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Brain Dynamics of Distractibility: Interaction Between Top-Down and Bottom-Up Mechanisms of Auditory Attention

Aurélie Bidet-Caulet · Laure Bottemanne ·
Clara Fonteneau · Marie-Hélène Giard ·
Olivier Bertrand

Abstract Attention improves the processing of specific information while other stimuli are disregarded. A good balance between bottom-up (attentional capture by unexpected salient stimuli) and top-down (selection of relevant information) mechanisms is crucial to be both task-efficient and aware of our environment. Only few studies have explored how an isolated unexpected task-irrelevant stimulus outside the attention focus can disturb the top-down attention mechanisms necessary to the good performance of the ongoing task, and how these top-down mechanisms can modulate the bottom-up mechanisms of attentional capture triggered by an unexpected event. We recorded scalp electroencephalography in 18 young adults performing a new paradigm measuring distractibility and assessing both bottom-up and top-down attention mechanisms, at the same time. Increasing task load in top-down attention was found to reduce early processing of the distracting sound, but not bottom-up attentional capture mechanisms nor the behavioral distraction cost in reaction time. Moreover, the impact of bottom-up attentional capture by distracting sounds on target processing was revealed as a delayed latency of the N100 sensory response to target sounds mirroring increased reaction times. These results provide crucial information into how bottom-up and top-down mechanisms dynamically interact and compete in the human brain, i.e. on the precarious balance between voluntary attention and distraction.

Keywords Novelty · Involuntary attention · Unexpected sound · Distraction · Arousal

Introduction

You are in a classroom, listening to the teacher and suddenly you hear a car horning in the street. Everybody has experienced such a situation when an unexpected salient sound interrupts the task you were concentrated on by capturing your attention. And in most cases, you were able to focus back on the task at hand, unless the sound was evaluated as significant or even vitally important (e.g. fire alarm) and required an adapted response. This capacity to be task-efficient while being aware of our surrounding environment without been fully distracted is supported by a good balance between *bottom-up* and *top-down* mechanisms of attention. *Top-down* or voluntary attention enables the good performance of an on-going task by selecting the relevant information. Top-down attention can operate via several distinct mechanisms such as facilitatory and inhibitory mechanisms (review in Bidet-Caulet et al. 2007; Bidet-Caulet et al. 2010) and anticipatory/preparatory attention (Foxe and Snyder 2011; Jensen and Mazaheri 2010; Brunia and van Boxtel 2001). *Bottom-up* attention is manifested by the involuntary capture of attention by an unexpected salient stimulus, and is necessary to be aware of potentially important events that are nonetheless irrelevant to the on-going task. The tendency to have one's attention captured is commonly referred to as distractibility.

A. Bidet-Caulet (✉) · L. Bottemanne · C. Fonteneau ·
M.-H. Giard · O. Bertrand
Brain Dynamics and Cognition Team, Lyon Neuroscience
Research Center; CRNL, INSERM U1028, CNRS UMR5292,
University of Lyon 1, Lyon, France
e-mail: aurelie.bidet-caulet@inserm.fr

Bottom-up and top-down mechanisms have been mostly explored in separate experiments or trials. Functional magnetic resonance imaging studies found that top-down and bottom-up mechanisms are sustained by partially overlapping brain networks: the top-down network would include the parietal and posterior frontal cortices, whereas the bottom-up networks would be composed of the temporo-parietal junction and the ventral frontal regions mainly in the right hemisphere (review in Corbetta and Shulman 2002).

Activation of these networks has also been observed using electroencephalography (EEG) recordings. Top-down anticipatory and selective forms of attention are indexed by the deployment of frontally distributed event-related potentials (ERPs), the contingent negative variation (CNV) (Brunia and van Boxtel 2001), and the processing negativity (Naatanen 1982; Giard et al. 2000), respectively. Bottom-up attentional capture by unexpected salient sounds would be signaled by a P3 complex, also called novelty-P3 or P3a (Polich 2007; Ranganath and Rainer 2003; Friedman et al. 2001), with early and late components, and frontal and parietal generators (review in Escera et al. 2000).

Several attempts have been undertaken to investigate the balance between bottom-up and top-down attention, however only few studies have explored how an unexpected stimulus outside the focus of attention can disturb the top-down attention mechanisms necessary to the good performance of the ongoing task, and how these top-down mechanisms can modulate the bottom-up mechanisms of attentional capture triggered by an unexpected event.

Distraction has been mostly investigated using audio-visual oddball paradigms during which task-irrelevant standard or novel sounds precede visual targets to be discriminated (see Escera et al. 2000, 2003 for reviews). These studies showed that novel sounds, compared with standard sounds, caused prolonged reaction times to the visual targets. Moreover, novel sounds were found to be followed by a novelty-P3 response. These results led the authors to propose that the novelty-P3 response reflects an actual switching of attention towards the unattended stimuli resulting in a cost in reaction times to visual targets. This interpretation was based upon the assumption that the sounds provided no task-relevant information. However, this assumption was challenged in recent studies (Parmentier et al. 2010, 2011; SanMiguel et al. 2010a, b; Ljungberg et al. 2012; Wetzel et al. 2012, 2013); showing that the sounds were also used as warning signals predicting the onset time of the following visual targets since the interval between sound and target was constant. The sounds could thus have been attended by the subjects and have acted as warning cues triggering top-down

mechanisms of attention instead of acting only as genuine distracting sounds activating bottom-up attentional capture. Interestingly, when sounds actually provided no task-relevant information, the cost in reaction time was not observed after novel sounds (Parmentier et al. 2010, 2011; Ljungberg et al. 2012; Wetzel et al. 2012, 2013). These results question the adequacy of these audiovisual oddball paradigms to investigate distractibility and the balance between bottom-up and top-down attention. The distraction effect of these sounds is not clear for several reasons. First, distraction was measured by comparing the reaction times in trials with novel sounds and trials with standard sounds: what about the comparison with the reaction times in the absence of any sound? Second, the sounds were embedded in sequences that could be inhibited by top-down mechanisms of selective attention similarly to the unattended stream in a classic dichotic paradigm (Hillyard et al. 1973). Interestingly when distracting sounds are not presented within a sound sequence the cost in reaction time is highly reduced (Berti 2013). To our knowledge, the most ecological paradigm used to study distraction consisted in the presentation of rare single environmental sounds while subjects were playing a video game (Miller et al. 2011). The authors could show that enhancing the recruitment of top-down attention mechanisms by increasing the game difficulty resulted in reduced ERPs to distracting sounds. Unfortunately, they could not measure the impact of the distracting sounds on the game performance neither at the behavioral nor at the electrophysiological level.

