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Review

Performance monitoring in children and adolescents: A review of developmental changes in the error-related negativity and brain maturation

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ABSTRACT

To realize our goals we continuously adapt our behavior according to internal or external feedback. Errors provide an important source for such feedback and elicit a scalp electrical potential referred to as the error-related negativity (ERN), which is a useful marker for studying typical and atypical development of cognitive control mechanisms involved in performance monitoring. In this review, we survey the available studies on age-related differences in the ERN in children and adolescents. The majority of the studies show that the ERN increases in strength throughout childhood and adolescence, suggesting continued maturation of the neural systems for performance monitoring, but there are still many unresolved questions. We further review recent research in adults that has provided important insights into the neural underpinnings of the ERN and performance monitoring, implicating distributed neural systems than include the dorsal anterior and posterior cingulate cortex, the lateral prefrontal cortex, insula, basal ganglia, thalamus and white matter connections between these regions. Finally, we discuss the possible roles of structural and functional maturation of these brain regions in the development of the ERN. Overall, we argue that future work should use multimodal approaches to give a better understanding of the neurocognitive development of performance monitoring.

Contents

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1. Introduction

A critical function of our cognitive system is the ability to monitor and evaluate the outcomes and consequences of behavior and adapts subsequent behavior accordingly in order to realize goals. To accomplish this, we rely on some form of feedback on our actions, and when the feedback is self-generated, we refer to this ability as "self-monitoring" (Segalowitz and Dywan, 2009). Electrophysiological methods provide important evidence about the neurocognitive systems associated with this form of performance monitoring because "action slips" – typically fast and impulsive errors, based on insufficient processing of relevant stimuli (van Veen and Carter, 2006) – are known to elicit a negative electrical potential called error-related negativity (ERN) or error negativity (Ne) (Falkenstein et al., 1991; Gehring et al., 1993). Studies indicate that the ERN increases in strength during childhood and adolescence, presumably reflecting development of cognitive control functions and assumed to be caused, in part, by the structural and functional maturation of the brain. Here, we provide a critical account and review of studies on age-related differences in the ERN in children and adolescents. We then review studies on the neural basis of the ERN, and finally discuss how the maturation of distinct neural networks might underlie developmental changes in the ERN and performance monitoring.

The ERN is a sharp response-locked event-related potential (EPR) often evoked by commission of errors in speeded response tasks, that peaks 50–100 ms following the erroneous response, and has a maximum at frontocentral midline scalp recording sites (Bush et al., 2000; Hajcak, 2012; Simons, 2010) (Fig. 1). The ERN signal is believed to lead to remedial or compensatory action such as error correction (Rodriguez-Fornells et al., 2002) or the long-known slowing down of performance immediately after an incorrect response; post-error slowing (PES) (Rabbitt, 1966). Several theories on the functional significance of the ERN have been proposed, including the conflict monitoring theory (Botvinick et al., 2001, 2004; Carter and van Veen, 2007; Yeung et al., 2004) and the reinforcement learning theory (Holroyd and Coles, 2002; Holroyd et al., 2005), suggesting that ERN reflects either the detection and processing of cognitive conflict or an evaluative function signifying "worse than expected events", respectively. Across the diverging theoretical perspectives, there is, however, general consensus that the ERN indexes modality nonspecific cognitive control mechanisms involved in performance monitoring (Taylor et al., 2007; van Veen and Carter, 2006). Additionally, there is also evidence that the ERN is related to motivation and affect (Hajcak, 2012; Segalowitz and Dywan, 2009). In children, this seems to be the case for instance for social evaluation, as larger ERNs have been reported in children being observed by a friend compared to children performing a task alone (Kim et al., 2005).

As we will review in detail below, a growing number of studies document developmental changes in the ERN throughout childhood and adolescence, and converging evidence from a range of different methods indicate that medial frontal brain regions, particularly the dorsal (caudal) anterior cingulate cortex (ACC) and the posterior cingulate cortex (PCC), are critically involved in the generation of the ERN. Research further suggests that the ERN is substantially influenced by genetic factors and that it may be of utility as a biological marker in studies of risk for certain psychiatric disorders (Olvet and Hajcak, 2008; Ullsperger, 2010). A twin study found that 47% of the variance in the ERN amplitude in adolescents was accounted for by genetic factors (Anokhin et al., 2008), while studies making use of polymorphisms of candidate genes affecting neurotransmission point to involvement of dopamine and serotonin in particular (Biehl et al., 2011; Fallgatter et al., 2004; Holmes et al., 2010; Kramer et al., 2007; Meyer et al., 2012a; Mueller et al., 2011). Since the neural sources of the ERN are relatively well described, and several specific genetic contributions have been indicated, this electrophysiological marker of performance monitoring constitutes a very promising model system for studying

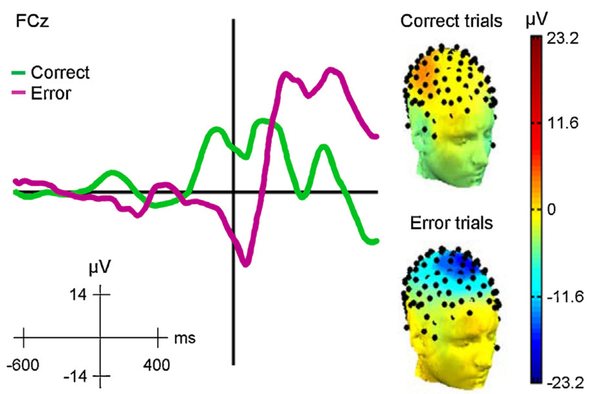

Fig. 1. The error-related negativity. Left panel, Grand average response-locked ERPs from a speeded arrow flanker task from 76 participants 8–19 years old for correct incongruent trials (green) and error incongruent trials (purple). Right panel, 3D topographical maps of scalp potentials at 50 ms after responses for correct and error trials from a representative participant. Unpublished data.