

Electrophysiological evidence of atypical motivation and reward processing in children with attention-deficit hyperactivity disorder

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ABSTRACT

Behavioral and neurophysiological evidence suggest that attention-deficit hyperactivity disorder (ADHD) is characterized by the impact of abnormal reward prediction error signals carried by the midbrain dopamine system on frontal brain areas that implement cognitive control. To investigate this issue, we recorded the event-related brain potential (ERP) from typical children and children with ADHD as they navigated a “virtual maze” to find monetary rewards, and physically gave them their accumulated rewards halfway through the task and at the end of the experiment. We found that the amplitude of a reward-related ERP component decreased somewhat for typical children after they received their first payment, but increased for children with ADHD following the payment. This result indicates that children with ADHD are unusually sensitive to the salience of reward and suggests that such sensitivity may be mediated in part by the midbrain dopamine system.

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Attention-deficit hyperactivity disorder (ADHD) is one of the most commonly diagnosed disorders of childhood, occurring in approximately 3–7% of the school-age population (American Psychiatric Association, 2000) and making up nearly 50% of child referrals to outpatient clinics (Sutker & Adams, 2001). Children with ADHD show a “persistent pattern of inattention and/or hyperactivity–impulsivity that is more frequent and severe than is typically observed in individuals at a comparable level of development” (American Psychiatric Association, 2000, p. 85). Current theories of ADHD emphasize disruption of frontal–striatal brain systems mediating cognitive control, especially the inability to inhibit inappropriate behaviors (Nigg, 2006; Sergeant, Geurts, Huijbregts, Scheres, & Oosterlaan, 2003; Sonuga-Barke, 2002, 2003). It has been proposed that some of the challenging behaviors seen in children with ADHD closely resemble those seen in individuals with frontal lobe pathology (Barkley, 1997a; Chelune, Ferguson, Koon, & Dickey, 1986) and neuropsychological investigations have supported a “frontal lobe hypothesis” of ADHD (Barkley, 1997a; Gorenstein, Mammato, & Sandy, 1989; Pennington & Ozonoff, 1996; Shue & Douglas, 1992). In addition, both structural and functional neuroimaging studies have suggested dysfunction

within frontal–striatal systems in these children (e.g., Casey, 2001; Casey et al., 1997; Krain & Castellanos, 2006; Lou, Henriksen, Bruhn, Borner, & Nielsen, 1989; Zametkin et al., 1993; for review see Bush, Valera, & Seidman, 2005).

The underlying biochemical abnormality in ADHD is most strongly associated with a disturbance of the midbrain dopamine system (DiMaio, Grizenko, & Joobar, 2003; Faraone et al., 2005; Levy, 1991; Levy & Swanson, 2001; Oades et al., 2005; Seeman & Madras, 2002; Solanto, 2002; Swanson et al., 2000), which densely innervates the frontal–striatal system. Several sources of evidence support this position. First, the principal pharmacological treatment for the disorder, methylphenidate (Ritalin), acts by blocking the dopamine transporter (DAT) which uptakes dopamine from the synapse (see Cragg & Rice, 2004 for review), thus causing greater amounts of dopamine to accumulate at the synaptic cleft (Grace, 2001; Seeman & Madras, 2002). Second, studies of the primary animal model of ADHD – the “Spontaneously Hypertensive Rat” – suggest midbrain dopamine system dysfunction (Johansen & Savgolden, 2005a, 2005b; Johansen, Sagvolden, & Kvande, 2005; Leo et al., 2003; Russell, de Villiers, Sagvolden, Lamm, & Taljaard, 1995; Sagvolden et al., 1992). Third, polymorphic sites at several dopamine-related genes have recently been associated with ADHD (DiMaio et al., 2003; Swanson et al., 2000). In particular, the DAT is relatively more expressed in children with ADHD than in typical children (Krause, Dresel, Krause, la Fougere, & Ackenheil, 2003; Madras, Miller, & Fischman, 2002; Madras, Miller, & Fischman, 2005), leading to lower levels of synaptic and extrasyn-

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naptic dopamine; methylphenidate is believed to block the DATs and reverse this process.

