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Review

Brain systems underlying the affective and social monitoring of actions: An integrative review

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ABSTRACT

Action monitoring allows the swift detection of conflicts, errors, and the rapid evaluation of outcomes. These processes are crucial for learning, adaptive behavior, and for the regulation of cognitive control. Our review discusses neuroimaging and electrophysiological studies that have explored the contribution of emotional and social factors during action monitoring. Meta-analytic brain activation maps demonstrate reliable overlap of error monitoring, emotional, and social processes in the dorsal mediofrontal cortex (dMFC), lateral prefrontal areas, and anterior insula (AI). Cumulating evidence suggests that action monitoring is modulated by trait anxiety and negative affect, and that activity of the dMFC and the amygdala during action monitoring might contribute to the 'affective tagging' of actions along a valence dimension. The role of AI in action monitoring may be the integration of outcome information with self-agency and social context factors, thereby generating more complex situation-specific and conscious emotional feeling states. Our review suggests that action-monitoring processes operate at multiple levels in the human brain, and are shaped by dynamic interactions with affective and social processes.

Contents

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1. Overview and motivation

In order to adapt their behavior, to detect and learn from errors, and ultimately to increase their chances of survival, humans and other animals have to monitor their actions (Rabbitt, 1966). Flexible regulation of behavior requires its constant evaluation in terms of performance and outcomes, as well as in terms of costs and future consequences. Action and error monitoring have been studied for several decades in psychology and neuroscience (for previous reviews see e.g. Bush et al., 2000; Falkenstein et al., 2000; Taylor et al., 2007; Ullsperger et al., 2010), mainly using relatively abstract interference paradigms (such as Stroop, Flanker, Simon or go/no-go tasks), and primarily from a cognitive perspective. The first part of this review provides a brief overview of the classical findings in this literature, outlining the main methods (electrophysiology and brain imaging), as well as the central brain systems involved in performance and error monitoring. In the main part, we review and discuss a growing literature that suggests close ties of action monitoring systems with emotional and social processes. In line with other recent accounts that suggest reciprocal interactions between cognitive control and emotion processing brain systems in dorsal mediofrontal cortex (dMFC) (Etkin et al., 2011; Moser et al., 2013; Pessoa, 2008; Proudfit et al., 2013; Shackman et al., 2011; Shenhav et al., 2013), we propose that error and action monitoring is an intrinsically affective and social process. However, we show that meta-analytic activation maps support overlapping brain responses to error processing, emotional, and social information processing not only in dMFC, but also in several other brain regions, including anterior insula and lateral prefrontal cortex. Further, recent intracranial electrophysiological recordings showed error-related activity in the amygdala (Pourtois et al., 2010), suggesting this limbic region may contribute to affective responses to errors and negative action outcomes. In the closing part, we outline an integrative framework for understanding the brain systems underlying affective and social interactions with action monitoring, which may be crucial to foster behavioral control in real life.

2. Behavioral and neurophysiological correlates of action monitoring

2.1. Basic concepts and behavioral findings

Action monitoring has mainly been studied by investigating behavioral and neural correlates of conflict, response error, and feedback processing in various reaction time tasks (for recent comprehensive reviews, see e.g. Holroyd and Yeung, 2012; Shackman et al., 2011; Shenhav et al., 2013). In this context, *conflict* has been defined as crosstalk interference between different ongoing processes (Botvinick et al., 2001) and studied using interference or go/no-go tasks (for an overview on experimental paradigms see Nee et al., 2007; Shackman et al., 2011). Behaviorally, conflict is associated with longer reaction times and a greater number of errors than non-conflict trials (Botvinick et al., 1999; Gratton et al., 1992; Sheth et al., 2012).

Errors are incorrect responses (in relation to the task instructions) and occur more frequently in incongruent (conflict) than in congruent trials (Carter, 1998; Gehring and Fencsik, 2001; Gratton et al., 1992). They can be easily evoked as "false alarms" in no-go trials, especially when time pressure is high (e.g. Vocat et al., 2008) or when no-go trials are very infrequent (Simmonds et al., 2008). Errors are sometimes followed by post-error slowing, i.e. longer RTs on the (correct) trial following errors due to adjustments in response tendencies (Danielmeier et al., 2011; Danielmeier and Ullsperger, 2011; King et al., 2010) or as a reflection of attentional orienting to these deviant and worse than expected events (Notebaert et al., 2009; Wessel et al., 2012). Errors can lead to increased post-error accuracy (Danielmeier and Ullsperger, 2011), indicating a potential shift in speed/accuracy trade-off.

External *feedback* processing is studied with experimental tasks, in which participants are not able to infer the action outcome based on their response or based on an internal monitoring process exclusively (Gehring and Willoughby, 2002; Holroyd and Coles, 2002; Miltner et al., 1997), but have to rely on externally provided feedback. Examples include gambling tasks in which outcome is randomized or probabilistic in nature (Eppinger et al., 2008; Frank et al., 2005), or time-estimation tasks (e.g. Hirsh and Inzlicht, 2008; Miltner et al., 1997). Feedback about the action outcome (e.g. win or loss, correct or incorrect) is usually presented as visual or auditory information (Walsh and Anderson, 2012).

2.2. Investing the time-course of action monitoring with electrophysiology

For several reasons, electrophysiology provides an important methodological approach to the study of action monitoring brain processes. First, techniques such as EEG and intracranial electrophysiological recordings allow inferences about the time course of neurophysiological processes underlying error and conflict processing (Pourtois et al., 2010) with millisecond temporal resolution that is unattainable by brain imaging methods based on more sluggish hemodynamic contrasts (such as fMRI or PET). Second, event-related potentials (ERPs) have revealed several phasic components of conflict, error, and outcome monitoring, which have specific temporal and topographical properties, such as the N2, error-related negativity (ERN), and feedback-related negativity (FRN). These ERP components may partially reflect a common underlying process (Van Veen and Carter, 2002; Wessel et al., 2012; Yeung et al., 2004) that is characterized by phasic bursts in theta band activity (Cavanagh et al., 2012; Cohen, 2011). Beyond this common functional role, they can be considered as characteristic physiological markers of conflict, error, and outcome processing (for overviews see Falkenstein et al., 2000; Simons, 2010). Given the combination of these properties, i.e. high time resolution and the specificity of action monitoring ERP components, electrophysiology can inform us about the temporal sequence of psychological processes during action monitoring, as well as the timing of their modulation by various affective, social, or cognitive factors.

Depending on the task characteristics, electrophysiological indices of action monitoring can be observed at different stages,