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Abstract

The mere presence of task-irrelevant auditory stimuli is known to interfere with cognitive functioning. Disruption can be caused by changing auditory distractors (the changing-state effect) or by a sound that deviates from the auditory background (the deviation effect). The unitary account of auditory distraction explains both phenomena in terms of attentional capture whereas the duplex-mechanism account posits that they reflect two fundamentally different forms of distraction in which only the deviation effect is caused by attentional capture. To test these predictions, we exploited a physiological index of attention orienting: the pupillary dilation response (PDR). Participants performed visual serial recall while ignoring sequences of spoken letters. These sequences either comprised repeated or changing letters, and one letter could sometimes be replaced by pink noise (the deviant). Recall was poorer in both changing-state and deviant trials. Interestingly, the PDR was elicited by deviant sounds but not changing-state sounds. This physiological dissociation of the changing-state and the deviation effects suggests they are subtended by distinct mechanisms thereby procuring support for the duplex-mechanism account over the unitary account.

Keywords: Auditory distraction; Pupillometry; Irrelevant sound; Attention capture; Interference-by-process

Is Auditory Distraction by Changing-State and Deviant Sounds Underpinned by the Same Mechanism? Evidence from Pupillometry

The presence of task-irrelevant stimuli in the environment can disrupt performance on an ongoing cognitive task. Such sensitivity to irrelevant stimuli is a consequence of the balance that must constantly be maintained between focusability and permeability (Allport, 1989; Hughes & Jones, 2003a). More specifically, selection of task-relevant stimuli in our environment must be balanced against the need to remain open to other stimuli that may be relevant, whether they are considered as such because of task-related goals (contingent on attentional set; e.g., Folk, Remington, & Johnston, 1992) or because of their characteristics (stimulus-driven; e.g., Theeuwes, 1994). Given that some unattended auditory information is obligatorily processed for this purpose (e.g., Hughes & Jones, 2003a), one's performance on a concurrent cognitive task can be impaired by irrelevant extraneous sound. Such auditory distraction can even be caused when, for instance, one is concentrating only on the focal task while trying to ignore the irrelevant sound stream. The present study aims to investigate whether the two types of auditory distraction—the deviation effect, produced by a sound deviating from the auditory context, and the changing-state effect, produced by a sequence of changing as compared with nonchanging auditory tokens—are underpinned by common, or different, mechanisms.

Literature on auditory distraction mainly points toward two modes through which irrelevant sounds can disrupt performance. The first form of auditory distraction, called the *deviation effect*, is caused by the unexpected presence of a rare sound that diverges from the auditory environment in which it is embedded (e.g., A A A A A A *B* A). This effect, as has been shown in many studies, occurs when participant's performance on a concurrent visual task is impaired by the presentation of a deviant sound (e.g., Hughes, Vachon, & Jones, 2007; Lange, 2005; Marsh, Röer, Bell, & Buchner, 2014; Muller-Gass, Macdonald, Schröger, Sculthorpe, & Campbell, 2007; Parmentier, 2008; Sörqvist, 2010; Vachon, Labonté, & Marsh, 2017). Several studies have also highlighted another form of auditory distraction, the *changing-state effect*, whereby the presence of to-be-ignored (TBI) sequences of sounds that change acoustically from one another (e.g., B H P C Q W L T) are invariably more disruptive to serial short-term memory than an auditory sequence within which a single stimulus is repeated (e.g., A A A A A A A A)[1]. This phenomenon has widely been demonstrated within a setting in which participants are required to perform a visual serial recall task. Herein, participants are instructed to attempt to recall a list of sequential, visually-presented digits in their order of presentation (e.g., Beaman & Jones, 1997; Bell, Dentale, Buchner, & Mayr, 2010; Hughes et al., 2007; Jones & Macken, 1993; Sörqvist, 2010). However, there are conflicting theoretical explanations of the deviation effect and the changing-state effect. Two main theoretical positions have been proposed to explain how these effects arise: the unitary account and the duplex-mechanism account. Despite their agreement on the origin of the deviation effect, both theories differ on the cause of the changing-state effect.

[1] It may be worth specifying that the changing-state effect can sometimes be studied in terms of a more simple "acoustic changing-state effect" by using changing, unrelated auditory stimuli as distractors (e.g., TBI letters, nouns, or digits), but also in terms of a "complex changing-state effect" whereby meaningful sentences or speech (presented in a participant's first language) are typically used as distractors. It could hence be argued that a potential confound between meaning and acoustics is present while referring to the changing-state effect regardless of the nature of the distractor. However, Jones and Macken (1993) showed that serial recall performance was similarly disrupted for participants exposed to TBI changing tones and to TBI speech (see also Tremblay, Nicholls, Alford, & Jones, 2000, who observed no difference between TBI sine wave sound perceived as speech or nonspeech). Given that the content of the auditory distractors seems to play a minor role in determining performance disruption by changing sound, we refer here to the changing-state effect without differentiating between its acoustic, simpler, and semantic, complex counterparts.

Explanatory Models of the Changing-State and Deviation Effects

The *unitary account*, based on the embedded-processes model of Cowan (1995, 1999), posits that both changing-state and deviation effects are caused by a single mechanism of attentional capture (e.g., Bell, Dentale, Buchner, & Mayr, 2010; Bell, Röer, Dentale, & Buchner, 2012; Chein & Fiez, 2010; Cowan, 1995; Elliott, 2002; Rinne, Särkkä, Degerman, Schröger, & Alho, 2006). When a new sound (either deviant or changing) is presented in the irrelevant auditory stream, an exogenous orienting of the attentional focus toward that auditory stimulus is produced. Given that attention has been removed from the prevailing mental activity, performance on the task is disrupted. The unitary account assumes that such an attentional response is caused by the detection of a sound that mismatches characteristics registered in a so-called neuronal model (cf. Sokolov, 1963) representing an aggregation of the stimulus sequence or a prototypical representation of the sounds previously presented (see Hughes, Vachon, & Jones, 2005). More specifically, physical characteristics of the auditory environment are automatically registered in the neuronal model and when the acoustical features of an incoming sound do not match those registered in the neuronal model (i.e. when there is no neuronal model corresponding to the capturing stimulus; see Näätänen, 1990, and Öhman, 1979), a call for attention is elicited and attention is reoriented toward that mismatching event. Presenting a deviant sound within a steady-state auditory sequence (e.g., A A A A A A *B* A) produces attention orienting as the deviant differs from the preceding sounds and, therefore, is not represented in the neuronal model. Likewise, a series of changing sounds (e.g., A B C D E F G H) repetitively captures attention given that each item deviates from the aggregate-based neuronal model of the stimuli making up the sequence produced by each of its predecessor(s).

Hence, the unitary account considers that changing and deviant sounds are equivalent as they produce similar attentional responses. Consequently, studies supporting the unitary account report functional similarities between both auditory distraction effects. For instance, it has been shown that the deviation effect can show habituation—or decrease—as deviant sounds are presented (e.g., Cowan, 1995; Sörqvist, 2010; Vachon, Hughes, & Jones, 2012). Such habituation is assumed to take place because the characteristics of the deviant sound are embedded into the neuronal model through its previous presentation(s). Bell, Röer, Dentale, and Buchner (2012) have shown that the changing-state effect can also habituate following a preexposure phase to the irrelevant sound prior to the serial recall task in which the distractors were also presented (see also Banbury & Berry, 1997; Röer, Bell, & Buchner, 2014; but see Jones, Macken, & Mosdell, 1997; Tremblay & Jones, 1998). Given that such habituation represents a decrease in the attentional response triggered by the sounds, the authors suggested that this supports the assertion that both effects are underpinned by a common attentional-capture mechanism.

