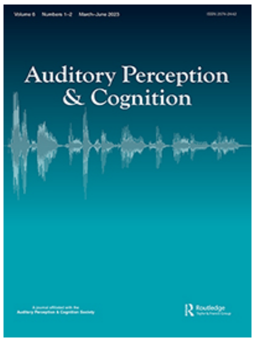

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Psychophysiological Markers of Auditory Distraction: A Scoping Review

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ABSTRACT

Short-term memory can be disrupted by task-irrelevant sound. Auditory distraction has been globally studied under the lens of two main phenomena: the deviation effect and the changing-state effect. Yet, it remains unclear whether they rely on common cerebral mechanisms and, concomitantly, what psychophysiological responses they can trigger. This scoping review provides a state of knowledge regarding psychophysiological indices of auditory distraction. Records published between 2001 and 2021 on the deviation effect and the changing-state effect with psychophysiological measures were extracted from PubMed, ERIC, PsycNet, Web of Science, and ScienceDirect. Records investigating task-relevant sounds, as well as those that failed to observe performance disruption, or to include a control condition or a concurrent cognitive task, were excluded from the review. The Revised Cochrane risk-of-bias tool for randomized trials was used for bias evaluation. Fifteen records were reviewed, mainly characterized by randomization, measurement and selection of results biases. Some markers were specific to the distraction type, but nonspecific responses were also found. Overall, we outline the main markers used to index auditory distraction, present their meaning for understanding underpinning mechanisms, and discuss implications and knowledge gaps that need to be filled to fully exploit psychophysiology for auditory distraction research.

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Auditory distraction; Psychophysiology; Deviation effect; Changing-state effect; Scoping review

Introduction

Literature offers a substantial amount of evidence that cognitive activity can be hindered by the mere presence of task-irrelevant sound. This auditory distraction can be observed in the lab (e.g., Bell et al., 2010; Campbell et al., 2002; Vachon et al., 2012; for review and meta-analysis papers, see; Hughes, 2014; Szalma & Hancock, 2011; Vasilev et al., 2018), but also in one's daily life (e.g., Beaman, 2005; for review papers, see; Banbury et al., 2001; Dalton & Behm, 2007; Ferdinand & Menachemi, 2014; Mentis et al., 2016). One explanation of this permeability to extraneous sounds, regardless of their relevance for the ongoing action, is the necessity for the organism to remain open to stimuli, even if

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they are outside the focus of attention. These stimuli may become relevant and signal danger or opportunity (Allport, 1989; Neumann, 1987) because of controlled task-related goals (top-down processing of behaviorally relevant stimuli; e.g., Folk et al., 1992), or because of the automatic analysis of the auditory scene (e.g., bottom-up processing of salient or unexpected stimuli; e.g., Theeuwes, 1994).

A wide range of studies highlights the deleterious impact of extraneous sound on cognitive activity. Short-term memory is particularly vulnerable to task-irrelevant sound. For example, visual serial recall, digit categorization, probed recall, and the *n*-back task have all been shown to be susceptible to irrelevant sound (e.g., Berti, 2013; Chein & Fiez, 2010; Mahajan et al., 2020; Marois et al., 2019). Reduction in performance on short-term memory tasks has been widely observed while to-be-ignored sound is presented, both during presentation of the task-relevant stimuli and a retention interval (Colle & Welsh, 1976; Ellermeier & Zimmer, 1997; Elliott, 2002; Jones et al., 1992; Neath, 2000; Röer et al., 2011; Salamé & Baddeley, 1982). Generally, two main forms of auditory distraction effects on short-term memory are reported in the literature[1]:

(1) The *changing-state effect*, demonstrated through superior performance disruption by the presence of sequentially-presented changing sounds (or tokens) that differ from one another, such as *G W P F S X N T*, compared with a condition of steady-state sound comprised of a unique repeated sound, such as *B B B B B B B B* (e.g., Beaman & Jones, 1997; Hughes et al., 2007; Jones & Macken, 1993; Klatte et al., 2010; Marois et al., 2019; Meiser & Klauer, 1999; Sörqvist, 2010; Tremblay & Jones, 1999); and

(2) The *deviation effect*, representing the impairment produced by the unexpected presentation of a sound deviating from the auditory context in which it is embedded, compared with a standard – i.e., no-deviant – condition (B B B B B *A* B B vs. B B B B B B B B; see, e.g., Hughes et al., 2005, 2007; Marois et al., 2019, 2020; Marsh et al., 2014; Parmentier, 2008; Vachon et al., 2017, 2018).

Sounds conveying particular meaning, such as conversations (either full dialogs or half-alogues; e.g., Marsh et al., 2018), emotionally valent and taboo words (e.g., Marsh et al., 2018; Röer et al., 2017) or one's own name (e.g., Röer et al., 2013), can also induce performance disruption due to postcategorical (semantic) content analysis (see Marsh & Jones, 2010; Vachon et al., 2020). In the current paper, we focus however on precategorical forms of auditory distraction, whereby it is the acoustic properties of the sound that disrupt performance. Together, the changing-state effect and the deviation effect outline how short-term memory performance can be affected by the low-level properties of irrelevant sound.

Underlying Mechanisms of the Distraction Effects

While these phenomena have been widely observed, there is a debate as to the theoretical explanations of the changing-state effect and the deviation effect. Indeed, two main theoretical positions can be found in the literature. The first one, the unitary account, posits that the impact of irrelevant sound – regardless of its nature – triggers exogenous reorienting of attention from the ongoing task toward the sound (Bell et al., 2010, 2012, 2019a, 2019b; Chein & Fiez, 2010; Cowan, 1995; Elliott, 2002; Rinne et al., 2006). Such attention capture, whether it takes place in a transient (e.g., Cowan, 1995) or in a graded fashion (e.g., Bell et al., 2019a; Röer et al., 2014), affects performance on the primary task because attention is removed from the prevailing mental activity, hence preventing processing of task-relevant stimuli. According to this view, the attention-capture power of a sound would be determined by the degree of mismatch between a new stimulus and recently heard objects (Bell et al., 2019a), which characteristics would be registered in a so-called neural model (Sokolov, 1963) containing an aggregation of the stimulus sequence or a representation of the sound properties presented earlier. In that regard, if a sound is absent from the recent auditory past, its presentation can trigger a call for attention and elicit attention reorientation. From this standpoint, any (new) sound has potential to capture attention, including changing sound or speech and deviant stimuli as well.

Opposed to the unitary account is the duplex-mechanism account of auditory distraction (Hughes, 2014; Hughes et al., 2005, 2007, 2013; Marois et al., 2019; Sörqvist, 2010). This model distinguishes the deviation effect from the changing-state and proposes different explanatory mechanisms. This distinction is mainly driven by a different conceptualization of Sokolov's (1963) neural model. According to this view, the neural model does not register an aggregate of the physical characteristics of the sound, but it rather extracts a memory representation – or an algorithm – of the rules underlying any structure, pattern or sequence present within the auditory environment (e.g., Bendixen et al., 2007; Marois et al., 2020; Vachon et al., 2012; Winkler et al., 2009). Here, a sound is endowed with attention-capture power only if it violates implicit predictions that can be extrapolated from the regularities of the unfolding auditory stimulation. From this perspective, a series of changing tokens (e.g., G W P F S X N T) all differing from each other on the same aspects (e.g., voice, pace, intensity) contains no deviant (or irregularity) because no token violates predictions derivable from the sequence (i.e., none is predictable at the level of the token identity and none violates this pattern). Consequently, each token of such a sequence should not trigger attention reorientation because each sound is (equally) unpredictable and cannot be predicted from the history of the previous stimulus, hence conforming to the rule that every stimulus changes from one another. A deviant sound embedded within a steady-state sequence (e.g., B B B B B *A* B B) should however prompt attention orienting because its presence violates the rule extracted from the preceding sounds that the auditory background is comprised of repetitions of the letter B.

While the preceding algorithm-based model is used by proponents of the duplex-mechanism account to explain the deviation effect (see Hughes et al., 2005), the distraction caused by non-deviant, changing irrelevant sound subtends a different explanation. Given that (predictable) changing auditory patterns cannot capture attention, their disruptive power would rather lie in a processing conflict between goal-relevant material and task-irrelevant sound. In fact, changing sound is obligatorily and involuntarily segmented into a perceptual stream (Bregman, 1990) and information regarding each element would be processed automatically to extract cues pertaining to the order of the sounds (Jones & Tremblay, 2000; Jones et al., 1993; Macken et al., 1999). Such obligatory seriation process would compete with the deliberate seriation processing involved in the focal task. This interference by process would then explain why serial memory performance is specifically disrupted by changing sound as opposed to similar tasks that do not involve any seriation processes such as the missing item task (Beaman & Jones, 1997; Hughes & Marsh, 2020; Hughes et al., 2007). Interference-by-process is not limited to serial processing and can also be extended to semantic processing, whereby the automatic processing of the meaning of task-irrelevant speech interferes with the same processing applied deliberately in a focal task (see, e.g., Marsh et al., 2008, 2009; Meng et al., 2020; Neely & LeCompte, 1999).

Both unitary and duplex-mechanism accounts have been supported by empirical evidence related either to functional similarity or distinctiveness between the deviation effect and the changing-state effect. Proponents of the duplex-mechanism account first propose that cognitive control can be exerted on the deviation effect, but not on the changing-state effect. Indeed, it was shown that contrary to the changing-state effect, the deviation effect could be eliminated by increasing task demands, hence precluding attention reorientation from the ongoing task (Hughes et al., 2013; Hughes & Marsh, 2019; Marsh et al., 2020; but see Kattner & Bryce, 2022). Moreover, foreknowledge of the incoming deviant sound could reduce the magnitude of the deviation effect, but the same was not necessarily observed with the presentation of changing sound (Hughes & Marsh, 2020; Hughes et al., 2013). Some studies also found that working memory capacity – i.e., a measure of individual differences in the amount of attentional resources that can be used to inhibit task-irrelevant material (Engle, 2002) – is related to the amplitude of the deviation effect but not to that of the changing-state effect (Hughes et al., 2013; Labonté et al., 2021; Sörqvist, 2010; Sörqvist et al., 2013).

Advocates of the unitary account however reported opposing results regarding the cognitive control of auditory distraction. Bell et al. (2021) showed that both deviation and changing-state effects were unaffected by an increase in task engagement induced by monetary incentive. Röer et al. (2015) found that specific foreknowledge of an upcoming to-be-ignored spoken sentence could reduce its disruptive power, suggesting that the changing-state effect could be controlled as the deviation effect. Yet, Hughes and Marsh (2020) showed that such foreknowledge effect was in fact driven by the attentional diversion caused by the additional properties of a natural sentence that are absent from the repeated single word used by Röer et al. in their steady-state condition. Working memory capacity is also not systematically related to the amplitude of auditory distraction. Körner et al. (2017) found no correlation between working memory capacity and the size of both the deviation and changing-state effects, arguing in favor of a common mechanism between these phenomena. It must be noted however that the magnitude of the deviation effect found by Körner and colleagues was particularly small and that variability within the sample was relatively low, hence decreasing the odds of finding a significant correlation.