Further genetic evidence suggests a link between the dopamine system and cognitive control in ADHD. For example, a polymorphism of the COMT gene, which controls an enzyme involved in the metabolic degradation of dopamine after its release into the synapse, is thought to impair cognitive control in children with ADHD (Bellgrove et al., 2005) as well as in typically developing children (Diamond, Briand, Fossella, & Gehlbach, 2004). Similarly, a polymorphism of the DRD4 gene that regulates the expression of the dopamine receptor D4, which in the rat is found most densely frontal cortex (Ariano, Wang, Noblett, Larson, & Sibley, 1997), is also strongly associated with ADHD; although initial reports yielded conflicting results (Barr et al., 2000; Faraone et al., 1999; Holmes et al., 2002; Rowe et al., 1998; Swanson et al., 1998), two meta-analyses (Faraone, Doyle, Mick, & Biederman, 2001; Maher, Marazita, Ferrell, & Vanyukov, 2002) and a study with a larger sample size (Manor et al., 2002) have supported the link between the gene and ADHD. In children with ADHD the DRD4-2 and DRD4-7 repeat alleles are associated, respectively, with greater attentional impairment on a continuous performance measure (Manor et al., 2002) and with greater impulsivity (Langley et al., 2004). Suggestively, this latter allele is associated with novelty seeking and exploration in normal individuals (Benjamin et al., 1996; Dulawa, Grandy, Low, Paulus, & Geyer, 1999; Ebstein et al., 1996; but see Kuhn et al., 1999; Vandenbergh, Zonderman, Wang, Uhl, & Costa, 1997), an attribute which appears to have been selected for in evolution (Ding et al., 2002). Still a different polymorphism of the DRD4 gene has been linked to better performance and greater activation of anterior cingulate cortex during a cognitive control task (Fan et al., 2003).

These considerations suggest that the function of the mid-brain dopamine system may provide a key for understanding cognitive control problems associated with ADHD. Recent neurophysiological evidence has indicated that the activity of the midbrain dopamine system codes for a reward prediction error, such that its firing rate briefly increases above baseline following unexpected rewards, and briefly decreases below baseline following the absence of expected rewards (Schultz, 2002); these signals are thought to be used by the targets of the dopamine system for the purpose of reinforcement learning (Montague, Hyman, & Cohen, 2004). Thus, if the dopamine system in children with ADHD differs from that of typical children, then one might expect to see commensurate differences in reward processing and reinforcement learning between the two populations as well.

In fact, an extensive literature documents abnormalities in the ability of children with ADHD to adapt their behavior in response to rewards and punishments (see Luman, Oosterlaan, & Sergeant, 2005 for review). Wender (1972) proposed that children with ADHD are compelled to seek out rewards because of a diminished sensitivity to reinforcement; this concept was later developed by Haenlein and Caul (1987), who proposed that the diminished sensitivity results from an elevated reward threshold. Similarly, in a series of studies Douglas, Parry and others championed the ideas that children with ADHD are strongly inclined to seek immediate reward and that they respond with unique frustration when failing to receive anticipated rewards (Douglas & Parry, 1983, 1994; Parry & Douglas, 1983; Tripp & Alsop, 2001). This position seems consistent with the suggestion of Grace (2001) who, based on a detailed examination of the kinematics of dopamine release and reuptake, suggested that the phasic dopamine response in children with ADHD is elevated to both rewarding and non-rewarding events, such that a ceiling effect causes both minor and major rewards to yield maximal reinforcement (positive reward prediction error); and that the absence of expected rewards yield

