) or auditory (Berti and Schröger, 2003; Rinne et al., 2006; Schröger, 1996; Wetzel et al., 2006) targets. These novel sounds would elicit attention capture, also referred as involuntary orienting of attention in the literature (Wetzel et al., 2013), and their processing would require resources that are then unavailable for the maintenance of attention on the task at hand (Escera et al., 2000; Näätänen, 1992).

At the electrophysiological level, novel distracting sounds elicit a well-described sequence of event-related potentials (ERPs) which includes the N1 and a P3 complex (Escera et al., 2003, 1998). The N1 response to unexpected sound is deemed to index a transient detector mechanism (Berti, 2013; Escera et al., 1998) that would trigger an attention switch to salient stimuli (Näätänen, 1990; Näätänen and Picton, 1987; Näätänen and Winkler, 1999). The P3 complex, also called novelty-P3 or P3a (Friedman et al., 2001; Olofsson and Polich, 2007; Ranganath and Rainer, 2003), is composed of a fronto-central early phase peaking around 235 ms, referred as the early-P3 in the following, and a fronto-parietal late phase peaking around 320 ms referred as the late-P3 in the following (Escera et al., 2000, 2000; Escera and Corral, 2007; Yago et al., 2003). This dissociation has been recently confirmed using a Principal Component Analysis (PCA) compiling data from different oddball paradigms (Barry et al., 2016). The functions attributed to each phase are still under debate. Nevertheless, the P3a has been considered to reflect the attention processing of distracting stimuli (Polich and Criado, 2006) and has been frequently associated with impaired performances due to unexpected novel sounds (Berti and Schröger, 2003; Escera et al., 1998; Schröger and Wolff, 1998; Wetzel et al., 2006) leading to the assumption that this ERP would index distraction.

However, in the last decades, a growing number of studies challenged the idea that unexpected rare novel sounds only yield distraction (for a review, see Parmentier, 2014). Indeed, a behavioral cost was not always observed after novels sounds (Li et al., 2013; Ljungberg et al., 2012; Parmentier et al., 2011, 2010; Wetzel et al., 2013, 2012). In some oddball paradigms, novel sounds could even enhance performances (SanMiguel et al., 2010b, 2010a; Wetzel et al., 2013, 2012). Several mechanisms can account for such facilitation effects in the oddball paradigms. Novel sounds could act as warning signals which trigger a top-down anticipation of the onset of the

incoming target. They could also induce a phasic increase in unspecific arousal (SanMiguel et al., 2010b, 2010a; Wetzel et al., 2013, 2012), which results in enhanced readiness to process and respond to any upcoming stimulus. These findings led to propose that novel sounds generate a combination of facilitation and distraction effects which final effect on the performance of an unrelated task depends on the level of the task demands (SanMiguel et al., 2010a, see also Eysenck, 2012; Kahneman, 1973; Yerkes and Dodson, 1908 for the interaction of arousal with task demands) and the properties of the novel sounds (Parmentier et al., 2010; SanMiguel et al., 2010a; Wetzel et al., 2012).

In a recent study, using a different paradigm, Bidet-Caulet and colleagues managed to temporally dissociate facilitation and distraction components elicited by unexpected task-irrelevant sounds played between a visual cue and an auditory target (Bidet-Caulet et al., 2015). Two hypotheses can account for the facilitation effect they observed. As mentioned above, distracting sounds could trigger an increase in unspecific arousal. Alternatively, the auditory distractors could result in an earlier attentional shift from the cue modality to the target modality, facilitating the processing of the auditory target. The "arousal hypothesis" is consistent with a model of the orienting response towards unexpected novel sounds which comprises an arousal component to account for behavioral benefits and an attentional component, a reflexive attentional switch to the eliciting stimulus, to explain behavioral costs (Näätänen, 1992). Nevertheless, only few studies have investigated the link between the behavioral benefit and the properties of the distracting sounds (Max et al., 2015; Wetzel et al., 2012). To our knowledge, the differential impact of arousal and emotional properties on the facilitation effect has not been explored. We define here arousal as a state of enhanced physiological reactivity that leads to a condition of unspecific sensory alertness and readiness to respond to any upcoming stimulus (Aston-Jones and Cohen, 2005; Coull, 1998; Näätänen, 1992; Nieuwenhuis et al., 2011; Sturm and Willmes, 2001), enabling improved performance, in this particular case target detection.

In the same line, the P3 complex has been observed in response to novel sounds resulting in facilitation effects (SanMiguel et al., 2010b; Wetzel et al., 2013), leading to alternative explanations of the cognitive functions underlined by this brain response. Wetzel and colleagues proposed that the P3 complex reflects novelty evaluation of the stimulus whereas San Miguel and colleagues proposed that the P3 complex reflects the summation of different brain operations triggered by the novel event, such as arousing, orienting and executive control processes. Accordingly, if we consider the different P3a phases, the early-P3 has not been necessarily linked to distraction in the literature. In oddball paradigms, in contrast to the late-P3, the early-P3 amplitude remains unchanged when behavioral distraction increases (SanMiguel et al., 2008) leading the authors to propose that the early-P3 may reflect a process other than the involuntary orienting of attention. In a similar fashion, behavioral distraction by deviant sounds is not always associated with the elicitation of an early-P3 (Horváth et al., 2011). On the other hand, the late-P3 has been more consistently considered as a signature of involuntary attention capture (Bidet-Caulet et al., 2015; Escera et al., 2000, 1998; Roye et al., 2007). This undermines the idea that the P3a indexes solely

distraction. It is imaginable that other properties of novel or distracting sounds (such as their arousing value) are linked to the P3a and especially to its early phase, the early-P3.

The goal of this study is to characterize the facilitation effect triggered by unexpected salient stimuli at the behavioral and electrophysiological levels. In a first behavioral experiment, we used adaptations of the Bidet-Caulet et al. (2015) paradigm to test if the facilitation effect is related to an increase in arousal or to an earlier attentional switch. In a second behavioral experiment, we used another adaptation of the paradigm to characterize the durability of the facilitation effect. Finally, in an EEG experiment, we investigated the brain underpinnings of the facilitation effect by exploring the relationship between the arousing properties of distracting sounds and distractor-related ERPs.