Conversely, according to the *duplex-mechanism account* of auditory distraction (Hughes, 2014; Hughes et al., 2005, 2007; Sörqvist, 2010), the deviation and changing-state effects are subtended by distinct mechanisms. This account also explains the deviation effect in terms of attentional capture, but through a different conceptualization of the neuronal model than the unitary account. From this standpoint, the neuronal model instead describes the rules underlying any structure or pattern in the unfolding auditory stimulation (e.g., Bendixen, Roeber, & Schröger, 2007; Vachon et al., 2012; Winkler, Denham, & Nelken, 2009). Attentional capture is then caused by a violation of the implicit predictions—or expectancies—extrapolated from those regularities. Hence, the key for attention to be captured is not the absence of a memory—or neuronal model—for the deviant sound (as in the unitary account), but rather the presence of a memory for a pattern of sounds in which the deviant does not fit. Thus, in a sequence such as *A X N B D R L E* (all spoken in the same voice and presented at a regular pace), the identity of each letter cannot be predicted from the history of previous stimuli. However, none of the stimuli in such a sequence—just as is the case in a steady-state sequence—is a deviant given that none violate predictions that can be derived from the sequence. In fact, each stimulus conforms to, for example, the predictions that each item of the auditory stream will be in the same voice, will be a letter, will be presented after a gap of x ms, will differ from the preceding sound, and so forth; hence, none of the stimuli would capture attention. From this standpoint, the deviation effect is thus driven by an algorithm-based neuronal model representing any rule or pattern that can be extracted from the auditory environment instead of an aggregate of the acoustical characteristics of recently encountered auditory events.

Given that constant—hence predictable—changes in the auditory stream do not capture attention (Hughes et al., 2007; Max, Widmann, Schröger, & Sussman, 2015; Vachon et al., 2012), the duplex-mechanism account attributes the changing-state effect to an origin different to that of the deviation effect. In fact, this account assumes that performance impairment by changing sounds results from an automatic conflict between the obligatory—yet involuntary—processing of order in the TBI sound and the deliberate ordering of the relevant (visual) material (Jones, Alford, Bridges, Tremblay, & Macken, 1999; Jones & Macken, 1993; Jones & Tremblay, 2000; Macken, Phelps, & Jones, 2009). More specifically, the account argues that the auditory input is preattentively organized into a perceptual stream (see Bregman, 1990) that extracts order information from the sound sequence. It is the presence of segmentable, acoustically changing, elements that gives rise to cues pertaining to the order of the sounds (e.g., Jones, Macken, &

Murray, 1993); order cues are thus impoverished in steady-state sequences. This extraneous order information interferes with the seriation processes involved in the retention of stimuli in serial order. Hence, this interference-by-process form of distraction is held to be the result of a competition-for-action between two processes that both involve the processing of the order of events, one being intentional, the other being automatic and ineluctable (see also Macken, Tremblay, Alford, & Jones, 1999).

Since the duplex-mechanism account posits that both distraction effects are explained by different mechanisms, studies supporting this theory report how the changing-state and deviation effects differ. For example, many studies have shown that the deviation effect can be observed on a wide range of cognitive tasks, including serial recall (e.g., Hughes et al., 2007; Sörqvist, 2010), continuous visual tracking (e.g., Muller-Gass et al., 2007), the missing item task (e.g., Hughes et al., 2007; Vachon et al., 2017) and speeded discrimination judgements (e.g., Parmentier, 2008). On the contrary, the changing-state effect tends only to emerge when seriation is a key component of the focal task. For instance, the changing-state effect has been observed for serial recall (e.g., Beaman & Jones, 1997; Hughes et al., 2007; Kattner & Ellermeier, 2018) and visual statistical learning tasks (Neath, Guérard, Jalbert, & Surprenant, 2009). However, Beaman and Jones (1997; see also Hughes et al., 2007; Kattner & Ellermeier, 2018) failed to find a changing-state effect when participants undertook the missing-item task, a task in which seriation is not the dominant mnemonic strategy (Morrison, Rosenbaum, Fair, & Chein, 2016). Given that seriation processes seem to be necessary for the changing-state effect to occur, proponents of the duplex-mechanism account suggest that this latter effect is caused by order-based processes that are independent of the attentional—and nonserial—processes underpinning the deviation effect.

Given that what distinguishes the unitary and duplex-mechanism accounts is whether the changing-state effect is underlain by attentional capture or not, one way to tease these models apart is to exploit physiological indices of attention capture. Indeed, the attentional response to auditory stimuli has been linked to various physiological reactions, notably to the event-related potentials (ERPs). Presenting a deviant sound that triggers attentional capture has been shown to elicit three particular ERPs (see, e.g., Horváth, Winkler, & Bendixen, 2008). A N1 can first be observed, representing preattentional perceptual processing of the sound (e.g., Näätänen, 1990). This ERP is usually followed by the mismatch negativity (MMN), elicited when a deviance in the auditory stream is detected (Näätänen, Gaillard, & Mäntysalo, 1978). The MMN is known to reflect a preattentive process responsible for preparing the organism for further processing of the deviant stimulus through attentional orienting (e.g., Näätänen, 1990; Winkler, 2007). When this "call for attention" from the MMN is answered, a P3a response—reflexive of the actual attentional response to the deviant sound—is then triggered (e.g., Escera, Alho, Schröger, & Winkler, 2000; Escera, Alho, Winkler, & Näätänen, 1998; Friedman, Cycowicz, & Gaeta, 2001; Squires, Squires, & Hillyard, 1975). Campbell, Winkler, and Kujala (2007) measured ERPs while participants were exposed to deviant and changing sounds as they performed the serial recall task. Their results showed that, compared with repeated sounds, changing and deviant sounds both produced a significant N1 and that this N1 was superior for changing sounds (see also Campbell, Winkler, Kujala, & Näätänen, 2003). However, only deviant sounds produced a significant MMN, which is consistent with the duplex-mechanism account on which only the deviation effect is related to expectancy and regularity violation. However, Bell and colleagues (2010) obtained conflicting results to those reported by Campbell et al. (2007) in relation to changing sounds. Indeed, their results showed that changing stimuli, in comparison with steady-state repeated sounds, not only yielded a larger N1 but also elicited a P3a. Such demonstration of a change-elicited P3a suggested to the authors that changing sounds produced attention orienting, in line with the predictions of the unitary account of auditory distraction.

The Current Study

Considering the incongruence in empirical evidence, the question as to whether the changing-state and the deviation effects are both of attentional nature remains unanswered. To address this issue, the current study aimed to test whether the deviation and changing-state effects are underpinned by common attentional processes by measuring the psychophysiological attentional response produced by both irrelevant changing and deviant sounds presented while participants performed a visual serial recall task. Instead of relying on ERPs, the present study used the pupillary dilation response (PDR) to index the sound-evoked attentional response. By now there is convincing evidence that the PDR—a phasic (rapid) dilation of the pupil diameter—can be used as a proxy for auditory attentional capture (Liao, Yoneya, Kidani, Kashino, & Furukawa, 2016; Marois, Labonté, Parent, & Vachon, 2018; Marois & Vachon, 2018; Nieuwenhuis, De Geus, & Aston-Jones, 2011; Wang & Munoz, 2015; Wetzel, Buttelmann, Schieler, & Widmann, 2016). Notwithstanding the pupil sensitivity to environmental visual factors (e.g., Tryon, 1975), the PDR can also serve such a purpose while visual serial recall is being executed despite the systematic variations in the pupillometric signal attributable to focal changes in luminance produced by the appearance and disappearance of the visual stimuli (cf. Marois & Vachon, 2018). Given that ERP experiments seem to generate inconsistent results, using the PDR to address the difference between the changing-state and deviation effects represents an innovative and promising method that could provide further support for either the unitary or the duplex-mechanism account.

According to Körner, Röer, Buchner, and Bell (2017), very few comparisons of the deviation and changing-state effects have been made within the same experiment:

> A recurring problem is that the arguments in favor of a dissociation of the changing-state effect and the deviation effect more often than not rely on comparisons across different experimental setups that do not allow one to compare the two phenomena directly. This is not ideal for drawing conclusions because dissociations might have been produced by methodological differences between experiments rather than by differences between the changing-state effect and the deviation effect per se (p. 123).

