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Research report

Lesions to the prefrontal performance-monitoring network disrupt neural processing and adaptive behaviors after both errors and novelty

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ABSTRACT

Unexpected events can have internal causes (action errors) as well as external causes (perceptual novelty). Both events call for adaptations of ongoing behavior, resulting, amongst other things, in post-error and post-novelty slowing (PES/PNS) of reaction times (RT). Both types of events are processed in prefrontal brain areas, indexed by event-related potentials (ERPs): Errors are followed by a complex of ERPs comprised of the error-related negativity (ERN) and error positivity (Pe), whereas novels are followed by a N2/P3 complex. However, despite those overlapping properties, past neuroscientific studies of both types of events resulted in largely separate branches of research. Only recently have theoretical efforts proposed overlapping neuronal networks for the computation of 'unexpectedness' in general. Crucially, in a recent study, we have shown that both errors and novelty are indeed processed in the same neuronal network in the human brain: the prefrontal-cingulate performance-monitoring network (PCMN) underlying the ERN also explained significant parts of the N2/P3 complex.

Here, we attempt to take this research further by investigating the causal role of the PCMN in both error and novelty processing. Eight patients with ischemic lesions to the PCMN and eight control participants performed a version of the flanker task in which they made errors, while also being presented with unexpected action effects on a subset of otherwise correct trials.

In line with our predictions, lesions to the PCMN lead to significant reductions in ERP amplitude following both errors and perceptual novelty. Also, while the age-matched control participants showed the expected pattern of adaptive RT slowing to both errors and novelty, patients did not exhibit adaptive slowing behaviors following either event. These results support recent theoretical accounts according to which a general PCMN reacts to surprising events, regardless of valence and/or source of the unexpectedness.

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1. Introduction

The ability to make adaptive changes to ongoing behavior is of utmost importance to many situations in everyday life, particularly when faced with unexpected events and action outcomes. Whether one makes a sudden mistake in a repetitive task, e.g., shifting into a wrong gear when driving a car with a manual transmission, or whether an unexpected event happens in the environment, e.g., a ball rolling into a street one is driving on, immediate behavioral adaptation is crucial to resolve such situations in an efficient manner.

In neuroscientific literature, the processing of internally generated unexpectedness ('errors') and externally generated unexpectedness ('novelty') has classically been investigated in separate paradigms, leading to two mainly separate branches of research. Electrophysiological investigations using speeded reaction time (RT) paradigms like the flanker task (Eriksen & Eriksen, 1974) have helped to identify cortical event-related potential (ERP) signatures of error processing, namely the error-related negativity (ERN/Ne, Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993), a negative voltage deflection with a fronto-central scalp distribution which peaks around 50–100 msec following an error, and the subsequent error positivity (Pe) (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000). The ERN has been reliably localized to the anterior midcingulate cortex (aMCC, Debener et al., 2005; Dehaene, Posner, & Tucker, 1994; Gehring and Willoughby, 2002; Holroyd, Dien, & Coles, 1998; Ullsperger and von Cramon, 2001; Van Veen and Carter, 2002; but see: Agam et al., 2011). ERP research on novelty processing mostly utilizes novelty-oddball paradigms, in which a stream of frequent 'standard' stimuli is interspersed with infrequent and/or unexpected oddball or novel trials (Courchesne, Hillyard, & Galambos, 1975; Squires, Squires, & Hillyard, 1975). Such investigations have revealed a fronto-centrally distributed N2/P3a-complex as the main neurophysiological concomitant of novel, unexpected events (Folstein and Van Petten, 2008; Näätänen & Gaillard, 1983), with particular focus on the P3a (Knight, 1984; Polich, 2007).

Recently, however, new theoretical developments and empirical findings in both humans and animals have started to unite these two branches of research. A prominent theory of error processing hypothesizes that the ERN (or aMCC activity in general) is generated by the negative reward prediction error associated with action slips (Holroyd and Coles, 2002) (for alternative theories of ERN function, see Botvinick, Braver, Barch, Carter, & Cohen, 2001; Coles, Scheffers, & Holroyd, 2001). However, a recently developed computational model (Alexander and Brown, 2011) widens the focus of that theory by hypothesizing that aMCC activity reflects unsigned reward prediction error (or, simply put: 'surprise') associated with an action outcome. This is in line with evidence from animal research demonstrating reward prediction-error coding independent of valence in the monkey-homologue of the human aMCC (Hayden, Heilbronner, Pearson, & Platt, 2011). It is also in line with more general conceptualizations of brain function such as the 'free energy' principle, according to which the brain largely functions by detecting and minimizing prediction errors in any exchange with the environment (Friston, 2005, 2010).

Crucially, in a recent study (Wessel, Danielmeier, Morton, & Ullsperger, 2012), we could demonstrate that the model can be extended even further. We used a hybrid error-monitoring novelty-oddball task, in which action outcomes could either be correct responses followed by standard visual action feedback (triangles), erroneous responses followed by standard feedback, or correct responses followed by novel, unexpected visual action feedback (pictures of objects or animals). By showing that the brain network underlying the ERN is also active on correct trials with unexpected action feedback (perceptual novelty), and, in fact, also explains significant parts of the N2/P3a-complex, we demonstrated that the prefrontal-cingulate performance-monitoring network (PCMN) not only monitors actions for internally generated unexpected events (errors), but also for externally generated unexpected events (novels) that are independent of the accuracy of one's actions. In a second experiment, we then used conjunction analyses of functional magnetic resonance imaging (fMRI) to delineate brain areas that were sensitive towards both error and novelty processing. This network encompassed the prefrontal brain network classically reported in studies of performance monitoring (Kerns et al., 2004; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004), including structures in the fronto-median wall (aMCC, pre-supplementary motor area), lateral prefrontal cortex (lPFC) (bilateral inferior frontal gyrus), anterior insular cortices, thalamus, subthalamic nucleus, and dopaminergic midbrain regions.

Regarding adaptive behaviors following unexpected events, a remarkably similar trajectory of research progression could be found. On the one hand, RT slowing following unexpected or infrequent perceptual stimuli [henceforth referred to as post-novelty slowing – PNS] has been a widely reported effect within many behavioral studies of distractibility (Barcelo, Escera, Corral, & Perianez, 2006; Ljungberg & Parmentier, 2012; Parmentier, Elford, Escera, Andrés, & San Miguel, 2008; Parmentier, Elsley, Andres, & Barcelo, 2011; Vachon, Hughes, Jones, 2012). On the other hand, error-induced RT prolongation (post-error slowing – PES) has been reported in some of the earliest systematic investigations of action errors and remedial behaviors (Rabbitt, 1966; see Danielmeier & Ullsperger, 2011 for a review). Recently, it has been proposed that PES could be a 'side-effect' of the unexpected/infrequent nature of action errors: When in a choice reaction task difficulty was increased such that errors were more frequent than correct trials (a contingency that is usually reversed), relative RT slowing occurred following correct trials instead of error trials (Notebaert et al., 2009). Together, these behavioral and brain imaging findings point toward the possibility of a universal PCMN in prefrontal cortex, which monitors for unexpected events regardless of valence (positive or negative) and regardless of source of origin (external or internal), and implements remedial actions (Debener et al., 2005; Wessel and Ullsperger, 2011; Wessel et al., 2012). However, a causal link between the occurrences of either type of unexpected events, induced activity in the PCMN, and the implementations of remedial actions is still lacking.