an exaggerated phasic decrease in dopamine (negative reward prediction error). In contrast, Sonuga-Barke et al. argued that, rather than maximizing or seeking immediate reward *per se*, children with ADHD are motivated to reduce the overall amount of time they spend waiting for an outcome—that is, they are “delay averse” (Sonuga-Barke, Taylor, Sembi, & Smith, 1992; cf. Kuntsi, Oosterlaan, & Stevenson, 2001). Taking a somewhat contrarian position, Quay (1988) extrapolated from the work of Gray (1982) to argue that ADHD impairments do not result from a disturbance of a dopamine reward processing mechanism, but rather from a disturbance of a noradrenergic “behavioral inhibition system” that causes them to be less sensitive to cues of non-reward or punishment. Other evidence suggests that children with ADHD are relatively more influenced by the latest reward they obtain rather than by their previous reward history (Tripp & Alsop, 1999), and that they are insensitive to changing rates of reinforcement (Kollins, 1997). The general hypothesis that a reward processing mechanism is impaired in ADHD has been supported by recent physiological evidence, as reward and penalty feedback stimuli differentially affect heart rate in typical children but less so in children with ADHD (Crone, Jennings, & van der Molen, 2003; see also Luman, Oosterlaan, Hyde, van Meel, & Sergeant, 2007). Further, symptoms of hyperactivity and impulsivity are correlated with activation of the ventral striatum during reward anticipation (Scheres, Milham, Knutson, & Castellanos, 2007). Nevertheless, although a consensus appears to have emerged that ADHD is at least partly associated with an impairment in reward processing, thirty years of research have failed to yield a consensus about what exactly that deficit is (Cunningham & Knights, 1978; Gordon, 1979; Iaboni, Douglas, & Baker, 1995; Itami & Uno, 2002; McClure & Gordon, 1984; Milich, 1994; Pelham, Milich, & Walker, 1986; Rosenbaum & Baker, 1984; Scheres et al., 2006; Scheres, Oosterlaan, & Sergeant, 2001; Schweitzer & Sulzer-Azaroff, 1995; Solanto, 1990; Wilkison, Kircher, McMahon, & Sloane, 1995; Worland, 1976).

Perhaps the most ambitious and comprehensive of the ADHD reward theories is Sagvolden, Johansen, Aase, and Russell’s (2005) recent Dynamic Developmental Theory. After considering the evidence that links ADHD with a disturbance of the midbrain dopamine system, they proposed that many of the symptoms associated with the disorder result from hypofunction of midbrain dopamine neurons. Importantly, they suggested that this hypofunction manifests as reduced tonic and phasic dopamine activity that together yield smaller reward prediction errors, both positive and negative. Note that this position contrasts with that of Grace (2001), who argued that these reward prediction errors are exaggerated in ADHD. Because the reward prediction errors mediate the reinforcing effects of dopamine, the Dynamic Developmental Theory appears to account for much of the behavioral evidence discussed above, for example, that stronger and more salient rewards are needed to reinforce behavior in ADHD (Haenlein & Caul, 1987; Wender, 1972), and that children with ADHD are less sensitive to changes in reinforcement contingencies (Kollins, 1997). The theory also accommodates the results of Sagvolden et al.’s own experimental work, in which they demonstrated that the altered reinforcement process in ADHD can be characterized by a relatively steep delay-of-reinforcement gradient (the mathematical formalism that relates the temporal delay between a response and reinforcer and the size of the reinforcer to the degree of reinforcement obtained; Johansen, Aase, Meyer, & Sagvolden, 2002; Sagvolden, Aase, Zeiner, & Berger, 1998; Sagvolden, Slatta, & Arntzen, 1988), and is consistent with the observation that children with ADHD are relatively sensitive to immediate reinforcement (Barkley, 1997a; Douglas & Parry, 1983, 1994; Parry & Douglas, 1983; Tripp & Alsop, 2001). Sagvolden et al. (2005) have also argued

that a hypofunctioning midbrain dopamine system would give rise to the impulsiveness and attentional impairment that are signatures of the disorder. At the same time, because the Dynamic Developmental Theory was mainly derived from an animal model, it has been criticized for being an essentially behaviorist, overly simplistic theory of human behavior (Rubia, 2005). Further, it has been contended that the theory overlooks the contribution of the mesocortical (as opposed to mesolimbic and mesostriatal) dopamine system toward reward processing, together with the impact that dysfunction of this system would have on cognitive control (Carrasco, Lopez, & Aboitiz, 2005).