The absence of consensus regarding the mechanisms underlying the deviation and changing-state effects may partly arise from this methodological concern. While only a few studies have investigated the deviation and changing-state effects within the same study, most of them investigated each phenomenon either in independent experiments or in independent blocks of trials (e.g., Campbell et al., 2007; Körner et al., 2017; Körner, Röer, Buchner, & Bell, 2018). To our knowledge, only Hughes and colleagues (2005, 2007) presented both deviant and changing sounds within the same block of trials in a random manner, allowing an assessment of the interaction between deviant and changing-state distractors.

Following Hughes and colleagues' (2005, 2007) approach, we propose a systematic examination of both deviation and changing-state effects whereby deviant sounds could be embedded in both steady-state and changing-state auditory sequences. In the current study, participants performed a visual serial recall task while being exposed to TBI auditory sequences. These irrelevant sequences were composed of either steady-state (SS) or changing-state (CS) spoken items, in which a deviant item (a pink noise) could sometimes be inserted (SS+d and CS+d). Using the PDR, we sought to verify whether both changing and deviant sounds are endowed with the power to trigger an attentional response. Our goal was not to determine whether the pupil reaction to deviant and changing sounds is equivalent, but rather to test whether these two types of distractors can actually elicit a PDR. According to the unitary account, each deviant and changing sound captures attention. Therefore, this account predicts that a significant PDR should be elicited by the deviant sound of SS+d and CS+d trials as well as by all sounds but the first of a changing-state sequence (i.e. in CS and CS+d trials) given that the first presentation of a sound different from its predecessor would first occur at the second position. From the duplex-mechanism standpoint, however, attention capture is restricted to auditory deviation. Thus, this account predicts that only deviant sounds should trigger a significant PDR. This means that changing sounds should not differ from repeated (or steady-state) sounds—when they do not contain a deviant, in SS and CS trials—regarding their impact on the sound-evoked phasic PDR[2].

The insertion of a deviant item in both steady-state and changing-state sequences confers an additional theoretical advantage beyond independently studying the “pure” changing-state and deviation effects: it allows further testing of the distinct predictions of the two distraction accounts at the behavioral level (cf. Hughes et al., 2005, 2007). Whereas both accounts expect the classical changing-state effect to take place (a changing-state sequence should produce more disruption to serial recall than a steady-state sequence), they make different predictions with

[2] One could contend that these predictions regarding the PDR are incorrect as the first sound of the auditory sequence should elicit attention orienting. From a unitary account standpoint, this sound captures attention because its characteristics differ from those registered in the neuronal model, associated with quietness. From the duplex-mechanism account perspective, the nature of the sound presented at the beginning of a trial is unpredictable, which should also trigger an attentional response (even if its presentation per se is predictable). This orienting response (OR) to the initial stimulus (initial OR) has been shown to be different in nature from that triggered by a change in the auditory environment (change OR; Näätänen & Gaillard, 1983; see also Kenemans, Verbaten, Roelofs, & Slangen, 1989; Steiner & Barry, 2011). In the present study, we are concerned by what has mainly been described as the change OR, that is attention orienting elicited by a “change” (or a deviant event) within the auditory stream. Besides, Vachon et al. (2012) showed that behavioral performance is disrupted by the change OR but not by the initial OR.

regard to the modulatory effect of sequence context on the disruptive impact of a deviant sound. According to the unitary account, changing-state sounds repetitively attract attention by virtue of the fact that each sound is discrepant from the neuronal model of its predecessor(s). Therefore, the introduction of another attention-capturing sound (here, a deviant) within a changing-state sequence should have little, if any, additional disruptive impact on serial recall compared to a sequence of repeated sounds that do not already divert attention away from the focal task. Consequently, the unitary account predicts an interaction between the changing-state effect and the deviation effect by which the latter would be larger in the context of a steady-state sequence than a changing-state sequence. From the perspective of the duplex-mechanism account, the deviant sound is the first and only event of the auditory sequence to have the power to capture attention. In this case, presenting an attention-capturing, deviant item should have roughly the same impact on recall whether it occurs within a steady-state or changing-state sequence. Thus, the duplex-mechanism account predicts that the deviation effect should be additive to the changing-state effect.

Method

Participants

Thirty-four students from Université Laval, Canada (19 females) with a mean age of 26.0 years (*SD* = 4.9) volunteered to take part in this experiment in return of a small monetary compensation. All reported having normal or corrected-to-normal vision and hearing and having no diagnosed neurological disease. No participants reported having used psychoactive substances up to 12 hours pre-experiment, as well as having consumed coffee, tea, or tobacco products up to 6 hours before the experiment as this could impact the baseline pupil diameter (Abokyi, Owusu-Mensah, & Osei, 2017; Lie & Domino, 1999).

Apparatus and Material

The experiment was conducted in a dimly-lit room on a PC computer running an E-Prime 2.0 (Psychology Software Tools) program used to present the instructions, control the presentation of the auditory and visual stimuli, and record participants' responses. Measures of the pupil diameter were garnered binocularly at 120 Hz using a Tobii TX300 eye tracker (Tobii Technologies). Participants were seated approximately 60 cm from the monitor on which the eye tracker was mounted.

Focal task. Participants were asked to perform a visual serial recall task. Following the brief presentation of a fixation cross, a series of eight to-be-remembered (TBR) digits (from the 2-to-9 set) was displayed at the center of the monitor (see Figure 1). Each digit was presented for 350 ms in a Times New Roman 48 bold font and the interstimulus interval (ISI; from the offset of a digit to the onset of the next one) was 400 ms. Once all eight TBR stimuli were presented, they were all simultaneously re-displayed in ascending order next to the others in bold Times New Roman 24-point font. Participants were required to select the digits according to their presentation order using a computer-driven mouse.

Irrelevant auditory sequences. The auditory sequences presented while participants performed the focal task were comprised of ten 250-ms letters with an ISI of 350 ms, starting in synchronicity with the list of TBR items (see Figure 1). These TBI sequences were edited with SoundForge (Sony Creative Software). In SS trials, the sequence was composed of ten repetitions of the letter *B* spoken in a male voice. In CS trials, the sequence was composed of ten different letters (from the set B, F, H, K, L, M, Q, R, X, Z), presented in a random order, also spoken in a male voice. For SS and CS trials in which a deviant sound was embedded—namely SS+d and CS+d—the sound presented at the sixth position was replaced with a 250-ms pink noise, that is a pure sound with a power spectral density inversely proportional to the frequency of the signal. Pink noise was chosen as the deviant sound because it possesses no particular semantic information and is known to be potent at capturing attention (see Wetzel et al., 2016). Characteristics of the other sounds in SS+d and CS+d trials were identical to that of their counterpart non-deviant trials (SS and CS trials, respectively).