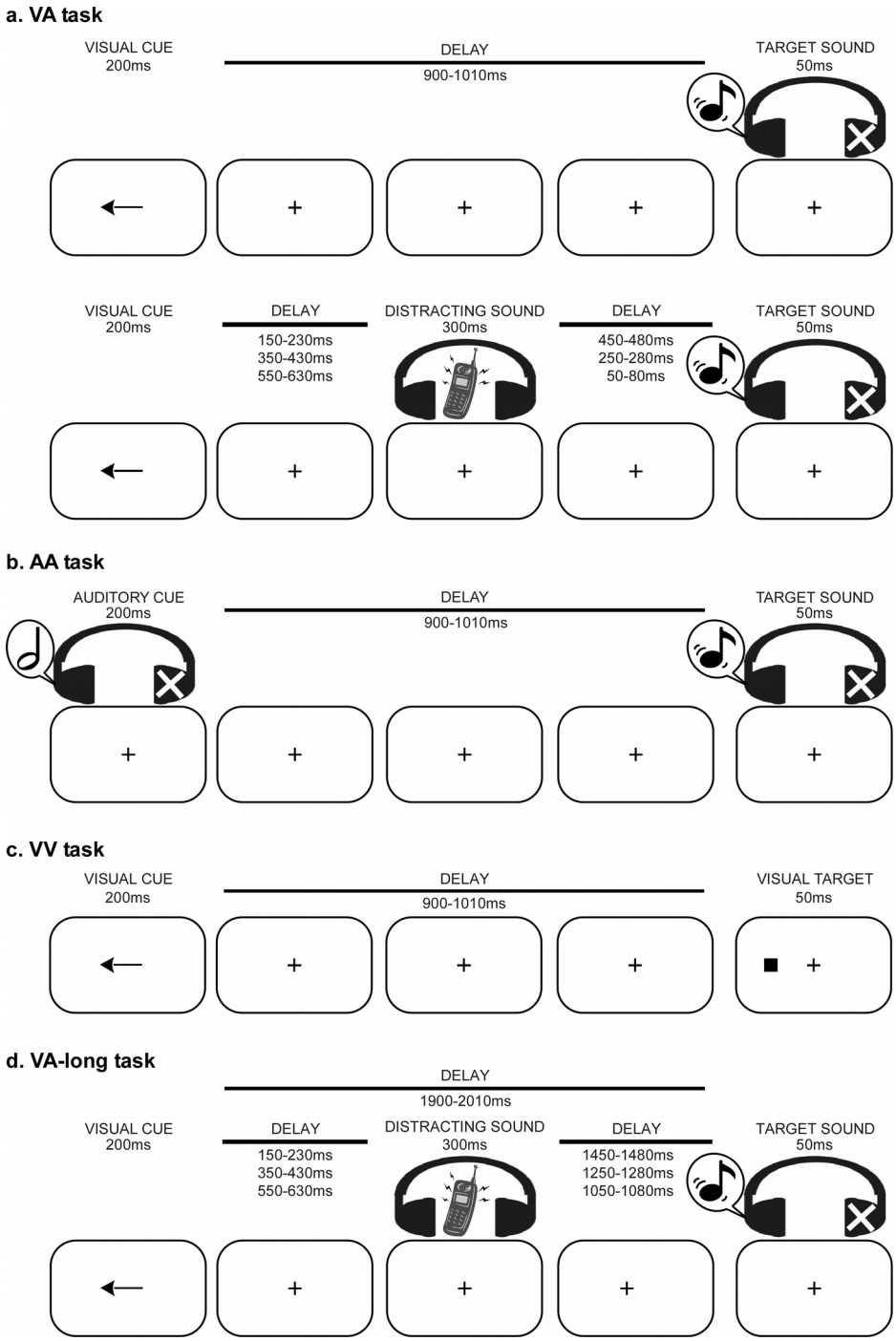

Fig. 1. Experimental paradigms. **a. VA task.** First row: Example of a distractor-free trial (75% of the trials). A visual cue (200 ms) precedes the onset of a monaural target sound (50 ms) by a random delay (900-1010 ms). In 66.6% of the trials, a one-sided cue indicates in which ear (left or right) the target sound will be played (informative trial). In the other 33.4 % of the trials, a two-sided visual cue does not provide any indication in which ear (left or right) the target sound will be played (trial not depicted in the figure). Second row: Example of a trial with a distractor (25% of the trials). All parameters are identical to trials with no distracting sound, except that a binaural distracting sound (300 ms duration), such as a phone ring, is played during the delay between cue and target. The distracting sound can equiprobably onset in three different time periods after the cue offset: in the 150–230 ms range, in the 350–430 ms range, or in the 550–630 ms range. **b. AA task.** Example of a distractor-free trial. All parameters are identical to the VA task, except that the cue is a monaural (informative cue) or binaural (uninformative cue) 200 ms sound. **c. VV task.** Example of a distractor-free trial. All parameters are identical to the VA task, except that the target is a squared dot presented at the left or the right side of the screen. **d. VA-long task.** Example of a distractor-free trial. All parameters are identical to the VA task, except that the cue-target delay is comprised between 1900 and 2010 ms. VA: Visuo-auditory, AA: Audio-auditory, VV: Visuo-visual.

2. First behavioral experiment

2.1. Materials and Methods

2.1.1. Participants

Fifteen paid participants (all right-handed, 9 females, aged 20-47) took part to the first behavioral experiment. All participants were free from neurological or psychiatric disorder, and had normal hearing and normal or corrected-to-normal vision. All participants gave written informed consent.

2.1.2. Design of distracting sounds

Thirty ringing sounds (clock-alarm, door bell, phone ring, etc.) were used as distracting sounds in this study. These sounds were from several origins: Anne Guillaume's sound library (Guillaume et al., 2004); Michael Marcell's collection of environmental sounds (Marcell et al., 2000); audio CDs: sound library sonoteca, Mon imagier sonore (Olivier Tallec, Gallimard Jeunesse), Sound effects (DOM); and various websites: http://www.findsounds.com/, http://www.sound-effects-library.com/, and http://www.sounddogs.com/. When necessary, sounds were re-sampled at 44 kHz on 16 bits and edited to last 300 ms (5ms rise-time and 20ms fall-time), with Adobe Audition software (Adobe). All sounds were then RMS normalized with MATLAB (Mathworks). Finally, loudness was subjectively equalized by two listeners. Sounds were delivered at an intensity level judged comfortable by the participants at the beginning of the experiment.

2.1.3. Stimuli and task

We manipulated the sensory modality of the cue and the target in three different cueing tasks (Fig.1a,b,c). In the visuo-auditory task (VA, see Fig 1a), 75 % of the trials (NoDIS trials) consisted in a visual cue (200 ms duration), a delay (randomly chosen between 900 and 1,010 ms) followed by a target sound (50 ms duration). The cue was centrally presented on a screen (grey background) and could be a green arrow pointing to the left, to the right, or to both sides. The target sound was a monaural harmonic sound (fundamental frequency: 200 Hz, 5 harmonics; 5 ms rise-time, 5 ms fall-time) presented at 15 dB SL in earphones. In the other 25 % (DIS trials), the same trial structure was used, but a binaural distracting sound was played during the delay. The cue and target categories were manipulated in same proportion for trials with and without distracting sound. In 33.3 % of the trials, the cue was pointing left and the target sound was played in the left ear, and in 33.3 % of the trials, the cue was pointing right and the target sound was played in the right ear, leading to a total of 66.6 % of informative trials. In the last 33.4 % of the trials, the cue was uninformative, pointing in both directions, and target sound was played in the left (16.7 %) or right (16.7 %) ear. The distracting sound could be equiprobably presented in three different time periods after the cue offset: in the 150–230 ms range (DIS1), in the 350–430 ms range (DIS2), or in the 550–630 ms range (DIS3).

Participants were instructed to perform a detection task by pressing a mouse button as fast as possible when they heard the target sound. They were asked to allocate their attention to the cued side in the case of informative cue. Participants were informed that informative cues were 100 % predictive and that a distracting sound could be sometimes played. In the absence of the visual cue, a blue fixation cross was presented at the center of the screen. Participants were instructed to keep their eyes fixating on the cross and to minimize eye movements and blinks while performing the task.

In the two other variants of the task were designed. The structure remained the same but the sensory modality of the cue or of the target was modified. In the audio-auditory task (AA, see Fig. 1b), the cue was a harmonic sound (200 ms duration, 25 dB SL, fundamental frequency: 500 Hz, 5 harmonics; 5 ms rise-time, 5 ms fall-time) played at the left or at the right ear (informative trials) or in both ears (uninformative trials). In the visuo-visual task (VV, see Fig. 1c), the target was a gray squared dot presented at the left or at the right side of the screen (visual angle: 6°) displayed for 50 ms.

Effects of the informational value of the cue is beyond the scope of this article and will not be presented. For a discussion of top-down attention deployment during the VA task, see Bidet-Caulet et al. (2015).

2.1.4. Procedure

Participants were seated in a comfortable armchair in a sound attenuated room, at a 1.5 m distance from the screen. All stimuli were delivered using Presentation software (Neurobehavioral Systems, Albany, CA, USA). Sounds were delivered through earphones. First, the auditory threshold was determined for the target sound, in each ear, for each participant using the Bekesy tracking method. Second, participants were trained with a short sequence of the task for each task.

Participants performed 5 blocks (72 trials each) for each of the tasks. Participants were thus presented, in each task, with 270 NoDIS, 30 DIS1, 30 DIS2, 30 DIS3 trials, irrespective of the cue category. No EEG was recorded in this experiment. The order of the tasks was randomly chosen for each participant. Participants had 2,500 ms to answer after targets.

2.1.5. Behavioral data

A button press before target onset was considered as a false alarm (FA). A trial with no button press after target onset and before the next cue onset was considered as a missed trial. A trial with no FA and with a button press after target onset was counted as a correct trial. Reaction-times (RTs) to targets were analyzed in the correct trials only. Based on previous results (Bidet-Caulet et al., 2015), the difference in RTs between the NoDIS and DIS1 conditions can be considered as a measure of the facilitation effect triggered by distracting sounds whereas the difference in RTs between the DIS3 and DIS1 conditions can be considered as a good approximation of the distraction effect.

2.1.6. Statistical Analysis of Behavioral data

RTs and percentages of correct trials were submitted to rmANOVAs with DISTRACTOR (four levels: NoDIS, DIS1, DIS2, DIS3) and MODALITY (three levels: AA, VA, VV) as within-participant factors. Post-hoc analyses of DISTRACTOR effects were planned to be done between $RT_{NoDIS} - RT_{DIS1}$ (as a measure of the facilitation effect) or $RT_{DIS3} - RT_{DIS1}$ (as a measure of attention capture) and zero, using non-parametric Wilcoxon signed rank tests. Post-hoc analyses of MODALITY effects on the facilitation effect ($RT_{NoDIS} - RT_{DIS1}$) and the attention capture effect ($RT_{DIS3} - RT_{DIS1}$) were conducted using the non-parametric Friedman test.

For all statistical effects involving more than one degree of freedom in the numerator of the F value, the Greenhouse-Geisser correction was applied to correct for possible violations of the sphericity assumption. We report the uncorrected degree of freedom and the correct probabilities. In the “Results” section, mean values and the standard error of the mean are indicated.

2.2. Results

2.2.1. Percentage of correct responses

Participants correctly performed the detection task in 97.7% ± 1.1% of the trials. The remaining trials were either missed trials (0.1%) or trials with FAs (1.9% ± 0.3%). The percentage of correct responses was not found significantly modulated by the DISTRACTOR and MODALITY factors.

