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Brain dynamics in the auditory oddball task as a function of stimulus intensity and task requirements

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A B S T R A C T

We examined relationships between the phase of narrow-band electroencephalographic (EEG) activity at stimulus onset and the resultant event-related potentials (ERPs) in an auditory oddball task, varying both stimulus intensity and active vs. passive task requirements between groups. We used a novel conceptualisation of orthogonal phase effects (cortical *negativity* vs. positivity, *negative driving* vs. positive driving, *waxing* vs. waning). This study focused on the operation of three previously-reported phase-influenced mechanisms, involving prestimulus amplitudes, poststimulus amplitude changes, and the prestimulus contingent negative variation (CNV), in various EEG frequency bands. ERP responses to the standard stimuli were analysed. Prestimulus narrow-band EEG activity (in 1 Hz bands from 1 to 13 Hz) at Cz was assessed for each trial using digital filtering. For each frequency, the cycle at stimulus onset was used to sort trials into four phases, for which ERPs were derived from both the filtered and unfiltered EEG activity at Fz, Cz, and Pz. The occurrence of preferred phase-defined brain states was confirmed at a number of frequencies, crossing the traditional frequency bands. These preferred states were associated with more efficient processing of the stimulus, as reflected in differences in latency and/or amplitude of all ERP components, and provided evidence of the operation of the three separate phase-influenced mechanisms. The preferred brain states occurred similarly across groups, suggesting that they reflect reflexive aspects of brain function associated with the timing of the stimuli, rather than voluntary attention. The impact on markers of cognitive function, such as the P3, suggests their important contributions to the efficiency of brain dynamics involved in perceptual and cognitive processing.

1. Introduction

Over recent years it has become clear that responses to individual stimuli depend on the dynamics of the electroencephalogram (EEG) at stimulus onset (Başar, 1980; Makeig et al., 2004; Barry, 2009). One interesting line of research in this field, particularly relevant to the phase-resetting model of the ERP, began with Başar and Stampfer (1985). They noted that when stimuli were presented at regular intervals, phase reordering occurred in the delta and alpha frequencies to produce a “preferred phase angle”, leading to maximum negativity at stimulus onset. Previous work had reported shorter reaction times (Callaway and Yeager, 1960; Trimble and Potts, 1975), and enhanced ERP components (Rémond and Lesèvre, 1967), for stimuli presented at negative peaks of the alpha cycle, so this preferential phase occurrence appears important in perceptual and cognitive functioning. Further evidence for such dynamic phase adjustment was reported by Başar et al. (1984), Rockstroh et al. (1989), and Pleydell-Pearce (1994).

Conceptualisation of comparative phase angles and their effects is not simple, and hence Barry et al. (2003) introduced two more-intuitive physical dimensions based on the phase divisions shown in Fig. 1. Cortical *negativity*/positivity compares effects of (A+B) versus (C+D), thus accommodating the phase effects just described. A second dimension, *negative*/positive *driving*, comparing (A+D) versus (B+C), reflects changing of the cortical *negativity* variable—is it increasing (phases A, D) or decreasing (phases B, C)? This accommodates differential ERP effects reported when stimuli are presented at or near the positive–going zero crossing of alpha activity (Rémond and Lesèvre, 1967; Jansen and Brandt, 1991). With four means representing activity in the phases, it is possible to construct various sets of three orthogonal (statistically independent) comparisons among the means. Continuing with these two prior comparisons, an alpha phase study by Barry et al. (2004) introduced the only possible third mutually-independent contrast on the phases, comparing effects of EEG *waxing* (A+C) versus waning (B+D) at stimulus onset. Note that this dimension can be conceptualised directly in terms of its root mean square (RMS) amplitude correlates — *waxing* corresponds to increasing RMS amplitudes, waning to decreasing amplitudes. In this paper, we use italics to label one extreme of each of these novel orthogonal dimensions of EEG

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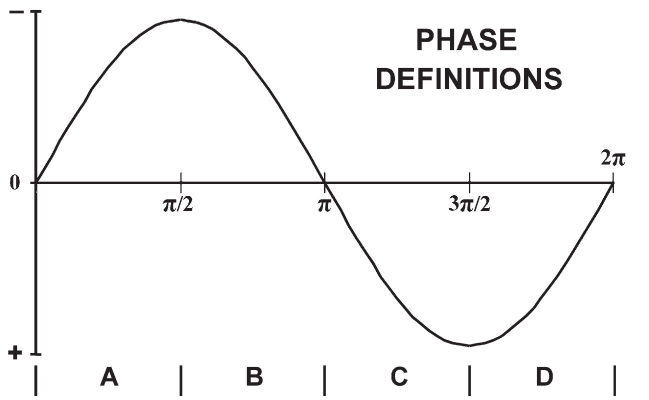

Fig. 1. A schematic representation of the narrow-band EEG phases as defined here. Phases (A + B) define cortical *negativity*, (A + D) define *negative driving*, and (A + C) define *waxing*. For each pair defining a dimension (e.g., A + B), the remaining two phases (e.g., C + D) define the other extreme of that dimension. These three orthogonal dimensions are easier to conceptualise than differences in traditional phase measures (degrees or radians).

phase: *negativity*, *negative driving*, and *waxing*, and use this shorthand to aid communication and save space.

