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Predicting errors from patterns of event-related potentials preceding an overt response

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ABSTRACT

Everyday actions often require fast and efficient error detection and error correction. For this, the brain has to accumulate evidence for errors as soon as it becomes available. This study used multivariate pattern classification techniques for event-related potentials to track the accumulation of error-related brain activity before an overt response was made. Upcoming errors in a digit-flanker task could be predicted after the initiation of an erroneous motor response, ~90 ms before response execution. Channels over motor and parieto-occipital cortices were most important for error prediction, suggesting ongoing perceptual analyses and comparisons of initiated and appropriate motor programmes. Lower response force on error trials as compared to correct trials was observed, which indicates that this early error information was used for attempts to correct for errors before the overt response was made. In summary, our results suggest an early, automatic accumulation of error-related information, providing input for fast correction processes.

1. Introduction

The immediate detection and correction of performance errors is an important feature of adaptive behaviour in everyday environments that are subject to dynamic changes. Often, we correct for our errors so quickly that we are not even aware that we have made them, for example when we are about to press the wrong button on the telephone but automatically stop the movement, just before execution. For this mechanism to be sufficiently efficient to result in better performance, error detection as well as corrective processes have to start early, ideally before response execution. These early error-related processes have been investigated in humans using event-related potentials (ERPs), recorded with electroencephalography (EEG). Two specific ERP components, the error-related negativity (Ne/ERN) and the error positivity (Pe) have been used to investigate error processing. The Ne/ERN seems to start around or slightly before the overt response (Yeung, Botvinick, & Cohen, 2004) and it peaks ~80–100 ms after an overt erroneous response (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993). The Ne/ERN shows a fronto-central scalp distribution and has been associated with activity of the anterior cingulate cortex (ACC) (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). The error positivity (Pe, Falkenstein et al., 1991) follows the Ne/ERN (i.e., approximately 300 ms after an erroneous response) and shows a centro-parietal scalp distribution. The Pe has been discussed to reflect conscious error processing mechanisms such as error detection (Murphy, Robertson, Allen, Hester, & O'Connell, 2012; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Steinhauser & Yeung, 2010) and behavioural adaptation (Overbeek, Nieuwenhuis, Ridderinkhof, 2005). It has been suggested that the Ne/ERN is associated with a fast error detection mechanism, which compares the representation of a desired goal with the actual response outcome (Falkenstein et al., 1991; Falkenstein, Hohnsbein, & Hoormann, 1995; Gehring et al., 1993; Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996), potentially achieved via efference copies accompanying motor response preparation (Angel, 1976; Kopp, Rist, & Mattler, 1996; Taub, 1976). In contrast to the error detection view, response conflict theories suggest that the Ne/ERN might reflect the degree of ongoing response conflict, resulting from the simultaneous activation of two or more response processes competing for neural resources that are monitored by the ACC (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen, Servan-Schreiber, & McClelland, 2000; Yeung et al., 2004). In this framework, an error and the Ne/ERN are both the result of response conflict, but the error is not causing the Ne/ERN itself. Based on the observation that a similar ERP component also

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occurs on correct trials, Vidal and colleagues (Vidal, Hasbroucq, Grapperon, & Bonnet, 2000; Vidal, Burle, Bonnet, Grapperon, & Hasbroucq, 2003) have proposed that the Ne/ERN and related components represent the activity of a more general action monitoring process, subsuming more than error processing and response conflict monitoring. Finally, Holroyd and Coles (2002) suggested in their reinforcement-learning theory that the Ne/ERN is related to a violation of expectation. As an error reflects a violation of the expectation to respond correctly, such prediction errors would lead to a change in ACC activity modulated by the basal ganglia. Components temporally overlapping with the Ne/ERN have also been shown to be predictive for whether an error is made in the next trial of an experiment, reflecting long-term adjustments and performance monitoring (Ridderinkhof, Nieuwenhuis, & Bashore, 2003).

While the above-mentioned theories derive explanations for how errors are caused and detected, successful behaviour also requires fast error correction (Rabbitt, 1966, 1978, 2002). However, for fast error detection and immediate error correction, the peak of the Ne/ERN would occur too late to reflect the true starting point of error processing. Effective error detection might require the ongoing accumulation of evidence for an upcoming error already beginning with the initial incorrect response initiation. Our study aimed to test this hypothesis by determining how early prediction of errors was possible, based on patterns of brain activity measured immediately following the initiation of a motor response on a cortical level that served as the first indicator of the initial decision, and preceding the overt response.