In the present study, we propose a novel paradigm to assess both bottom-up and top-down mechanisms of auditory attention in a situation that matches as close as possible the situation of a school pupil distracted by a rare unexpected single environmental sound (not embedded in a stream) outside the focus of attention. We adapted a cueing paradigm using visual cues and monaural auditory targets. Top-down anticipatory attention could be measured by comparing trials with informative cues with trials with uninformative cues. Bottom-up attentional capture was triggered by binaural distracting sounds played during the cue-target period, in only 25 % of the trials. Distraction was assessed as the impact of distracting sound on task performance. Scalp EEG was recorded from 18 young adults to explore how bottom-up and top-down mechanisms of attention dynamically interact in the healthy brain. We could dissociate the neurophysiological responses associated with top-down attention from those to distracting sounds corresponding to bottom-up attentional capture. We address the following questions: How distracting sounds disturb on-going top-down mechanisms? How top-down mechanisms can protect from bottom-up attentional capture?
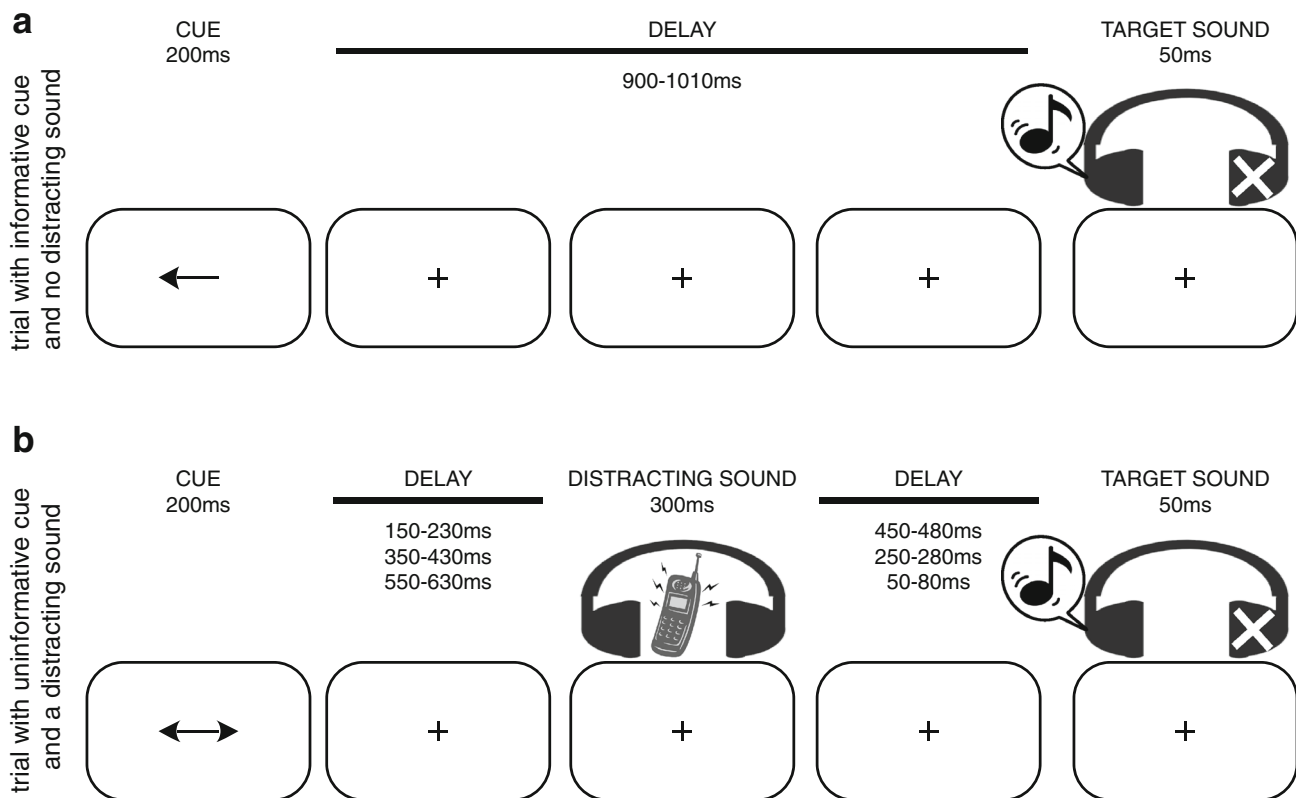
Fig. 1 Protocol. **a** In informative trials, a one-sided visual cue (200 ms duration) indicated in which ear (*left* or *right*) the target sound will be played (50 ms duration) after a random delay (900–1,010 ms). **b** In uninformative trials, a two-sided visual cue (200 ms duration) did not provide any indication in which ear (*left* or *right*) the target sound will be played. In 25 % of the trials a binaural distracting sound (300 ms duration), such as a phone ring, was played during the delay between cue and target. The distracting sound could 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

Materials and Methods

Subjects

Eighteen paid subjects (all right-handed, 11 female, aged 19–26 years) participated in this experiment. All subjects were free from neurological or psychiatric disorder, and had normal hearing and normal or corrected-to-normal vision. All subjects gave written informed consent.

Stimuli and Task

75 % of the trials (Fig. 1a) 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 % (Fig. 1b), the same trial structure was used, but a binaural distracting sound (300 ms duration, 70 dB SL) was played during the delay (Fig. 1b). A total of 30 different ringing sounds were used as distracting sounds (clock-alarm, door-bell, phone ring, etc.) in each participant.

The cue and target categories were manipulated in the 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 33.3 % of the trials, the cue was *uninformative*, pointing in both directions, and the target sound was played in the left (16.7 %) or right (16.7 %) ear.