Habituation is another phenomenon used to either unite or distinguish how deviant and changing sounds can disrupt memory performance. Whereas there is ample evidence that the response to acoustic deviations tends to diminish with repeated exposure (e.g., Littlefair et al., 2022; Sörqvist et al., 2012b; Vachon et al., 2012), Bell et al. (2012) showed that both deviation and changing-state effects could decrease as a function of repetition. The authors ascribed this diminution of distraction over time to the habituation of the orienting response, hence supporting the idea that both effects would be driven by attention capture. Indeed, this suggests that the repeated presence of either the deviant sound or the changing sound could be integrated into the neural model, reducing their attention-capture power (see also Banbury & Berry, 1997; Röer et al., 2014). However, other studies failed to observe significant decrease over time of – i.e., a "habituation" pattern for – the changing-state effect (Jones et al., 1997; Tremblay & Jones, 1998), inconsistent with the predictions of the unitary account.

Finally, differences can also be found regarding the nature of the tasks that can be impacted by the distracting sound. The deviation effect – which is allegedly driven by attention capture – can be observed with a range of memory and non-memory cognitive tasks (e.g., serial recall, continuous visual tracking, missing item, speeded discrimination judgments; see Hughes et al., 2007; Parmentier, 2008; Sörqvist, 2010; Vachon et al., 2017). Yet, it seems that changing-state sounds are mainly disruptive for tasks requiring seriation processes (i.e., serial recall, probe task, and visual statistical learning; see Beaman & Jones, 1997; Hughes et al., 2007; Kattner & Ellermeier, 2018; Neath et al., 2009). Such a changing-state effect seems generally absent from tasks with no seriation underpinnings such as the missing item task (Beaman & Jones, 1997; Hughes et al., 2007; Kattner & Ellermeier, 2018). Yet, evidence of performance disruption by irrelevant speech was sometimes found for non-seriation tasks. For example, Bell et al. (2021) observed a changing-state effect using an item-color binding task, that was assumed not to rely on serial order. Samper et al. (2021) also observed that changing sounds hindered performance in the running memory span task conducted under conditions that discouraged the use of seriation processes. Overall, behavioral evidence for the support of the unitary and the duplex-mechanism accounts is characterized by a range of conflicting findings.

Psychophysiological Measures

Using only behavioral evidence to identify the underlying mechanisms of auditory distraction may limit the extent of information that can be extracted from each phenomenon studied. Behavioral outcomes represent the product of a chain of actions for the processing of a stimulus from its reception by the perceptual system to task-relevant motor output. For example, in serial recall studies, the disrupting effect of the sound on recall performance depends on many internal processes including, but not limited to, encoding, maintenance, recollection, while also being affected by contextual factors such as the perceptual organization of the auditory environment (Hughes & Marsh, 2017) and the level of engagement in the task (Hughes et al., 2013). Moreover, there is sometimes some mismatch between the behavioral manifestation of distraction and the timing of the distracting event. For instance, disruption of serial recall at encoding can provoke a propagation and a back propagation of error through the to-be-remembered list, meaning that the disrupting effect of a deviant sound is usually visible across the whole serial-recall curve (see Hughes et al., 2005). In the same vein, the deviation effect has been restricted to those cases whereby the deviant sound occurred during the encoding of the to-be-remembered items (e.g., Hughes et al., 2005), but there is evidence that the effect can also arise when a deviant is presented during a retention interval (Körner et al., 2019).

Psychophysiology represents a sound technique to understand the underpinnings of psychological phenomena through a more direct lens given the possibility to examine how a phenomenon (e.g., a task-irrelevant distracting sound) may impact specific brain processes underlying one's cognitive activity. Two broad families of physiological measures can be used for that matter: direct measures of the central nervous system and indirect, peripheral measures of the nervous system. On the one hand, direct measures of the central nervous system are concerned with directly assessing the activity of the brain, e.g., its electrical activity or blood oxygen concentration. This includes event-related potentials (ERPs), which are highly used to represent the electrical response over a given region of the brain measured with an electroencephalogram (EEG), time-locked on a stimulus or an event (see Wetzel & Schröger, 2014, for a review). Showing either positive or negative deflections, ERPs provide a sensitive measure of real-time stimulus processing at various underlying stages of processing. Literature on auditory distraction identified a range of ERPs triggered by deviant sounds such as: a) the N1, a negative wave reflecting a first-order change-detection process; b) the mismatch negativity (MMN), a negative deflection indexing a sensory memory-based deviance-detection process; c) the P3a, a positive component often taken to reflect the process of involuntary attention orientation itself; and d) the reorienting negativity (RON), assumed to index the reorientation of attention toward the main task (see Horváth et al., 2008). Direct measures of the central nervous system also comprise brain power bands, i.e., the different frequency of electric waves measured with an EEG. On the other hand, peripheral measures rather represent physiological responses caused by the brain activity in descending pathways across the body. For instance, it can include variations in the size of the pupil (e.g., the pupil dilation response [PDR], assumed to reflect the attentional response to deviant events; e.g., Marois et al., 2018, 2019, 2020), in cardiac activity, in respiration or in the electrical conductance of the skin.

Contrary to behavioral measures, psychophysiological measures can be time-locked to specific events or stimuli, hence directly representing their effect on the brain/body, and not the outcome of a chain of cognitive processes (Marois et al., 2020; Wetzel et al., 2013). In the case of ERPs, for instance, a given response can be measured only 100 ms after the onset of the stimulus of interest. In some cases, however, delays can be more important, especially for peripheral physiological responses (i.e., resulting from a [rapid] chain of physiological reactions from the brain to descending body areas) and for measures with lower temporal resolution (i.e., with slower biological reactions or measuring techniques such as the blood-oxygen-level-dependent [BOLD] signal, detected in functional magnetic resonance imaging [fMRI]).

In this regard, psychophysiological measures can be useful to study auditory distraction and to help understand the underlying mechanisms of the changing-state and deviation effects. For example, Bell et al. (2010) as well as Campbell et al. (2007) used ERPs to examine brain activity while participants performing a visual serial recall task were exposed to changing-state sound. Marois et al. (2019) rather relied on the PDR, a proxy for attention orienting, to assess whether both deviant and changing-state sounds had the same attention-grabbing power. Although psychophysiology draws on strong and objective evidence, this technique still remains rarely used among the auditory distraction research community. In this regard, it remains unclear what psychophysiological measuring tools can be used, what specific indices can be exploited from these techniques, and what information can emerge from these psychophysiological responses regarding mechanisms of auditory distraction.

Understanding the bases of auditory distraction could be achieved by focusing on physiological substrates of attention. As indicated earlier, the main debate concerning the underlying mechanisms of auditory distraction relates to whether both deviation and changing-state effects ensue from the same attention-orienting mechanism, as suggested by the proponents of the unitary account, or from distinct mechanisms, respectively attention capture and interference-by-process, as proposed in the duplex-mechanism account. Focusing on physiological markers of attention thus represents an interesting avenue to challenge these two theoretical explanations.

Activity of the locus coeruleus-norepinephrine (LC-NE) system is considered a key element of such mechanisms. The LC represents one of the main points of origin for the secretion of NE into the brain, a neurotransmitter related to vigilance, attention orientation, selective attention, and arousal. It is secreted in many regions of the brain including cerebral cortices, limbic structures, but also midbrain and diencephalon areas as well as the spinal cord (e.g., Aston-Jones et al., 1994; Bouret & Sara, 2004; Miller & Cohen, 2001; Nieuwenhuis et al., 2005; Sara & Bouret, 2012; Southwick et al., 1999). Its activity would mainly facilitate decision making and selection/processing of task-relevant (or potentially relevant) stimuli (Aston-Jones & Cohen, 2005; Bouret & Sara, 2004; Nieuwenhuis et al., 2005). LC secretion in certain areas of the brain would make synapse-like appositions with postsynaptic specializations on target neurons and, in turn, would generate electric activity in some regions of the brain (Koda et al., 1978; Olschowka et al., 1981; Papadopoulos & Parnavelas, 1990; in Aston-Jones et al., 1991). Through other connections (e.g., via the nucleus gigantocellularis that possesses direct afferent projections from the LC), the spinal cord receives efferences from the LC-NE system (Benarroch, 2009; Berridge & Waterhouse, 2003; Sara & Bouret, 2012), eliciting a sequence of descending actions of the peripheral pathway for both parasympathetic inhibition (through the Edinger-Westphal nucleus) and sympathetic activation (via the superior cervical ganglion; Nieuwenhuis et al., 2011; Sara & Bouret, 2012; Steinhauer et al., 2004; Wang & Munoz, 2015). Therefore, it seems that activity of the LC-NE system (and the different central and peripheral responses produced) is involved when attention-related mechanisms of distraction are triggered. Still, it remains unclear to what extent – and how specifically – these responses relate to the mechanisms responsible for the deviation and changing-state effects. Besides, many different responses related to the inhibition of irrelevant stimuli processing, seriation processing and executive control could also be relevant for understanding auditory distraction, but the role of these responses needs to be better examined.

The Current Study

The goal of this study was to provide a state of the current knowledge about the underpinnings of auditory distraction through the study of psychophysiological markers. To do so, we conducted a scoping review of empirical studies published between 2001 and 2021 through several databases following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-ScR; Tricco et al., 2018).[2] We sought to identify relevant literature regarding the psychophysiological responses elicited by distracting sound in the context of the deviation and changing-state effects. The scoping review approach was favored over the traditional and systematic review counterparts due to the larger scope of the paper, i.e., to identify potential physiological markers of auditory distraction and how they might contribute to better understanding the underpinnings of this phenomenon (see Munn et al., 2018; Peters et al., 2015; Verdejo et al., 2021).

Similar to the method employed by Jaén et al. (2021) and Marois et al. (2023, key information regarding the psychophysiological responses triggered by irrelevant sound was extracted. This enabled to, first, identify markers that can be used to index auditory distraction, and, second, to provide further information about the mechanisms underpinning the disrupting effects of sound on cognitive performance. Following this analysis, we discuss the implications of using these markers to index auditory distraction. We also present some considerations that should be addressed in an agenda of future studies to improve the comprehension of the relationship between physiological and behavioral effects of distraction.

Method

Search Strategy

No preregistered review protocol existed for the current scoping review. Hence the following protocol was developed. An online search of PubMed, ERIC, PsycNet, Web of Science and ScienceDirect was conducted on 31 August 2021 by the first author (AM). The inclusion criteria were that the document: a) was published between 2001 and 2021[3]; b) was an English-written peer-reviewed article; c) presented empirical evidence of behavioral auditory distraction in a paradigm related to either the deviation effect or the changing-state effect; and d) contained physiological measures triggered by the distracting sound. In this regard, the terms combined to carry on the online database search were: (“sound” OR “audi*”), AND (“auditory distraction” OR “irrelevant sound” OR “attentional capture” OR “attention capture” OR “deviation effect” OR “irrelevant sound effect” OR “changing-state effect” OR “interference-by-process”), AND (“psychophysiology” OR “psychophysiological measure*” OR “electrodermal activity” OR “galvanic skin response” OR “cardiovascular” OR “cardiac response” OR “heart rate*” OR “MEG” OR “EEG” OR “fNIRS” OR “respi*” OR “fMRI” OR “pupil*” OR “brain” OR “eye” OR “blink” OR “ERP” OR “event-related potential”). An example of search keywords among the PubMed and PsycNet databases is provided in the Appendix (see Table A1). When possible, the keywords were searched among titles and abstracts of the records. The year criterion (i.e., between 2001 and 2021) was systematically used. For some databases, the search was split into multiple sets given the number of keywords. A few records identified through other sources were also included in the records database. These included key sources identified through snowballing, which is deemed complementary to the systematic keyword-driven approach (Chapman et al., 2010).

