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The neural correlates of deficient error awareness in attention-deficit hyperactivity disorder (ADHD)

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ABSTRACT

The ability to detect and correct errors is critical to adaptive control of behaviour and represents a discrete neuropsychological function. A number of studies have highlighted that attention-deficit hyperactivity disorder (ADHD) is associated with abnormalities in behavioural and neural responsiveness to performance errors. One limitation of previous work has been a failure to determine the extent to which these differences are attributable to failures of conscious error awareness, a process that is dependent on the integrity of the frontal lobes. Recent advances in electrophysiological research make it possible to distinguish unconscious and conscious aspects of error processing. This study constitutes an extensive electrophysiological investigation of error awareness and error processing in ADHD. A Go/No-Go response inhibition task specifically designed to assess error awareness was administered to a group of adults diagnosed with ADHD and a group of matched control participants. The ADHD group made significantly more errors than the control group but was less likely to consciously detect these errors. An analysis of event-related potentials elicited by errors indicated that an early performance monitoring component (early positivity) was significantly attenuated in the ADHD group as was a later component that specifically reflects conscious error processing (Pe). Dipole source modelling suggested that abnormal Pe amplitudes were attributable to decreased activation of the anterior cingulate cortex. Decreased electrodermal activity in the ADHD group also suggested a motivational insensitivity to performance errors. Our data provide evidence that neuropsychological deficits associated with ADHD can be exacerbated by error processing abnormalities. Error awareness may represent an important cognitive and physiological phenotype for ADHD.

1. Introduction

In everyday life the ability to detect errors is critical for smooth and dynamic interaction with our environment, providing us with the opportunity to re-align our behaviour with prevailing goals and to learn the consequences of different behaviours (Norman & Shallice, 1986). Recent evidence from functional imaging shows that error processing is a discrete component of executive control supported by distinct brain networks dedicated to the detection and correction of performance errors (Fiehler, Ullsperger, & von Cramon, 2004; Garavan, Ross, Murphy, Roche, & Stein, 2002). The anterior cingulate cortex (ACC) and lateral prefrontal cortex have been identified as the cortical areas that are critical for effective error processing (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). Hypoactivation of these same regions and a reduced tendency to correct performance following errors have also been highlighted in a number of putatively frontal disorders including schizophrenia (Mathalon et al., 2002; Morris, Yee, & Nuechterlein, 2006), obsessive-compulsive disorder (Ruchsow et al., 2005), substance abuse (Franken, van Strien, Franzek, & van de Wetering, 2007) and attention-deficit hyperactivity disorder (ADHD) (e.g. Burgio-Murphy et al., 2007; Rubia, Smith, Brammer, Toone, & Taylor, 2005; Schachar et al., 2004). However, one area of uncertainty in this clinical work, is the explicit role played by conscious error awareness. Damage to the frontal lobes has been associated with decreased awareness of one's deficits including a tendency to 'miss' errors during neuropsychological tasks (McAvinue, O'Keeffe, McMackin,

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& Robertson, 2005; O'Keeffe, Murray, et al., 2007). Reduced awareness of one's deficits predicts behavioural disturbances in brain injured populations (Prigatano & Schachter, 1991) and may be tied to failures of goal-directed attention (O'Keeffe, Dockree, Moloney, Carton, & Robertson, 2007; Shalgi, O'Connell, Deouell, & Robertson, 2007). Consequently there is an imperative for studies to investigate whether reduced awareness might contribute to the self-monitoring deficits observed in other clinical populations. Here we examine the behavioural and electrophysiological correlates of error processing in adults with ADHD while distinguishing explicitly between errors made with and without conscious awareness.

ADHD is characterised by primary behavioural symptoms of inattention, impulsivity and hyperactivity (A.P.A., 2000). The high incidence of ADHD and controversy regarding the use of subjective behaviour reports in its diagnosis has directed research towards clarifying its biological bases and identifying core cognitive or physiological markers that could contribute to an objective diagnosis. Neuropsychological studies have convincingly demonstrated that these behavioural symptoms are attributable, at least in part, to an underlying executive dysfunction, including problems of response inhibition, working memory and aspects of attention (Seidman, 2006). Morphometric analyses have indicated subtle volumetric reductions of the prefrontal cortex and ACC in both children and adults with ADHD (Seidman, Valera, & Makris, 2005; Sowell et al., 2003) while numerous functional imaging studies have reported decreased activation of these regions during the performance of a range of executive tasks (Bush, Valera, & Seidman, 2005). However, executive control is typically assessed in terms of overall accuracy on a given task without consideration of differences in post-error behaviour. Since executive control is dependent on efficient error processing to signal the need for increased levels of attentional or cognitive resources, a basic failure to detect errors or a difficulty reacting to errors could be a separable and important component of neuropsychological task performance. Hence, the study of error processing and error awareness might reveal a novel basis for the broad profile of executive deficits in ADHD.

