International Journal of Psychophysiology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Registered reports

Eyes have ears: Indexing the orienting response to sound using pupillometry

Alexandre Marois*, Katherine Labonté, Mark Parent, François Vachon

Université Laval, Québec, Canada

ARTICLE INFO

Keywords:
Pupillary response
Orienting response
Attention capture
Habituation
Auditory deviation

ABSTRACT

The rare occurrence of a sound deviating from the auditory background tends to trigger attentional orienting. While some sympathetic physiological responses can be used to index this orienting response, findings surrounding the pupillary dilation response (PDR) as a proxy for the orienting response are conflicting. The current study was tailor-designed to examine whether the PDR satisfies specific criteria of an orienting response index, namely the classic habituation pattern and a sensitivity to the size of the deviation. The PDR decrement to a repeated standard sound, recovery to a deviant sound, and dishabituation to the re-presentation of the standard were assessed for small and large deviations embedded in irrelevant auditory sequences. The PDR not only showed habituation and dishabituation, but also recovered in correspondence with the magnitude of the acoustic deviation. This consistency between variations of the PDR and orienting response's properties indicates that the PDR is a valid index of the auditory orienting response.

1. Introduction

Human sensitivity to changes in the environment is well documented. More particularly, the presentation of irrelevant and divergent (or deviant) stimuli in many sensory modalities can drive to consequences on the cognitive system and attentional focus (e.g., Basevitch et al., 2011; Schröger and Wolff, 1998; Theeuwes and Chen, 2005; Vachon et al., 2012). Research focusing specifically on the auditory modality has shown that the unexpected presentation of a sound that deviates from the recent auditory past can induce exogenous attention orienting, therefore drawing attention away from the ongoing task. This disengagement of attention from a relevant task toward a distracting element in the environment refers to the orienting response. Such vulnerability to changes in the auditory environment can be explained by the orienting response theory (e.g., Sokolov, 1963b). According to this theory, the acoustical characteristics of the recent auditory context are automatically registered by the cognitive system. Such integration forms a mental representation of the acoustic environment called the neuronal model. A sound becomes more and more incorporated into the neuronal model with repetition. This attenuates the degree of mismatch between the (repeated) sound and the content of the neuronal model, reducing the orienting response to that sound accordingly. However, when an incoming sound does not respect the predictions arising from the model, expectancies are violated, which leads to a recovery of the orienting response (e.g., Schröger, 1997; Vachon et al., 2012).

Attention orienting toward a deviant sound can be demonstrated either behaviorally by the disruption of an unrelated focal task(e.g., Hughes et al., 2007; Lange, 2005; Parmentier, 2008; Röer et al., 2014; Sörqvist, 2010; Vachon et al., 2017), or physiologically by the triggering of reactions known to enhance selective attention and receptivity to the auditory stimulus (e.g., Barry, 1990; Escera et al., 1998; Näätänen et al., 2001; Schröger and Wolff, 1998; Sokolov, 1963a, b). The behavioral consequences of attentional capture arise from the involuntary orienting of attention toward the deviant event, which impairs performance of the ongoing task (e.g., Eimer et al., 1996; Hughes et al., 2007). Physiological reactions associated with the orienting response rather arise from an activation of the sympathetic system and neurons of the locus coeruleus. Once a deviant event occurs, this nucleus, as well as the nucleus gigantis cellularis, are both activated in parallel while being modulated by descending cerebral influences dependent on the cognitive context. This produces a rapid (phasic) response, allowing secretion of norepinephrine in several target regions responsible for sensory and motor sensitivity such as the thalamus (including the pulvinar nucleus, which is known to exert an active role in the attentional network; Fischer and Whitney, 2012), cerebral cortices, limbic structures, the cerebellum, and the spinal cord (e.g., Nieuwenhuis et al., 2005, 2011; Sara and Bouret, 2012). This locus coeruleus-norepinephrine system activity hence triggers many sympathetic-related physiological reactions—including a skin conductance response and changes in respiration and heart rate—that increase the system's receptivity to the deviant stimulus and thereby behavioral adaptation.