The distracting sound could equiprobably be 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*).

To compare brain responses to acoustically matched sounds, the same distracting sounds were played in each

combination of cue category (*informative left*, *informative right* or *uninformative*) and distractor condition (*DIS1*, *DIS2* or *DIS3*). Each distracting sound was thus played nine times during the whole experiment, but no more than once during each single block to limit habituation.

Subjects 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. Subjects were instructed to keep their eyes fixating on the cross and to minimize eye movements and blinks while performing the task.

Procedure

Subjects were seated in a comfortable armchair in a sound-attenuated and electrically-shielded 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. Finally, EEG was recorded while subjects performed 15 blocks (72 trials each). Subjects had 2,500 ms to answer after target sounds, each trial lasted therefore from 3,600 to 3,710 ms, leading to block duration of ~5 min and EEG session of ~1 h 15 min (breaks included).

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.

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. On average across subjects, the number of considered trials for analysis was in *informative* trials 314 *NoDIS*, 30 *DIS1*, 32 *DIS2*, and 33 *DIS3*, and in *uninformative* trials 162 *NoDIS*, 16 *DIS1*, 16 *DIS2*, and 16 *DIS3*.

ERPs were averaged for each stimulus event: cue-related potentials (cueRPs) were averaged locked to cue onset, target-related potentials (targetRPs) were averaged locked to target onset, and distracter-related potentials (disRPs) were averaged locked to distractor onset. Different baseline corrections were applied according to the investigated processes.

To investigate the deployment of top-down attention mechanisms in the absence of distracting sound (*NoDIS*), cueRPs were baseline corrected to the mean amplitude of the −100 to 0 ms period before cue onset, and targetRPs were corrected to the mean amplitude of the −100 to 0 ms period before target 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.

To explore the impact of distracting sounds on target sound processing, targetRPs were baseline corrected to the mean amplitude of the −100 to 0 ms period before cue onset in all trials.

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).

Statistical Analysis

For statistical analysis, when more than one factor was considered, repeated measure ANOVAs (rmANOVA) were applied to the data. 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 corrected probabilities.

For comparison of two conditions and post hoc tests, permutation tests based on randomization (Edgington 1995) were used. Each randomization consisted in (1) the random permutation of the 18 pairs (corresponding to the 18 subjects) 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 10,000 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.

In the "Results" section, mean values and SEM are indicated.

Behavioral Data

A button press before target onset was considered as a false alarm (FA). A FA during the presentation of the distracting sound was counted as a response to the distracting sound. 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.

RTs and percentages of correct trials were submitted to rmANOVAs with CUE category (two levels: *uninformative*, *informative*) and DISTRACTOR condition (four levels: *NoDIS*, *DIS1*, *DIS2*, *DIS3*) as within-subject factors.

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) and at the latency-windows corresponding to the main ERP components (N1, P2, P3 and CNV).

To investigate the deployment of top-down attention mechanisms in the absence of distracting sound, the CUE category effect was measured on cueRPs and targetRPs using permutation tests (see above). CUE effects were measured on the mean amplitude of the cueRPs in successive 50 ms time-windows, from 550 to 1,100 ms post cue onset at the fronto-central electrode group. Post-target CUE effects were measured on the N1 mean amplitude in the 80–120 ms window at the fronto-central group, on the P2 mean amplitude in the 150–200 ms window at the fronto-central group, and on the target-P3 mean amplitude in successive 50 ms time-windows from 200 to 500 ms at the parietal electrode group.

To explore the effect of top-down attention mechanisms on distracting sound processing, the CUE category effect was measured on the disRPs using permutation tests. Post-distractor onset CUE effects were measured on the N1 mean amplitude in the 80–120 ms window at the fronto-central electrode group, on the P2 mean amplitude in the 160–200 ms window at the fronto-central group, on the early-P3 mean amplitude in the 220–260 ms window at the fronto-central group, and on the late-P3 mean amplitude in
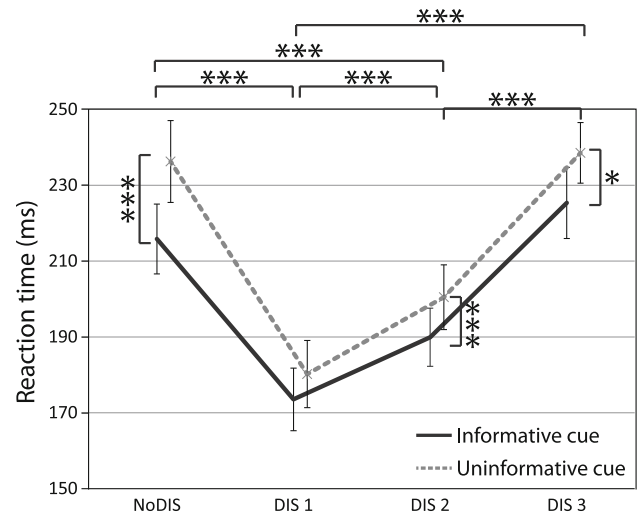

Fig. 2 Behavioral results. Reaction time as a function of the cue category (*informative* or *uninformative*) and of the distractor condition (*NoDIS*, *DIS1*, *DIS2*, *DIS3*). *P < 0.05, ***P < 0.001. *Error bars* represent 1 SEM

the 300–340 ms window on the frontal and parietal groups. Later components were not investigated because the shortest duration between the distracting sound and the following target sound onset was 350 ms.

To explore the impact of distracting sounds on target sound processing, target-RPs were submitted to rmANOVA with CUE category (two levels: *uninformative*, *informative*) and DISTRACTOR condition (four levels: *NoDIS, DIS1, DIS2, DIS3*) as within-subject factors. This rmANOVA was applied on the N1 latency (latency of the minimum amplitude in the 55–155 ms window after target onset at Cz electrode).

Results

Behavioral Results

Participants correctly performed the detection task in 92.0 ± 1.7 % of the trials. The remaining trials were either missed trials (0.7 ± 0.1 %) or trials with FAs (7.3 ± 1.6 %). Within trials with FAs, 1.0 % was with responses to distracting sounds, 4.6 % with anticipatory responses within the 200 ms before the target sound onset (and not during a distracting sound) and the remaining with random FAs.