Eligibility Criteria

Eligibility assessment for inclusion was performed first through an initial generic assessment and, in a second step, through detailed assessment of the paper. In the first assessment, records were excluded for the following reasons:

(1) If the task required participants to actively listen to the sound for task-relevant goals or if participants were asked to passively listen to sound without any specific task. This was to ensure that the observed (psychophysiological) measures were really representative of the disruption of an ongoing cognitive task by irrelevant sound;
(2) If they contained no measure of the physiological activity of the participants;
(3) If participants were exclusively sampled from a clinical population, a population of elders or of children, or if they were non-humans. This exclusion criterion aimed at controlling for any potential noise on the autonomic responses ensuing from factors (e.g., sampling) other than the acoustic characteristics of the distracting sound;
(4) If no distracting sound was presented.

The second detailed assessment aimed at excluding records that did not fit with the irrelevant sound paradigm for the following reasons:

(1) If no evidence of behavioral distraction was observed on performance. The goal of this criterion was to make sure distraction truly took place. Note that to avoid any bias in the theoretical model it could support, we did not use any exclusion criterion regarding whether the ongoing task involved mnemonic processes or not[4];
(2) If the physiological measures reported were elicited by task-relevant stimuli rather than the sound itself (e.g., the P3b of the ERPs triggered by a task-relevant visual item; see Cid-Fernández et al., 2016)[5];
(3) If no control condition was employed, that is, if the effect of the distracting sound was not compared to an appropriate control condition;
(4) If the sound condition of the study could not be ascribed specifically to either the deviation effect or the changing-state effect.

Eligibility assessment was conducted by the first author (AM) and reviewed by the second author (FV). Then, the final sample of records was established for the qualitative synthesis and each of these records were carefully read.

Critical Appraisal and Analysis of Bias

In line with the PRISMA framework (Liberati et al., 2009; Tricco et al., 2018), we performed a bias analysis on the different records sought for analysis for the current review as a critical appraisal of individual sources of evidence. This analysis allows to remain critical on the different studies reviewed and to be transparent on the different aspects that can bias the validity of the psychophysiological responses to auditory distraction. To do so, we used the Revised Cochrane risk-of-bias tool for randomized trials (ROB2; Sterne et al., 2019). This method was deemed appropriate given that participants in all these studies were exposed to orthogonal interventions that were not ascribed to participants because of their individual characteristics, but rather presented randomly (or quasi-randomly) regardless of their nature. The RoB2 tool, in the form of an Excel sheet[6] containing different macros, was used to collate and analyze information for all the studies. For each of the papers, outcomes of interest (i.e., dependent variable) for the review and the main interventions (i.e., the independent variable with the levels of factor) were identified. Given the context of auditory distraction, factors of the intervention were related to the type of sound presented, that is, the distracting sound (either deviant [Dev] or changing-sound [CS]) for the experimental condition and the control sound (either steady-state [SS] sound or CS) for the comparator.

The method allows analysis of each study on five key domains where biases can be observed: a) Randomization process; b) Deviations from intended interventions; c) Missing outcome data; d) Measurement of the outcome; and e) Selection of the reported result. The technique also provides capacity to compute an overall estimate of bias based on the five subdomains. For the overall risk-of-bias judgment, the following rule is used: a) overall low risk of bias is related to studies with only low risk of bias classification for all domains; b) overall "some concerns" classifications are associated with studies that possessed at least one domain for which mild concerns were found; and c) overall high risk of bias is ascribed to studies with a majority (≥3) of "some concerns" and for studies possessing at least one domain with high risks for bias. More details are presented in the documentation of the RoB2 tool regarding the decision flowchart of the bias analysis for each domain. Results of the bias analysis and of the aspects inducing biases were discussed.

Data Charting and Collating

Key data was first charted by the first author (AM) based on Levac et al. (2010) suggestion. The following general information was first extracted from each of the records identified: a) study (authors, year of publication); b) sample size of participants concerned by the manipulations; c) type of psychophysiological technique; and d) nature of the distracting paradigm. This information was presented in a summary table comprised of all records. Records were classified per the type(s) of auditory distraction phenomena they discussed according to the author(s)' viewpoint.

Further data was then charted for more elaborate qualitative synthesis and analysis: a) specific psychophysiological outcomes of interest; b) focal task; c) type of distracting sound; d) study design; e) summary of the main findings; and f) meaning for the auditory distraction literature and the debate on the underlying mechanisms. Data from elements a) to e) were presented in summary tables and the main conclusions/implications for the auditory distraction literature were discussed together within the results section. Note that if psychophysiological outcomes were reported both for the task-irrelevant auditory stimuli and the processing of task-relevant information, only the former were retrieved to keep the focus exclusively on psychophysiological proxies of sound-evoked distraction.

Results

The scoping review conducted in the five online databases with the additional records from other sources yielded a total of 580 records (PubMed = 129; ERIC = 8; PsycNet = 102; Web of Science = 254; ScienceDirect = 87). In addition, nine studies considered relevant for the scope of the review were added from key sources through snowballing.

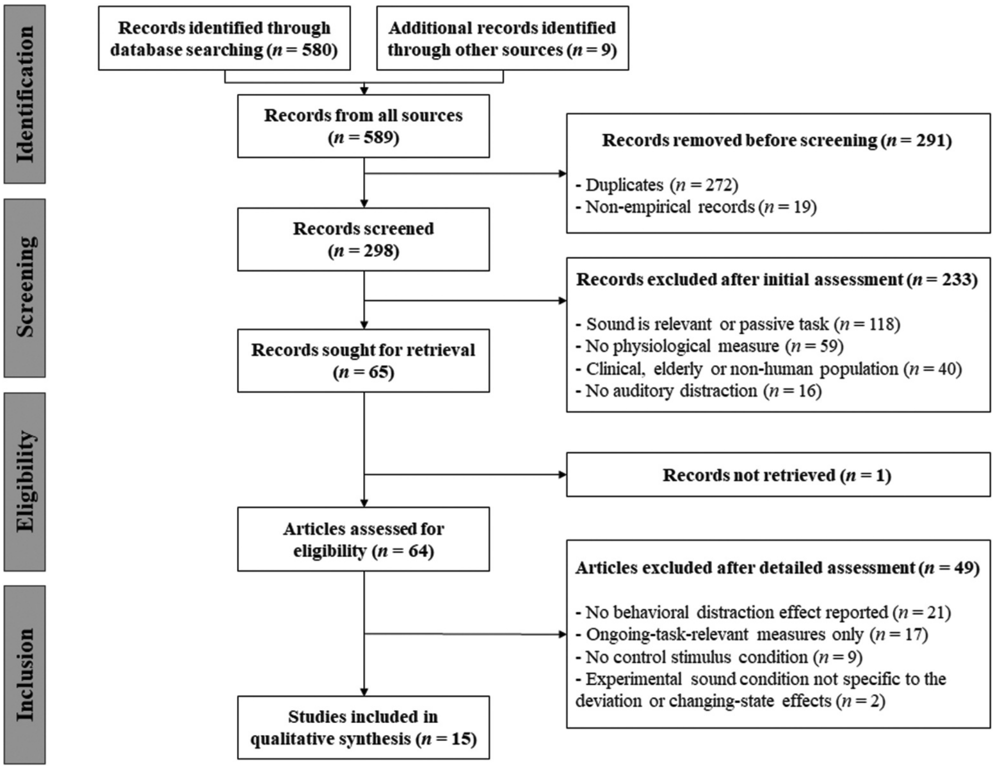

Figure 1. PRISMA flowchart diagram of the study selection process.

This led to a total of 589 records. After removing duplicates and non-empirical records ($n = 291$), 298 records went through the first generic screening. This initial assessment removed 233 records. A total of 65 records were sought for retrieval and 64 of them were retrieved and deemed eligible for detailed assessment (one full-paper record could not be accessed). Finally, the detailed assessment removed 49 records, identifying 15 records to be included in the qualitative synthesis of this review. Figure 1 depicts the PRISMA flowchart of the study selection process.

Bias Analysis

Per the PRISMA-ScR framework (Tricco et al., 2018), we analyzed the risks of bias in each individual study to provide a critical appraisal of the individual sources of evidence (see also Item 12, Liberati et al., 2009) using the RoB2 method (Sterne et al., 2019). Figure 2 depicts the overall evaluation of the bias for all studies analyzed (Panel A) and displays a detailed presentation of the RoB2 analysis for each of the 15 studies (Panel B). The overall bias evaluation for these 15 papers yielded mild concerns on the method employed by the authors for 86.67% of the papers and high risks for bias for 13.33% of the papers.

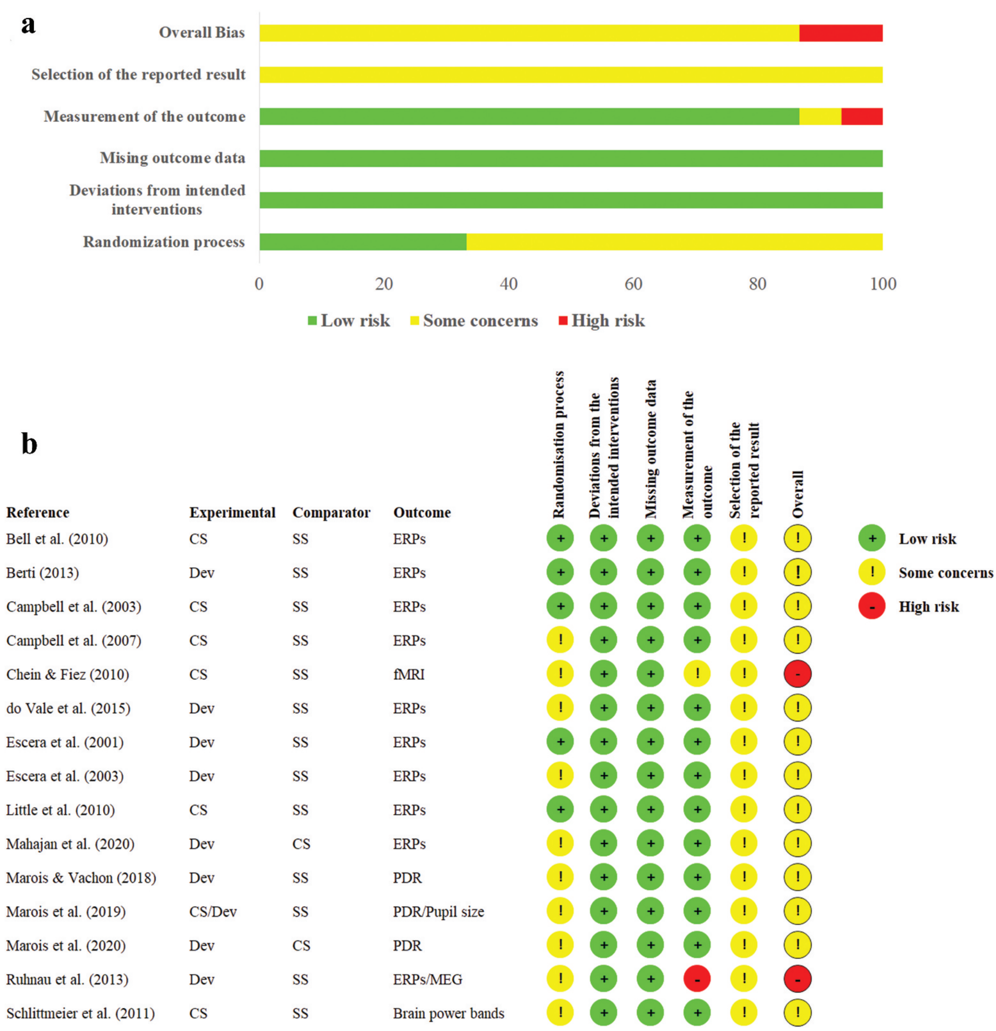

Figure 2. Depiction of the RoB2 bias analysis for the 15 papers included in the review (panel A: global overview; panel B: detailed analysis). CS: changing-state; Dev: Deviant; and SS: steady-state.