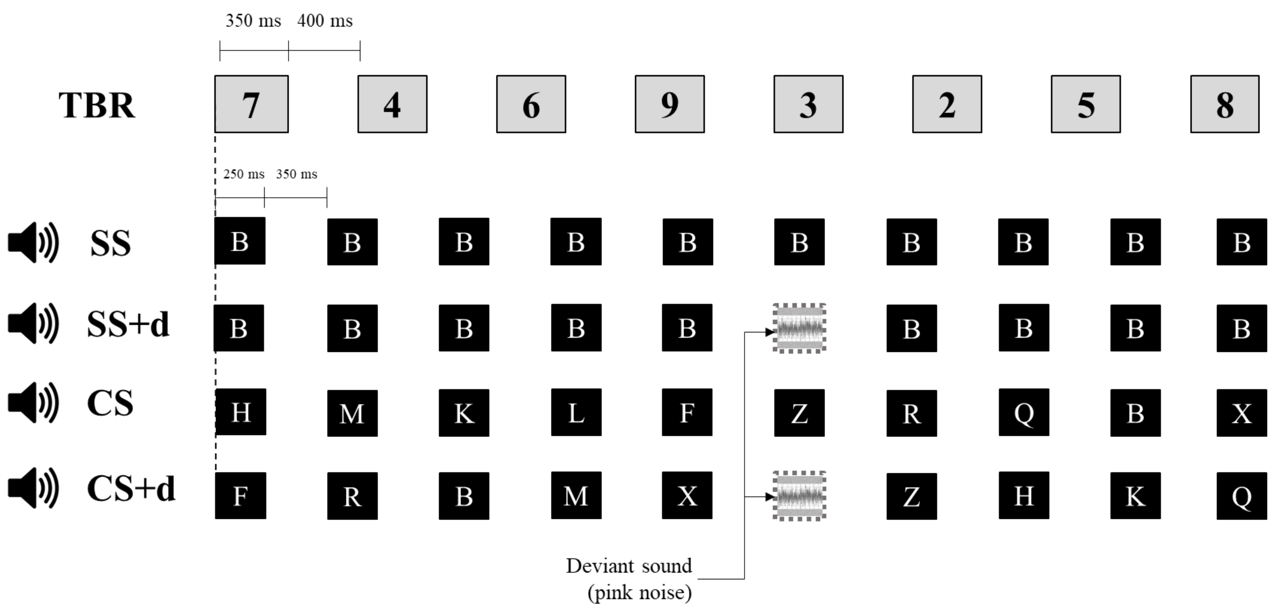

Figure 1. Schematic illustration of the stimuli used in the visual serial recall task performed by participants. A visual sequence of eight to-be-remembered (TBR) digits was presented concurrently to to-be-ignored auditory sequences composed of 10 sounds. These auditory sequences either comprised steady-state (SS) repeated sounds (the letter *B*) or changing sounds (CS; the letters *B*, *F*, *H*, *K*, *L*, *M*, *Q*, *R*, *X*, *Z*) presented in a random order. The sound presented at the sixth position in deviant trials (SS+d and CS+d) was replaced by a pink noise, whereas every other sound remained equivalent to SS and CS trials.

Procedure

Participants were first asked to provide informed consent and to complete a brief sociodemographic survey. The eye tracker used to measure participants' eye movements was then calibrated for each participant. Afterwards, participants were given the instructions regarding the visual serial recall task. In each trial, eight TBR digits were sequentially presented and, after presentation of the last stimulus, they reappeared horizontally and had to be selected in their presentation order. Once selected, a digit turned green and could not be unselected. Following selection of all digits, the next trial began automatically. Auditory sequences were simultaneously presented through headphones and participants were instructed that they were irrelevant to the task. The experimental session consisted of 120 trials, separated into two 60-trial counterbalanced blocks. Each block comprised 25 SS trials, 25 CS trials, five SS+d trials and five CS+d trials. These types of trials were distributed quasi-randomly with the constraint that two SS+d or CS+d trials could not be presented sequentially. Once participants had completed the task, they received their monetary compensation and were thanked for their participation.

Analyses

Four participants were removed from the analyses because they did not comply with, or misunderstood, the task instructions. Data for the remaining 30 participants was analyzed. Inferential analyses of both behavioral and physiological data were performed by using null-hypothesis significance tests and Bayesian factor analysis. This latter analysis followed Masson's (2011) procedure by providing Bayesian posterior probabilities regarding the null hypothesis given the set of data, namely p_{BIC} (H_0|D). Posterior probabilities of .50 to .75, .75 to .95, .95 to .99 and larger than .99 were respectively associated with weak, positive, strong and very strong evidence for the null hypothesis (see Raftery, 1995). Posterior probabilities of .50 to .25, .25 to .05, .05 to .01 and smaller than .01 were rather associated with weak, positive, strong and very strong evidence against the null hypothesis, respectively.

Behavioral performance. For each type of trial, performance on the visual serial recall task was defined as the percentage of the correctly recalled digits, i.e. recalled in the serial position in which they had previously been presented. Performance was compared between each type of trials, that is between SS, SS+d, CS and CS+d trials. Such comparison was performed using a repeated-measure analysis of variance (ANOVA) with the factors State (steady vs. changing), Deviation (deviant vs. no deviant) and Serial Position (Positions 1 to 8). When the sphericity assumption of the within-participant effects was violated, the Greenhouse-Geisser procedure was applied.

Pupillometry and preprocessing. Raw pupil data were epoched from 200 ms before the beginning of each trial to 2,000 ms after the presentation of the last TBR digit. An average of the pupil diameter of both eyes was computed to obtain a single measure. Raw pupillary data that were not rated as perfectly valid by the eye tracker software were removed. Withdrawn data and missing measures caused by the eye tracker malfunctions or blinks were linearly interpolated using MATLAB (MathWorks). Pupillary measures were low-pass filtered using a cutoff frequency of 10 Hz, with a maximum attenuation in passband of 1 dB and a minimum attenuation in stopband of 40 dB. Finally, epochs comprising more than 50% of interpolated data were removed (see Marois et al., 2018). Overall, an average of 3.7% of the trials were excluded from the analyses.

Data extraction. Analyses of the sound-evoked PDRs were based on the method employed by Marois and Vachon (2018; see also Liao et al., 2016). The averaged pupillometric waveforms of the four conditions (SS, CS, SS+d and CS+d) were computed. The attentional response produced by the deviant sounds, presented 3,000 ms after the beginning of the trial, was isolated by subtracting the pupillometric waveforms on SS and CS trials from that on SS+d and CS+d trials, respectively. The magnitude of the PDRs was then quantified as the mean amplitude of the difference waves over the 500-2,000-ms post-deviant time window from which a 200-ms baseline value was subtracted. These PDRs were then compared to zero by using one-sample *t*-

tests. The deviant-elicited PDRs triggered in SS trials and CS trials were also compared using a paired-samples *t*-test. Such analysis aimed at assessing whether the deviant-no deviant difference was similar regardless of whether steady-state repeated sounds or changing sounds were presented.

Similar analyses were performed to isolate the PDR produced by changing sounds. This response was isolated by subtracting the pupillometric waveforms on SS and SS+d trials from that on CS and CS+d trials, respectively. An average of the PDRs triggered by the second to the tenth and final sound presented in the irrelevant auditory stream was measured by computing, for each sound, the mean amplitude of the difference waves over the 500-2,000-ms post-sound time window from which a baseline-correction was performed. The first changing sound was excluded from the analysis given that the difference between CS and SS conditions, that is the presentation of a different sound than the preceding one, occurred at the second sound.

Results

Behavioral Performance

Figure 2 shows the mean percentage of items correctly recalled in the four types of trials (SS, CS, SS+d and CS+d) across the eight serial positions. The repeated-measures ANOVA performed on these data revealed a significant main effect of State, $F(1, 29) = 37.27$, $p < .001$, $\eta^2_p = .57$, Bayes factors (BF) = 2.28×10^{-5}, p_{BIC} (H_0|D) < .001, which indicated that recall was significantly poorer in CS conditions than in SS conditions, confirming the presence a changing-state effect. The significant main effect of Deviation, $F(1, 29) = 7.31$, $p = .011$, $\eta^2_p = .20$, BF = 0.18, p_{BIC} (H_0|D) = .158, established the presence of a deviation effect: serial recall was impaired in the presence of a deviant sound. The main effect of Serial Position was also significant, $F(7, 203) = 56.35$, $p < .001$, $\eta^2_p = .66$. More importantly, the interaction between State and Deviation was not significant, $F(1, 29) = 0.29$, $p = .866$, $\eta^2_p < .01$, BF = 5.40, p_{BIC} ($H_0|D$) = .844, suggesting that the magnitude of the deviation effect was not affected by the context in which the deviant was embedded. All remaining interactions (involving Serial Position) failed to reach significance, $Fs(7, 203) < 1.78$, $ps > .134$, $\eta^2_p < .06$.