The percentage of correct responses was independently modulated by the CUE category and the DISTRACTOR condition.

rmANOVAs revealed a significant main effect of CUE ($F_{1,17} = 14.7$, $P = 0.0013$), surprisingly indicating that subjects were globally less accurate when the cue was

informative (87.3 ± 2.3 %) rather than *uninformative* (90.6 ± 2.0 %).

A significant main effect of DISTRACTOR ($F_{3,51} = 55.6$, $P < 0.0001$) was also observed. Post-hoc tests indicated that subjects were more accurate in the absence of distracting sound (*NoDIS* 94.3 ± 1.3 %) than in the *DIS1* (83.6 ± 3.3 %, $P < 0.0001$), *DIS2* (89.0 ± 2.0, $P < 0.0001$), *DIS3* (88.9 ± 2.2, $P < 0.0001$) conditions. Moreover subjects were less accurate in the *DIS1* than in the *DIS2* or *DIS3* condition (both $P > 0.0001$).

In correct trials, the RTs were really short on average (216.9 ± 9.0 ms) and were modulated by both the CUE category and the DISTRACTOR condition (Fig. 2).

rmANOVAs revealed a significant main effect of CUE ($F_{1,17} = 33.6$, $P < 0.0001$), indicating that RTs were shorter when the cue was *informative* rather than *uninformative*.

A significant main effect of DISTRACTOR ($F_{3,51} = 55.6$, $P < 0.0001$) was also observed. Post-hoc randomization tests indicated that, irrespective of the CUE category, RTs were shorter in the *DIS1* than in the *DIS2*, *DIS3* or *NoDIS* condition (all $P < 0.0001$), and in the *DIS2* than in the *DIS3* or *NoDIS* condition (both $P > 0.0001$), revealing an increase in RTs with distractor onset time during the CUE-TARGET delay: the later the distracting sound, the longer the RT.

Finally, a CUE by DISTRACTOR interaction ($F_{3,51} = 33.6$, $P = 0.0342$) was found significant, suggesting that the DISTRACTOR condition can influence the CUE effect. Post-hoc tests indicate that the CUE effect was significant in the *NoDIS* ($P < 0.0001$), *DIS2* ($P = 0.0003$), and *DIS3* ($P = 0.0109$) conditions, but not in the *DIS1* ($P = 0.0862$) condition. Moreover, planed post hoc tests, indicated that the difference in RT between *DIS3* and *DIS1* conditions were not significantly different in the *informative* (49.9 ± 30.0 ms) and *uninformative* (54.7 ± 27.3 ms) trials ($P = 0.2275$).

Deployment of Top-Down Attention Mechanisms (Fig. 3)

In trial with no distracting sound, analyses were focused on the deployment, during the delay, of top-down processes indexed by a CNV response, and on the impact of these top-down processes on target processing. The hypothesis was that *informative* cues would trigger a larger deployment of top-down processes, i.e. a larger CNV amplitude, and facilitate target processing.

Following the visual ERPs to the cue, a slow negative wave with fronto-central topography, the CNV, started around 550 ms after cue onset and slowly increased until target sound onset. The CNV amplitude was found to be larger after *informative* than *uninformative* cue onset

between 650 and 800 ms, at the fronto-central electrode group ($P < 0.01$).

In response to target sounds, the fronto-central N1 response (∼100 ms) was followed by a fronto-central P2 response (∼175 ms) and a parietal target-P3 (200–500 ms). Amplitude of either N1 or P2 to target sound was not found to be significantly affected by the CUE category, at the fronto-central electrode group ($P > 0.2$). However, the target-P3 amplitude was found reduced when the cue was *informative* compared to *uninformative* between 250 and 500 ms after target onset, at the Parietal electrode group ($P < 0.001$).

Effect of Top-Down Attention Mechanisms on Distracting Sound Processing (Fig. 4)

In response to distracting sounds, the fronto-central N1 response (∼100 ms) was followed by a small fronto-central P2 response (∼180 ms) and a P3 complex that could be dissociated in two parts: an early-P3 (220–260 ms) with a fronto-central distribution, and a late-P3 (300–340 ms) with frontal and parietal components. At the fronto-central electrode group, the amplitudes of N1 and early-P3 to distracting sounds were significantly smaller in trials with *informative* compared to *uninformative* cue (N1: $P = 0.01243$, early-P3: $P < 0.0001$), whereas the P2 amplitude was not affected by the CUE category ($P > 0.4$). At both Frontal and Parietal electrode groups, the amplitude of the late-P3 to distracting sounds was not affected by the CUE category ($P > 0.05$).

Effect of Distracting Sounds on Target Processing (Fig. 5)

In response to target sounds, a decrease in the amplitude of the fronto-central N1 response (∼100 ms) with later distracting sound is clearly visible. Because of large difference in the pre-stimulus amplitude between conditions, this effect, probably due to refractoriness, was not further investigated. However, the effect of distracting sound on the N1 latency could be statistically analyzed.

rmANOVAs on the latency of the N1 to target sounds revealed a significant main effect of the DISTRACTOR condition ($F_{3,51} = 7.3$, $P = 0.0003$), but no main effect of CUE ($F_{1,17} = 0.8$, $P > 0.3$), nor CUE by DISTRACTOR interaction ($F_{3,51} = 0.9$, $P > 0.4$). Post-hoc randomization tests indicated that the N1 latency was significantly shorter in the *DIS1* than in the *DIS2* ($P = 0.0115$), or *DIS3* ($P < 0.008$) condition. The latency difference between the *DIS2* and *DIS3* conditions nearly reached significance ($P = 0.074$). The N1 latency in the *NoDIS* condition did not significantly differ than in the *DIS1* condition ($P > 0.6$), but was shorter than in the *DIS2* ($P = 0.0172$),