All studies were considered as having some concerns in regard of the selection of reported results. This mainly originated from the fact that multiple methods of analysis exist in the literature. For instance, PDR analyses can be performed with or without baseline correction, or the PDR in a given condition can be subtracted (or not) from another control condition. Similar observations can also be observed for other psychophysiological measures (where a response can be measured independently or in relation with another response). In that regard, the analysis strategy varied between studies and can represent some form of bias. The Measurement of the outcome domain was mainly related to low risks (i.e., 86.67%), though some concerns were raised for Chein and Fiez (2010, Exp. 1) and high risks identified for Ruhnau et al. (2013). For this study, limitations came from the fact that the analysis strategy was driven by the data rather than a priori. While being common, such a strategy might bias the results toward the identification of significant responses. Yet, in the case of Chein and Fiez, they also ran a parallel analysis from an a priori perspective and achieved similar results, thus reducing the risk of bias to mild (i.e., "some concerns").

Domains pertaining to missing data and to derivations from the intended interventions did not yield any risks for biases in all records selected for review. However, a majority of studies (66.67%) raised some concerns for the Randomization process domain. These concerns were related to the quasi-randomization used to generate the auditory sequences and their order of presentation. This practice is frequent in the literature on auditory distraction, e.g., to augment the deviation potential of a given deviant sound or to improve the disrupting power of an auditory sequence given the possibility for habituation (e.g., Debener et al., 2002; Friedman et al., 2001; Sörqvist et al., 2012a). Yet, such foreknowledge from the experimenter and the absence of a complete randomization process might have induced some bias in the outcomes measured. Overall, Ruhnau et al. (2013) and Chein and Fiez (2010) were thus related to higher risks of bias (driven by a posteriori analysis for Ruhnhau et al. and for a majority of moderate concerns for Chein and Fiez) while all other studies were considered having some moderate concerns.

Reviewed Studies Discussion

Among the 15 studies[7] sought for qualitative synthesis, nine records were related to the deviation effect and seven records to the changing-state effect.[8] Note that some studies presented more than one type of distracting sound. The mean number of valid participants across all the studies was 19.87 ($SD = 8.25$) with the lowest number being $N = 9$ (Campbell et al., 2007; Escera et al., 2003) and the largest being observed for Bell et al. (2010; $N = 34$). The following psychophysiological methods were found among all the records assessed for eligibility: EEG, magnetoencephalography (MEG), fMRI, pupillometry, electrocardiography, and electrodermal activity measures. Following records removal after the detailed assessment,

Table 1. Generic information of the 15 studies selected for review.

Record	Type of distraction phenomenon	Valid *N*	Psychophysiological method
Bell et al. (2010)	CS	34	EEG
Berti (2013)	Dev	16	EEG
Campbell et al. (2003)	CS	18	EEG
Campbell et al. (2007)[a]	CS	9	EEG
Chein and Fiez (2010, Exp. 1)	CS	14	fMRI
Do Vale et al. (2015)	Dev	21	EEG
Escera et al. (2001)	Dev	10	EEG
Escera et al. (2003)	Dev	9	EEG
Little et al. (2010)	CS	25	EEG
Mahajan et al. (2020)[b]	Dev	16	EEG
Marois et al. (2019)	CS/Dev	30	Pupillometry
Marois et al. (2020)	Dev	30	Pupillometry
Marois and Vachon (2018, Exp. 1)	Dev	30	Pupillometry
Ruhnau et al. (2013)[b]	Dev	20	EEG/MEG
Schlittmeier et al. (2011)	CS	16	EEG

Note. CS: Changing-state effect; Dev: Deviation effect; EEG: Electroencephalography; fMRI: Functional magnetic resonance imagery; MEG: Magnetoencephalography.

[a]While Campbell et al. (2007) also presented deviant sounds, no disrupting effect of the deviant was observed. Consequently, this paper is not analyzed under the lens of the deviation effect, but only for the changing-state effect.

[b]Although two different age populations were studied, we only focus on analyzing the younger adults to stay consistent with the population selection criterion, hence the *N* represents only this group.

only the first four measures remained (i.e., EEG, MEG, fMRI, and pupillometry). Table 1 presents the generic information of the 15 records selected for synthesis. A more detailed summary for each record included in the review can be found in the Supplementary Material.

Deviation effect

Nine studies included in the current review focused on the deviation effect (see Table 2). They either reported measures of EEG, MEG, or pupillometry. The task used varied between a visual serial recall task (Marois & Vachon, 2018; Marois et al., 2019, 2020), a digit categorization task (Berti, 2013; Escera et al., 2001, 2003), a face recognition task (Do Vale et al., 2015), a visual *n*-back task (Mahajan et al., 2020), and a visuospatial alternative forced choice task (Ruhnau et al., 2013). From an electrophysiological perspective, the reviewed studies were mainly related to three ERPs evoked by the deviant sound: the N1, the MMN, and the P3a. The N1 is often considered an index related to preattentional perceptual processing of a sound (Näätänen, 1990). The MNN typically reflects the preattentive cerebral mechanisms responsible for detecting irregularities in stimulus features and eliciting a "call-for-attention" to prepare the organism to better process any stimulus worthy of capturing attention (Escera et al., 1998; Näätänen, 1990; Schröger & Wolff, 1998; Winkler, 2007). The P3a is considered a reliable index of the actual reorientation of attention triggered by an irrelevant sound deviating from the auditory context (Escera et al., 1998, 2000; Friedman et al., 2001; Squires et al., 1975).

The elicitation of a larger N1 by deviant relative to standard sounds was reported by Berti (2013), Escera et al., (2001, 2003) and Mahajan et al. (2020) while the deviant-elicited MMN was only reported by Escera et al. (2001) and Ruhnau et al. (2013). In this context, one could consider the N1 and the MMN to represent an index of the deviation effect. It must be noted, however, that the magnitude of both ERPs failed to match the size of the observed deviation effects. In Berti (2013), novel sounds were presented both within a silent context and among repetitive steady-state sequences. While the amplitude of the N1 was larger for deviants presented in silence than embedded in steady-state sound, the deviation effect was of similar magnitude across both conditions. In Escera et al. (2001), novel environmental sounds (e.g., drill, hammer, or rain noise) induced longer response times than deviant (frequency) sounds, suggesting that the former were more disruptive than the latter. Yet, these two types of deviant induced an N1 and an MMN of similar amplitude. In Escera et al. (2003), both identifiable and unidentifiable environmental novel sounds were used and compared to standard sounds. Identifiable novels increased response times relative to both unidentifiable novels and standards, which showed similar response times. Still, the two types of novel sound provoked an N1 of similar amplitude, which was larger than that of the standard sounds. Taken together, this suggests that whereas deviant sounds are endowed with the power to trigger the N1 and the MMN, the mismatch between their amplitude and the size of behavioral disruption casts doubts about the potential of these ERPs to index the deviation effect. At best, their presence can indicate that a sound departing from the acoustic context in which it is presented has been detected by the auditory system.

The P3a reported in the reviewed literature (Do Vale et al., 2015; Escera et al., 2001, 2003; Mahajan et al., 2020; Ruhnau et al., 2013) seems to represent a response that is closer to the behavioral disruptive effect of deviant sounds. Indeed, there appears to be

Table 2. Characteristics of the studies related to the deviation effect.

Study	Physiological measure	Focal task	Distracting sound	Study design*	Main results
Berti (2013)	N1	Digit categorization	Deviant novel sound embedded within a no-tone or a SS sequence	Sound preceding visual digit	Deviants induced an increase in reaction time compared to steady-state sounds. Deviants in no-tone condition elicited larger N1 compared to deviants among standards, subsequent positive deflection elicited by deviants, earlier in no-tone trials.
Do Vale et al. (2015)	P3	Face recognition (neutral or negative faces)	Standard repeated tone burst vs. deviant environmental sound	Sound preceding face stimulus	Longer reaction time in deviant vs. standard trials, and in negative vs. neutral trials. Novelty P3 elicited by the deviants compared to standards, equivalent across both face conditions.
Escera et al. (2001)	N1, MMN, and P3a	Digit categorization	Standard repeated tone burst vs. deviant tone burst vs. deviant environmental novel sound	Sound preceding visual digit with short or long ISI	Relative to standards, both types of deviant disrupted digit categorization accuracy and increased response time with a larger effect for novels. Relative to standards, both types of deviant elicited an MMN, some N1 enhancement, and a P3a with larger P3a for novels. Overall, no effect of ISI.
Escera et al. (2003)[a]	N1 and P3	Digit categorization	Standard repeated tone burst vs. deviant environmental sound (identifiable or not)	Sound concurrent to digit	No effect on hit rate. Longer response times in identifiable novel trials compared to standard and non-identifiable novel trials. Larger N1 for deviants compared to standards, equivalent for identifiable and non-identifiable. P3 triggered by deviants compared to standards, larger P3 for identifiable than non-identifiable deviants (central).
Mahajan et al. (2020)[b]	N1, P2, and P3a	Visual *n*-back (0-back or 1-back)	Standard repeated tone burst vs. deviant environmental sound	Sound preceding visual digit	Response times increased in deviant trials similarly across 0-back and 1-back tasks. Deviants elicited larger N1, P2 and P3a compared to standards, similar amplitude across both task difficulties.
Marois et al. (2019)[c]	PDR	Visual serial recall	Steady-state letters with or without deviant (pink noise) vs. changing letters with or without deviant (pink noise)	Sound concurrent to TBR visual material	Deviants embedded in both SS and CS sound disrupted recall equally. Deviants elicited a PDR (relative to equivalent standards) of similar amplitude in SS and CS conditions.
Marois et al. (2020)	PDR	Visual serial recall	2 alternating letters vs. 2 alternating letters with deviant novel letter vs. 2 alternating letters with deviant repetition	Sound concurrent to TBR visual material	Novel and repetition deviants equally disrupted recall. PDR for both types of deviant compared to SS sounds, with larger PDR for novel than repetition deviants.
Marois and Vachon (2018, Exp. 1)	PDR	Visual serial recall	Steady-state letters with vs. without deviant (different voice, letter or word)	Sound concurrent to TBR visual material	Recall disruption in deviant trials. PDR for deviants compared to SS sounds. Positive correlation between the size of behavioral and physiological effects.
Ruhnau et al. (2013)[b]	MMN and P3a magnetic responses	Visuospatial alternative forced choice	Standard repeated tone burst vs. deviant environmental sound	Sound preceding visual stimulus	Increased reaction time in deviant trials. Larger MMN elicited by deviants compared to standards (central and parietal). Larger P3a for deviants compared to standards, early and late mismatch response observed around superior temporal gyrus and sulcus, including primary auditory cortex (left lateralized for early response, right lateralized for late response).