Many of the physiological changes ensuing from the presentation of a deviant event have been studied and defined as indices of auditory

---

* Corresponding author at: École de psychologie, Pavillon Félix-Antoine-Savard, 2325 rue des Bibliothèques, Université Laval, Québec, QC G1V 0A6, Canada.
E-mail address: alexandre.marois.1@ulaval.ca (A. Marois).

http://dx.doi.org/10.1016/j.ijpsycho.2017.09.016
Received 12 March 2017; Received in revised form 15 September 2017; Accepted 25 September 2017

Please cite this article as: Marois, A., International Journal of Psychophysiology (2017), http://dx.doi.org/10.1016/j.ijpsycho.2017.09.016

attentional capture, i.e. responses that indicate the involuntary orientation of attention toward a deviant sound (e.g., Schröger and Wolff, 1998; Steiner and Barry, 2011). The P300 of the event-related potentials (ERPs) is an example of a valid proxy for auditory attentional capture (e.g., Barry, 1990; Polich, 2007). This ERP component is triggered by rare irrelevant auditory stimuli (Demiralp et al., 2001). It peaks between 250 and 500 ms after stimulus onset (e.g., Schröger and Wolff, 1998), and originates from distraction-related frontal mechanisms (e.g., Escera et al., 1998; Gumenyuk et al., 2004).

Some authors have proposed that the pupillary dilation response (PDR) could, as the P300 or the skin conductance response, be associated with auditory attentional capture (e.g., Nieuwenhuis et al., 2011; Wang and Munoz, 2015). The PDR is a physiological response known to be linked to several cognitive and attentional processes such as intensity of processing (Just and Carpenter, 1993) and workload demands (Beatty and Wagoner, 1978). It is also known to represent activity of the locus coeruleus neurons (e.g., Aston-Jones and Cohen, 2005). Although some studies have related the PDR to auditory attentional capture (e.g., Friedman et al., 1973; Murphy et al., 2011; Steiner and Barry, 2011; Wetzel et al., 2016), whether or not it can be used as a valid index of the auditory orienting response is still unclear.

If a physiological response is to be correctly identified as a valid index of the orienting response, it must satisfy specific criteria (see Sokolov, 1963b), including sensitivity to novelty, habituation, and correspondence with the deviation amplitude. Though many studies have shown that the pupil diameter seems sensitive to the novelty of a sound and that a noticeable PDR could be triggered by a deviant sound (e.g., Friedman et al., 1973; Liao et al., 2015, 2016; Qiyuan et al., 1985; Steiner and Barry, 2011; Wetzel et al., 2016), findings from studies on other criteria are scarce and somewhat conflicting. The goal of the present study was to determine whether the PDR could be used as a valid index of the auditory orienting response, with an emphasis on two particular criteria: the correspondence between the amplitude of the response and that of the auditory change, and the respect of the habituation criteria.

1.1. *Amplitude of the orienting response*

According to early evidence on the orienting response, the magnitude of the response must be related to the amplitude of the deviation, that is, the size of the difference between the context and the deviant event (Sokolov, 1963b). In the auditory domain, this means the greater the discrepancy between the deviant and standard sounds, the larger the response, and vice versa. For example, embedding a 600-Hz tone within a series of 500-Hz standard sounds should produce a larger orienting response than inserting a 520-Hz deviant tone.