2.2.2. Reaction times (Fig. 2)

A significant main MODALITY effect was observed on RTs ($F_{2,28}$=8.2, ε=0.96, p=0.002). On average, participants were faster (p=0.039) in the VA task (234.0 ± 3.2 ms) than in the VV (241.8 ± 2.5 ms) and even faster (p=0.026) in the AA task (211.5 ms ± 4.0 ms): $RT_{AA} < RT_{VA} < RT_{VV}$.

A main DISTRACTOR effect ($F_{3,42}$=24.8, ε=0.67, $p<10^{-6}$) and a DISTRACTOR by MODALITY interaction ($F_{6,84}$=3.76, ε=0.57, p=0.002) were found significant. Post hoc analyses showed that in each task the facilitation effect (RT_{NoDIS} vs. RT_{DIS1}) was significant (p_{AA}=0.011, p_{VA}=0.001, p_{VV}=0.002) and that it was not significantly modulated by the MODALITY condition (p=0.37). On average, between NoDIS and DIS1, RT dropped by 9.5% ± 2.7%. In all tasks, attention capture (RT_{DIS3} vs. RT_{DIS1}) was significant (p_{AA}<0.001, p_{VA}<0.001, p_{VV}=0.015) but it was significantly smaller in the VV than in the VA and AA tasks (respectively p=0.003 and p=0.023).

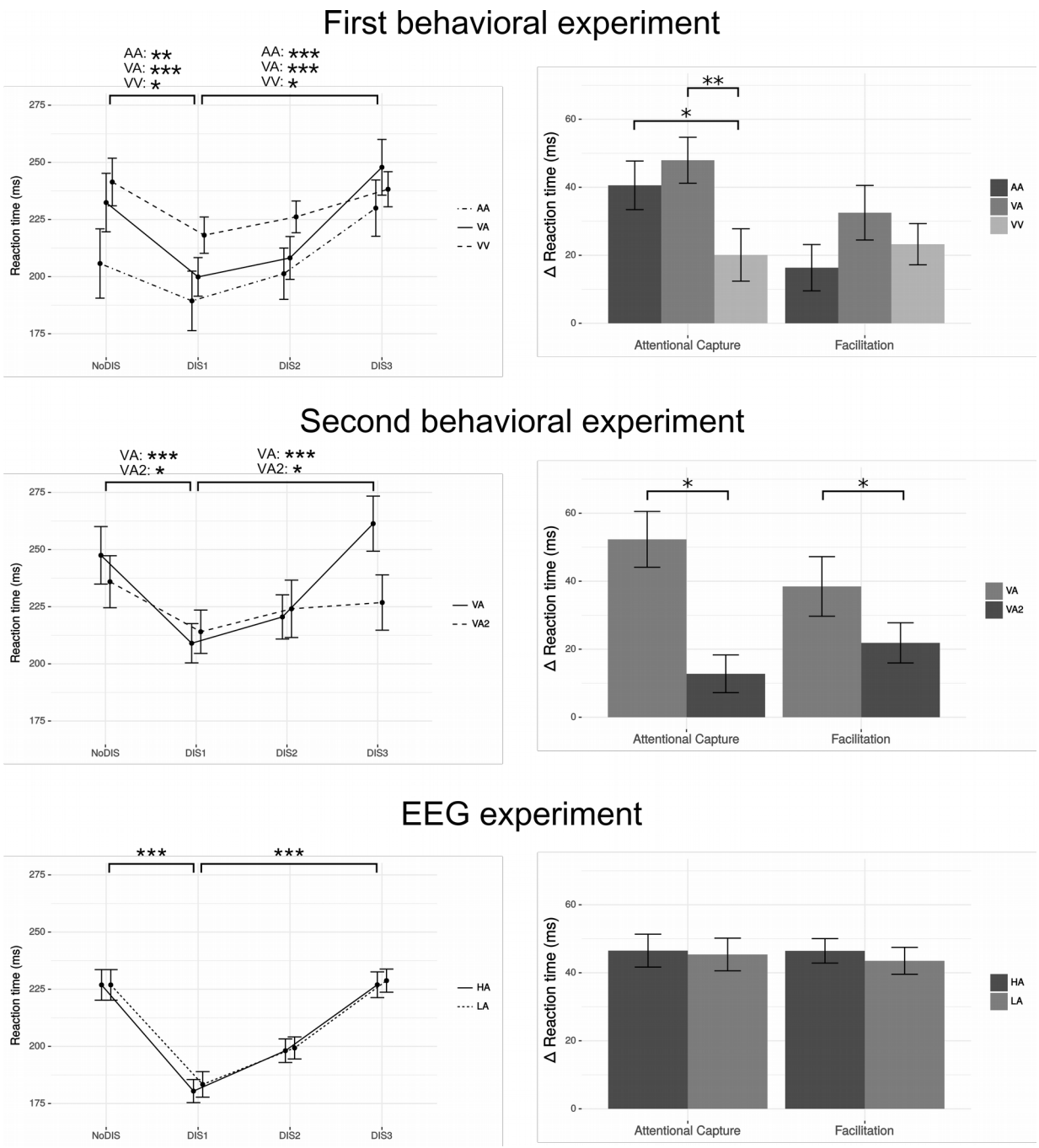

Fig. 2. Behavioral results for the three experiments. **Left.** Mean reaction time (RT) as a function of the distractor condition (NoDIS, DIS1, DIS2, DIS3). **Right.** Attentional capture (RT to DIS3 minus RT to DIS1) and facilitation (RT to NoDIS minus RT to DIS1) effects. *p < 0.05, **p < 0.01, ***p < 0.001. Error bars represent +/- 1 SEM. VA: Visuo-auditory, AA: Audio-auditory, VV: Visuo-visual.

2.3. Discussion

This first experiment confirms that distracting sounds can result in a facilitation effect at the behavioral level, and shows that this benefit is independent of the cue and target sensory modalities.

2.3.1. Facilitation and distraction effects of distracting sounds

In agreement with a previous study using the same experimental paradigm (Bidet-Caulet et al., 2015), participants responded faster to target sounds preceded by a distractor than not. With the present protocol, it has been possible to temporally dissociate facilitation and distraction effects of the same distracting sounds within the same task. Distracting sounds elicit a facilitation effect that improves performances especially with long distractor-target intervals (i.e. DIS1 and DIS2 conditions). However, the gain in RT is cancelled out when the distractor onset is too close to the target sound (DIS3 condition), suggesting that distractors also trigger an attention capture. This timing effect indicates that when the target occurs, the balance between cost and benefit differs according to the onset time of the distracting sound, suggesting that the facilitation and distraction effects triggered by the distracting sounds have different time courses. The facilitation effect would be stable for at least 750 ms (longest interval between distracting and target sound onsets) and induce a similar benefit on target processing irrespective of the distractor onset time. On the contrary, the attentional capture would be a transient powerful phenomenon that could interfere with target processing only when the distracting sound occurs within a few hundreds of ms before target onset, and that would be low or completed when the distractor is played long before target onset. A short duration of the attentional capture phenomenon is consistent with previous findings showing a detrimental effect of task-irrelevant deviant sound on target processing with onset-to-onset interval of 200 ms but not of 550 ms (Schröger, 1996). According to our results, the facilitation effect of novel sounds is less likely to be observed, at the behavioral level, in classical oddball studies because the typical sound-target delay is 300 ms, thus the distraction effect has not yet vanished and masks any potential facilitation effect.

These present results confirm that an unexpected salient sound triggers several phenomena that may produce opposite effects on the reaction time to a subsequent target: a cost related to a short-lasting attention capture and the benefits of a more long-lasting facilitation effect. This duality in effects was previously observed in several recent studies (Ljungberg et al., 2012; Max et al., 2015; Parmentier et al., 2010; SanMiguel et al., 2010b, 2010a; Wetzel et al., 2013, 2012).

2.3.2. Nature of the facilitation effect

With this first experiment, we attempted to precise the nature of the facilitation effect. In the visuo-auditory task, two hypotheses may account for the gain in RT in distractor trials. (1) The facilitation effect is related to an unspecific burst of arousal triggered by the distracting sound because of its unexpectedness and its saliency and because of the low arousal level of the task, as proposed in previous studies (Bidet-Caulet et al., 2015; SanMiguel et al., 2010b, 2010a; Wetzel et al., 2013, 2012). (2) Facilitation is due to the facilitation by the distracting sound of the attentional shift from

the cue modality (visual) to the target modality (auditory, same as the distractor). A distracting sound placed between a visual cue and an auditory target could result in an earlier attentional shift leading to better performances compared to a no distracting sound condition. According to this second hypothesis, we should expect a smaller behavioral benefit if the cue and the target are in the same sensory modality. We tested this hypothesis in a visuo-visual and an audio-auditory cueing tasks and found similar significant facilitation effects triggered by distracting sounds than in the visuo-auditory task. This is in line with previous results that showed that auditory warning signals can trigger facilitation in both visual and auditory detection tasks (Posner et al., 1976). Therefore, the attentional reorientation towards the target modality cannot account for the facilitation effect of the distracting sound. Moreover, similar facilitation effects of the distracting sounds were found regardless of the target sensory modality, suggesting that the facilitation effect is independent of the sensory modality. These results rather support the first hypothesis that facilitation effect stems from a distractor-related burst of arousal.