In order to determine the initiation of the motor response, which constitutes the endpoint of the initial decision, the stimulus-locked and the response-locked lateralised readiness potentials (S-LRPs, R-LRPs) were identified. The LRP is the averaged difference waveform resulting from subtracting the motor activity form the ipsi- and contralateral motor cortex (for details see Section 2). The S-LRP reflects the period of the sensory information processing up to the selection of the motor response. The R-LRP has been used to index the beginning of response initiation on the level of the primary motor cortex (Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988) and its onset is usually found ~150 ms before response execution (for a review see, Smulders & Miller, 2012). For this study, the onset of response execution was determined by the onset of a force key press. The time window between response initiation (the onset of the R-LRP) and response execution (the key press) in particular was analysed using multivariate pattern classification (Bode et al., 2012; King & Dehaene, 2014) to predict upcoming errors from spatiotemporal patterns of ERPs, which were first subjected to a current source density (CSD) analysis to increase the topographical accuracy of each channel. Multivariate pattern classification does not rely on single channel ERPs but uses fine differences in patterns of ERPs between errors and correct responses, distributed across all channels, to predict whether an error will be made. This approach allowed us to search for error-related information in an unbiased fashion, and further to analyse which channels contribute to error classification at each point in time, tracking the evolution of error-information preceding response execution as well as the Ne/ERN. To elicit performance errors we used a speeded digit-flanker task with a parity decision about a central digit (Stahl, 2010). The flankers could either be congruent (same parity) or incongruent (different parity) to the central digit and thus provided supporting or conflicting information for the parity judgement. We hypothesised that after response initiation, the perceptual analysis of stimuli would continue, which, on error trials, would lead to an increase in evidence supporting the correct response. We reasoned that the pattern of brain activity should reflect these processes and thus provide early error-related information, starting with response initiation. The origin of this early error-related brain activity would then be informative about how input for a central error monitoring system is generated. Furthermore, congruent and incongruent trials should differ with respect to the conflict elicited by the flankers. This allowed us to test whether clearer evidence for errors, as reflected in higher classification accuracies, would be available in congruent trials in which no conflicting evidence was induced by the flankers. Finally, we also investigated whether errors and correct responses differed in response force (Gehring et al., 1993), as this could be an indicator of attempts to use the early error information in order to modify behaviour.

2. Materials and methods

2.1. Participants

All participants were healthy, had normal or corrected-to-normal visual acuity and gave written informed consent to participate in the study. 121 participants took part in the study, which also investigated a personality psychology research question that will be reported elsewhere (paper submitted). To be included in the analyses for the present paper, investigating the general research question of error processing, a participant's data set had to contain at least ten usable error trials (after EEG artefact removal) for each experimental condition. The final sample consisted of 109 participants (58 female, mean age 25.2 ± 5.8 SD years), who fulfilled this criterion for incongruent trials (83 of those also fulfilled the criterion for congruent trials). Note that, as in other studies using this kind of task, the number of errors strongly varied between participants, but it was estimated that the Ne/ERN could be reliably determined based on six trials only (see Olvet & Hajcak, 2009), and most our participants produced a larger number of errors in our study (see Section 3). The experiment was approved by the ethics committee of the German Psychological Society (DGPs) and was conducted according to the Declaration of Helsinki.

2.2. Experimental paradigm

Participants performed a digit-flanker task with a speed instruction (Stahl, 2010). On each trial they were asked to respond to the parity of a central white digit (1–8) presented in the centre of the black screen for 67 ms. The central digit was flanked by two identical digits (1–8), which were never the same digit as the central digit but either congruent or incongruent with respect to their parity. Participants were asked to press one of two force-sensitive response keys (sensitivity of <2 cN), operated with the left and the right index finger, to indicate their parity decision (Fig. 1A). The assignment of response hand and parity decision was counterbalanced between participants. Each response key was composed of a plastic cuboid (110 mm × 619 mm × 62 mm) attached to a spring steel plate held by an adjustable metal clamp at one end. Participants' fingertips of both index fingers rested on the cuboid at the open end while their forearms and palms rested on individually adjusted boards, which were located on the left and right sides of the computer screen. Participants' location and posture was fixed to 56 cm distance between eyes and screen using an adjustable chin rest. The response window lasted 1133 ms while a black screen was displayed. The experiment was comprised of a speed condition as well as an accuracy condition (the order was counterbalanced between participants). Here we only analysed the speed condition, which instructed participants to emphasise response speed; the accuracy condition did not result in a sufficient number of errors for the pattern classification analysis and will be only relevant for the personality psychology related study. In the speed condition, participants were shown one of three possible feedback screens for 200 ms after the response period. Either "R" ("Richtig", German for "correct") was displayed, indicating a fast-enough, correct response, or "H" was displayed, indicating a "hand/response error" (incorrect response, hereafter simply referred to as "error"), or "Z" ("Zeit", German for "time") was displayed indicating a "time error", which was a correct but too slow response. The required response time for correct responses was 90% of the individual average performance of a pre-test session comprising 40 trials (average 7.1% errors; SD = 1.2%). The feedback screen was followed by a fixed inter-trial interval (ITI) of 1500 ms in which the screen turned black. Ten blocks of the experiment were presented, comprising 40 trials in each block, 20 of which were congruent and 20 of which were incongruent, presented in a random order.

2.3. Response time and response force analysis

Response time (RT) was analysed for the congruent condition and the incongruent condition for correct and error trials separately. RT was defined as the temporal interval between the onset of stimulus presentation and the first response force exceeding 50 centinewtons (cN). Time errors were excluded from the analyses. The response force of the index finger was measured by strain gauges at the fixed end of the cuboids. The analogue signal was digitised at a sampling rate of 500 Hertz (Hz). Two response force parameters were extracted, the peak force (PF) (for a similar approach using PF, see Gehring et al., 1993) and the time-to-peak-force (TTP) were used as indicators of immediate error correction behaviour. The PF was defined as the peak amplitude of the force after response onset in each trial. The TTP was defined as the temporal delay between response onset and the time point at