Fig. 3 ERPs to cues and targets in *NoDIS* trials. **a** Mean cueRPs (pre-cue baseline correction) at the fronto-central group of electrodes as a function of the cue category (*informative* or *uninformative*). **b** Mean targetRPs (pre-target baseline correction) at the parietal group of electrodes as a function of the cue category. **c** Scalp topographies (*top views*) of the CNV and the target-*P3*, in trials with *informative* or *uninformative* cue, and their difference, in the 650–800 ms window after *cue onset* (*left*) and in the 250–500 ms window after *target onset* (*right*), respectively. **P < 0.01, ***P < 0.001
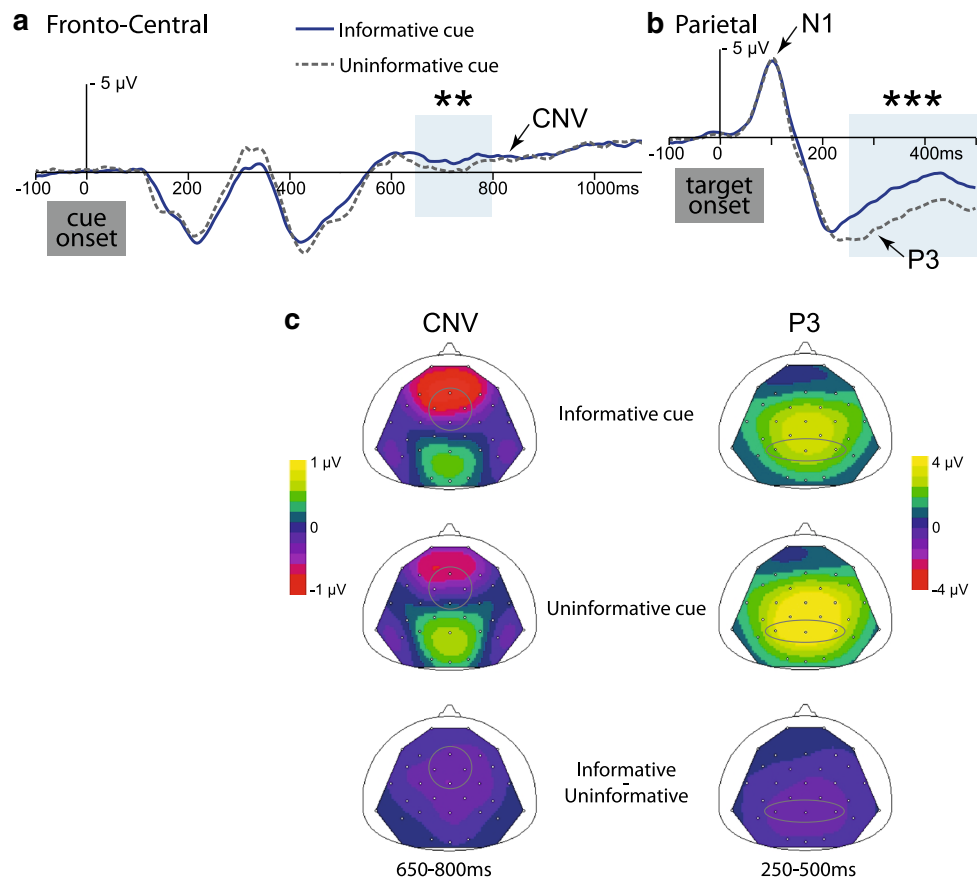
or *DIS3* (P = 0.0069) condition. These results thus reveal an increase in N1 latency with distractor onset time during the CUE-TARGET delay: the later the distracting sound, the later the N1 latency to target (*NoDIS* 104.1 ± 1.4 ms, *DIS1* 103.3 ± 2.2 ms, *DIS2* 110.9 ± 3.3 ms, *DIS3* 121.3 ± 5.2 ms).

Discussion

The present findings suggest that (i) the processing of distracting sounds can be modulated by the load of the task at hand; and that (ii) distracting sounds delay target processing and lengthen reaction times according to the time interval between distracting and target sound onsets. The dynamics of these electrophysiological effects provide crucial information into the competition between bottom-up and top-down mechanisms of auditory attention.

Behavioral Measure of Top-Down Anticipatory Attention

Behavioral results indicate that subjects took advantage of the cue information since they were faster to detect targets in trials with informative cue, in agreement with several

previous studies using cueing paradigms in the visual (e.g. Muller and Findlay 1988; Muller and Rabbitt 1989) or auditory (e.g. Golob et al. 2002) modality. This result is usually interpreted as the outcome of anticipatory top-down processes for the expected target. This effect is more likely to be related to anticipatory attention than motor preparation since the motor response was always the same and could be evenly anticipated in informative and uninformative trials.

Surprisingly, subjects were less accurate in trials with informative cue. A speed-accuracy trade-off could explain the reduction in reaction times in this case. However, the decrease in accuracy is accompanied by a rather important proportion of false alarms just before target onset, suggesting that subjects had the tendency to anticipate the targets when the cue was informative.