Outside of the literature on the oddball paradigm, it has also been known for decades that auditory warning signals, also referred to as "accessory stimuli", played before or concurrent to the onset of the target visual stimulus facilitate the processing of such target stimulus (Hackley and Valle-Inclán, 1999, 1998; Posner et al., 1976; Valls-Solé et al., 1995). Interestingly, it has also been proposed that the speeding of reaction times by warning signals/accessory stimuli stems from an increase in phasic arousal (Hackley, 2009; Tona et al., 2016).

In conclusion and in agreement with previous studies (SanMiguel et al., 2010b; Wetzel et al., 2013), we show that performances after a distracting sound result from the combination of the benefits due to an increase in unspecific arousal and to the costs of attention capture.

2.3.3. Effects of cue and target sensory modality on reaction times and distraction effects

On the one hand, subjects were faster in the audio-auditory task than in the visuo-auditory one. It could be easily explained by the fact that auditory cues are more arousing than the visual ones inducing a general gain in reactivity. On the other hand, subjects were slower overall in the visuo-visual task simply because the task was probably more difficult.

The distraction effect was significant regardless of the sensory modality of the cue and target. This result does not support the hypothesis that, in cross-modal tasks, distraction stems from the time penalty caused by shifting attention from one modality to the other (Parmentier, 2014; Parmentier et al., 2008). The distraction effect would be rather due to an involuntary capture of attention by the distracting event, diverting attention from the task at hand (Escera et al., 2000; Horváth et al., 2008; Näätänen, 1992).

We also found that the distraction effect is weaker in the visuo-visual task, but comparable in the visuo-auditory and audio-auditory tasks. In the visuo-visual task, the auditory modality is not relevant for the task: as a result, subjects may be more efficient at inhibiting sounds, and less sensitive to attentional capture by distracting sounds.

3. Second behavioral experiment

3.1. Material and methods

3.1.1. Participants

Twelve paid participants (all right-handed, 4 females, aged 19-36 years) took part to the second behavioral experiment. Six participants participate to both behavioral experiments.

All participants were free from neurological or psychiatric disorder, and had normal hearing and normal or corrected-to-normal vision. All participants gave written informed consent.

3.1.2. Stimuli and task

Participants performed the VA task and a variant of this task (VA-long, see Fig. 1d). The order of the tasks was randomized between subjects. The task structure remained the same however in the VA-long task, the cue-target delay was increased by 1000 ms (between 1900 and 2010 ms). Cue-distractor delays were unchanged: therefore, the distractor-target interval was increased by 1000 ms. The experimental procedure was identical than during the first experiment.

3.1.3. Statistical Analysis of Behavioral data

In the second behavioral experiment, RTs and percentages of correct trials were submitted to rmANOVAs with DISTRACTOR (four levels: NoDIS, DIS1, DIS2, DIS3) and DELAY (two levels: VA, VA-long) as within-participant factors. Post-hoc analyses of DISTRACTOR effects were planned to be done on the difference ($RT_{NoDIS} - RT_{DIS1}$) as a measure of the facilitation effect and on the difference ($RT_{DIS3} - RT_{DIS1}$) as a measure of attentional capture.

3.2. Results

3.2.1. Percentage of correct responses:

Participants correctly performed the detection task in 98.3% ± 0.4% of the trials. The remaining trials were either missed trials (0.1%) or trials with FAs (1.6% ± 0.4%). The percentage of correct responses was not found significantly modulated by the DISTRACTOR and AROUSAL factors.

3.2.2. Reaction times (Fig. 2)

The rmANOVA revealed no main DELAY effect. A main DISTRACTOR effect was observed ($F_{3,33}$=18.5, ε=0.71, $p<10^{-5}$): it is consistent with the results of the first experiment. An interaction DELAY by DISTRACTOR was also found ($F_{3,33}$=6.5, ε=0.75, p=0.002). Post-hoc analyses showed that the facilitation effect was found significant (p=0.035) in VA-long (21.4 ± 6.0 ms) but it was smaller (p=0.010) than in VA (37.1 ± 8.7 ms). Likewise, the attention capture effect was found

significant (p=0.042) in VA-long (13.6 ± 5.9 ms) but lower (p=0.010) than in VA (50.0 ± 7.4 ms). In the VA-long task, additional analyses showed no significant differences in RTs between DIS2 and DIS3 (p=0.47) but a significant increase in RTs between DIS1 and DIS2 (p=0.042).

3.3. Discussion

3.3.1 Durability of the facilitation effect

In this second experiment, we wanted to characterize the durability of the facilitation effect triggered by distracting sounds. In the longer version of the experiment (VA-long), participants still responded faster to targets preceded by a distracting sound despite a distractor-target delay reaching up 1750 ms. However, the facilitation effect was 42% lower with long than with short distractor-target intervals suggesting that it slowly dissipates with time. This is coherent with the hypothesis that unexpected salient sounds trigger an increase in phasic arousal, a transient phenomenon. This increase in phasic arousal appears to slowly decay over a few seconds. A facilitation effect of salient task-irrelevant sounds has already been observed for sound-target delay superior to 1000 ms (as well as for very short delays under 100 ms) in several studies (e.g. Posner et al., 1976; Ulrich, 1996). In a paradigm using auditory targets preceded by standard or novel pictures, novel pictures were found to reduce reaction times but only for picture-target delay of 0 and 200 ms and not for 800 ms (Schomaker and Meeter, 2014). This could be explained by the fact that the novel stimuli in the visual modality are less arousing than those in the auditory modality. Visual accessory stimuli trigger less facilitation than auditory accessory stimuli in both visual and auditory detection tasks (Posner et al., 1976).

Surprisingly, even with long intervals between the distracting and the target sounds (> 1000 ms), we observe shorter reaction times with the longest interval duration (1450 ms vs. 1250 or 1050 ms). This result is quite unexpected as attention capture was considered to quickly vanish after the distractor onset: another cognitive mechanism than attention capture is likely to explain this result. Since there is no difference between the two latest positions (DIS2 and DIS3), this effect seems to be related to shorter reaction times to targets following the earliest distracting sounds (DIS1) rather than to longer reaction times to targets preceded by later distracting sounds (DIS2 and DIS3). This result could be explained by a boost of the cue processing which is still ongoing when the earliest distracting sounds are played.

4. EEG experiment

4.1. Materials and Methods

4.1.1. Participants

Forty-one paid participants took part to the EEG experiment. Two of them were excluded from further analyses because of noisy EEG data, one because of low behavioral performances and one because of an issue with the experimental setup during the study. Consequently, only thirty-seven participants (21 females, all right-handed, aged 18-29) were included in further analyses. Data from 17 out of the 37 included participants have been presented in a previous publication (Bidet-Caulet et al., 2015).

No participant participated in both EEG and behavioral experiments. All participants were free from neurological or psychiatric disorder, and had normal hearing and normal or corrected-to-normal vision. All participants gave written informed consent.

4.1.2. Stimuli, task and procedure

The task was identical to the VA task (Fig. 1a) in behavioral experiments and to the experiment in Bidet-Caulet et al. (2015). EEG was recorded while participants performed 15 blocks (72 trials each) of the VA task. Participants were thus presented, with 810 NoDIS and 270 DIS trials. The experimental procedure was identical than during the previous experiments.

4.1.3. Behavioral ratings of distracting sounds

The same set of distracting sounds used in the behavioral experiments were used in the EEG experiment. Forty-one participants were asked to rate each sound for arousal (calm – exciting) and for valence (unhappy – happy) on a 9-point scale with the Self-Assessment Manikins (Bradley and Lang, 1994). Twenty of these participants were from the cohort of the EEG experiment and the twenty-one additional ones were only recruited for the sound rating. The thirty distracting sounds were presented in a different random order to each participant. After each sound, participants were successively presented with the arousal and the emotion scales. They had 5s to indicate their rating value by pressing the corresponding key on a keyboard for each scale.

High-arousing (HA) distracting sounds will comprise those rated above the median rating of all sounds, low-arousing (LA) distracting sounds will comprise those rated beneath the median rating of all sounds. Sound characteristics were analyzed with the MATLAB MIRtoolbox (Lartillot et al., 2008).

4.1.4. Statistical Analysis of Behavioral data

In the EEG experiment, RTs were submitted to rmANOVAs with DISTRACTOR (three levels: DIS1, DIS2, DIS3) and AROUSAL (two levels: HA, LA) as within-participant factors. Post-hoc

analyses of DISTRACTOR effects were planned to be done on the difference ($RT_{NoDIS} - RT_{DIS1}$) as a measure of the facilitation effect and on the difference ($RT_{DIS3} - RT_{DIS1}$) as a measure of attention capture effect, using the non-parametric Wilcoxon signed rank test.