Note. ISI: Interstimulus interval; MMN: Mismatch negativity; PDR: Pupillary dilation response; TBR: To-be-remembered.
*All studies used a within-subject design.
[a]Only the results of the auditory-visual condition are reported to respect the distraction paradigm selection criterion.
[b]Although two different age populations were studied, we only focus on analyzing the younger adults to stay consistent with the population selection criterion.
[c]Only the analyses related to the deviation effect, and not those for the changing-state effect, are reported.

a correspondence between the magnitude of the detrimental impact of the deviant sound on behavioral performance and that of the deviant-elicited P3a component. In the studies of Escera et al., (2001, 2003) the type of deviant sound impacted the size of the deviation effect on response times and the amplitude of the P3a in a similar fashion. More specifically, the longer response times found with environmental deviant sounds compared to deviant tone bursts (Escera et al., 2001) as well as with identifiable (or meaningful) deviant sounds relative to unidentifiable (or meaningless) deviant sounds (Escera et al., 2003) were accompanied by a larger P3a. In their study, Mahajan et al. (2020) assessed the impact of working memory load on distraction by auditory deviation by contrasting the behavioral and electrophysiological effects of a deviant tone across a condition requiring working memory (1-back) and a condition that did not (0-back). In a group of young adults, the deleterious effect of presenting a novel sound on response time was similar across the 1-back and 0-back conditions. The pattern of behavioral results also matched the pattern of ERP results; younger adults showed similar amplitude of the deviant-elicited P3a in the 0-back and 1-back tasks. Mahajan and colleagues also reported data collected from a group of older adults. They outlined a reduction of the disruptive impact of the deviant sound on response times in the 1-back condition relative to the 0-back condition, indicative of a shielding effect of an increase in the level of task engagement against distraction (cf. Hughes et al., 2013; Marsh et al., 2020; SanMiguel et al., 2008). Consistently, the amplitude of deviant-elicited P3a was attenuated in the 1-back task compared to the 0-back task. Despite the difference in the distraction shielding effect of working memory load between younger and older adults, findings from Mahajan and colleagues revealed that variations in the amplitude of deviant-elicited P3a can be found only when the size of behavioral distraction is modulated accordingly. Finally, in studying the effects of steroids on emotional processing, Do Vale et al. (2015) also reported that the failure to modulate the amplitude of behavioral deviant distraction was associated to an absence of change in the size of deviant-triggered P3a. Taken together, these findings exposed a correspondence between the magnitude of behavioral and electrophysiological distraction by auditory deviations, whereby the amount of behavioral impairment induced by deviant sounds and the amplitude of deviant-elicited P3a seemed to vary accordingly.

The last two responses raised by the records of the current review relate to MEG and pupillometry. Ruhnau et al. (2013) observed both early and late mismatch magnetic responses to deviant sounds. According to the authors, these responses represent deviance-related responses similar to the MMN. These responses were mainly observed in the primary auditory cortex and the superior temporal gyrus and sulcus. The early response could be found in both hemispheres, but more largely in the left hemisphere while the late response was more important in the right hemisphere. The authors considered the late mismatch response to represent deviance detection and target discrimination mechanisms. These conclusions are consistent with those raised by the literature on MMN and the deviation effect where the former would activate a "call-for-attention" that may result in the latter (Escera et al., 1998, 2001; Näätänen, 1990; Schröger & Wolff, 1998; Winkler, 2007).

As for pupillometric responses, the records sought for review were related to three published papers (Marois et al., 2019, 2020; Marois & Vachon, 2018, Exp. 1).

In these papers, the PDR – a phasic rapid dilation of the pupil aperture – was used to index deviance distraction observed while participants performed a visual serial recall task. A PDR was elicited following the presentation of deviant sounds, whether they induced an unexpected change in the acoustic properties of the auditory sequence (Marois & Vachon, 2018; Marois et al., 2019), or they violated a repetitive alternating pattern (Marois et al., 2020). In Marois et al. (2019), a deviant sound (pink noise) was inserted among both steady-state and changing-state spoken letters. Consistent with previous work (see Hughes et al., 2007), the deviation effect observed in both steady-state and changing-state conditions was similar in magnitude. Similarly, the amplitude of the deviant-elicited PDR was similar across both contexts. In Marois and Vachon (2018, Exp. 1), a significant positive correlation was found between the amplitude of the PDR elicited by the deviant and the magnitude of the deviation effect; the larger the behavioral disruption, the larger the PDR. Yet, inconsistent results were found in Marois et al. (2020). In this study, performance on the visual serial recall task was hindered to a similar extent by deviants breaking the alternation pattern between two spoken letters, regardless of whether it was a novel letter absent from the sequence or a repetition of one of the two letters forming the alternating pattern. However, the PDR elicited by the deviant repetition was smaller than the PDR triggered by the deviant novel. Therefore, it seems that the magnitude of PDR does not perfectly match that of the deviation effect. Nonetheless, similar to the P3, its elicitation seems to indicate the engagement of attention-capture mechanisms.

Regarding the debate around the underlying mechanisms of auditory distraction, little information can be extracted from the records identified above. As indicated earlier, both proponents of the unitary and duplex-mechanism accounts ascribe the deviation effect to attentional capture. A difference between these two theoretical positions however lies in what can be construed as a deviant sound. For the unitary account, a deviant represents any new sound whose characteristics are absent from the neural model, which registers an aggregate of the recent auditory past. From the duplex-mechanism viewpoint, a deviant possesses acoustic characteristics that violate the expectations ensuing from any algorithm extracted from the regularities of the auditory environment. In the studies reviewed, only Marois et al. (2020) focused on comparing two types of deviation and on controlling novelty vs. expectation violation. The observation that a repetition deviant is endowed with the power to trigger a significant PDR is congruent with the algorithmic view of the neural model adopted by the duplex-mechanism account while being incongruent with the aggregate view of the unitary account. Indeed, the PDR was evoked because the unexpected repetition of a sound in an otherwise non-repeated auditory sequence violated implicit predictions extrapolated from the alternating pattern characterizing the irrelevant auditory sequence and registered into the neural model. As predicted by the duplex-mechanism account, acoustic novelty is not necessary for attentional capture – hence the PDR – to take place. From the unitary account perspective, the repetition of a sound just presented should have instead reduced the potential of that sound to elicit a PDR because its acoustic properties were already represented within the neural model and, therefore, were not registered as novel relative to the recent auditory past.

Changing-state effect

Seven studies identified for synthesis concerned the changing-state effect (see Table 3). These studies comprise EEG, fMRI, and pupillometric measures. The bulk of the literature identified for synthesis mainly employed EEG measures. The focal task always implied seriation processes. Overall, much information can be extracted from the literature reviewed in this section. First, it seems that changing-state sound is mainly related to the elicitation of the N1, which is particularly potent in frontal areas (Bell et al., 2010; Campbell et al., 2003, 2007; Little et al., 2010). Yet, as noted by Campbell et al., (2003; see also Little et al., 2010) the elicitation of the N1 does not necessarily map exactly the presence of performance disruption by changing sound given that such distraction was sometimes absent despite the observation of an N1. Therefore, the presence or absence of an N1 response does not contribute to resolving the debate surrounding the mechanisms of the changing-state effect. Indeed, this ERP typically reflects preattentional perceptual processing of the sound. Even if its amplitude can be increased in the face of novelty or predictions mismatch (Näätänen, 1990) as a call-for-attention for generating further attention-orienting ERPs, its presence does not systematically incur attention switching. Besides, as stated by Little et al. (2010), the frontal distribution of the N1 and its association with attention areas can be construed as evidence of an increase in the amount of attentional resources necessary to process the order of the to-be-remembered material caused by the interference of the to-be-ignored sound (cf. the duplex-mechanism account).

While the N1 might not represent a specific proxy for the changing-state effect, Schlittmeier et al. (2011) suggested that the target-induced gamma band could serve this purpose as such oscillatory activity is deemed reflecting the interruption of task-relevant processes. The authors identified seriation processes as a potential victim, in line with the duplex-mechanism account, which construes the changing-state effect as a consequence of the ineluctable competition between controlled processing of the order of the to-be-remembered material and the automatic seriation processing of the to-be-ignored sound (Hughes, 2014; Hughes et al., 2005, 2007; Sörqvist, 2010). Still, Schlittmeier et al. also stated that the reduction in gamma band could be viewed as evidence of attention disengagement. This hypothesis rather serves the unitary account and the fact that performance disruption by changing sound would rather incur from auditory attentional capture (Bell et al., 2010, 2012; Chein & Fiez, 2010; Cowan, 1995; Elliott, 2002; Rinne et al., 2006).

Results from Bell et al. (2010) would also be consistent with this latter viewpoint; indeed, they observed P3a responses to the presentation of changing sound, an ERP that has been systematically ascribed to attention reorientation (e.g., Demiralp et al., 2001; Escera et al., 1998; Gumenyuk et al., 2004). Indeed, the P3a response is considered a strong and reliable index of the attention capture triggered by deviant sounds. Yet, Bell et al.'s study is the only one reporting this effect; Campbell et al. (2003, 2007) failed to observe such a response to changing-state sound. Moreover, the words used by Bell et al. to build the irrelevant speech sequences had a mean frequency of 8/1,000,000 in the German language (Baayen et al., 1993), which has been shown to possess important attention-grabbing power (Buchner & Erdfelder, 2005; but see Elliott & Briganti, 2012). One could then argue that the attention capture (and P3a) produced by their changing-

Table 3. Characteristics of the studies related to the changing-state effect.

