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Single-trial event-related potentials and autonomic measures of the orienting reflex

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ABSTRACT

We aimed to clarify the event-related potentials (ERPs) associated with elicitation and habituation of the basic Orienting Reflex (OR). Participants were presented with 16 innocuous tones, alternating in intensity, at long variable inter-stimulus intervals, with no task. This allowed us to examine stimulus novelty and intensity effects in the absence of stimulus-related task demands. Single-trial ERPs were extracted to obtain estimates of the early N1 and the late positive complex (LPC) to each stimulus. Electrodermal responses showed substantial main effects of trials and intensity, supporting their functionality as an OR index. Cardiac deceleration showed no systematic change with intensity or trials, suggesting that it marks the transient onset of each stimulus, early in the stimulus-processing sequence. Respiratory pause showed a substantial main effect of trials but no intensity effect, suggesting that it reflects an intermediate processing stage. A main effect of intensity, but no simple trial effect, was apparent in the N1, suggesting that it reflects a different intermediate processing stage. The subsequent LPC showed only a topographic interaction with trials and intensity, failing to support any substantive role in OR processing. These different stimulus–response profiles are discussed in the context of a sequential processing model of the OR.

1. Introduction

The orienting reflex (OR) or "investigatory reflex" orients the organism towards the slightest perceivable change in its environment — a fundamental survival mechanism (Pavlov, 1927). This area of research was brought to prominence in the West by Evgeni N. Sokolov, who focused on particular attributes of the stimulus event – novelty, intensity, and significance – and employed physiological measures, such as the galvanic skin response (GSR), respiratory pause, blood volume changes, EEG alpha desynchronisation, pupil dilation, and eye movements to assess ORs (Sokolov, 1963a,b). According to Sokolov's conceptualisation of the OR, similar patterns of responses should be observed in different measures when novelty, intensity, and significance are manipulated, reflecting a unitary OR. This unitary aspect has not been empirically supported (e.g., Siddle and Heron, 1977).

For example, a number of early studies (e.g., Barry, 1977a,b) parametrically tested the influence of intensity, novelty, and significance, using heart rate (HR) deceleration, peripheral vasoconstriction, cephalic vasodilation, respiratory pause, GSR, and EEG alpha desynchronisation as measures. All these (except the phasic HR response — not available to Sokolov) were broadly compatible with those used by Sokolov as measures of the OR. The results displayed unique stimulus–response patterning for the separate measures, indicating response fractionation. Only GSR met the expectations of the phasic OR derived from Sokolov's work: habituation with stimulus repetition, and sensitivity to stimulus intensity and significance. GSR and peripheral vasoconstriction were sensitive to intensity, while EEG, GSR, and respiratory pause measures showed response decrement across trials. The HR deceleration and cephalic vasodilation responses displayed neither intensity nor trial effects, and this is compatible with an early perceptual process of stimulus registration (Meyers, 1969; Orlebeke and Passchier, 1976).

Subsequent work (e.g. Barry and James, 1981a,b) demonstrated the robust nature of this fractionated response patterning, and Preliminary Process Theory emerged to accommodate these S–R patterns. Preliminary Process Theory incorporates sequential processing of stimulus information, based on physical stimulus characteristics, with the outputs of each separate process becoming inputs to further processing. The final outputs of the processing interact to produce the involuntary (reflexive) OR to indifferent (or non-significant) stimuli, or a cortically-moderated voluntary OR if the stimuli have significance for the subject. Each of the intervening processes and the final phasic OR are indexed by autonomic and central measures. The stimulus onset (indexed by immediate HR deceleration) and energy (indexed by peripheral vasoconstriction) impact on the transient and energy detectors respectively (subsystems of the permanent feature detector). The output of the permanent feature detection system passes the information forward for novelty processing (indexed by respiratory pause) and to the arousal system (sensitive to stimulus energy and serving to amplify system outputs). Intensity and novelty are processed in parallel, with the resultant interaction eliciting the phasic OR (marked by the skin conductance response [SCR, the modern version of the GSR]). Forward connections with the central executive

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trigger automatic attention switching to the indifferent stimulus (Barry, 1996).

Traditionally, the OR has been investigated using autonomic variables such as electrodermal activity, with inter-stimulus intervals (ISIs) sufficient to allow resolution of the waveform of the phasic responses. High signal/noise ratios in the autonomic system require relatively few trials in an experiment. In contrast, OR research involving ERPs generally uses ISIs of approximately one second, and the time-locked responses are averaged over corresponding trials within trains to increase the signal/noise ratio. Efficiently bridging the paradigm gap between autonomic and ERP studies would permit comparisons to be made between the two systems, and potential placement of ERP measures within Preliminary Process Theory (Barry, 2009).

An early paper by Simons et al. (1998) crossed this gap by collecting data in oddball paradigms with long ISIs (12, 16, and 20 s), and measuring both HR and ERPs. The biphasic HR wave was characterised by an initial deceleration and a later acceleration (for targets). The HR deceleration remained unchanged over trials. Clear N1 (central) and P300 (parietal) peaks were apparent. The N1 and HR deceleration were both described in terms of transient detection. The P300, rather than discriminating between targets and non targets, represented an earlier stage of stimulus processing. The authors speculated that long, variable ISIs should make stimuli less predictable and more conducive to the elicitation of ERPs responsive to novelty.

