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EEG indices of reward motivation and target detectability in a rapid visual detection task

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ABSTRACT

A large corpus of data has demonstrated the sensitivity of behavioral and neural measures to variation in the availability of reward. The present study aimed to extend this work by exploring reward motivation in an RSVP task using complex satellite imagery. We found that reward motivation significantly influenced neural activity both in the preparatory period and in response to target images. Pre-stimulus alpha activity and, to a lesser degree, P3 and CNV amplitude were found to be significantly predictive of reward condition on single trials. Target-locked P3 amplitude was modulated both by reward condition and by variation in target detectability inherent to our task. We further quantified this exogenous influence, showing that P3 differences reflected single-trial variation in P3 amplitude for different targets. These findings provide theoretical insight into the neural indices of reward in an RSVP task, and have important applications in the field of satellite imagery analysis.

Introduction

People are able to recognize target images very reliably even when presented with successive images for a tenth of a second or less (Keysers et al., 2001; Thorpe et al., 1996), and even when asked to search according to general descriptions rather than specific low-level perceptual features (Intraub, 1981; Potter, 1975). Complementing this behavioral evidence, neuronal recordings have tracked the emergence of category-specific activity in occipitotemporal cortex of both humans (Liu et al., 2009) and non-human primates (Hung et al., 2005) within 100 ms of stimulus presentation. These findings bear on fundamental theoretical issues in vision—in particular, the necessity of recurrent information flow for rapid and accurate perceptual processing (Thorpe and Fabre-Thorpe, 2001; Serre et al., 2007)—and have important practical applications: Emerging technologies in military and industrial settings produce vast quantities of data that potentially outstrip the processing capacity of human operators. Harnessing the speed of sight in these settings, for example by presenting relevant imagery in rapid serial visual presentation (RSVP) format, in which a quick succession of images is presented at fixation, promises to alleviate these problems of information overload—a focus of current research in the field of augmented cognition (Mathan, 2008).

The present study investigated the impact of motivational (endogenous) and stimulus-driven (exogenous) influences on behavior and neural activity in RSVP search for operationally relevant target stimuli: military–industrial sites in satellite imagery. Previous research with such stimuli has focused on the use of target-related neural activity—primarily the P3 component of the scalp-recorded electroencephalogram (EEG)—in brain–computer interfaces to complement or replace overt motor responses for signaling target detection (e.g., Gerson et al., 2006; Mathan, 2008; Mathan et al., 2006a,b, 2008; Parra et al., 2008; Poolman et al., 2008). Here we were additionally interested in EEG activity preceding task performance that might be indicative of users' attentional or motivational state and, hence, might be predictive of their level of task performance. Positive evidence on this point would have theoretical and practical significance. Sensitivity of RSVP detection to motivational factors would indicate that fast perceptual processing of complex visual stimuli is subject to endogenous modulation, complementing and extending recent evidence from experiments using near-threshold detection paradigms (e.g., Ergenoglu et al., 2004; Hanslmayr et al., 2005, 2007). Practically, neural measures of user state might prove useful in brain–computer interfaces to flag periods of reduced motivation or attentional focus in which missed targets or false alarms would be more likely (Grier, et al., 2003; Mathan et al., 2006a). Indeed, recent evidence has highlighted neural markers that directly correlate with trial-to-trial variations in participants' self-reported attentional state (Macdonald et al., 2011). The present study utilized similar single-trial analysis techniques (Parra et al., 2002) to assess the

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potential utility of both ERP and oscillatory EEG activity in assessing participants' motivation on single trials.

We manipulated motivation via reward: In some blocks of trials, our participants received a financial reward for good performance in the RSVP detection task, while in others they received no financial incentive. A large corpus of data has demonstrated the sensitivity of behavioral and neural measures to variation in available reward (Pessoa and Engelmann, 2010), accompanied by increased activity in frontoparietal networks implicated in visual attention (Engelmann et al., 2009).

Of particular relevance here are previous reports of the impact of reward incentives on activity in the scalp-recorded EEG. Such effects have been investigated both in relation to the processing of stimuli associated with reward, and in relation to anticipatory pre-stimulus activity. Regarding the former, numerous studies have shown that the amplitude of the P3, an ERP marker of the processing of motivationally significant events (e.g. Donchin and Coles, 1988; Polich and Criado, 2006), is modulated as a function of reward (Ramsey and Finn, 1997; Yeung and Sanfey, 2004; Gruber and Otten, 2010). Meanwhile, pre-stimulus ERP effects of reward have been studied in relation to the contingent negative variation (CNV), a slow negative potential that develops prior to the onset of stimuli to which participants are required to make some form of response (Walter et al., 1964). The results have been somewhat mixed. For example, whereas some studies report variability in CNV amplitude as a function of whether warning signals are associated with reward or punishment (Pierson et al., 1987), other studies have reported negative results (Sobotka et al., 1992). Adopting a blocked design similar to the present study, Goldstein et al. (2006) explored the effect of reward on a ERP activity during preparation for the onset of a task relevant stimulus, with participants earning rewards for fast responses in some blocks but not in others. They found that whereas P3 amplitude to the warning stimulus increased as a function of reward, there was no significant difference in CNV amplitude.