4.1.5. EEG Recording

EEG was recorded from 32 active Ag/AgCl scalp electrodes mounted in an electrode-cap (actiCap, Brain Products, Gilching, Germany) following a sub-set of the extended International 10–10 System. Four additional electrodes were used for horizontal (external canthi locations) and vertical (left supraorbital and infraorbital ridge locations) EOG recording and two other electrodes were placed on earlobes. The reference electrode was placed on the tip of the nose and the ground electrode on the forehead. Data were amplified, filtered and sampled at 1,000 Hz (BrainAmp, Brain Products, Gilching, Germany). Data were re-referenced offline to the average potential of the two earlobe electrodes.

4.1.6. EEG Data Analysis

EEG data were band-pass filtered (0.5–40 Hz). Prior to ERP analysis, eye-related activities were detected using independent component analysis (ICA) and were selectively removed via the inverse ICA transformation. Only 1 or 2 ICs were removed in each participant. Trials including false alarms or undetected target, and trials contaminated with excessive muscular activity were excluded from further analysis. For the purpose of the present study, only trials with distracting sounds were considered (see Bidet-Caulet et al., 2015 for analysis of the other trials). On average across participants, the number of considered trials for analysis was 119 ± 12 trials (mean ± SD) with HA and 119 ± 11 trials with LA distracting sounds.

ERPs were averaged locked to distractor onset and were baseline corrected to the mean amplitude of the -100 to 0 ms period before distractor onset. To analyze ERPs to distracting sound, for each distractor onset time-range, surrogate disRPs were created in the NoDIS trials and subtracted from the actual disRPs. The obtained disRPs were thus clear of cue-related activity.
ERP scalp topographies were computed using spherical spline interpolation (Perrin et al., 1989). ERPs were analyzed using the software package for electrophysiological analysis (ELAN Pack) developed at the Lyon Neuroscience Research Center (elan.lyon@inserm.fr; Aguera et al., 2011).

4.1.7. Statistical Analysis of ERP data

Statistical analyses were performed on electrode groups (fronto-central group: Fz, FC1, FC2 and Cz; Frontal group: F3, Fz and F4 electrodes; parietal group: Pz, P3 and P4) from the distractor onset to 350 ms after onset as previously done in Bidet-Caulet et al., 2015. Later responses were not investigated because the shortest duration between the distracting sound and the following target sound onset was 350 ms.

To explore the effect of the arousal content on the ERPs to distracting sound, permutation tests based on randomization (Edgington, 2014) were used. Each randomization consisted in (1) the random permutation of the 37 pairs (corresponding to the 37 participants) of values, (2) the sum of

squared sums of values in each of the two obtained samples, and (3) the computation of the difference between these two statistic values. We performed 1,000 such randomizations to obtain an estimate of the distribution of this difference under the null hypothesis. We then compared the actual difference between the values in the two conditions of interest to this distribution. The analysis was performed over 10 ms window, moving by step of 5 ms. To correct for multiple tests in the time dimension, we used a randomization procedure to estimate the minimum number of consecutive time-windows that must be significant to detect an effect in the entire time-period of interest (Blair and Karniski, 1993).

Correlations across distracting sounds between ratings for arousal and valence and the median across participants of the mean amplitude of each of the ERPs mentioned below were conducted using multiple linear regression. Tests were applied to the N1 mean amplitude in the 80–120 ms window at the frontocentral electrode group, to the P2 mean amplitude in the 140–180 ms window at the fronto-central group, to the N2b mean amplitude in the 180–220 ms windows at the the fronto-central group, to the early-P3 mean amplitude in the 220–260 ms window at the fronto-central group, and to the late-P3 mean amplitude in the 300–340 ms window on the frontal and parietal groups. We report the degree of freedom, the F-value, the p-values and the multiple R-squared for the results of the multiple linear regression.

If the effect of ratings was found significant, we compared the coefficients of the correlation with arousal ratings and with valence ratings using Fisher's z score (Steiger, 1980). We report the z score and the p-values. We also report the partial R-squared for both arousal and valence ratings.

4.2. Results

4.2.1. Properties of distracting sounds

The median arousal rating of all distracting sounds was 5.5. 15 high-arousing (HA) sounds (Mean ± standard deviation = 6.0 ± 0.4) were found significantly more arousing than the 15 low-arousing (LA) sounds (Mean ± SD = 5.1 ± 0.3) (Mann-Whitney U test: $p<0.001$). We found a trend for a significant difference in valence ratings of HA and LA (HA: 4.7 ± 0.4, LA: 5.0 ± 0.5, Mann-Whitney U test: $p=0.056$). Ratings for arousal and valence were negatively (slope = -0.603) and significantly correlated ($F_{1,28}=7.8$, $p=0.009$, $R^2=0,217$): negative sounds tended to be rated more arousing than neutral and positive sounds. Overall, sounds were rather neutral in valence (min=4.0, max=5.8, median=4.9).

No significant difference in low-level sound characteristics such as pitch, attack slope, roughness and brightness was found between HA and LA sounds (Mann-Whitney U test: all p-values > 0.35).

4.2.2. Percentage of correct responses

Participants correctly performed the detection task in 93.1% ± 0.9% of the trials. The remaining trials were either missed trials (1.5%) or trials with FAs (5.4% ± 0.9%). The percentage of correct responses was not found significantly modulated by the DISTRACTOR and AROUSAL factors.

4.2.3. Behavioral results (Fig. 2)

As expected, rmANOVAs revealed a significant main effect of DISTRACTOR on RTs ($F_{2,72}$ = 89.1, ε=0.69, $p<10^{-6}$). We found a trend for a significant main effect of AROUSAL ($F_{1,36}$=3.7, p=0.063). The attention capture effect (RT_{DIS3} vs. RT_{DIS1}) was significant ($p<10^{-10}$) and so was the facilitation effect (RT_{NoDIS} vs. RT_{DIS1}, $p<10^{-10}$). Participants tend to present an enhanced facilitation effect with HA distractors (46.5 ± 3.6 ms) compared to LA distractors (43.5 ± 4.0 ms) but this failed to reach significance (p=0.090). Attentional capture was fairly similar regardless of the type of distractor (HA: 46.5 ± 4.8 ms, LA: 45.4 ± 4.8 ms, p=0.84).

4.2.4. EEG response to distracting sounds (Fig. 3)

In response to distracting sounds, the fronto-central N1 response (~100 ms) was followed by a small fronto-central P2 response (~160 ms), a tiny fronto-central N2b response (~200 ms) and a P3 complex that could be dissociated in two parts: an early-P3 (~240 ms) with a fronto-central distribution, and a late-P3 (~320 ms) with frontal and parietal components.

At the fronto-central electrode group, the amplitude of the ERPs was significantly more positive for HA distractors from 175 ms to 285 ms, with the maximal difference at 222 ms. At the frontal electrode group, the amplitude of the ERPs was significantly more positive for HA distractors from 175 ms to 350 ms. At the parietal group, the amplitude of the ERPs was significantly more positive for HA distractors from 45 ms to 105 ms and from 165 ms to 340 ms.

4.2.5. Correlation across distracting sounds of EEG responses with sound ratings (Fig. 4, Table 1)

In our linear models, the collinearity is not excessive (despite correlation between arousal and valence ratings) with a Variance Inflation Factor (VIF) equal to 1.278, under the commonly accepted cutoff value of 5 or 10 (O'brien, 2007).

No significant effect of sound ratings on the mean amplitude of the fronto-central N1 was found ($F_{2,27}$=0.7, p=0.49, R^2=0.0510).

A significant effect of sound ratings on the mean amplitude of the fronto-central P2 was found ($F_{2,27}$=6.3, p=0.005, R^2=0.323). The mean amplitude of the fronto-central P2 did not correlate with ratings in arousal (p=0.096, $R^2_{arousal}$=-0.019) but positively correlated with ratings in valence (p=0.001, $R^2_{valence}$=0.234). The more positive the valence, the larger the P2. The correlation with arousal ratings was found significantly greater than the correlation with arousal ratings (Z=-2.54, p=0.011).

A significant effect of sounds ratings on the mean amplitude of the fronto-central N2b was found ($F_{2,27}$=10.4, p<0.001, R^2=0.436). The mean amplitude of the fronto-central N2b negatively correlated with ratings in arousal (p<0.001, $R^2_{arousal}$=0.432) but not with ratings in valence (p=0.13, $R^2_{valence}$=0.083). The more arousing, the smaller the N2b. The correlation with arousal ratings was found significantly greater than the correlation with arousal ratings (Z=-3,53, p<0.001).