Donchin noted that the P300, or Late Positive Complex (LPC), is elicited by the first of a sequence of stimuli, regardless of its relevance, suggesting its association with the OR (Donchin, 1981; Donchin et al., 1984). The LPC has been reported to include a number of subcomponents, identified as the Novelty P3, P3a, P3b, and the Slow Wave, and displaying fractionation according to stimulus parameters and situational factors (Friedman et al., 1978; Rushby et al., 2005). In an auditory dishabituation paradigm, Rushby et al. (2005) presented trains of innocuous stimuli (50 and 80 dB, 15 ms rise/fall times, 1000 Hz) in which novelty (within-subjects: stimulus repetition), intensity (between-subjects), and significance (between-subjects: button press to the change tone) were manipulated. Each train consisted of 5 repeated tones of one intensity (to test habituation), a change tone of the other intensity, and re-presentation of the original tone (to test dishabituation); the order of tone intensities was counterbalanced between subjects. There were 15 trains presented with an inter-train interval of 30 s and ISI of 8 s. The SCR displayed habituation, increased response to the change stimulus, and dishabituation. Results indicated that the LPC and SCR had similar stimulus–response patterning with respect to novelty, intensity, and significance. The LPC correspondence to the SCR was supportive of the LPC as a central index of the OR.

Rushby and Barry (2009) extended investigations into OR stimulus–response patterning, again using SCR as the OR index. The major components of their single-trial ERPs (P1, N1, P2, N2, and LPC) were examined in an auditory habituation paradigm with a very long ISI (2 min). Participants received 12 tones (80 db) with prior instructions to alternately open and close their eyes when they heard the tone, starting with eyes closed. Both the N1 and the LPC failed to demonstrate response decrement with stimulus repetition, contrasting with the Rushby et al. (2005) study with much shorter ISIs, where a notable LPC response decrement over trials was obtained.

Barry et al. (2011) examined a behavioural OR measure, HR, SCR and single-trial ERPs in terms of the phasic OR. In a simple auditory habituation paradigm, eight indifferent 80 dB tones, with long variable ISI, were delivered monaurally to participants. Horizontal eye movements towards the ear of tone presentation were taken as the behavioural OR measure. On trial 1 directional differences in eye-movements (eyes turning in the perceived direction of the tone) were significant, and this difference decreased over trials. This decrement over trials also occurred with SCR, confirming its close association with the phasic OR. HR deceleration was insensitive to stimulus repetition, linking it to earlier processing triggered by stimulus onset. A topographic change over trials was evident for the N1, but not the LPC, suggesting that these responses were largely unaffected by trials and so not closely connected to phasic OR generation.

The present study further explores the relationships between central and autonomic measures, from the perspective of Preliminary Process Theory. Intensity is manipulated within the innocuous range, and the tones are considered indifferent (no task requirements). Large single-trial ERP components appear to be evoked reliably at long ISIs (e.g., Rushby and Barry, 2009; Barry et al., 2011; Steiner and Barry, 2011-in press), and these preserve rapidly changing information unavoidably lost in averaging ERPs across stimuli. It is rare to collect data from more than 2 autonomic measures, along with ERP data, within the one study, yet this presents the opportunity to strengthen and clarify the placement of measures that index processes in Preliminary Process Theory. It is hypothesised that HR deceleration will be triggered by stimulus onset and that this response will not systematically decrease over trials. The stimulus will also produce a respiratory pause (lengthening of the respiratory cycle), and this will decrease over trials (see Barry and James, 1981a,b). Both HR deceleration and respiratory pause will be insensitive to intensity (ibid). The SCR is expected to demonstrate intensity and novelty dependency, confirming it as an index of the phasic OR. The N1, in the light of previous work, should not be strongly influenced by trials, but could show some intensity dependency (see Lawrence and Barry, 2009). The LPC, as a potential OR index, should be influenced by trials and intensity, but the studies reviewed above do not strongly support this prediction.

2. Methods

2.1. Participants

Eighteen university students participated in an experimental session as one means of fulfilling a course requirement (age 20–24, mean 21.4 years; 10 females; 13 right-handed). The procedure was explained and written consent was obtained in accordance with a protocol approved by the joint South East Sydney and Illawarra Area Health Service/University of Wollongong Human Research Ethics Committee, in line with the Declaration of Helsinki (World Medical Organization, 1996). Participants were required to complete a demographic and screening questionnaire, and only those with normal hearing participated. Individuals with a history of seizures, psychiatric illness or severe head injury were excluded, as were those currently taking psychoactive drugs.

2.2. Procedure

Participants were seated in a dimly-lit, sound attenuated, air-conditioned testing booth with a fixation cross displayed on a computer monitor placed at a distance of 1.5 m. Once comfortably seated, the participants were instructed that they would occasionally hear sounds over the headphones, but that there was no task in relation to them. They were asked to focus their eyes on the fixation cross presented on the monitor screen, try not to move or blink, and to stay relaxed.

Auditory stimuli were 1000 Hz tones at 60 and 80 dB intensity, with a duration of 50 ms (15 ms rise/fall times) and a random, variable ISI of 50–70 s, administered in an alternating series through stereo headphones. Participants were randomly assigned to one of two counterbalanced groups, starting with 60 or 80 dB. Participants received either 16 or 17 tones in the paradigm. The first 16 tones were used for analysis, yielding 8 trials at each intensity.

2.3. Physiological recording

A digital signal-processing hardware and software package from Associative Measurement (AMLAB II) was used for the acquisition and storage of data.