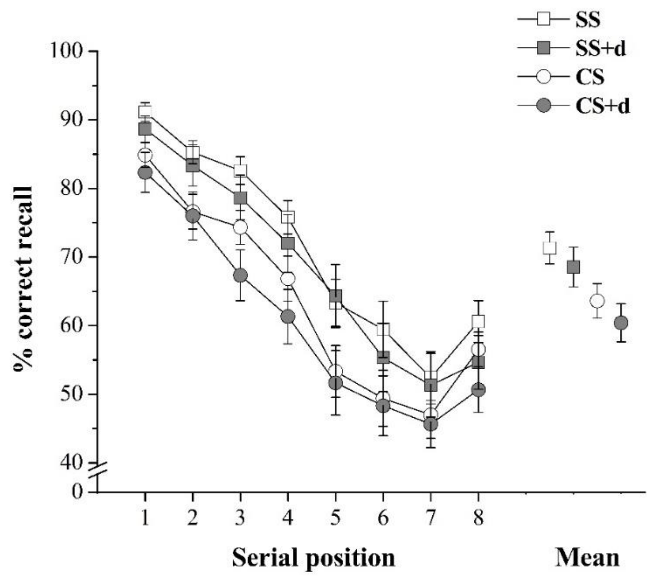

Figure 2. Mean percentage of items correctly recalled in each serial position in steady-state (SS), steady-state + deviant (SS+d), changing-state (CS) and changing-state + deviant (CS+d) trials. Error bars represent the standard error of the mean.

Pupillometry

Figure 3 displays the variation in the pupil diameter averaged for each type of trial as participants performed the visual serial recall task. Consistent with the observation of Marois and Vachon (2018), the pupil size enlarged as the visual sequence of the serial recall task unfolded. Moreover, the eight "ups" and "downs" observed for each type of trial in the pupillometric signal corresponded to the appearance and disappearance of each TBR visual digit. This likely represents the light reflex (e.g., Tryon, 1975), that is the automatic increase and decrease of the aperture of the pupil following darker and lighter visual stimulations, respectively (see also Marois & Vachon, 2018).

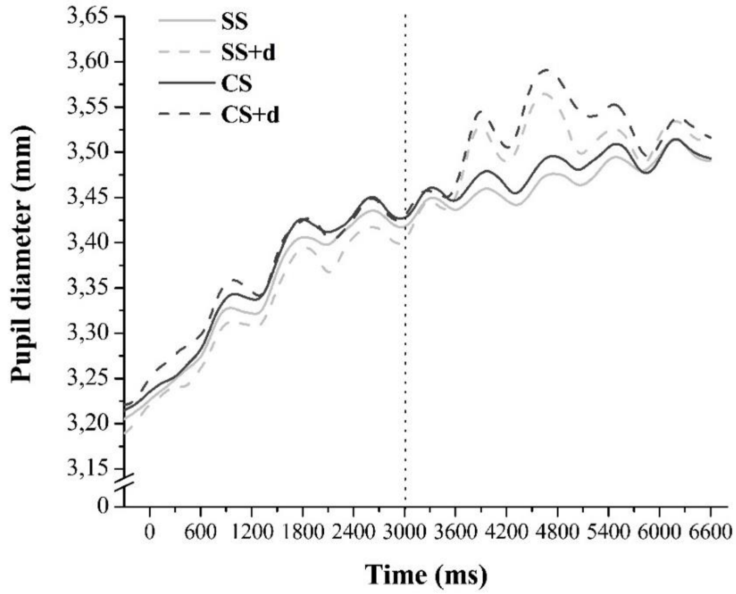

Figure 3. Variation of the mean pupil diameter (in mm) as a function of time (in ms) for all types of trials. Time 0 represents the onset of the first to-be-remembered item and to-be-ignored sound. The stimulus onset asynchrony of the to-be-ignored sounds was 600 ms. The dashed line (3,000 ms) represents the onset of the sixth sound, which corresponds to the deviant sound in deviant trials (SS+d and CS+d).

Interestingly, the global pupil diameter was larger for trials that included changing sounds compared with trials that contained repeated sounds. Based on the method employed by Marois et al. (2018), we analyzed the mean pupil diameter measured throughout the whole trial for each type of trial. The mean pupil size was 3.41 mm (*SD* = 0.41) in SS trials, 3.42 mm (*SD* = 0.41) in SS+d trials, 3.42 mm (*SD* = 0.42) in CS trials and 3.45 mm (*SD* = 0.41) in CS+d trials. A repeated-measures ANOVA with the factors State (steady-state vs. changing-state) and Deviation (deviant vs. no deviant) revealed a significant main effect of State, $F(1, 29) = 9.51$, $p = .004$, $\eta^2_p = .25$, BF = 0.08, p_{BIC} (H_0|D) = .075, but neither a main effect of Deviation, $F(1, 29) = 3.40$, $p = .076$, $\eta^2_p = .11$, BF = 1.05, p_{BIC} (H_0|D) = .513, nor a two-way interaction between State and Deviation, $F(1, 29) = 2.97$, $p = .095$, $\eta^2_p = .09$, BF = 1.03, p_{BIC} (H_0|D) = .508.

Deviant-elicited PDRs. The deviant-control differences in pupil size for trials that comprised steady-state sounds (SS+d minus SS) and changing-state sounds (CS+d minus CS), averaged across all participants, are presented in Figure 4A. Presenting a deviant sound within a series of repeated or changing sounds produced a dilation of the pupil diameter. This was confirmed by one sample *t*-tests showing that the deviant-elicited PDR in steady-state trials (M = 0.08 mm, SD = 0.05) and in changing-state trials (M = 0.07 mm, SD = 0.06) both differed significantly from zero, $t(29) = 8.71$, $p < .001$, Cohen's $d = 1.59$, BF = 1.64×10^{-7}, p_{BIC} (H_0|D) < .001, and $t(29) = 5.98$, $p < .001$, Cohen's $d = 1.09$, BF = 7.11×10^{-5}, p_{BIC} (H_0|D) < .001, respectively (see Figure 4B). Both deviant-elicited PDRs were also compared. Using a paired-samples *t*-test, we showed that the amplitude of the deviant-elicited PDRs in both steady-state and changing-state trials did not significantly differ from one another, $t(29) = 1.17$, $p = .250$, Cohen's $d = 0.21$, BF = 2.09, p_{BIC} (H_0|D) = .677.

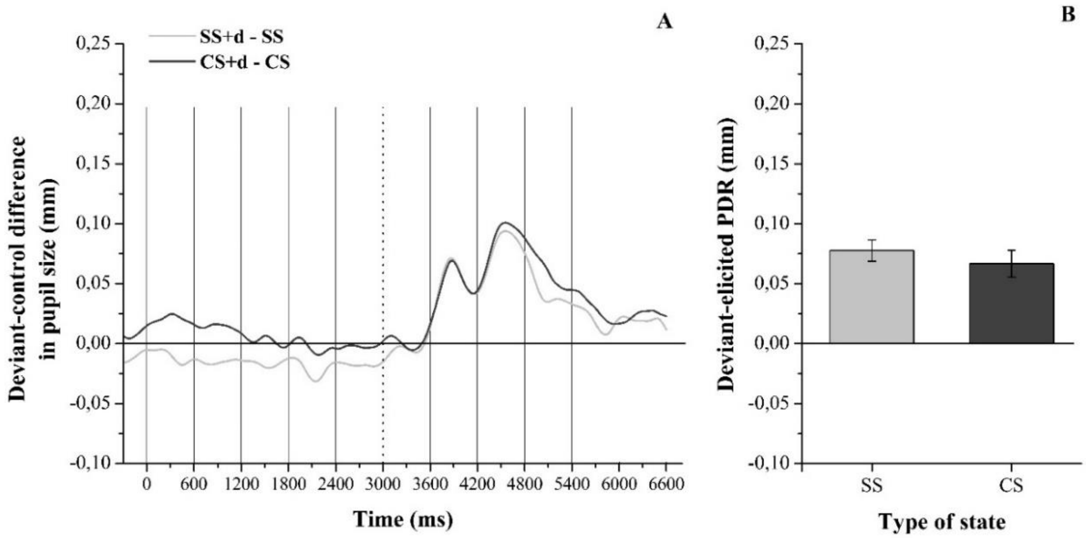

Figure 4. (A) Averaged deviant-control difference in pupil size (in mm) as a function of time (in ms). Time 0 represents the onset of the first to-be-remembered item and to-be-ignored sound. The stimulus onset asynchrony of the to-be-ignored sounds was 600 ms. The dashed line corresponds to the onset of the deviant sound whereas the solid lines represent the onset of the standard sounds (either repeated, in SS and SS+d trials, or changing, in CS and CS+d trials). (B) Mean baseline-corrected deviant-elicited PDRs (in mm) as a function of State (either steady or changing). Error bars represent the standard error of the mean.