Study	Physiological measure	Focal task	Distracting sound	Study design*	Main results
Bell et al. (2010)	N1 and P3a	Visual serial recall	Silence vs. SS one-syllable words vs. CS one-syllable words	Sound concurrent to TBR material and during and retention	Incremental performance disruption from silence, to SS to CS words. Larger N1 for CS than SS sound (central and medial anterior), followed by larger positive frontal deflection (P3a).
Campbell et al. (2003)	P1, N1, and P2	Visual serial recall	1-token vs. 2-token vs. 5-token syllabes	Sound during retention	Increase in error production in 5-token trials. Reduction in P1 and P2 and increase in N1 at frontal locations with increases in set size. Increase in N1 at anterior-frontal sites apparent only for increments in set size from 1 to 2 tokens.
Campbell et al. (2007)[a,b]	N1 and MMN	Visual serial recall	SS letters vs. SS letters with deviant vs. CS letters	Sound concurrent to TBR material and during and retention	CS letters disrupted recall. Earlier peak latency of the N1/MMN complex for CS sound compared to SS and deviant (frontocentral and mastoid), amplitude of N1 increased from SS sound to CS sound to deviant, more important at anterior frontal and central.
Chein and Fiez (2010, Exp. 1)	BOLD response	Probed order recall	Silence vs. silent articulatory suppression vs. CS digits between 1 and 4 vs. CS 5-token white noise bursts	Sound concurrent to TBR material	Increase in performance from articulatory suppression condition, to CS digits, to CS noise bursts and to quiet condition, respectively. Reduced and later activity in working memory areas (anterior cingulate, left dorsal and ventral inferior frontal, bilateral anterior insula, left basal ganglia) for CS speech condition compared with silence, similar results for CS non-speech, increased activity in these regions for silent articulatory suppression.
Little et al. (2010)	N1	Visual serial recall (phonologically dissimilar or similar consonants)	SS and CS spoken words vs. SS and CS correlated noise	Sound concurrent to TBR material and during and retention	Both words and noises produced a CS effect (larger for words). With phonologically dissimilar TBR material, larger N1 for CS words and sounds compared to silence and larger N1 for CS words than CS sounds (frontal); with phonologically similar TBR items, larger N1 for SS sound than silence (frontal).
Marois et al. (2019)[a]	PDR and pupil size	Visual serial recall	SS letters with or without deviant (pink noise) vs. CS with or without deviant (pink noise)	Sound concurrent to TBR material	Performance disruption by CS sound (with and without deviant) compared to SS equivalents. Larger tonic pupil size across the whole trials and absence of PDR for CS sound compared to SS sounds.
Schlittmeier et al. (2011)	EEG power bands	Visual serial recall	SS pink noise vs. SS (1-token) syllable vs. CS (3-token) syllables	Sound concurrent to TBR material	Recall performance disrupted in CS condition. Early positive cluster for SS noise compared with other conditions followed by larger negative cluster for CS sound (frontocentral), early gamma-band reduction for CS sound and inferior theta-power band for CS sound compared to SS noise (left frontotemporal).

Note. BOLD: Blood-oxygen-level dependent; CS: Changing-state; EEG: Electroencephalography; MMN: Mismatch negativity; PDR: Pupillary dilation response; SS: Steady-state; TBR: To-be-remembered.

*All studies used a within-subject design.

[a]Only the analyses related to the changing-state effect, and not those for the deviation effect, are reported.

[b]The impact of deviant sound on this study were not reported in the deviation effect section given the absence of a significant performance disruption elicited by the deviants.

Table 4. Summary of the physiological responses observed in the auditory distraction studies reviewed.

Response	Deviation effect (*n* = 9)	Changing-state effect (*n* = 7)
N1	4	4
P1	1	0
P2	1	1
MMN	2	0
P3	5	1
Theta-band reduction	0	1
Gamma-band reduction	0	1
BOLD activity in working memory areas	0	1
Phasic PDR	4	0
Tonic pupil diameter	0	1

state sound rather tapped into processes of attention capture not because of their changing nature, but rather because of their scarcity in the German language (Marois et al., 2019).

The only study that has looked at the changing-state effect using pupillometry revealed the absence of change-elicited PDR (Marois et al., 2019), suggesting that changing sounds do not elicit any attentional response, as predicted by the duplex-mechanism account. Such a finding is also inconsistent with the position of the unitary account that disruption by changing-state sound ensues from a succession of deviants that repetitively capture attention from the serial recall task. Yet, Marois et al. (2019) also reported an enlargement of the pupil diameter throughout changing-state trials relative to their steady-state counterparts. Given tonic pupil size is deemed reflecting mental effort, whereby increased effort translates into increased pupil size until processing resources are exceeded (see Beatty, 1982; Mathôt, 2018), this finding provides support to the unitary account, which posits that the processing of changing-state sound consumes a larger amount of cognitive resources – hence produces larger disruption – than steady-state sound. Since changing sounds failed to triggered attention-orienting PDRs, Marois and colleagues, following the precepts of the interference-by-process view of the changing-state effect embraced by the duplex-mechanism account, hypothesized that this increased tonic pupil size could instead reflect the greater mental effort entailed by the need to resolve the conflict between the deliberate seriation processes involved in the serial recall task and the automatic ordering of the irrelevant changing sounds, possibly through inhibitory mechanisms (cf. Hughes et al., 2007). It must however be noted that Marois et al.'s demonstration of larger tonic pupil size during exposure to changing sound has not been replicated yet, and so this result must be taken with caution.

The inferior cerebral BOLD activity measured in working memory areas reported by Chein and Fiez (2010, Exp. 1) seems inconsistent with the duplex-mechanism account. As stated by the authors, such an effect may support reduced attention toward the to-be-remembered content supporting that changing sounds can trigger attention reorientation. BOLD activity in working memory areas has however been previously positively correlated with memory performance (e.g., D'Esposito et al., 2000; Jansma et al., 2004; Rypma et al., 1999), and more particularly with optimal manipulation and maintenance of task-relevant material. Negative correlations between BOLD activity in some memory-related areas and level of interference have also been reported (Bomyea et al., 2018; Gruber & von Cramon, 2003). Hence, the reduction in working memory areas observed by Chein and Fiez could also be driven by mechanisms of interference between controlled and automatic seriation processes. Besides, other studies have shown that deviant sounds can in fact increase BOLD activity in these regions (Halgren et al., 1998; McCarthy et al., 1997; Polich, 2007). This means that a reduction in BOLD activity does not necessarily represent attention reorientation (i.e., disengagement from the to-be -remembered item followed by reorienting toward the to-be-ignored sound), hence challenging the unitary account interpretation.

Discussion

The goal of this scoping review was to outline the literature related to the psychophysiological responses elicited by distracting auditory stimuli. To do so, we went through an online search of PubMed, ERIC, PsycNet, Web of Science and ScienceDirect databases for studies that used psychophysiological measures to assess auditory distraction with evidence of behavioral performance disruption. Over the 589 sources found, 15 studies were selected for review. This comprised nine studies on the deviation effect and seven on the changing-state effect (one study addressed both phenomena). Two studies raised higher risks of bias, mainly driven by measurement outcome limitations and a high number of moderate concerns, while all other studies raised some concerns, especially because of the existence of a large variety of physiological analysis strategies. Overall, the main physiological responses elicited by distracting sound that were extracted from the literature covered could be measured using EEG, MEG, fMRI, and pupillometry. These responses were: a) for the deviation effect, the N1, the MMN, the P2, and the P3 of the ERPs, as well as the PDR; and b) for the changing-state effect, the N1, P1, P2, and P3a of the ERPs, BOLD activity in working memory areas, gamma-band and theta-band activity, and tonic pupil size.

Overall, it seems that some physiological responses seem more specific to certain auditory distraction phenomena whereas others seem to be generally present, regardless of the type of disrupting stimuli. The N1 response seems to be elicited by all distracting sounds irrespective of their nature, that is, in the context of either the deviation effect (Berti, 2013; Escera et al., 2001, 2003; Mahajan et al., 2020), or the changing-state effect (Bell et al., 2010; Campbell et al., 2003, 2007; Little et al., 2010). This means that the N1 might be sensitive to auditory distraction but lacks specificity. The MMN seems however more specific to the deviation effect as it was observed only in studies employing deviant sounds embedded into a steady-state auditory stream (Escera et al., 2001; Ruhnau et al., 2013) and absent for all the studies related to the changing-state effect. P3 responses also appear mostly related to the deviation effect (Do Vale et al., 2015; Escera et al., 2001, 2003; Mahajan et al., 2020; Ruhnau et al., 2013; but see Bell et al., 2010). Finally, it seems that the PDR is observed for deviant sounds (Marois & Vachon, 2018; Marois et al., 2019, 2020), but not changing-state sounds (Marois et al., 2019). Other responses (i.e., gamma-band increase, theta-band reduction, tonic pupil size, P1, P2 and BOLD activity in working memory areas) may lack evidence because they were only observed in single studies across the literature collated in the current scoping review. Table 4 presents all the responses observed in the studies collated, as well as the number of studies in which they were observed for each paradigm.

From the results collated and their interpretations, only Marois et al. (2019) and Marois et al. (2020) possess strong evidence favoring the duplex-mechanism. In fact, these are the only studies, to our knowledge, that were tailored-designed to tease apart the unitary and duplex-mechanism accounts using psychophysiology. All other studies either had no evidence favoring one of the two perspectives (e.g., most of the studies focusing only on the deviation effect) or, as presented in each section, their results could also be interpreted from the opposite viewpoint. However, from a more general perspective, the pattern in physiological responses elicited by the different studies can also shed light on the underlying mechanisms of auditory distraction. The fact that the N1 potential could be observed in relation with the deviation effect and the changing-state effect supports that auditory distraction might be driven by common mechanisms regardless of the nature of the disrupting sound. Yet, the fact that the P3 component (Do Vale et al., 2015; Escera et al., 2001, 2003; Mahajan et al., 2020; Ruhnau et al., 2013) and the PDR (Marois & Vachon, 2018; Marois et al., 2019, 2020) are elicited almost exclusively by deviants sounds and not by (non-deviant) changing sounds undermines the unitary account perspective. First, it indicates that deviant and changing sounds are functionally distinct. Second, since these two biomarkers are deemed reflecting the attentional response to a stimulus, it argues against an interpretation of the changing-state effect in terms of a succession of orienting responses to attention-grabbing distractors.

Generally, the current scoping review provides evidence favoring the duplex-mechanism account given the psychophysiological indices found to be specific to certain auditory distraction effects. Indeed, the specificity of the MMN, P3 and PDR to the deviation effect (and their general absence among changing-state studies) supports the idea that performance disruption from a deviant sound embedded within an invariant/predictable auditory stream is underpinned by attention capture. More studies will be necessary to further confirm whether these responses are really specific to the deviation effect. To better contribute to resolving this debate, future studies should focus on examining both the deviation and the changing-state effects concurrently with the same set of physiological responses (cf. Marois et al., 2019). As suggested by Körner et al. (2017), most of the studies interested in the unitary and duplex-mechanism account rely on different experiments, across different individuals and designs. This can preclude optimal comparison between the effects given that methodological differences may explain how both phenomena vary or not.