Behavioral Measure of Auditory Distraction

The most interesting behavioral result is the modulation of reaction times by distracting sounds. On average, subjects were faster in trials with a distracting sound than in trials with no distracting sound. Instead of inducing a cost in reaction time related to a distraction effect, distracting sounds induced a benefit in reaction time. This benefit for
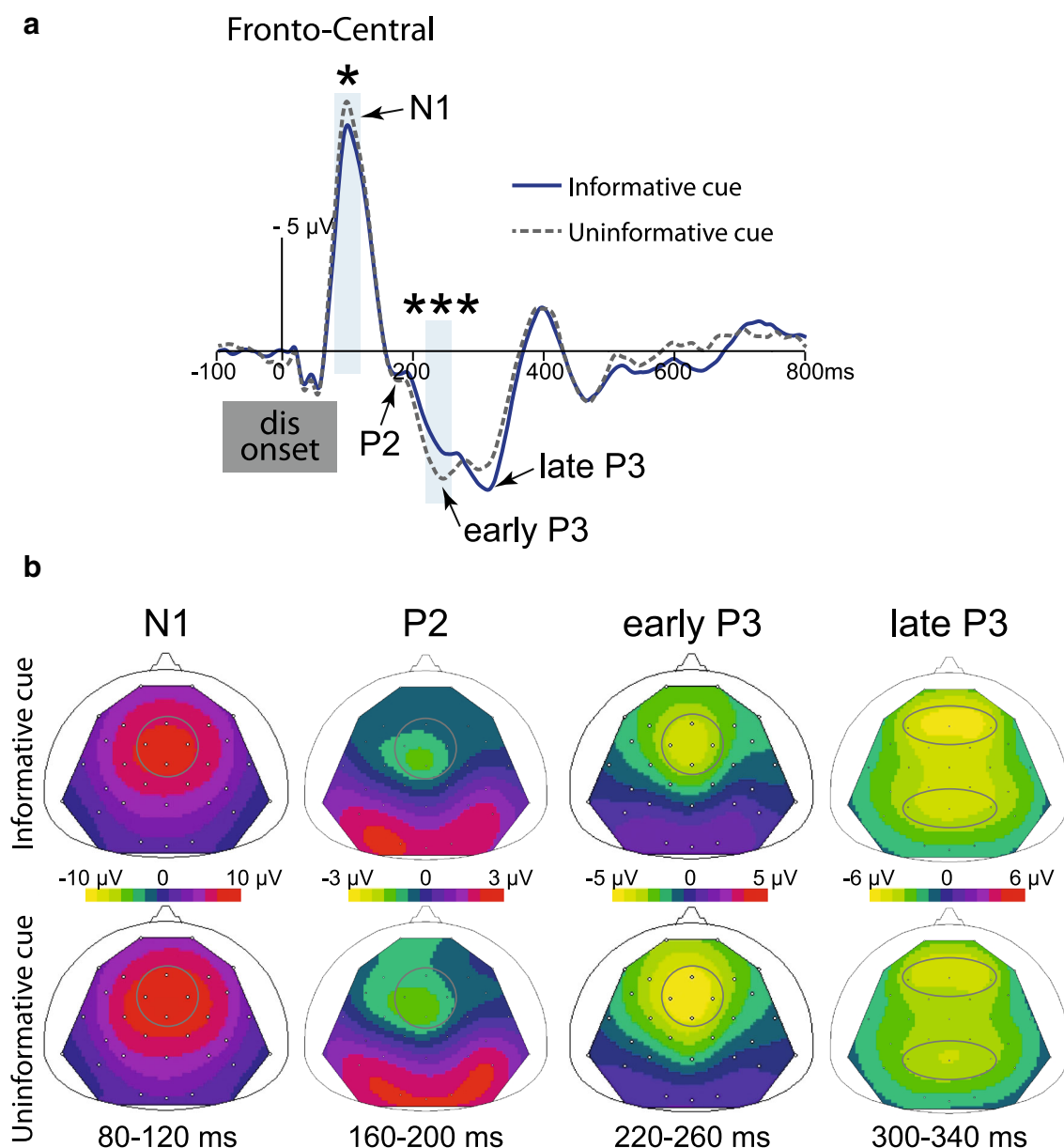
Fig. 4 ERPs to distracting sounds. **a** Mean disRPs (after subtraction of surrogate disRPs in the *NoDIS* condition) at the fronto-central group of electrodes as a function of the cue category (*informative* or *uninformative*). **b** From *left* to *right*, scalp topographies (*top views*) of the *N1*, *P2*, *early P3* and *late P3*, in trials with *informative* or *uninformative cue*, in the 80–120, 160–200, 220–260 and 300–340 ms windows after *distractor onset*, respectively. *P < 0.05, ***P < 0.001

the ongoing task is most likely to be due to an increase in unspecific arousal that would result in enhanced reactivity of the subject, facilitating the processing of any upcoming stimulus (Coull 1998; Näätänen 1992), in this particular case the target.

Nevertheless, the increase in reaction time with later distracting sound suggests that the distracting sounds also triggered an orienting response or attentional capture that resulted in a cost in reaction time and could partially cancel benefits from increase in arousal. 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 two phenomena triggered by the distracting sounds, i.e. an orienting response and an increase in arousal, have different time courses. The increase in arousal 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
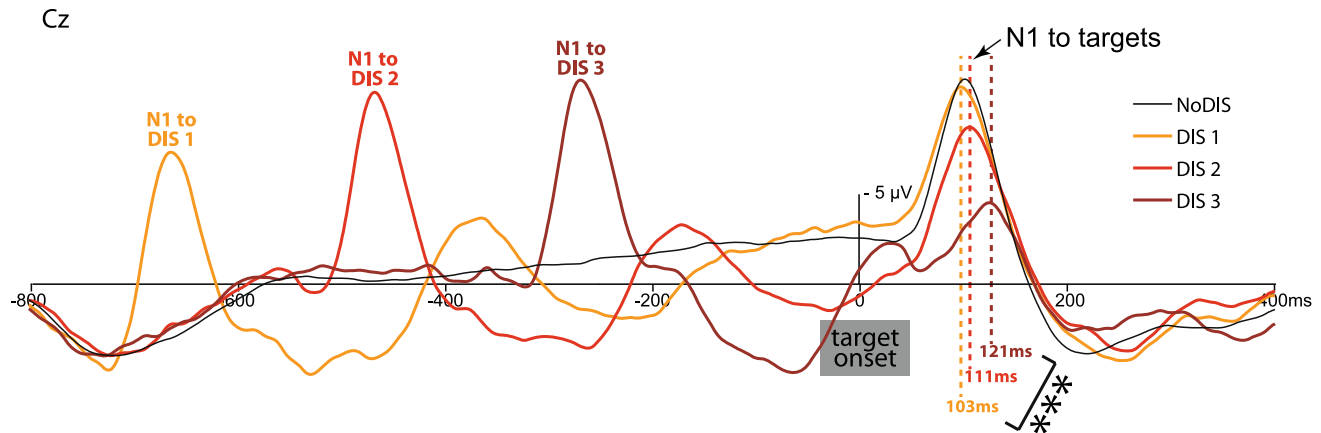
Fig. 5 ERPs to targets according to distractor onset time. **a** Mean targetRPs (pre-cue baseline correction) at Cz electrode as a function of the distractor condition (*NoDIS*, *DIS1*, *DIS2*, *DIS3*). One can note that in the *DIS1* condition, there is enough time between distractor and *target onsets* for the CNV to develop when distracting sound processing is completed.***$P < 0.001$

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 560 ms (Schröger 1996). Further studies will be essential to specify the time courses of these two phenomena triggered by unexpected salient sounds.