Change-elicited PDRs. The CS-SS differences in pupil size for trials that comprised no deviant (CS minus SS) or a deviant (CS+d minus SS+d), averaged across all participants, are presented in Figure 5A. An average of the change-elicited PDRs produced by Sounds 2 to 10 was computed. The mean amplitude of the baseline-corrected PDRs for these sounds for each deviation type of trial (either deviant or no deviant) are displayed in Figure 5B. Presenting changing sounds did not seem to elicit significant dilation in the pupil diameter, and even triggered slight pupil constrictions (i.e. negative PDRs). To test this, one sample *t*-tests were carried out for each deviation type of trial on the mean change-elicited PDRs. These tests showed that change-elicited PDRs in trials that included no deviant (*M* = -0.003 mm, *SD* = 0.01) or a deviant (*M* = -0.008 mm, *SD* = 0.03) did not differ significantly from zero , $t(29) = -1.43$, $p = .162$, Cohen's $d = -0.26$, BF = 1.54, p_{BIC} (H_0|D) = .606, and $t(29) = -1.56$, $p = .130$, Cohen's $d = -0.28$, BF = 1.29, p_{BIC} (H_0|D) = .564, respectively.

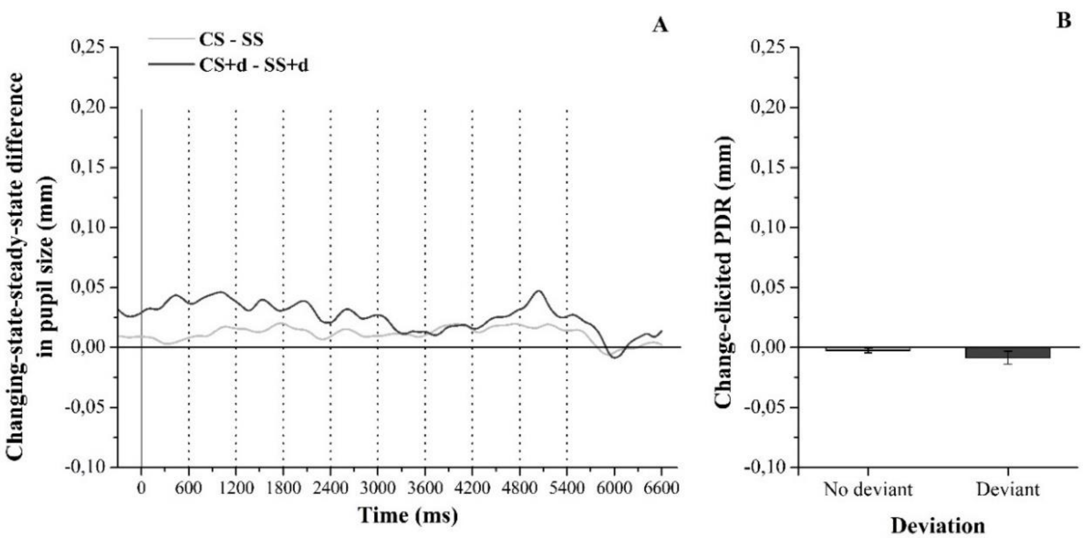

Figure 5. (A) Averaged changing-state-steady-state difference in pupil size (in mm) as a function of time (in ms). Time 0 represents the onset of the first to-be-remembered item and to-be-ignored sound. The stimulus onset asynchrony of the to-be-ignored sounds was 600 ms. The dashed lines correspond to the onset of the changing sounds included in the change-elicited mean PDR (Sounds 2 to 10) whereas the solid line represent the onset of the first sound. (B) Mean baseline-corrected change-elicited PDRs (in mm) as a function of the type of deviation trial (either no deviant or deviant) averaged across Sounds 2 to 10. Error bars represent the standard error of the mean.

In the present experiment, we measured the PDR—which usually peaks between 0.5 and 1 s post-stimulus (e.g., Andreassi, 2007; Lowenstein & Loewenfeld, 1962)—to sounds with a stimulus onset asynchrony of 600 ms. This means that when elicited, a PDR is likely to impact the pupillometric signal associated with the immediately following sounds. One could argue that such overlapping could create enough distortion in the signal to make the detection of a subsequent PDR impossible in CS trials. For instance, the dilation response to a particular changing sound could carry over and increase the baseline value of the following sounds. In such a case, computing PDRs relative to the artificially large baseline would tend to erroneously reduce their amplitude. Although there is no evidence of change-elicited PDR in the raw pupillometric signal displayed in Figure 3, this alternative hypothesis deserves further attention. The 'carryover hypothesis' yields two distinct predictions. First, the first changing sound (i.e. the second sound of a CS sequence) should not be contaminated by the carryover effect because the preceding sound (i.e. the one starting the sequence) is not expected to trigger an attentional response, hence a PDR (cf. Vachon et al., 2012). Consequently, if changing sounds have the power to capture attention, we should then be able to obtain a significant PDR at least for that second sound. To test this prediction, we assessed the pupil reaction separately for each sound of the CS and SS sequences. The first sound was excluded from this analysis as it did not induce any acoustical change relative to a previous sound. Figure 6 shows the mean amplitude of the baseline-corrected PDR for each of the last nine sounds of the auditory stream for non-deviant and deviant trials. These data were submitted to a 2 (No deviant vs. Deviant) × 9 (Sounds 2 to 10) repeated-measures ANOVA. The analysis revealed no significant effect of Deviation, $F(1, 29) = 0.91$, $p = .349$, $\eta^2_p = .03$, BF = 3.33, $p_{BIC}(H_0|D) = .769$, no effect of Sound position, $F(8,$

232) = 1.71, p = .184, η^2_p = .06, BF = 3.45 × 10^5, p_{BIC} (H_0|D) > .999, and no two-way interaction, F(8, 232) = 0.44, p = .712, η^2_p = .02, BF = 6.51 × 10^5, p_{BIC} (H_0|D) > .999. Such results clearly indicate that any changing sound failed to elicit a PDR.

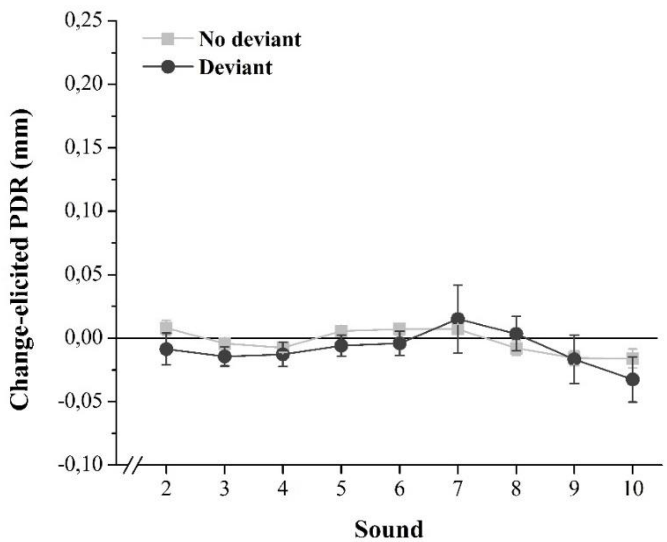

Figure 6. Change-elicited PDRs (in mm) computed from the changing-state-steady-state difference waves, averaged for all participants, as a function of the sound position. Error bars represent the standard error of the mean.

The second prediction of the carryover hypothesis is that the baseline level should be higher for the latest sounds of the CS sequence than for the earlier ones. The baseline levels observed for all sounds but the first, computed from the changing-state-steady-state difference waves, shown in Figure 7, were then compared by using a 2 (No deviant vs. Deviant) × 9 (Sounds 2 to 10) repeated-measures ANOVA. The analysis revealed no effect of Deviation, F(1, 29) = 2.29, p = .141, η^2_p = .07, BF = 1.76, p_{BIC} (H_0|D) = .638, no effect of Sound position, F(8, 232) = 0.72, p = .516, η^2_p = .02, BF = 5.56 × 10^5, p_{BIC} (H_0|D) > .999, and no interaction between the two factors, F(8, 232) = 0.65, p = .566, η^2_p = .02, BF = 5.79 × 10^5, p_{BIC} (H_0|D) > .999. These results confirmed that the absence of PDR to acoustically changing sounds cannot be attributed to baseline measures being compromised by the overlap of the pupil reaction across sounds.