Implications and Future Directions

Results of the current scoping review outlined the main physiological markers of auditory distraction, more specifically those related to the deviation effect and the changing-state effect. Some insight could also be found with regard to the debate around the underpinnings of auditory distraction. Globally, these results can benefit researchers from the auditory distraction community interested in assessing the impact of distracting sounds across different experimental setups. While behavioral measures can generally provide information about the disrupting power of sound, they can sometimes lack sensitivity. For example, the absence of behavioral impairment does not necessarily mean that no distraction took place, as there are instances where a deviant-elicited attentional response, as measured by the PDR, was observed in the context of very easy, undisrupted behavioral tasks (e.g., Marois & Vachon, 2018; Marois et al., 2018). In other cases, deviant-evoked attentional responses of various amplitudes led to a similar amount of behavioral disruption (e.g., Marois et al., 2020). Physiological responses can represent interesting indices that can complement the information provided by classical behavioral measures, or even help studying auditory distraction in contexts where no behavioral measurements can take place. Given that the current review focused only on the physiological responses observed along with behavioral disruption, this means that the indices reviewed herein might have potential to complement behavioral indices, e.g., when the ongoing task does not allow proper collection of performance metrics. Such could be the case with tasks impervious to auditory distraction or too sensitive to performance disruption by sound (e.g., Campbell et al., 2007; Marois & Vachon, 2018; Marois et al., 2018).

Outside of the lab, the physiological markers identified in this review could also be useful to assess in real time the presence of auditory distraction. The emergence of new technologies allows more and more for the development of capabilities that collect physiological data and provide information on the state of users. Multiple applied domains, including the military (Friedl, 2018; Salvan et al., 2022) or the field of human-machine collaboration (Blackhurst et al., 2012; Parnandi et al., 2013; Zhao et al., 2020), have become interested by such an approach. Physiological state-driven adaptive systems could be of use for operational domains where auditory alarms and other sound-related media provide key information to the operator (e.g., in intensive care units, security surveillance rooms, air traffic control operation centers, or in aircraft cockpits; Ahlstrom & Panjwani, 2003; Dehais et al., 2014; Hodgetts et al., 2017; Momtahan et al., 1993). Relying on these proxies, a system could be able to detect whether a particular sound has induced any desirable (or undesirable) distracting effect. This capability could serve well an automated system responsible for triggering actions designed to promote the conscious detection of the alarm or to execute automatically a relevant countermeasure related to the alarm. With the increase in portability of several physiological measurement tools such as head caps, glasses, garments and embarked systems (see, e.g., Friedl, 2018; Marois et al., 2020; Salvan et al., 2022), such an application could become possible in the near future.

Nevertheless, multiple considerations still need to be addressed to fully understand the full list of physiological markers of auditory distraction. Indeed, several questions related to auditory distraction or more generally to physiological measures remain unanswered by the current scoping review. These questions, which can be split into three categories, should be addressed more comprehensively in future studies.

Cognitive load and mental effort

The first aspect that should be considered is the effect of cognitive load on the measures of auditory distraction. As outlined previously, higher cognitive load of the ongoing focal task has been shown to reduce the deviation effect (Hughes et al., 2013; Marsh et al., 2015, 2020; but see Kattner & Bryce, 2022). This means that when task demands increase, the difference in performance between deviant and standard trials tends to disappear. Previous research outlined that an increase in cognitive load could induce a lower brainstem response (Sörqvist et al., 2012) as well as a reduction in the auditory-temporal cortex response (Sörqvist et al., 2016). Such an impact on brain activity would be the cause of a cross-modal suppression of the neural activity elicited by the distractor modality (i.e., the auditory modality; Weissman et al., 2004). The cognitive control of the deviation effect can thus be construed as a by-product of the increase in brain activity related to attention and working memory processing for the task-relevant stimuli (Sörqvist et al., 2016). Therefore, an increase in cognitive load should modulate the amplitude of distraction-related physiological responses. This seems to be the case with the P3a, where a high-load context reduces the emergence of the P3 response following a deviant (Causse et al., 2016; Giraudet et al., 2015; SanMiguel et al., 2008). To our knowledge, however, the sensitivity of the amplitude of deviant-evoked PDR to cognitive load has yet to be tested. It is therefore necessary to demonstrate that the size of the PDR to deviant sounds should decrease along with behavioral disruption under contexts of high cognitive load.

Once demonstrated, the PDR and the P3a could then be used as markers of attentional capture in studies designed to investigate the impact of cognitive load on both the deviation and changing-state effects. The duplex-mechanism account predicts the effects of cognitive load to be restricted to forms of distraction underpinned by attentional capture. Hence, under high load, the magnitude of both the deviation effect and the deviant-elicited biomarkers (i.e., the P3a and the PDR) should be reduced while that of the changing-state effect should remained unaffected. From the unitary account viewpoint, the decrease in the size of the deviation effect and of the P3a and/or PDR under high load should also take place for the changing-state effect. Besides, if an increase in cognitive load decreases background sound processing (Sörqvist & Marsh, 2015; Sörqvist et al., 2012, 2015, 2016), one would expect that high cognitive load could also reduce the magnitude of the changing-state effect as it attenuates the peripheral processing of the acoustical change within the irrelevant auditory channel. While this hypothesis has been generally challenged at the behavioral level (Hughes & Marsh, 2019; Hughes et al., 2013; Kattner & Bryce, 2022; Marsh et al., 2020), no study has yet examined the impact of cognitive load on the elicitation of physiological markers of the changing-state effect. As such, measures such as EEG theta bands or fMRI BOLD response in working memory areas could be used to investigate how cognitive load might affect the cerebral activity induced by changing sound. Overall, the moderating impact of cognitive load on the physiological markers of auditory distraction needs to be better understood in order to anticipate any variations in the physiological signal measured and to correctly ascribe it to variations in load, and not to the sole effect of auditory distraction.

Fundamental to the unitary account is how the processing of irrelevant sound may draw cognitive resources away from the ongoing task and result in performance costs. Accordingly, changing-state distractors tend to recruit more processing resources than steady-state distractors because of their larger mismatch with the content of the neural model, which leaves less resource available to execute the focal task and leads to more performance disruption (e.g., Bell et al., 2019a). Given that tonic pupil size is an index of mental effort, that is, the deployment of cognitive resources, pupillometry could become a tool to test the predictions of the unitary account. Consistent with an attentional view of the changing-state effect, Marois et al. (2019) reported larger tonic pupil diameter in changing-state trials relative to steady-state trials. Of course, this sole demonstration would need to be replicated. The addition of appropriate controls such as a silent condition could also help to determine to what extent repeated sounds consume processing resources to produce a "steady-state effect" (cf. Bell et al., 2019a). Pupillometry could also enable testing the proposition of Bell et al. (2021; see also Bell et al., 2013) that the absence of changing-state effect in the context of the missing-item task (e.g., Beaman & Jones, 1997; Hughes et al., 2007) is not due to the fact that this task does not require memory for serial order, as suggested by the duplex-mechanism account, but simply because the task is less cognitively demanding than serial recall, making it less sensitive to resources being drawn away by changing-state sound. From that viewpoint, tonic pupil diameter should be smaller during the encoding phase of the missing-item task than during the same phase of a task known to be susceptible to disruption by changing-state auditory distractors such as the serial recall task or the probe task. Moreover, this account predicts that increasing the demand for processing resources in the context of the missing-item task, as indexed by an enlargement of tonic pupil size, should increase the likelihood to observe a changing-state effect.

Postcategorical auditory distraction

Postcategorical processing represents a second component that must be addressed in future studies. Analysis of the semantic properties of the distracting sound – added to those related to precategorical acoustic properties – can sometimes induce further performance disruption and might need to be considered when trying to measure the distracting effects. For example, there is evidence that performance can be disrupted by the insertion in the auditory stream of a spoken item that deviates from the semantic context characterizing the auditory sequence, such as a change in semantic category (e.g., a spoken letter inserted within a series of spoken digits; Labonté et al., 2021; Littlefair et al., 2022; Vachon et al., 2020) or a word that is semantically unexpected (Röer et al., 2019, 2022). In both the categorical deviation effect and the semantic mismatch effect, respectively, it was not the individual meaning of the mismatching item that entailed it with distracting power, but rather a violation of the expectations derived from the semantic content of irrelevant sound. Logically then, these forms of distraction were first ascribed to attentional capture. Yet further investigation challenged this assumption. For instance, both phenomena are not subject to habituation (e.g., Littlefair et al., 2022; Röer et al., 2019), which is at odds with the attenuation of the attention-grabbing power of deviant sounds over time (e.g., Marois et al., 2018; Vachon et al., 2012). Contrary to attentional capture, the categorical deviation effect seems immune to top-down cognitive control. Indeed, the magnitude of the phenomenon remained unaffected by top-down control manipulations (Vachon et al., 2020) and was not predicted by individual differences in the ability to control attention, as measured through working memory capacity (Labonté et al., 2021). Another potential candidate mechanism is the semantic version of interference-by-process, whereby the semantic activation of the to-be-ignored sound competes with the semantic representations activated through the deliberate semantic processing of the task-relevant items, hence disrupts focal task performance (e.g., Marsh et al., 2008, 2009; Sörqvist et al., 2010). However, since the categorical deviation effect was found regardless of the processes involved in the focal task and of the type of stimuli used as task-relevant items and irrelevant speech (Vachon et al., 2020), it is unlikely that this form of distraction is underpinned by interference-by-process.

Hitherto, behavioral data has been insufficient to identify the origins of the categorical deviation effect and the semantic mismatch effect. Hence psychophysiological markers could be of good help in uncovering the mechanisms underlying these postcategorical forms of auditory distraction. For example, if precategorcial and postcategorical deviation effects are underpinned by distinct mechanisms, one might expect biomarkers of the response to acoustic deviations to differ from those that would index the response to semantic deviations. And yet postcategorical deviation effects have been shown to be particularly resistant to several manipulations, hence the report of numerous statistically null effects, leaving the door open to various alternative explanations. In such a context, markers of attentional orienting as sensitive as the PDR and the P3a could serve useful to determine with more certainty whether the disrupting impact of semantic deviants is driven by attentional capture or not. Literature in language processing also reveals a range of ERPs that are sensitive to the semantic context in which stimuli are embedded, but that were not addressed by the current scoping review. For instance, the N400 component has been shown to be sensitive to semantic anomalies (see Kutas & Federmeier, 2011, for a review) while the P600 component can be found in response to syntactic violations (see Kutas et al., 2006, for an overview). There is also the semantic prediction potential (SPP), which exhibits greater amplitudes in the interval preceding expected versus unexpected critical words (Pulvermüller & Grisoni, 2020). Despite the existence of different theories of these components' functional significance (e.g., Brouwer et al., 2017; Grisoni et al., 2021; Kutas & Federmeier, 2011), assessing the potency of semantic auditory deviants to elicit such components could help to better understand the mechanisms underlying their distractive power.

Physiological and behavioral correspondence

While auditory distraction can be considered as an "all-or-nothing" phenomenon (e.g., whether a deviant sound has captured or not captured attention from the ongoing task; but see the graded view of attention capture, Bell et al., 2019a), performance disruption can in fact be of different amplitude according to the magnitude of interference from the distracting sound. For instance, deviant sounds of different degrees of divergence according to the auditory context may elicit physiological responses of different amplitudes with larger divergences related to larger physiological responses (Liao et al., 2016; Marois et al., 2018). This amplitude has sometimes been associated with the magnitude of performance disruption (e.g., Marois & Vachon, 2018, Exp. 1), while it is sometimes unrelated (e.g., Marois & Vachon, 2018, Exp. 2).