Thus, previous work has revealed robust effects of reward on cue- and stimulus-locked P3 amplitude but less consistent influence on the pre-stimulus CNV. Our first analyses focused on the influence of reward on these ERP components. In addition, we measured oscillatory EEG activity as a potentially informative index of motivation and attentional state. A wealth of evidence has documented the relationship between EEG alpha activity—oscillations in the 8–12 Hz range—and attention (Klimesch, 1999): Alpha power typically varies inversely with attentional focus, reducing in a topographically focused manner (i.e., over contralateral occipital electrodes) when visual attention is directed to spatially conscribed regions (e.g., Thut et al., 2006) and reducing more broadly over occipitoparietal scalp regions when attention is directed towards visual stimuli and away from other sensory modalities or internal cognitive operations (e.g., Ray and Cole, 1985). Correspondingly, reduced pre-stimulus alpha activity has been shown to be predictive of conscious visual perception in near-threshold detection tasks. For example, decreased alpha activity in the period prior to stimulus onset is associated with improved detection of briefly flashed light stimuli (Ergenoglu et al., 2004), variations in pre-stimulus alpha correlate with subjective ratings of attentional state (Macdonald et al., 2011), and participants with decreased pre-stimulus alpha tend to perform better at detection of backward masked near-threshold stimuli (Hanslmayr et al., 2005). Moreover, phase coupling of pre-stimulus alpha power across scalp electrodes has been shown to be an effective predictor of subsequent correct performance at the level of individual trials with such tasks (Hanslmayr et al., 2007). We therefore anticipated that the motivational influence of reward would be reflected in reduced alpha power in the period before stimulus onset.

A key aim of the present study was to investigate the influence of reward on these EEG components in the context of a task—detection of military-industrial sites in satellite imagery—that is analogous to the work performed by intelligence analysts (e.g., Gerson et al., 2006; Mathan, 2008; Mathan et al., 2006a,b, 2008; Parra et al., 2008; Poolman et al., 2008). In this way we extended previous investigations of rapid visual categorization and motivational influences on perception in two crucial respects. First, our design enabled us to assess the possible utility of EEG markers of attentional and motivational state in applied settings. Of interest was whether EEG neural markers of attentional and motivational state might be sufficiently clear and robust to be useful markers of user state in an operational brain–computer interface. To this end, we conducted multivariate analyses to attempt to classify the pre-stimulus correlates of motivation/reward on single trials, as a preliminary investigation of whether the consistent between-condition differences we observed in averaged EEG data would translate to effective prediction of user state as it varies across trials.

A second crucial feature of the present task is that it involves stimuli that are considerably less controlled than those used in many typical lab paradigms that investigate fast visual categorization and motivational influences on perception: Our stimuli included 20 different target images (satellite images of surface-to-air missile sites) and over 150 different distractor images (satellite imagery of varying terrain), which were selected at random on each trial. Thus, the particular target stimulus used on a given trial, as well as the distractors presented alongside it, might predict a significant portion of the variance associated with accuracy. This aspect of our design enabled us to assess the robustness of observed effects of reward to variability in stimulus discriminability. In addition, it allowed us to investigate exogenous, stimulus-driven influences on behavior and neural activity in fast perceptual categorization.

Previous work has demonstrated that the P3 is robustly elicited by target stimuli in RSVP streams and may provide a useful single-trial marker of target detection in brain–computer interfaces (Gerson et al., 2006; Mathan, 2008; Mathan et al., 2006b, 2008; Parra et al., 2008; Poolman et al., 2008). We aimed to extend these findings by combining conventional ERP and multivariate single-trial EEG analysis to analyze the informational content of this target-locked P3 as it varied across stimuli and across trials. In particular, one possibility is that the P3 indexes a categorical decision about whether or not particular stimuli are salient targets, with little variability attributable to the specific identity of those targets. However, recent evidence on the error positivity (Pe), a P3-like ERP component elicited by incorrect responses in decision making tasks, has shown that this component contains information about the trial-varying strength of evidence that an error has occurred (Steinhauser and Yeung, 2010). Here we assessed whether the target-locked P3 in fast visual categorization conveys similarly rich information, in terms of varying reliably with perceptual evidence strength, in which case it should vary in amplitude as a function of the visibility of the particular target presented (rather than reflecting an all-or-none categorical decision about target presence or absence).

Thus, the present study investigated the impact of exogenous and endogenous factors—motivation and stimulus difficulty, respectively—on rapid visual categorization in a task with direct applied relevance. Regarding endogenous influences, we anticipated that reward incentives would improve behavioral performance and would influence key pre-stimulus neural markers of motivational state—the P3 to reward-signaling cues, the pre-stimulus CNV, and pre-stimulus oscillatory alpha power—thus demonstrating the sensitivity of fast perceptual processes to endogenous modulation. Extending this analysis, we investigated the degree to which these EEG markers might provide robust estimates of motivational and attentional state on single trials using multivariate classification analyses. Regarding exogenous influences, we predicted that stimulus discriminability would significantly impact behavioral and neural markers of target processing. Of crucial interest was the degree to which post-target P3 amplitude would vary with the discriminability of the presented target, as an index of whether this component reflects a binary classification of target identity or a continuous measure of the strength of perceptual evidence relevant to the current decision.