In recent years, electrophysiological research has isolated distinct neural signatures associated with error monitoring and error awareness thus affording a fine-grained analysis of error-related processing in ADHD than was possible previously. A growing number of recent ERP studies have investigated error-processing amongst children with ADHD and have pointed to abnormalities in two well established error-related components (Burgio-Murphy et al., 2007; Jonkman, van Melis, Kemner, & Markus, 2007; Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005; van Meel, Heslenfeld, Oosterlaan, & Sergeant, 2007; Wiersema, Van der Meere, & Roeyers, 2005). The first is the error-related negativity (ERN), a fronto-centrally distributed negative wave seen approximately 100 ms following an erroneous response, while the second is the Error Positivity (Pe) which peaks 300–500 ms after an error and is maximal over centro-parietal regions. No studies have examined these components in adults with ADHD.

In their 2001 study, Nieuwenhuis and colleagues explored the extent to which the ERN and Pe are affected by error awareness. Using an antisaccade paradigm the authors demonstrated that the error-related negativity was equally present following errors that participants had or had not consciously perceived, but the Pe was only present if an error was consciously perceived. O'Connell et al. (2007) replicated these findings in the manual response modality. In O'Connell et al. (2007) participants performed a Go/No-Go response inhibition task that was specifically designed to assess levels of error awareness and it was noted that the Pe was preceded by an early positive deflection with a fronto-central maximum. No influence of error awareness was found for either the ERN or the early positivity but the Pe was only evident if participants were consciously aware of committing errors.

The ERN has been the subject of intense investigation within the error processing field and convergent lines of evidence suggest that its generator lies in a dorsal region of the ACC (Brazdil, Roman, Daniel, & Rektor, 2005; Herrmann, Rommler, Ehlis, Heidrich, & Fallgatter, 2004; Van Veen & Carter, 2002). Since an ERN-like component, known as the correct-response negativity (CRN), is also evident on correct Go trials there is growing consensus that, rather than detecting errors *per se*, the ERN indexes performance monitoring processes that are continuously active throughout task duration but enhanced on erroneous trials (Vidal, Hasbrouc, Grapperonc, & Bonnet, 2000). This view seems to fit with recent evidence that, rather than detecting errors themselves, the primary role of the ACC may be to continually monitor performance in order to identify changes in error likelihood (Brown & Braver, 2005 but see also Nieuwenhuis, Schweiser, Mars, Botvinick, & Hajcak, 2007) or outcome value (Holroyd, Niuwenhuis, Mars, & Coles, 2004). Although it is apparently dependent on error awareness, far less is known about the precise functional significance of the Pe. A recent review by Overbeek, Nieuwenhuis, and Ridderinkhof (2005) highlights that there is evidence to support a number of hypotheses (originally proposed by Falkenstein, 2004) including the initiation of behavioural adaptation, neuroaffective processing, or a P3-like evaluation of the error event as well as the possibility that the Pe directly reflects error awareness or processes leading to error awareness.

The latest ERP evidence therefore indicates that the human error processing system possesses distinct pre-conscious and conscious detection mechanisms. As such, the ERN, early positivity and Pe can provide useful markers for investigating the time-course of error monitoring difficulties while also distinguishing between unconscious and conscious processing. Nevertheless, an important message that emerges from this past work is that the Pe, although dependent on error awareness, does not necessarily provide a direct measure of error awareness. This distinction is particularly important in the context of clinical studies in which Pe abnormalities could potentially emerge because fewer errors have reached awareness, or because there is a difference in the processing of detected errors or even a combination of both possibilities. While previous ERP studies in ADHD have provided good evidence to suggest that error processing is disrupted (Burgio-Murphy et al., 2007; Jonkman et al., 2007; Liotti et al., 2005; van Meel et al., 2007; Wiersema et al., 2005), the role that error awareness plays in this disruption can only be fully elucidated through the inclusion of an explicit measure of error awareness.

The present study constitutes an extensive electrophysiological investigation of error processing in adults with ADHD. Eighteen adults diagnosed with ADHD performed the Error Awareness Task (EAT, Hester, Foxe, Molholm, Shpaner, & Garavan, 2005) and were compared to a group of 21 matched controls. ERP measures were acquired from 14 participants with ADHD and 12 control participants in order to verify pre-conscious and conscious aspects of error processing. Measures of electrodermal activity (EDA) were also acquired during task performance. EDA is a measure of autonomic arousal commonly used as an index of psychophysiological responsiveness to motivationally significant events (Dawson, Schell, & Filion, 2000). Investigations of the cortical influences on EDA have indicated that prefrontal regions play a central role in integrating motivationally important information with adaptive changes in bodily states of arousal (Critchley et al., 2003).

2. Methods

2.1. Participants

Eighteen outpatient adults diagnosed with the combined subtype of ADHD and 21 controls matched for age, sex (one female) and handedness (one left-handed) participated in this study. The two groups had comparable IQ scores as measured by the vocabulary and block design subtests of the Wechsler Adult Intelligence Scale III and