It is important to note that only very few studies investigating distraction have taken into account the effect of arousal provided by the distractor (SanMiguel et al. 2010a; Wetzel et al. 2012, 2013). In the audiovisual odd-ball paradigms described in the Introduction, distraction is estimated in the difference in reaction time to targets according to whether the distractor is a standard or a novel sound (see Escera et al. 2000; Escera and Corral 2007 for reviews). However, if novel sounds are quite likely to capture more attention than standard sounds, they might also result in a higher arousal level, which could explain why, when sounds actually provided no task-relevant information, the cost in reaction time disappeared (Parmentier et al. 2010, 2011; Ljungberg et al. 2012; Wetzel et al. 2012, 2013).

In summary, these behavioral 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 by an attentional capture mechanism, and a benefit due to an increase in arousal. This has to be taken into account to get an accurate behavioral measure of distraction. In the present paradigm, the difference in reaction time to targets between trials with late distracting sounds (DIS3) and trials with early distracting sounds (DIS1) provides a good approximation of the distraction effect with no or little contamination by the

increase in arousal (the assumptions being that the increase in arousal is similar irrespective of the distractor onset time and the arousal level remains stable for about one second).

Behavioral Measure of the Interaction Between Top-Down Attention and Distraction

Surprisingly, the reaction time benefit resulting from informative cue was significant only in trials with late distracting sounds but not with the earliest ones, i.e. when the subjects had more time to re-orient their attention back to the ongoing task. One possible explanation of the absence of cue-related reaction time benefit with early distractors is that in this condition, the reaction times are so short (<180 ms) that they can hardly be further shortened by the cue information. Therefore the presence of a distracting sound seems to have little impact on the behavioral advantage provided by informative cue.

Similarly, loading more top-down attention seems to have no impact on the distraction effect, since this effect (difference in reaction times to targets between trials with late and early distracting sounds) is not modified by the cue information. This finding is consistent with previous studies showing no influence of increased memory load on distraction effect measured as the difference in reaction times between trials with novel and standard sounds (Ruhnau et al. 2010; Lv et al. 2010; but see SanMiguel et al. 2008).

Deployment of Top-Down Attention Mechanisms

As expected, a sustained brain activity started around 550 ms after cue onset over fronto-central areas and slowly increased until target onset. This CNV response is considered to reflect both attentional and motor preparation for

the imperative (target) stimulus (review in Brunia and van Boxtel 2001) and is considered as a good index of top-down attention (Gomez et al. 2007). In the present study, informative cues resulted in an enhanced CNV during its early phase (650–800 ms). This effect is more likely to be related to attentional processes than motor preparation since the motor response could be evenly anticipated in all trials. Therefore, the increased CNV confirms that more top-down attention was loaded to perform the task in informative trials.

This enhanced CNV in informative trials was accompanied by a reduced target-P3 response, in agreement with previous auditory cued attention ERP studies (Golob et al. 2002; Hugdahl and Nordby 1994; Ofek and Pratt 2004). This reduction in target-P3 amplitude is quite likely to be related to the decrease in target uncertainty (Suwazono et al. 2000; Mars et al. 2008; Duncan-Johnson and Donchin 1977) in informative trials compared to uninformative ones.

Taken together, the enhanced CNV associated with reduced target-P3 and reaction times to targets, indicate that the task load in top-down attention was more important in informative than in uninformative trials.

Effect of Top-Down Attention on Bottom-Up Processes

The present study shows that the processing of distracting sounds is reduced when more top-down attention is engaged, i.e. in informative trials. More precisely, the reduction was observed at early sensory stages (N1 response, ~ 100 ms) and at later stages (P3 complex, after 200 ms) of sound processing.

The N1 response to unexpected sound is deemed to index a transient detector mechanism (Escera et al. 1998; Berti 2013) that would trigger attention to salient stimuli (Näätänen 1990; Näätänen and Picton 1987; Näätänen and Winkler 1999), i.e. the N1 would index the first stage of bottom-up attention: the detection of the unexpected event. In the present study, the N1 response to distracting sounds was found reduced in informative trials when more top-down attention was engaged in the ongoing task. Increasing perceptual or memory load of the task has been shown to lead to inconsistent effects on the N1 response to task-irrelevant rare unexpected sound in the literature: the N1 amplitude was found enhanced (Zhang et al. 2006), reduced (Miller et al. 2011) or unaffected (SanMiguel et al. 2008). Interestingly, our results are consistent with findings of the only study using rare unexpected environmental sounds not embedded in a stream of standard sounds (Miller et al. 2011), suggesting that top-down attention might differently influence distracting sound processing according to the acoustic context. In agreement with Miller et al. (2011), the present study shows that increasing the

task load results in reduced early processing of task-irrelevant, rare unexpected single distracting sounds.

The P3 response to distractors has been interpreted as reflecting the orienting of attention towards the unexpected stimulus (Lyytinen et al. 1992; Marinkovic et al. 2001; Knight 1996; Barry et al. 2011), and is commonly referred to as the "brain orienting response" (see Friedman et al. 2001; Ranganath and Rainer 2003; Escera et al. 2000; Escera and Corral 2007 for reviews). It was suggested that the larger the P3 the stronger the orientation or capture of attention (Escera et al. 2003; Dominguez-Borras et al. 2008). The P3 reduction to distracting sounds with increasing task load in the present study is consistent with previous works showing that increasing visual perceptual load or working memory load leads to a decrease in amplitude of the P3 to task-irrelevant unexpected sounds (Lv et al. 2010; Miller et al. 2011; SanMiguel et al. 2008; Zhang et al. 2006; Harmony et al. 2000; Restuccia et al. 2005; but see Ruhnau et al. 2010; Muller-Gass and Schroger 2007 for a reverse effect of memory load).