A significant effect of sounds ratings on the mean amplitude of the fronto-central early-P3 was found ($F_{2,27}$=8.2, p=0.002, R^2=0.379). The mean amplitude of the fronto-central early-P3 positively correlated with ratings in arousal (p<0.001, $R^2_{arousal}$=0.373) but not with ratings in valence

($p=0.20$, $R^2_{valence}=0.060$). The more arousing, the larger the early-P3. The correlation with arousal ratings was found significantly greater than the correlation with arousal ratings ($Z=-3.16$, $p=0.002$).

No significant effect of sounds ratings on the mean amplitude of the late-P3 was found at frontal electrodes ($F_{2,27}=1.9$, $p=0.18$, $R^2=0.121$) nor on the mean amplitude of the late-P3 on parietal electrodes ($F_{2,27}=1.5$, $p=0.25$, $R^2=0.097$).

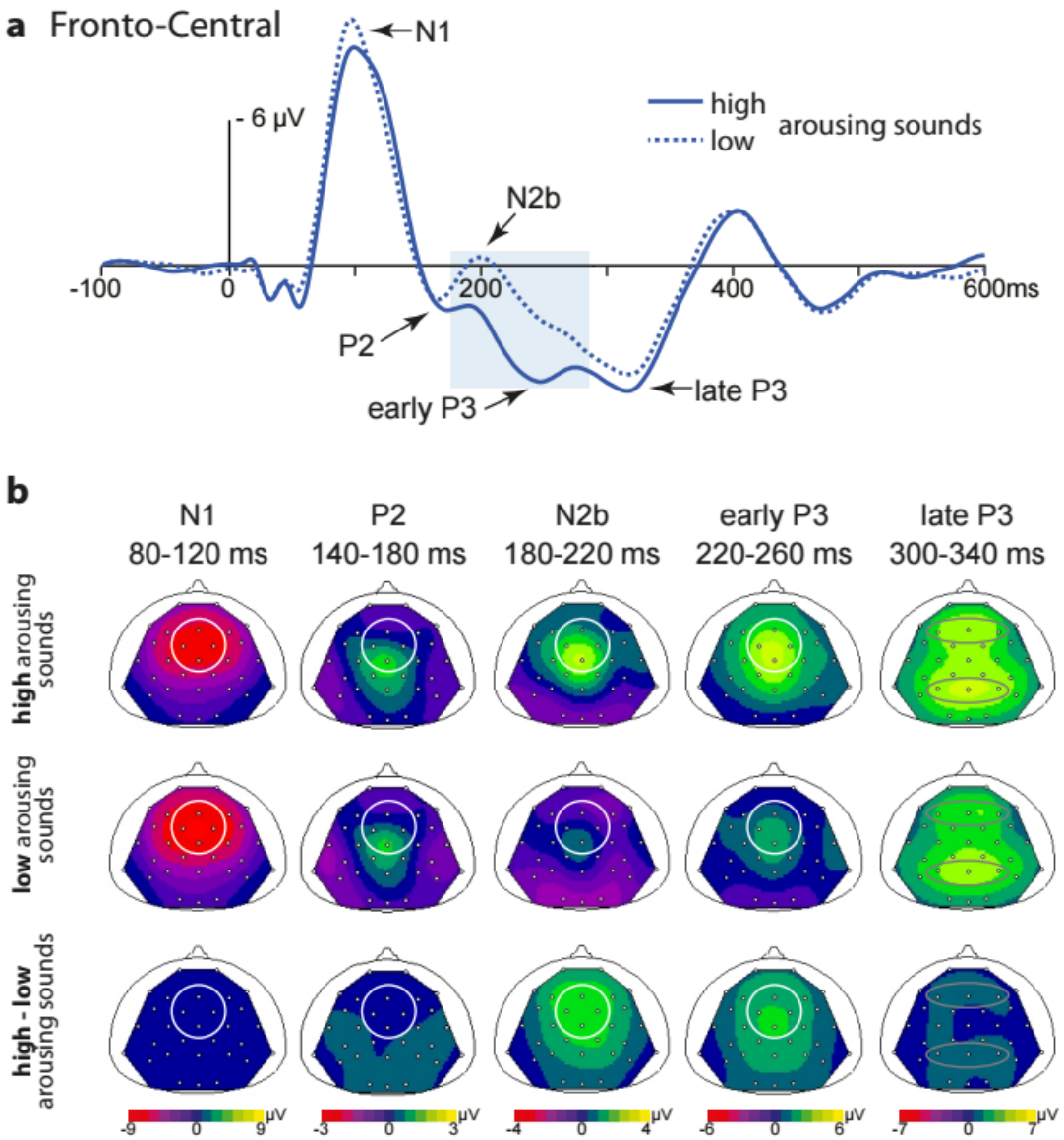

Fig. 3. ERPs to distracting sounds. **a.** Mean ERPs (after subtraction of surrogate ERPs in the NoDIS condition) at the fronto-central group of electrodes as a function of the arousal category (high-arousing or low-arousing). The blue square corresponds to latencies for which a significant effect of the arousal category is observed ($p < 0.05$). **b.** From left to right, scalp topographies (top views) of the N1, P2, N2b, early-P3 and late-P3, in the high and low arousing categories and their difference, in the 80–120, 140–180, 180–220 ms, 220–260 and 300–340 ms time-windows after distractor onset, respectively.

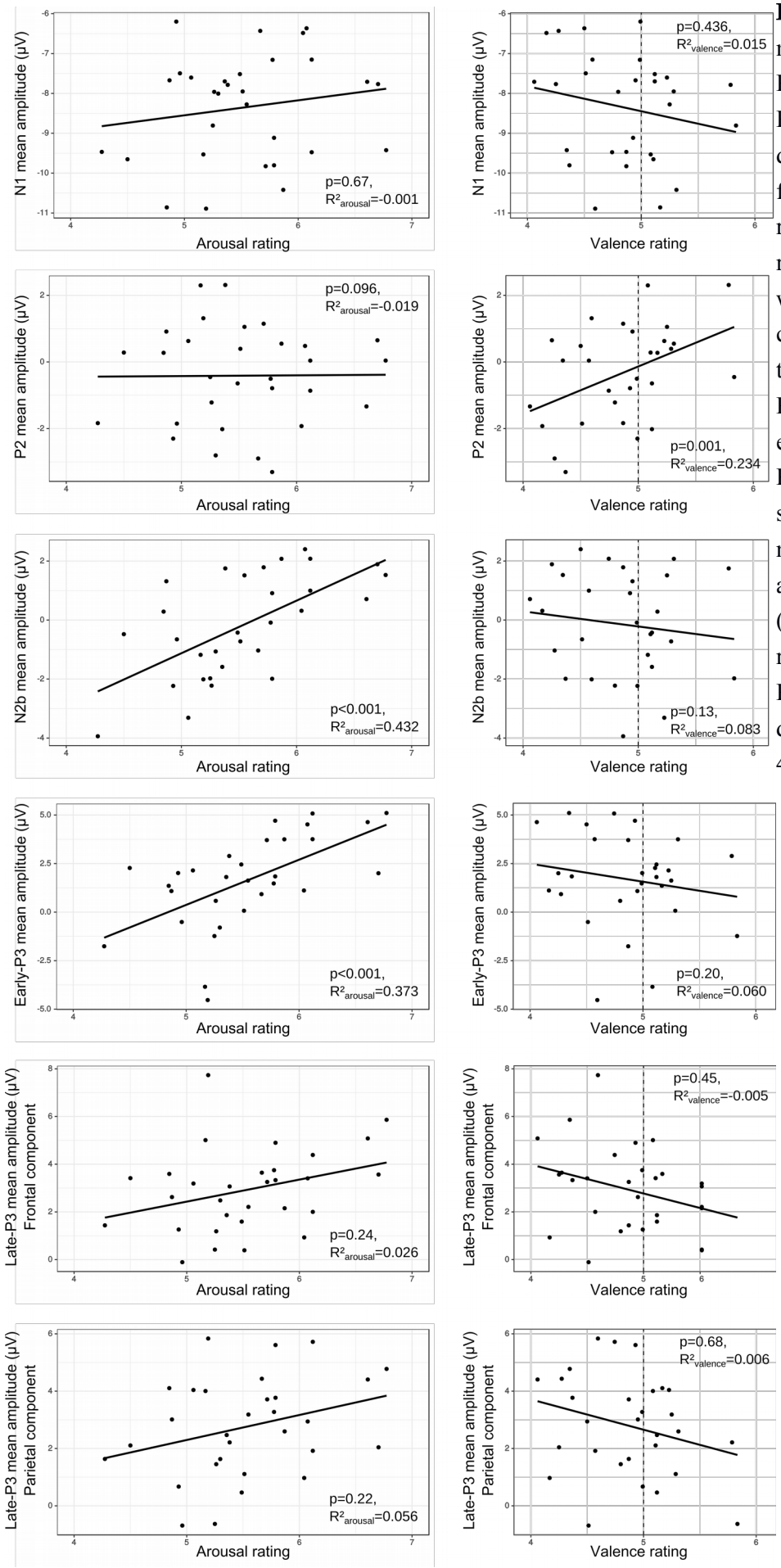

Fig. 4. Scatterplots of the mean amplitude of the N1, P2, N2b, early-P3 and late-P3 across subjects for each distracting sound as a function of the arousing ratings (left) or the valence ratings (right). Amplitudes were measured at the fronto-central electrode group for the N1, P2, N2b and early-P3 and at frontal and parietal electrode groups for the late-P3. A dashed vertical bar separates sounds rated as negative (below 5 out of 10) and sounds rated as positive (above 5 out of 10). We report p-values and partial R-squared (calculated as described in paragraph 4.1.7).