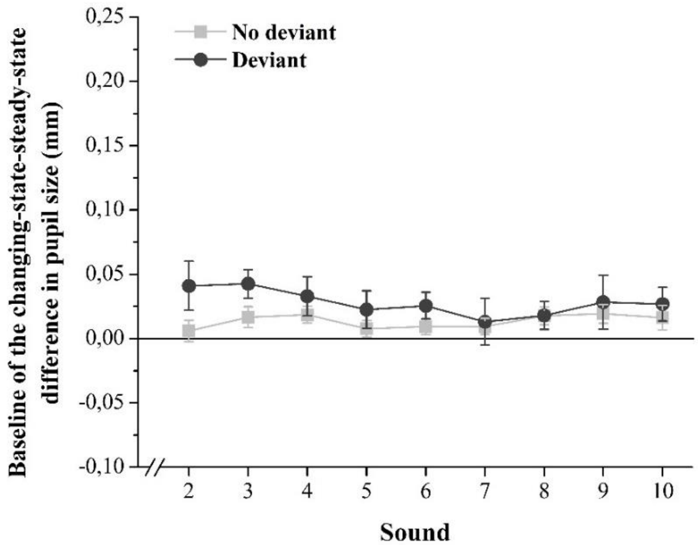

Figure 7. Baseline levels of the change-evoked PDRs (in mm) computed from the changing-state-steady-state difference waves, averaged for all participants, as a function of the sound position. Error bars represent the standard error of the mean.

Discussion

With the general aim of understanding how irrelevant sound disrupts cognitive functioning, the goal of the present study was to assess whether the two main forms of auditory distraction—the deviation and changing-state effects—are subtended by the same attentional mechanism or by two distinct mechanisms. Such examination was carried out by using the PDR, a valid index of auditory attentional capture (cf. Marois et al., 2018), to assess the attentional response elicited by deviant and changing sounds, and by analyzing the behavioral impact of those sounds on recall performance. At the behavioral level, both changing-state and deviation effects were replicated: serial recall was poorer on changing-state and deviant trials relative to steady-state (control) trials. Note that, consistent with previous studies (e.g., Hughes et al., 2005, 2007; Marois & Vachon, 2018; Sörqvist, 2010), the deviant disruption was not localized to the TBR items closest in time to the deviation (around the fifth item) but spread across the serial position curve. Such a result was expected since any disturbance to the encoding and/or rehearsal of the visual list is likely to cause a propagation and back propagation of errors throughout the list (see, e.g., Hughes et al., 2005). At the physiological level, significant PDRs were triggered *only* by the deviant sounds which suggests that changing sounds did not elicit any attentional response—i.e. attentional capture—despite their deleterious effect on recall performance.

Analysis of the pupillometric data indeed showed that, following the presentation of a deviant sound, a significant dilation of the pupil diameter was observed regardless of whether that deviant sound occurred in the context of a steady-state or a changing-state sequence of sounds. This replicates Marois and Vachon's (2018) results regarding the pupil sensitivity to auditory deviation in the context of a visual serial recall task. In addition, we also demonstrated that changing sounds did not trigger any significant attentional response as the change-elicited PDRs did not differ from zero. These results provide convincing evidence against the unitary account (Bell et al., 2010, 2012; Chein & Fiez, 2010; Cowan, 1995; Elliott, 2002; Rinne et al., 2006). According to the unitary account, both deviation and changing-state effects would arise from attentional capture. Accordingly, both deviant and changing sounds should trigger an attentional response. Yet, as shown by the presence of deviant-elicited PDR and the absence of change-elicited PDR, only deviant sounds were endowed with the power to elicit an attentional response.

While the results of this study undermine the predictions of the unitary account, one could argue that the usage of pink noise as the deviant did not afford a fair test of that account. Indeed, embedding pink noise among spoken letters entailed a much larger acoustical change than inserting a 'novel' letter. Given the sensitivity of the PDR to the magnitude of the deviation (Marois et al., 2018), such a deviant item is much more likely to elicit a larger PDR than a mere change of letter, biasing the results toward finding a larger attentional response for a change from a letter to a noise burst than for a change from a letter to another letter. Although the goal of the current study was not to test whether the PDR to deviant and changing sounds is equivalent or not, but instead whether both types of sound have the capability to trigger a PDR, one could nevertheless argue that among the auditory stimuli used in the present study, the pink noise was the only one to truly have the power to elicit a significant PDR. Germane to this hypothesis is the report by Wetzel and colleagues (2016) of particularly large PDRs elicited by pink noise bursts in comparison with those elicited by other types of deviants (e.g., pure tone, phone ring, baby cry) in the same experiment. Although plausible, the hypothesis that pink noise is a special case that specifically gives rise to a significant attentional response because of its nature is however questionable. Indeed, pink noise is not the only type of sound with the potential to produce a rapid dilation in the pupil size reflecting auditory attentional capture. First, we observed that the PDR to the pink noise sound, regardless of the type of trial in which it was embedded (SS+dev or CS+dev), was, on average, 0.07 mm, which is similar to the overall 0.08-mm PDR reported by Marois and Vachon (2018) in an experimental context similar to the one used here. In their study, Marois and Vachon presented TBI sequences composed of the repetition of the same letter in which they sometimes inserted different types of deviant (e.g., a color word, a different letter either spoken in the same or in a different voice), but no noise bursts were used. The fact that the size of the PDRs observed in the current study were similar to that elicited by non-noise deviants in the study of Marois and Vachon suggests that pink noise bursts are no special case for the elicitation of a significant attentional response. Second, and even perhaps more importantly, there is evidence that a simple change of letter does have the potential to produce a significant pupillary response when such a change induces a deviation in a sequence of repeated letters. To support this claim, we isolated and then analyzed the PDR produced by all same-voice deviant letters in Marois and Vachon's data, because such deviants produced an acoustical change equivalent to the one caused by every letter change of a changing-state sequence. The mean PDR to these same-voice deviant letter was 0.10 mm (*SD* = 0.13), which was significantly different from zero, $t(29) = 4.36$, $p < .001$, Cohen's $d = 0.80$. Interestingly, this response to a change of letter observed by Marois and Vachon (2018) was similar in magnitude to that elicited by pink noise in the present study, $t(58) = -1.15$, $p = .257$, Cohen's $d = 0.30$. Therefore, there is no reason to believe that the presence of a PDR exclusively to deviant sounds was attributable to the use of pink noise bursts as deviant items. In other words, the pattern of results obtained in the present study—the observation of a significant PDR for deviant sounds but not changing sounds—cannot be attributable to the type of auditory stimuli employed.

The sensitivity of the phasic PDR to the deviant sounds, but not to the changing sounds, is coherent with the algorithm-based version of the neuronal model to which the duplex-mechanism account subscribes. As predicted by this approach, continuously presenting changing sounds, like continuously presented repeated sounds (e.g., standards), does not violate any rule or algorithm. Indeed, each changing-state item fits the model of "each item differs from the previous one" in the same fashion as the steady-state items fits the algorithm of "each item is the same" (see Hughes et al., 2005, 2007). Hence, in both cases, no attentional capture should be triggered as expectancies of the neuronal model would be respected by the regularity of the changing and repeated sounds in CS and SS trials, respectively. The absence of sound-evoked PDR in CS—compared with SS—trials supports this view and further suggests that changing sounds are not considered relevant nor potentially-relevant by the neuronal model, as opposed to the deviant sounds which are indeed deemed relevant (Nieuwenhuis, Aston-Jones, & Cohen, 2005; Nieuwenhuis et al., 2011).