More specifically, in the present study, the early-P3 response around 240 ms after distracting sound onset was found reduced with increasing load, whereas the late-P3 (at 320 ms) was unchanged. The early- and late-P3 were first described by Escera et al. 1998 as subcomponents of the P3 complex evoked by unexpected rare sounds (see Friedman et al. 2001; Polich 2007 for reviews). The early-P3 is maximal centrally and inverts in polarity at posterior and lateral electrodes (Escera et al. 1998; Yago et al. 2003). The late-P3a is maximal frontally with no inversion of polarity at posterior or lateral electrodes, and can also present a parietal subcomponent (Escera et al. 1998; Yago et al. 2003), showing common features with the P3 response to target (target-P3). The respective functional role of these early- and late-P3 responses is still a matter of debate. It has been proposed that the early-P3 would index a novelty detection mechanism (Yago et al. 2003) or would reflect an alerting process governing the direction of the attentional move (Ceponiene et al. 2004). In the late-P3, the frontal subcomponent has been associated with the involuntary orienting of attention towards novel sounds (Yago et al. 2003), whereas the parietal subcomponent could reflect automatic higher-level analysis such as stimulus categorization, context-updating operations, or subsequent memory storage (Friedman et al. 2001; Polich 2007; Sutton et al. 1965). Indeed, this parietal subcomponent seems to appear when attention towards the stimulus increases (e.g. Polich 2007; Holeckova et al. 2006). In this framework, our results suggest that the increase in top-down attentional load can reduce distracting sound processing at early stages, in particular responses indexing transient and novelty detection (N1 and early-P3, respectively), but not bottom-up attentional capture since the

behavioral measures of distraction are not modulated by the attentional load. Therefore, loading more top-down attention would not have reduced early processing of distractors sufficiently to reach a level below the threshold triggering attentional capture, in agreement with the absence of late-P3 modulation by top-down attention. A more complex task recruiting more top-down attention could have resulted in reduction of both the late-P3 and behavioral measure of distraction. Although some studies have questioned the role of the P3 response to distracting events in involuntary attention switching (Schröger et al. 2013; Rinne et al. 2006; Horvath et al. 2008, 2013), the present results provide further arguments for the late-P3 as a signature of involuntary attentional capture.

In the present study, the reduced N1 and early-P3 responses with more top-down attention load could be explained by a reduction in the available cognitive resources because the task is more resource consuming during informative trials as indicated by the enhanced CNV amplitude. This reduction could also result from cognitive control, as suggested by Parmentier and Hebrero (2013). An active top-down inhibition mechanism would be more efficient at reducing processing of competing distractors when the task attentional demand increases. Further studies will be necessary to test whether reduction in distracting sound processing with increased top-down attentional engagement is due to a reduction in resources that can be allocated to the distracting sound or to an active top-down inhibition of any task-irrelevant stimulation.

The reduced N1 and early-P3 responses to the distracting sound with increasing attentional load in informative trials highly suggest that distracting sound processing is less effective when the task at hand requires more top-down attention. However, in the present task, bottom-up attentional capture by these distracting sounds seems to override top-down attention.

Effect of Bottom-Up Attentional Capture by a Distracting Sound on Target Processing

The N1 to targets was found to be delayed as a function of the distracting sound onset time: the later the distractor, the later the N1 to target, suggesting a delayed target processing with shorter interval between distracting and target sound onsets. This latency delay could be explained by a refractoriness effect. Indeed, when two successive sounds are presented, a refractoriness effect is reflected by reduced N1 amplitude with shorter interval between the sound onsets (e.g. Näätänen and Picton 1987; Czigler et al. 1992; Alcaini et al. 1994; Hari et al. 1982; Polich et al. 1988; Davis et al. 1966; Nelson and Lassman 1968; Miltner et al. 1991; Sussman et al. 2008; Imada et al. 1997; Gilley et al. 2005), also observed in the present study. However, to our

knowledge, none of the studies exploring the refractoriness effect found a decrease in N1 latency with increasing time interval between the sounds. Some rather observed the opposite effect (Polich et al. 1988; Alcaini et al. 1994; Miltner et al. 1991). One should keep in mind that a latency effect could be due to an amplitude effect on a sub-component or an overlapping response (see Alcaini et al. 1994 for an example). However the absence of double or smooth peaks in the N1 to targets rather argues for a genuine latency effect.

Nevertheless, the delayed N1 to target shortly after a distracting sound is more likely to be due to the attentional capture process per se. Indeed, with late distracting sounds, the attentional capture is still active at target onset, leaving less available resources to process the targets. The delayed N1 could also be due to the time necessary to move attention from the distracting sound back to the target stimulus (Parmentier et al. 2008; Corral and Escera 2008), this time being longer when the attentional capture is still going on. Delayed N1 to target after a distracting sound is consistent with the inhibition hypothesis proposed by Polich (2007): the P3 response to distractors would reflect an inhibitory process facilitating the processing of those distractors by inhibiting unrelated on-going activities, i.e. target processing. The inhibition process would be stronger shortly after the distracting sound and would decrease with time.

In summary, bottom-up attentional capture by distracting sound would result in delayed target processing and reaction times by reducing the available resources, by requiring time to move attention back to the target and/or by inhibiting target processing.

Conclusion

The present work proposes a new paradigm to measure distractibility and to assess the interaction between top-down and bottom-up mechanisms of auditory attention. This paradigm presents the advantage to place the subject in a setting close to ecological situations in which an isolated unexpected sound outside the attentional focus captures attention. Moreover this protocol takes into account a neglected aspect of the brain response to unexpected salient sound, namely the reaction of the arousal system. Therefore, this novel paradigm provides a good way to behaviorally and neurophysiologically estimate the distraction effect of isolated unexpected sounds, with no or little contamination from change in arousal.

In this framework, on one hand, increasing load in top-down anticipatory attention was found to decrease distracting sound processing at early stages corresponding to transient and novelty detection, but seemed to fail in

protecting from bottom-up attentional capture per se and in reducing the behavioral distraction effect. On the other hand, bottom-up attentional capture by distracting sounds could disturb top-down mechanisms by lengthening target processing and detection.

Therefore, in the present study, bottom-up attentional capture seems to have a stronger influence on the balance between bottom-up and top-down auditory attention, than top-down anticipatory attention. These results provide crucial information into how bottom-up and top-down mechanisms of attention interact and compete in the human brain. Further studies will be necessary to investigate the effect of the arousal level on this balance.

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