4.3. Discussion

4.3.1. Behavioral results

Unfortunately, the EEG experiment failed to reveal any significant modulation of the facilitation effect by the arousing content of the distracting sounds even if a trend towards increased facilitation with high-arousing sounds could be observed. The weakness of the effect may be explained by the fact that in our study, high-arousing and low-arousing distractors were quite close in their mean arousal rating. This result echoes a recent audio-visual oddball study in which it has been reported that negative arousing novel sounds can trigger a smaller increase in reaction times compared to neutral novel sounds (Max et al., 2015). The authors interpreted this facilitation effect as "an unspecific benefit of emotional arousal".

4.3.2. Influence of the arousal and valence contents on ERPs

In the present study, in response to distracting sounds, two phases of the P3 response could be separated: an early phase peaking fronto-centrally between 220 and 260 ms (early-P3) and a late phase peaking frontally and parietally between 300 and 340 ms (late-P3) in agreement with previous studies (Escera et al., 1998; Escera and Corral, 2007; Yago et al., 2003). The early-P3 was following a small N2b response (180-220ms).

We assessed the impact of the arousing value of distracting sounds on these electrophysiological responses: high-arousing distracting sounds elicited a smaller N2b and larger early-P3 and late-P3. The difference between responses to high-arousing and low-arousing sounds was maximal at the latency of the early-P3 at fronto-central electrodes. The fronto-central topography of the difference being stable between 180 and 260 ms, the effect observed at the latency of the N2b is most likely to be due to a larger and earlier early-P3 to high-arousing sounds than to a genuine reduction of the N2b wave. On the contrary, the topography of the difference at the latency of the late-P3 present a frontal and a parietal components, suggesting an increased late-P3 to high-arousing sounds. The finding of increased early and late P3 to high arousing sounds is quite consistent with previous studies in the literature. In the auditory modality, both the early-P3 and the late-P3 have been found enhanced after high-arousing negative sounds compared to less-arousing neutral novel sounds (Widmann et al., 2018). In the visual modality, high-arousing novels trigger larger P3a waves than low-arousing novels regardless of their valence (Olofsson and Polich, 2007; Rozenkrants and Polich, 2008). However, another study showed that only the P3b (and not the P3a) was enhanced when comparing responses to negative/positive high-arousing novel pictures compared to low-arousing neutral pictures (Delplanque et al., 2005).

The distinction between arousal and emotional effects on the P3 responses has been often ignored since previous studies compared responses to high-arousing negative and/or positive stimuli, to less-arousing neutral ones, leading to debatable conclusions as valence and arousal can interact (Cuthbert et al., 2000; Delplanque et al., 2006; Domínguez-Borràs et al., 2008; Olofsson and Polich, 2007; Widmann et al., 2018). Here, we aimed at disentangling the effects of the

arousing content of distracting sounds from the effects of their emotional content. First, we used distracting sounds that were rather emotionally neutral. Second, multiple regression analysis indicated that the ERP significantly correlated with arousal ratings, and not with the valence ratings, at the latencies of the N2b and early-P3. Moreover, at the latencies of the late-P3, no correlation with the arousal ratings, nor with valence ratings, were found significant. Finally, the valence ratings were only found correlated with ERP amplitude at the latencies of the P2, which amplitude was enhanced for negative sounds. This finding is consistent with previous studies in the visual modality which report enhanced P2 amplitude to disgusting and fearful stimuli compared to neutral ones (Carretié et al., 2011, 2004). The P2 remains one of the least investigated ERP in the auditory modality: very little is known about its functional significance (Crowley and Colrain, 2004). In the present study, it has proven to be sensitive to the valence of distracting sounds but not to their arousing value.

Taken together, these results suggest that the amplitude of the early-P3, only, is strongly related to the arousal rating of the distracting sounds.

5. General discussion

5.1. Distracting sounds and arousal

We showed that "distracting" sounds can trigger a facilitation effect on behavior when the distractor-target delay is superior to 300 ms. This facilitation effect was found not affected by the sensory modality of the target and to slowly dissipate in a few seconds, suggesting that salient task-irrelevant sounds can transiently increase general reactivity to any incoming stimulus.

All these results converge towards the idea that distracting sounds, on top of the behavioral costs related to attentional capture, can trigger a burst of arousal, which can result in a behavioral benefit. Phasic increases of arousal correspond to a state of enhanced physiological reactivity that leads to a condition of increased unspecific alertness and improved readiness to respond, which enables better performances . In tasks with low attentional demands, distracting sounds would temporarily increase arousal to a more optimal level enhancing reactivity during the task. This is consistent with a model of the orienting response which comprises an arousal component (Näätänen, 1992). Few studies investigating distraction have taken into account the arousal component provided by distracting sounds. In audio-visual oddball paradigms, distraction is measured as the difference in reaction time to targets preceded by a novel/deviant sounds compared to targets following a standard sound (Escera et al., 2000; Escera and Corral, 2007). It is important to note that since novel sounds can trigger both an attention capture and an increase in phasic arousal, the behavioral costs and benefits resulting from each process, respectively, are both contributing to the so-called distraction measure in oddball paradigms.

In summary, distracting sounds can be followed by an increase in phasic arousal and, depending on the sound properties and the participant's current level of tonic arousal, can lead to a

substantial behavioral benefit. The effects of the arousal burst persist for a couple of seconds but decline with time.

5.2. The role of the fronto-central P3a in phasic arousal

The P3a has been frequently associated with distraction as its elicitation often coincided with impaired performances (Berti and Schröger, 2003; Escera et al., 2003; SanMiguel et al., 2008; Schröger and Wolff, 1998). P3a amplitude and the increase of RT due to deviant sounds is also moderately correlated (Berti et al., 2004). Furthermore, in an oddball paradigm, if deviant sounds become task-relevant, the P3a decreases and performances improve compared to task-irrelevant deviant sounds (Hölig and Berti, 2010). These results have been interpreted as an implication of the P3a in both involuntary and voluntary attention switching.

However, in the present study, the elicitation of both P3a phases was associated with improved performances (early distractors) but also with unchanged performances (late distractors). This is consistent with previous studies reporting a dissociation between the P3a and observable behavioral distraction (Rinne et al., 2006; SanMiguel et al., 2010b; Wetzel et al., 2013). As demonstrated earlier, salient task-irrelevant sounds trigger an orienting response which comprises both attention capture and arousal components. These sounds can lead to improved, stable or impaired performances depending on task demands, distractor-target delays, the psychological state of the participant, etc. In other words, distracting sounds elicit both components of the orienting response, the final behavioral outcome depend on the balance between benefits and costs related to these two components. Therefore, linking the P3a solely to distraction may be reductive. In the light of our results and previous findings, the P3a can be seen as a more complex response which encompasses both components of the orienting response as it has been proposed by San Miguel and colleagues (2010).

In this line, previous results suggest that the early-P3 is not an adequate marker of attention reorientation. Contrary to the late-P3, the amplitude of the early-P3 is unchanged in a passive oddball paradigm compared to an active paradigm in which sounds precede the onset of visual targets (Escera et al., 2000, 1998). The authors concluded that as the early-P3 was insensitive to attentional manipulations, it was unlikely to reflect attentional reorientation. Sounds with personal significance (such as one's own first name spoken by a familiar voice or one's own ringtone) are expected to trigger stronger attention capture but unlike the late-P3, the early-P3 is impervious to personal significance (Holeckova et al., 2006; Roye et al., 2007). In contrast to the late-P3, the early-P3 is observable only for high magnitude deviant sounds and not for low-magnitude deviant sounds even if both result in behavioral distraction (Horváth et al., 2011). In clinical studies, the early-P3 does not appear to be a reliable index of distraction. In a study using an auditory oddball in children with ADHD, enhanced distractibility of the children was associated with a smaller early-P3 to novel sounds but also with a larger late-P3 (Gumenyuk et al., 2005). Similar results were observable among schizophrenic patients who displayed a smaller early-P3 to novel sounds in association with an increased behavioral distraction (Cortiñas et al., 2008). Different interpretations of the functional role of the early-P3 have emerged: the early-P3 was proposed to reflect an alerting

process governing the direction of the attentional move (Ceponiene et al., 2004), a stimulus-specific process (Horváth et al., 2011), or the violation of the regularity registered by the automatic deviance detection system (Escera et al., 2000, 1998).