According to the adaptive gain theory (Aston-Jones & Cohen, 2005), when a relevant or a potentially-relevant event is detected by the organism, neurons of the locus coeruleus-norepinephrine system are activated (Miller & Cohen, 2001; Sara & Bouret, 2012) while being mediated by descending influences of the frontal cortex responsible, in part, for the modeling of the auditory environment through the neuronal model (see, e.g., Alho, Woods, Algazi, Knight, & Näätänen, 1994; Sokolov, 1963, 1990). Activation of this system triggers a plethora of sympathetic-related responses such as a rapid increase in heart rate, respiratory rate, or a pupil dilation (Sara & Bouret, 2012). Given that no increase in pupil size was triggered following the changing sound in a continuously changing stream of sounds, it seems that this type of sound did not violate the neuronal model and, therefore, did not produce any attentional orienting. Still, when a different type of sound (the deviant) was presented, a call for attention was triggered, hence capturing attention and producing responses such as the PDR reported here. This functional dissimilarity is coherent with the duplex-mechanism account given that only the deviant sounds were endowed with the power to produce an attentional response by virtue of a violation of the algorithm-based neuronal model's expectancies. This pattern of results is also incoherent with the aggregate-based view of the neuronal model (Cowan, 1995, 1999). Indeed, according to this theoretical position, every changing sound repetitively captures attention because of its difference with the preceding stimuli. The absence of change-elicited PDR undermines such hypothesis as a change in stimulus would have been expected to trigger a significant PDR that would have indexed the orienting response. Rather, this suggests that each changing sound did not capture attention despite being different to the previous sound, which is contrary to the expectations of the aggregate-based version of the neuronal model.

Previous attempts to examine the attentional nature of the changing-state effect using psychophysiological markers have produced mixed results. Consistent with the present results, Campbell and colleagues (2003, 2007) measured ERPs to changing sounds and found no evidence that such auditory distractors have the power to capture attention. Yet, Bell and colleagues (2010) concluded the opposite after observing that each sound of a changing-state sequence triggered a P3a, an ERP indexing attentional orienting toward an irrelevant stimulus. It is possible that the findings of Bell and colleagues were peculiar to the distractor words they used to build the irrelevant speech sequences. Indeed, the words that were used as TBI distractors had a mean frequency of 8/1,000,000 in the German language (Baayen, Piepenbrock, & van Rijn, 1993). Low-frequency words have been shown to yield strong attention-attracting power when embedded in an irrelevant auditory sequence (see Buchner & Erdfelder, 2005). Speculatively, the use of low-frequency words as TBI items could explain, at least in part, why changing-state auditory distractors in the study of Bell and colleagues elicited a P3a. Still, this effect has not been systematically replicated (e.g., Elliott & Briganti, 2012) and more work may be needed to clarify the impact of word frequency on attentional capture.

Alternatively, however, it could be argued that the larger tonic (or slow) pupillary response measured throughout the CS trials represents the change-elicited attentional response predicted by the unitary account. This argument however is most unlikely. In fact, it has been established that the attentional response to deviation can be measured through phasic, not tonic, physiological responses (e.g., Aston-Jones, Rajkowski, Kubiak, & Alexinsky, 1994; Marois et al., 2018; Nieuwnehuis et al., 2011; Steiner & Barry, 2011). Such a phasic response would then be observed using the change-elicited PDR, not the global pupil diameter. Tonic enlargement of the pupil size is rather associated with an increase in cognitive effort (e.g., Beatty, 1982;

Kahneman, 1973; Marois & Vachon, 2018; Unsworth & Robison, 2017; for a recent review, see van der Wel & van Steenbergen, 2018). The larger tonic pupillary response observed for CS trials could thus represent an increase in cognitive effort measured for this type of trial.

Such potential increase in cognitive effort observed for CS trials, in comparison with SS trials, may possibly represent another important finding in the dissociation of the changing-state and deviation effects. According to the duplex-mechanism account, the changing-state effect is a by-product of a conflict between the deliberate seriation processes involved in the serial recall and the automatic ordering of the TBI sounds that one needs to resist possibly through reliance upon inhibitory mechanisms. Indeed, as put by Hughes and colleagues (2007):

> […] the disruption [by changing sound] may reflect the cost of having to select for action (possibly through the use of an inhibitory mechanism; see Hughes & Jones, 2003b) one amongst two streams of information, both of which represent plausible candidates for the deliberate skill of planning a gestural (e.g., articulatory) sequence (Hughes & Jones, 2005) (p. 1052).

The inhibition required to select the relevant action of processing the order of the TBR material, and not that of the TBI sounds, may yield greater cognitive demands, which could ultimately be observed through larger measures of the pupil aperture. It has indeed been previously shown that the pupil size is positively related to the efforts required to specifically inhibit several types of cognitive processes (e.g., Geller, Still, & Morris, 2016; Mathôt, Dalmaijer, Grainger, & Van der Stigchel, 2014; see also van der Wel & van Steenbergen, 2018, for a review). To our knowledge, this would represent the first physiological indication of the potential, effortful inhibitory mechanisms underlying the conflict between both seriation processes advocated by the proponents of the duplex-mechanism account. However, further studies are needed to confirm that such tonic enlargement of the pupil size is related to the efforts required for the inhibition of the automatic seriation processing of the TBI sound. One could, for instance, compare the cognitive load—through measures of the pupil diameter—of participants exposed to changing sound in conditions where such interference-by-process can occur (e.g., performing visual serial recall) and where the changing-state effect is unlikely to occur such as in a context wherein seriation is not involved (e.g., undertaking the missing-item task; Beaman & Jones, 1997; Hughes et al., 2007; Vachon et al., 2017) or is at least not the dominant strategy (Morrison et al., 2016). Comparing the tonic pupil size in changing-state as compared to steady-state trials between serial recall and missing-item tasks could thus help to further support the view that the changing-state effect does not originate from attentional capture mechanisms, but rather from a conflict between two ordering processes that could be observed through measures of cognitive effort.

Finally, it may be noteworthy that the interaction between the behavioral deviation and changing-state effects did not reach significance. As observed by Hughes et al. (2005, 2007) this suggests that the two distraction phenomena have an additive impact. From a unitary account standpoint, the impact of the deviant on performance should be smaller in CS+d trials compared to SS+d trials. More precisely, presenting pink noise in lieu of a change in letter should produce a significant, yet smaller, attentional response as it would replace another attention-capturing stimulus (the change in letter). This attentional response would then be smaller than when the deviant is embedded within steady-state sound as the repeated sounds yield no attention-capture power. At odds with this proposal, however, is that the amplitude of the deviation effect did not differ between CS and SS trials as no significant interaction was observed. Similar results were also obtained regarding the sound-evoked PDRs. Indeed, the deviant-elicited PDRs observed in the SS and CS conditions did not differ even though, as predicted by the unitary account, the attentional response triggered by the deviant in a SS context should be larger than that observed in a CS context. Hence, this consistent absence of difference in the attentional response to the deviant among behavioral and physiological results brings further evidence in favor of the duplex-mechanism account.

Conclusion

The present study supports the view that the deviation and changing-state effects are underpinned by two distinct and independent mechanisms. Indeed, the current results established, for the first time, a physiological dissociation between these two forms of auditory distraction whereby deviant sounds, but not changing sounds, have the power to elicit a PDR, a pupillometric index of attentional capture. These findings are in line with the duplex-mechanism account of auditory distraction, which posits that only the deviation effect can be explained in terms of attentional capture. From this theoretical standpoint, the changing-state effect is instead considered as a non-attentional form of distraction ascribed to a competition-for-action between two seriation processes. Using the PDR to bring further evidence for the dissociation of the deviation and changing-state effects is compelling as it represents the first use of this auditory attentional response proxy to solve a theoretical issue. While the PDR's validity and usability to index such phenomenon had previously been demonstrated (see, respectively, Marois et al., 2018; Marois & Vachon, 2018), the utility of this index was still to be proven (cf. Marois & Vachon, 2018). Our demonstration thus supports the view that the PDR represents a useful index of auditory attentional capture and its use should then be considered by researchers whose objectives are to study mechanisms of auditory distraction.

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