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Adaptive control deficits in attention-deficit/hyperactivity disorder (ADHD): The role of error processing

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Abstract

Cognitive performance of children with attention-deficit hyperactivity disorder (ADHD) is characterized by large moment-to-moment fluctuations in cognitive control reflected by a highly inconsistent and inaccurate response style. It has been suggested that abnormal error processing underlies this failure to implement adequate control. We investigated the error-related negativity (ERN), a negative deflection in the event-related potential (ERP) time-locked to erroneous responses in 16 rigorously screened ADHD boys aged 8–12 years and 16 age-matched normal control boys during a modified Eriksen flanker paradigm with two levels of time pressure. Children with ADHD responded as fast and regularly as controls, but committed significantly more errors, particularly when facing time pressure and response conflict. ADHD children produced shorter runs of correct responses than controls. In addition, with high time pressure, error runs were prolonged relative to control children, suggesting an increase in both frequency and magnitude of temporary lapses of control. ERP amplitude differences between correct and incorrect responses were diminished in ADHD children, whereas post-error slowing remained unaffected. This pattern of results indicates that a specific deficit in monitoring ongoing behaviour, rather than insufficient strategic adjustments, gave rise to performance limitations in ADHD. Findings are discussed in terms of anterior cingulate cortex (ACC) dysfunction, leading to a failure to predict the likelihood that an error occurs in a given context.

Keywords: Eriksen flanker task; Executive control; Error monitoring; Post-error slowing; Event-related potentials; Error-related negativity

1. Introduction

Children with attention-deficit hyperactivity disorder (ADHD) are characterized as being distractible and disorganized. Adaptive goal-directed behavior requires the constant comparison of ongoing actions with internal goals and standards. If discrepancies between expected and actual outcomes are being detected, adaptive control processes are called into play in order to make behavioral adjustments. Adaptive control processes are critical in novel situations, when multiple tasks need to be managed at the same time, or when information in the environment threatens to trigger an inappropriate action, situations in which patients with ADHD are typically impaired. Therefore, a deficit in high-level control processes, labelled "executive control" has been proposed (Barkley, 1997a; Douglas, 1999; Sergeant, 2000; Berger and

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Posner, 2000; Nigg et al., 2004). More specifically, it has been suggested that ADHD children fail to use performance errors and inappropriate response tendencies to determine whether control processes need to be tightened (Barkley, 1997b; Douglas, 1999; Sergeant, 2000). This inability leads to a deficit in flexibly regulating task performance as reflected by high error rates and variable response latencies (Sergeant, 1988; Leth-Steensen et al., 2000; Kuntsi et al., 2001; Castellanos and Tannock, 2002). Evidence for an inefficient utilization of errors to adjust performance comes from studies assessing the degree of response slowing after subjects have committed an error in speeded reaction time tasks. While normal children shift towards a more conservative speed/accuracy balance following an error, ADHD children do not use such a strategy to prevent future errors (Sergeant and van der Meere, 1988; Krusch et al., 1996; Schachar et al., 2004). It remains to be clarified why children with ADHD fail to implement appropriate control adjustment.

Since the discovery of the error-related negativity (ERN), considerable progress has been made in studying how the brain determines and communicates the need to recruit control. The ERN is a sharp negative deflection in the event-related potential (ERP) with a fronto-central distribution, which peaks approximately 80 ms after an incorrect response (Falkenstein et al., 1991; Gehring et al., 1993). Source localization studies have demonstrated that the ERN has a medial–frontal generator, most likely the anterior cingulate cortex (ACC; Dehaene et al., 1994). According to early theories, the ERN reflects a mismatch between intention and action (Gehring et al., 1993), or, alternatively, the simultaneous activation of two competing responses (Carter et al., 1998). A recent theory holds that when an error has been made, a fast alert and teaching signal, indicating unexpected absence of reward is carried via midbrain dopamine (DA) neurons from the basal ganglia to the ACC (Holroyd and Coles, 2002). Very recently, it has been proposed that the ACC detects conditions under which errors are likely to occur rather than errors or conflict itself (Brown and Braver, 2005). Modulation of activity in the ACC (related to monitoring) serves as a signal that engages control processes in lateral pre-frontal cortex (PFC) and, as a consequence, leads to changes in performance (Ridderinkhof et al., 2004) since stronger behavioral adjustment on the next trial is associated with increased lateral PFC activity (Garavan et al., 2002; Kerns et al., 2004).

A growing body of literature suggests that cognitive control deficits in ADHD arise from a dysfunction in a DA-rich fronto-striatal network of brain structures, including the ACC, since functional abnormalities have been reported during various effortful tasks that engage cognitive control (Lou et al., 1989; Vaidya et al., 1998; Rubia et al., 1999; Bush et al., 1999; Ernst et al., 2003; Durston et al., 2003; Fallgatter et al., 2004; Tamm et al., 2004; Schulz et al., 2004; Booth et al., 2005). The ERN has been shown to be altered in pathological conditions associated with fronto-striatal DA dysfunction, such as Parkinson's disease (Falkenstein et al., 2001), obsessive–compulsive disorder (Gehring et al., 2000), and Tourette's syndrome (Johannes et al., 2002).

In the present study, we employed a modified version of the Eriksen flanker Paradigm (Eriksen and Eriksen, 1974), a task frequently used in ERN research. The flanker task measures the ability to suppress inappropriate response tendencies elicited by irrelevant information. In order to further increase the likelihood of committing an error, the task was performed under time pressure. Response time variability and runs of errors and correct responses were calculated to determine the frequency and magnitude of performance fluctuations. Furthermore, using the ERN as a psychophysiological index of error detection, and post-error slowing as a measure of behavioral adjustment following an error, we investigated whether deficient error processing may underlie ADHD children's poor adaptive control.

2. Methods

2.1. Participants

Sixteen boys, aged 8 to 12 years (M = 128.5 months, S.D. = 15.4) with a clinical diagnosis of ADHD were recruited via advertisement on a website on the internet where they could sign up for participation in the study. Children with comorbid developmental disorders including learning difficulties and dyslexia, Tourette's syndrome, epilepsy and pervasive developmental disorder were excluded. Additional exclusion criteria included auditory or visual problems and medication other than methylphenidate. Children with comorbid oppositional defiant disorder (ODD) and conduct disorder (CD) were allowed to participate. Children with ODD often refuse to comply with rules, easily lose their temper, behave aggressively, and are frequently angry and resentful. CD is characterized by serious violations of rules, aggression to people or animals, destruction of property, and deceitfulness or theft. CD is considered a more serious form of ODD (American Psychiatric Association, 1994).

The Dutch version of the Disruptive Behavior Disorder rating scale (Pelham et al., 1992; DBD; Oosterlaan et al., 2000), an instrument with well-established psychometric properties measuring DSM-IV symptoms of ADHD, ODD, and CD, was used to screen for ADHD