In the present study, we found that the amplitude of the early-P3 is strongly related to the arousal rating of the distracting sounds. Therefore, we propose that the early-P3 is an index of the phasic arousal increase triggered by unexpected salient sounds. In agreement with previous articles, we hypothesize that the attention capture is more likely to be reflected by the late-P3 as already proposed in several previous articles (Barry and Rushby, 2006; Bidet-Caulet et al., 2015; Escera et al., 2000, 1998; Roye et al., 2007).

Nomenclature of the P3-complex has been inconsistent throughout the literature. In active and passive oddball paradigms, infrequent target or non-target deviant sounds trigger a fronto-central P3a (Escera et al., 2000, 1998; Schröger and Wolff, 1998; Squires et al., 1975). In "novelty oddball" paradigms, it has been observed that novel environmental sounds were followed by an ERP coined as "novelty-P3" (Courchesne et al., 1975; Friedman et al., 2001; Gaeta et al., 2003). In an influential study, the authors described the novelty-P3 and the P3a as indistinguishable and that the two labels could be used interchangeably (Simons et al., 2001). This result has been widely accepted in the literature (Polich, 2007) but it has not prevented both nomenclatures to persist in subsequent articles (Escera and Corral, 2007; SanMiguel et al., 2010b). Moreover, both the P3a and the novelty-P3 have been found to comprise two phases: a fronto-central early phase peaking around 235 ms and a fronto-parietal late phase peaking around 320 ms (Escera et al., 1998; Escera and Corral, 2007; Yago et al., 2003). A recent study has run a Principal Component Analysis (PCA) compiling data from different oddball paradigms (Barry et al., 2016). Based on latency, topography and conditions of elicitation, the authors suggest that the early P3a/novelty-P3 reflects the genuine P3a. In numerous articles, a monophasic fronto-central ERP peaking around 240 ms is referred to as "P3a": this would be equivalent to the early-P3 observed here and in previous studies.

In the light of previous and present findings, it seems important to consider, in future studies, the different phases of the P3 complex in response to novel or distracting sounds. The investigation of their link with the distinct arousal and attentional components of the orienting response should provide new insight on the contradictory effect observed at the behavioral level.

5.3. Relationships between the fronto-central P3a and arousal

From now on, "P3a" will refer specifically to the positive fronto-central ERP peaking around 240 ms, named early-P3 in the present study.

Both P3a and arousal have been linked to the locus coeruleus-norepinephrine (LC-NE) system in the literature. The locus-coeruleus is a brainstem neuromodulatory system that sends noradrenergic innervation to all cortical regions and to the amygdala and notably influences the cortical control of attention through arousal (for a review, see Sara and Bouret, 2012). It has been proposed that the interaction between the NE system and the prefrontal cortex is crucial for attentional regulation (Arnsten, 1998). Excessive release of norepinephrine coincides with amplified responses to distracting stimuli and degraded task performance in monkeys (Rajkowski et al., 1997). The LC-NE

would be closely linked to the orienting response: unexpected and/or arousing stimuli trigger a phasic activation of the LC-NE which consequently facilitates sensory processing (Aston-Jones and Cohen, 2005; Nieuwenhuis et al., 2005). P3a response and phasic activation of the LC-NE system share common antecedent conditions as both of them are elicited by motivationally significant stimuli such as novel stimuli in oddball tasks. In a passive auditory oddball study in monkeys, surgical lesions of the locus coeruleus were associated to decreased P3a-like response to deviant sounds (Pineda et al., 1989). It has been proposed that the LC-NE system phasic activation mediates both the P3a response and the behavioral facilitation effect following novel stimuli but such direct evidences in humans are still lacking (Schomaker and Meeter, 2015).

However, indirect evidences have accumulated. Autonomic components of the orienting responses such as the skin conductance response (SCR) and the pupil dilation response (PDR) are concomitant with the elicitation of the P3a and both would reflect the coactivation of the LC-NE system and the peripheral sympathetic nervous system (for a review, see Nieuwenhuis et al., 2011). In a recent oddball study, comodulation of the PDR response and the early- and late-P3a have been reported: both were enhanced in concert by high-arousing negative novel sounds compared to low-arousing neutral novel sounds (Widmann et al., 2018). However in another oddball study, at the single trial level, P3a did not correlate with the PDR amplitude (Kamp and Donchin, 2015). In oddball studies, a tendency towards a larger P3a has been observed in trials in which a SCR has been elicited (Lyytinen et al., 1992; Marinkovic et al., 2001) but other studies fail to link the SCR to any of the ERPs triggered by novel sounds (Barry et al., 2013; Rushby and Barry, 2009). In a recent auditory oddball study, large SCR to novel sounds were associated to large late-P3 amplitudes but no such association could be drawn with the early-P3 (Berti et al., 2017). Studies using drugs to modulate noradrenergic activity can also be useful to understand the links between the P3a and the LC-NE system. A drug facilitating noradrenergic neurotransmission has been found to increase specifically the P3a in an auditory oddball, and had no effect on the P3b (Missonnier et al., 1999). Clonidine, a drug which attenuates baseline noradrenergic activity, has been found to decrease the amplitude of the P3a (but to increase P3b) during an auditory oddball task (Brown et al., 2015). Further research will be necessary to corroborate the hypothesis of a causal link between the phasic increase of physiological arousal and the fronto-central early-P3 response after unexpected salient stimuli.

5.4. An arousal model

This model proposes that the fronto-central P3a reflect the phasic increase in arousal triggered by novel or distracting sounds. This alternative interpretation of the processes underlying the fronto-central P3a is in line with the Näätänen model of the orienting response including an arousal and an attentional components, and with a link between the P3a and the LC-NE system (see previous paragraph). In monkeys, the locus coeruleus is activated around 100 ms after stimulus onset (Aston-Jones et al., 1994; Rajkowski et al., 1994). It is imaginable that the P3a elicitation (whose peak is around 240 ms after stimulus onset) is the result of the general increase of cortical excitability following the LC-NE activation by novel stimuli.

This model is consistent with previous results and can help to shed light on them. First, it has been observed repeatedly that novel sounds trigger a larger fronto-central P3a than deviant sounds (e.g. Escera et al., 1998; Fabiani and Friedman, 1995; Gaeta et al., 2003; Spencer et al., 1999). This effect cannot be explained simply by deviance (both deviant and novel sounds deviate from the context of the standard sound sequence), nor by novelty (here understood as the association of rareness and unfamiliarity) because white noise distractors trigger a larger P3a than variable environmental novel sounds (Frank et al., 2012) and identical environmental sounds trigger a similar P3a than variable environmental novel sounds (Barkaszi et al., 2013). The difference in fronto-central P3a amplitude between novel and deviant sounds could, however, be explained by the fact that novel sounds are more salient due to their complexity and therefore more arousing, resulting in a steeper increase in phasic arousal and a larger fronto-central P3a. Second, one of the main characteristics of the P3a is to quickly decrement with repeated exposure (Barry et al., 2016; Courchesne et al., 1975; Debener et al., 2002). This is compatible with the observations that the locus coeruleus neural response to novel sounds or to novel environments quickly decreases after few presentations in rats (Hervé-Minvielle and Sara, 1995; Vankov et al., 1995).

Therefore, the arousal model of the P3a fits the classic theory of the orienting response and can account for the main properties of the P3a that have been highlighted in the literature.

6. Conclusions

In summary, the present findings show that unexpected salient sounds during a task trigger two distinct processes: a short-lived attention capture and a more lingering phasic increase in arousal. Consequently, performances are conditioned to both facilitation by phasic arousal and impairment by attention capture. Whether unexpected salient sounds will have detrimental or beneficial effects on performances partly depends on the design of the task (the sound-target delay in the present study but also the informational value or task-relevance of the sound, the task demand, etc.). Unexpected salient sounds trigger a biphasic P3, we found that the amplitude of the early-P3 is strongly related to the arousal rating of the distracting sounds. Therefore, we propose that both of the processes mentioned above are reflected in the P3 but that the phasic arousal response is more associated to the fronto-central early-P3, often named P3a in the literature.

P3a is widely considered as an index of distractibility and used as such in numerous clinical studies including for example healthy old adults (Getzmann et al., 2013), participants under the influence of alcohol (Marinkovic et al., 2001), patients with closed head injury (Kaipio et al., 2000), Alzheimer (Correa-Jaraba et al., 2018) or dyslexia (Rüsseler et al., 2002), healthy children (e.g. (Gumenyuk et al., 2001; Wetzel and Schröger, 2007) and children with ASD (Ferri et al., 2003), depression (Lepistö et al., 2004) or ADHD (e.g. Gumenyuk et al., 2005; Keage et al., 2006; van Mourik et al., 2007). It will be essential for further studies about distractibility to dissociate the two phases of the P3 complex to improve medical diagnosis.

7. Declarations of interest

None.

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