Barry et al. (2003) used a fixed inter-stimulus interval (ISI) auditory oddball requiring a button-press to targets, and showed that EEG frequencies were dynamically adjusted to provide what they termed "preferred brain states" at stimulus onset. That is, some of the phase states defined above (e.g. *negativity* c.f. positivity) occurred preferentially for different frequencies, at up to double the rate expected by chance. They demonstrated that these preferred states facilitate cortical processing, as indicated by effects in the event-related potential (ERP). The effects observed were not bound by the traditional EEG bands, suggesting that it would be valuable to continue with their narrow-band approach.

Subsequently, Barry et al. (2006) reported a preliminary study of phase effects using data from a passive auditory oddball paradigm with deviants differing from the standards in terms of intensity, and compared two groups of subjects with the deviant/standard intensities interchanged. The paradigm was broadly similar to that of Barry et al. (2003), but with a slightly-varying ISI. As expected, this reduced (but did not eliminate) the occurrence of preferred brain states. The observed preferential states were functionally effective, resulting in smaller N1, N2 and N3, and larger P2 and P3 amplitudes, and reduced N1, P2, N2 and P3 latencies, reflecting more efficient processing of the standard stimuli in the passive oddball paradigm. Barry et al. (2006) described three phase-influenced mechanisms, operating at different frequencies, which appeared to underlie many of the observed phase effects in the poststimulus ERPs: 1) prestimulus RMS EEG amplitudes were reduced at lower frequencies in *negative driving*, 2) poststimulus RMS amplitude changes in the alpha frequency range were enhanced in *waxing* phases, and 3) prestimulus contingent negative variation (CNV) was enhanced at lower frequencies in *negativity* and *negative driving* phases. These possible mechanisms did not contribute to stimulus-intensity effects in the ERPs, suggesting that they were non-specific in the passive task used.

To extend beyond the passive oddball, Barry et al. (2007) reported another preliminary study of these phenomena, exploring the impact of task demands. They compared the passive low-intensity standards group data from Barry et al. (2006) with data from another group of subjects presented with exactly the same auditory sequence, but who had to press a button in response to the deviant tones. It was expected that this task difference would result in the two groups showing different preparatory processes, ERP differences to both the deviant stimuli and the standard stimuli focused on, and perhaps different preferred brain states. Again, some states at stimulus onset were preferentially found, occurring up to 20% more than expected by chance, and these were associated with more-efficient processing. Evidence of the occurrence of the three phase-influenced mechanisms was also noted. However, relatively few phase effects of the active vs. passive task were obtained, suggesting that both the occurrence of the different phases, and their effects on ERP components, reflect largely reflexive brain processes.

The present study aimed to extend and integrate the results of the exploratory studies of Barry et al. (2006, 2007), by adding data from further subjects to form a factorial group design. We supplemented the three groups examined in our two preliminary studies [High and Low intensity standards in a passive task in Barry et al. (2006); Low intensity standards in active and passive tasks in Barry et al. (2007)] with a fourth group, which received High intensity standards in the active task paradigm. This factorial design allows potential confirmation of the previously-reported intensity and active/passive task effects with more power (associated with the doubled N), and the novel exploration of interactive effects between the two independent variables [standard stimulus intensity (High vs. Low) and task (active vs. passive)]. These data had originally been collected together in an ERP study designed for other purposes, and have been selectively data-mined in relation to this series of brain dynamics studies.

The subdivision and binning of EEG activity on the basis of phase at stimulus onset requires many trials, and thus these narrow-band oddball studies have examined responses to the more-numerous standard stimuli. Although we focus on the ERPs to standards rather than the commonly-reported ERPs to deviants, our approach and findings can be generalised. Early components in oddball ERPs, such as the N1, are relatively similar to both standards and deviants, largely reflecting the initial sensory processing necessary to identify whether the stimulus is a standard or deviant. Although subsequent late components, such as the P3, are usually smaller to standards than deviants, they are normally readily identifiable and reflect common aspects of stimulus processing (e.g., see Simons et al., 1998; Bledowski et al., 2004). Barry et al. (2007) provided comparative waveform plots for ERPs to standards and deviants, and the broad similarity of the waveforms was notable.

In this context we expect the study to confirm the occurrence of preferred phase-defined brain states in this paradigm, and to provide evidence of the operation of the three hypothetical phase mechanisms described above. We also expect to find clear phase effects in all the ERP components measured, and that the nature of these effects will confirm the functional efficiency of the preferred brain states in enhancing stimulus processing. Finally, the examination of intensity and task differences in these effects is expected to indicate little between-group variation, suggesting that they are reflexive in nature, largely determined by the timing of stimulus occurrence.

2. Materials and methods

2.1. Participants

Forty undergraduate students (33 females, seven males), aged between 19 and 54 years, participated in this study as one means of satisfying an undergraduate course requirement in Psychology. All claimed normal hearing, and gave written informed consent in accordance with a protocol approved by the Combined University of Wollongong/Illawarra Area Health Service Human Research Ethics Committee. Potential subjects with a history of seizures, psychiatric illness or severe head injury were excluded, as were those currently taking psychoactive drugs.

2.2. Procedure

Continuous EEG was recorded from 17 scalp sites using an electrode cap with tin electrodes, referenced to linked ears, with a gain of 50,000, a time constant of 5 s, and upper-cut-off frequency of 35 Hz, using an AMLAB II system (Associative Measurement). Vertical electro-