The distinction between the behavioral impact of sound as opposed to the elicitation of the physiological response may be mainly driven by the specific mechanisms involved in that response. For example, Näätänen (1990) proposed that the brain activity responsible for generating the N1 is closely related to the conscious detection of onsets, energy changes or transitions within a sequence of sound. Yet, even if attention is not necessarily oriented toward said sound (e.g., if the sound is not characterized by sufficient attention-grabbing power), the population of neurons related to the emergence of the N1 may still be engaged to a certain level (i.e., to process a "call-for-attention" that is subsequently denied as the threshold is not exceeded). In this situation, evidence for a certain level of brain activity (i.e., via the N1) may be recorded, but no specific performance disruption may be observed given that the sound is successfully ignored (cf. Campbell et al., 2003). Other situations of misalignment between behavior and physiology can also be caused by the focal task. For example, in Marois and Vachon (2018, Exp. 2), deviant sounds successfully elicited significant PDRs as opposed to control, steady-state sounds while participants were performing a reading comprehension task. Yet, despite that significant PDRs were elicited by the deviants (thus suggesting that they captured attention), no performance disruption on the focal task was observed. This could be explained by factors inherent to the task (e.g., participants had time to recover from attention being momentarily drawn away from the text and re-read disrupted passages) and to the properties of the sounds (e.g., a lack of meaningfulness of the deviants with respect to the text to read).

Another consideration lies in the fact that participants, in some studies, may try to overcome or compensate for distraction by being more engaged and trying harder to inhibit the distracting sounds (see Sörqvist & Marsh, 2015, for a discussion). More deliberate task-engagement could maintain task performance at a high level in the presence of irrelevant sound (e.g., Marsh et al., 2020), sometimes to a level as high as in silence. In such cases, the absence of disruption relative to a control condition could then be confounded with a lack of distraction. The sensitivity of tonic pupil diameter to mental effort (cf. Beatty, 1982) could enable detecting the effects of deploying further engagement – or effort – in the focal task, hence promoting a better comprehension of the processing dynamics between task engagement and auditory distraction. Understanding the relationship between behavioral and physiological responses (or absence thereof) could give more granularity to using certain physiological responses at the profit of others potentially unrelated to the extent of performance disruption.

Limitations

While the current review provides a general portrait of the literature on the physiological markers of auditory distraction, it contains some limitations that must be addressed. First, the type of distraction was sometimes difficult to define and, for that reason, some studies were removed from the review. For example, some authors consider virtually any distraction by sound as the irrelevant sound effect. Changing sounds are sometimes considered by proponents of the unitary account as deviant sounds presented repetitively. This can mitigate comparisons of physiological markers across the diverse auditory distraction phenomena.

Second, some physiological responses were not reported in the current review because of the exclusion criteria. This means that the list proposed herein is not exhaustive and is influenced by the criteria of the scoping review. For example, Potter et al. (2018) reported variations in electrocardiographic measures following the presentation of irrelevant sound during a task. However, the study possessed no control condition and was thus excluded. Another example relates to a study conducted by Berti et al. (2017) where the authors measured skin conductance response while participants remained passive or did a task without any behavioral performance measure. Many papers used an auditory discrimination task where participants must attend to the auditory stimuli and react on specific properties of the sound (e.g., Horváth et al., 2009; Jankowiak & Berti, 2007; Steiner & Barry, 2011, 2014;

Wetzel et al., 2013). However, in this case, the sound was considered task-relevant and, hence, the study was not considered for review. All these physiological markers could still potentially represent psychophysiological indices of auditory distraction and could ultimately inform on the underpinnings of auditory distraction. Future studies should try to evaluate their potential in a context more typical of auditory distraction paradigms.

Third, all task-specific responses were excluded from the review. Electrophysiological markers not related directly to the emergence of the distraction were also excluded. For instance, this is the case of the RON, which represents the subsequent disengagement of attention from the distractor toward the focal stimuli (e.g., Munka & Berti, 2006; Scheer et al., 2016). As briefly stated earlier, literature on auditory distraction and EEG has considered the MMN, P3a and RON to be the triumvirate of ERPs related to the deviation effect (see Horváth et al., 2008, for a discussion). Our choice not to address findings related to the RON may thus seem surprising. However, this type of ERP was excluded from the scoping review given its particular relationship with the focal task. More specifically, literature suggests that the RON component is comprised of two subcomponents: an early subcomponent reflecting the fast reorientation of attention on the level of working memory, followed by a later component reflecting more general allocation of attention (Berti, 2008; Munka & Berti, 2006), with a focus on task-relevant information in working memory (and not solely disengagement from task-irrelevant stimulus). For this reason, we did not address the RON and other task-relevant responses in this review. While these measures are neither solely nor specifically related to the actual distraction from a task-*irrelevant* stimulus, they could still represent useful markers that would give insight on the distraction effects.

Finally, the choice of year (2001–2021) and keywords may have influenced the papers identified and screened. In fact, some papers respecting the inclusion and exclusion criteria may have been missed (e.g., SanMiguel et al., 2008). Overall, these limitations may reduce the scope of the current review and in turn add some blind spots to the list of physiological markers defined herein. However, the inclusion and exclusion criteria defined aimed at avoiding confound within the studies selected and at ensuring that the physiological markers reviewed would be solely representative of auditory distraction, unaffected by other context considerations or cognitive state. Nonetheless, further studies with a larger scope could eventually be conducted, although risks of reduced validity of the markers found could arise from having a less constraining list of eligibility criteria.

Conclusions

The current scoping review aimed at identifying the main physiological markers of auditory distraction and at giving new perspective on the debate of the underlying mechanisms of auditory distraction. From the 15 studies reviewed, we found that the deviation effect has been associated with the N1, the MMN, the P2, and the P3 of the ERPs, as well as the PDR. The changing-state effect sometimes triggered the N1, P1, P2, and P3a of the ERPs, reduced and later BOLD activity in working memory areas, gamma-band and theta-band reduction, and increase in tonic pupil size. While the studies collated differed and could be challenged in their interpretation of the underpinnings of auditory distraction, the fact that the P3, the MMN and the PDR were mainly triggered by deviant sounds while changing sounds were more related to theta-band activity reduction favored the duplex-mechanism account. However, the unitary account could also be supported by the elicitation of the N1 irrespective to the type of distraction. Although further studies are still needed to provide a larger and more comprehensive portrait of the psychophysiological markers of auditory distraction and to better understand its underlying mechanisms, the current review could still define a list of responses that can serve the auditory distraction research community. It also opens for the integration of new tailored sensing intelligent technologies allowing to assess in real time the distraction level of human operators from online physiological measures.

Notes

1. Auditory distraction has been historically studied under the umbrella of the irrelevant sound effect, which initially referred to the idea that the effect of unwanted speech or sound could disrupt serial recall (Colle & Welsh, 1976; Jones et al., 1990; Salamé & Baddeley, 1982). However, since the changing nature of the sound has been identified as the main cause of the irrelevant sound effect (see Jones et al., 1992), the changing-state effect has been considered as the empirical signature of the irrelevant sound effect. For that reason, and to avoid any confusion, we chose to disregard studies that used the expression "irrelevant sound effect" in reference to distraction effects for which the role of acoustic change cannot be established. Hence, we refer to any performance disruption caused by changing tokens to the changing-state effect and others related to attention diversion to the deviation effect.
2. The PRISMA-ScR checklist can be found in the Supplementary Material.
3. This year criterion was established given that the bulk of the literature on differences between the changing-state effect and the deviation effect was published after the year 2000. It also allowed us to make sure that the physiological responses reviewed would be reliable and valid, employing most recent psychophysiological methods of analysis.
4. Although the changing-state effect has been widely related to visual serial recall, other tasks such as the missing item task and probed recall have also been studied along with this effect. In a different vein, the deviation effect – again widely related to visual serial recall – has also been observed while participants carried out digit categorization, visual *n*-back, probed recall, or the missing item task. For that reason, we did not restrict eligibility to visual serial recall as the focal task.
5. Such a criterion led to the exclusion of any result related the RON, a negative deflection associated to the reorienting of attention toward the focal task (e.g., Munka & Berti, 2006; Scheer et al., 2016). While this response is often measured following the presentation of a deviant, we decided to exclude it given that it is mostly ascribed to the task-relevant stimuli rather than the irrelevant sound. We provide more discussion about this in the Limitations section of the paper.
6. The tool, documentation and Excel sheet can be found on the following link: https://sites.google.com/site/riskofbiastool/welcome/rob-2–0-tool/current-version-of-rob-2
7. For the sake of transparency, note that the authors of the current review (AM and FV) authored three of the reviewed papers.
8. The 15 studies included for synthesis are identified by an asterisk in the reference section.

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Appendix

Table A1. Example of full electronic search strategy for the PubMed and PsycNet databases.

Database	Keywords
PubMed	((“sound”[Title/Abstract]) OR (“audi*”)) AND ((“auditory distraction”[Title/Abstract]) OR (“irrelevant sound”[Title/Abstract]) OR (“attentional capture”[Title/Abstract]) OR (“attention capture”[Title/Abstract]) OR (“deviation effect”[Title/Abstract]) OR (“irrelevant sound effect”[Title/Abstract]) OR (“changing-state effect”[Title/Abstract]) OR (“interference-by-process”[Title/Abstract])) AND ((“psychophysiology”[Title/Abstract]) OR (“psychophysiological measure*”[Title/Abstract]) OR (“electrodermal activity”[Title/Abstract]) OR (“galvanic skin response”[Title/Abstract]) OR (“cardiovascular”[Title/Abstract]) OR (“cardiac response”[Title/Abstract]) OR (“heart rate*”[Title/Abstract]) OR (“MEG”[Title/Abstract]) OR (“EEG”[Title/Abstract]) OR (“fNIRS”[Title/Abstract]) OR (“respi*”[Title/Abstract]) OR (“fMRI”[Title/Abstract]) OR (“pupil*”[Title/Abstract]) OR (“brain”[Title/Abstract]) OR (“eye”[Title/Abstract]) OR (“blink”[Title/Abstract]) OR (“ERP”[Title/Abstract]) OR (“event-related potential”[Title/Abstract])) AND (2001:2021[pdat])
PsycNet[a]	((“sound”) OR (“audi*”)) AND ((“auditory distraction”) OR (“irrelevant sound”) OR (“attentional capture”) OR (“attention capture”) OR (“deviation effect”) OR (“irrelevant sound effect”) OR (“changing-state effect”) OR (“interference-by-process”)) AND ((“psychophysiology”) OR (“psychophysiological measure*”) OR (“electrodermal activity”) OR (“galvanic skin response”) OR (“cardiovascular”) OR (“cardiac response”) OR (“heart rate*”) OR (“MEG”) OR (“EEG”) OR (“fNIRS”) OR (“respi*”) OR (“fMRI”) OR (“pupil*”) OR (“brain”) OR (“eye”) OR (“blink”) OR (“ERP”) OR (“event-related potential”))

[a]Note that the year filter was added manually through the user interface.