Using mainly the skin conductance response, early studies on the auditory orienting response have verified this assumption. Although some conflicting results have ensued from experiments with known methodological limits (e.g., James and Hughes, 1969; O'Gorman et al., 1970; Zimny and Schwabe, 1965; see also Graham, 1973, for a review), there is evidence showing a relationship between the skin conductance response amplitude and the magnitude of the difference between standard and deviant sounds in terms of pitch (Corman, 1967; Siddle and Heron, 1976; Sokolov and Paramonova, 1961; Williams, 1963) and intensity (Bernstein, 1968, 1969; Siddle and Heron, 1977). More recently, results from Escera et al. (1998) supported this phenomenon using the P300 of the ERPs. They revealed that the P300 elicited by slightly higher-pitched deviant sounds was smaller than the P300 triggered by much different environmental novel sounds such as those produced by a drill, a hammer, or rain. Such sensitivity of the skin conductance response and of the P300 to the amount of discrepancy between the deviant and the standard sounds is yet to be demonstrated with the PDR. For this latter physiological response to be a valid proxy for the orienting response, its amplitude should be sensitive to the size of the deviation. Therefore, a specific investigation is needed to confirm whether the PDR fulfills this criterion of a valid index of the orienting response.

1.2. *Habituation of the orienting response*

A valid index of the auditory orienting response must also follow a classic habituation pattern (Sokolov, 1963a, b). Habituation of the orienting response can broadly be defined as the decreasing of the orienting response with repeated exposure to the same stimulus (Rankin et al., 2009). Following the work of Thompson and Spencer (1966) and Rankin et al. (2009), Steiner and Barry (2011, 2014) proposed that characteristics for habituation include: i) a gradual response decrement to the repeated presentation of a standard stimulus; ii) a response recovery to a new and unexpected stimulus that differs from the standard (i.e. the deviant); and iii) a response dishabituation to the re-presentation of the standard stimulus on which the orienting response previously habituated.

Some attempts have been made to verify whether the PDR could follow the classic habituation pattern. Yet, conclusions about this criterion have been inconsistent. In an experiment conducted by Maher and Furedy (1979), a series of 16 sounds with a randomly-chosen interstimulus interval (ISI) of 15, 20, or 25 s was presented to the participants as the PDR and skin conductance response were measured. While the first 15 sounds were identical in pitch, the 16th had a different frequency. Results showed that the PDR and skin conductance response followed a similar pattern, whereby the amplitude of the response decreased to the repeated presentation of the same sound (showing habituation), before increasing significantly to the presentation of the deviant sound. Consequently, the authors concluded that, as the skin conductance response, the PDR could index the auditory orienting response. However, a study by Stelmack and Siddle (1982) contradicted this conclusion. Using a similar paradigm, their results showed a decrease in the amplitude of the PDR as the standard sound was repeated, but no PDR recovery to a sound deviating from the auditory context by its intensity.

More recently, Steiner and Barry (2011) compared the skin conductance response, the PDR and the P300 as correlates of the orienting response. They asked participants to either listen passively to sounds (indifferent condition) or count the number of sounds presented (significant condition). For both conditions, the auditory sequence first comprised a series of 10 repetitions of the same standard sound, followed by one deviant sound of a different frequency. Each sound lasted 50 ms with a randomly-chosen ISI varying between 5 and 7 s. The sequence ended with two to four re-presentations of the initial standard sound. Results showed that all three physiological measures habituated to the repeated presentation of the standard sound, recovered to the presentation of a different (deviant) sound, and dishabituated to the re-presentation of the initial standard sound.

Despite the lack of consensus, evidence tends to point toward the PDR complying with the habituation criteria. Yet, Steiner and Barry's (2011) experiment—in which dishabituation was assessed—employed a paradigm consisting of a single auditory sequence composed of the repetition of a standard sound, followed by the presentation of a single deviant tone and then by a few presentations of the initial standard sound. In such an auditory sequence, the reintroduction of the standard sound is immediately preceded by the deviant sound, which raises some concerns with regard to the dishabituation criterion. Some authors have hypothesized that dishabituation does not represent a response to the re-presentation of a habituated sound, but that it rather originates from a residual activation or sensitization ensuing from the preceding presentation of the deviant sound (e.g., Groves and Thompson, 1970; Thompson et al., 1973). Indeed, the response triggered by the re-presentation of the initial standard sound right after the deviant tone could be affected by the arousal produced by the latter. If the PDR is to be considered as a valid index of the auditory orienting response, it should respond to the re-presentation of the standard sound as specified by the