We hypothesize that many of the impairments associated with ADHD result from the impact of abnormal dopamine reward prediction error signals on frontal brain areas involved in cognitive control: By receiving the brain's reward signals at incorrect times, or not at all, the frontal system loses the ability to deploy control appropriately. Thus the control system withdraws control over behaviors that it should inhibit, and facilitates behaviors that it should not (see also Frank, Santamaria, O'Reilly, & Willcutt, 2006; Grace, 2001; Van Meel, 2005; Williams & Dayan, 2005). Here, we investigated this hypothesis by drawing upon a recent theory that holds that the impact of the dopamine reward prediction error signals on neurons in anterior cingulate cortex modulates the amplitude of an event-related brain potential (ERP) component called the error-related negativity (ERN; Holroyd & Coles, 2002). According to this position, the failure to find an expected reward is associated with the generation of a "feedback ERN," whereas the receipt of an unexpected reward does not elicit a feedback ERN (Miltner, Braun, & Coles, 1997; for review see Nieuwenhuis, Holroyd, Mol, & Coles, 2004). We recorded the ERP from children with ADHD and typical children as they navigated a "virtual maze" to find rewards (Baker, Brocki, Kerns, Segalowitz, & Holroyd, 2007; Baker & Holroyd, in preparation). We predicted that impaired reward processing associated with abnormal dopamine would manifest itself in the ERP as an abnormal feedback ERN (cf. Van Meel, Oosterlaan, Heslenfeld, & Sergeant, 2006). As Sagvolden et al. (2005) and Grace (2001) have proposed diametrically opposed accounts of the disturbance, characterizing both positive and negative dopamine reward prediction error signals as either excessively large (Grace) or small (Sagvolden), we expected our results to reveal either a relatively large or relatively small feedback ERN, depending on which theory is correct. Either way, a positive finding would provide insight into the reward-related control mechanisms that appear to be disrupted in ADHD.

1. Method

1.1. Participants

Fourteen boys with ADHD (combined type only; 11.1 ± 1.5 years old) and thirteen typical boys (10.4 ± 1.7 years old), ages 8–13, participated in the experiment. The participants did not differ in age between the two groups, $t(25) = 1.02$, $p = .32$, Cohen's $D = .42$. Children were recruited from advertisements in local papers and parent publications or through fliers placed with local pediatricians; all children with ADHD had been previously diagnosed with the disorder. Parents of control children and children with ADHD completed a history questionnaire and the Computerized Diagnostic Interview Schedule for Children Version IV (DISC-IV) modules for ADHD, Oppositional Defiant Disorder (ODD), Conduct Disorder (CD) and Generalized Anxiety Disorder (GAD). Three children with CD and one child with GAD were included in the ADHD sample; note that genetic evidence indicates that ADHD comorbid with CD appears to be a more severe subtype of ADHD in terms of genetic loading and clinical severity (Thapar, Harrington, & McGuffin, 2001). Due to high comorbidity rates, and to preserve the ability to generalize these findings to the majority of children with ADHD, children who also met criteria for ODD (in actual fact, none in the present study) and/or a learning disability (LD) were also included. Children with (1) a diagnosis of a psychiatric disorder other than ADHD combined type, ODD, or LD, (2) a diagnosis of a mental deficiency or a pervasive developmental disorder, (3) a head injury resulting in a loss of consciousness greater than 20 min, (4) color blindness, or (5) visual or hearing impairment, were excluded from this study.

The children with ADHD who were on medication for this disorder ($N = 7$, 50%; 2 children on Concerta, 5 children on Ritalin) were required to be off their medication for 24 h prior to testing. Parents received CAN\$ 10 for their participation, and children also received a CAN\$ 5 bonus, as described below. Immediately following the ERP experiment, children participated in a behavioral experiment for which they were given an additional CAN\$ 5; these data will be presented elsewhere. Parents and children provided informed consent/assent. The study was approved by the local research ethics committee and was conducted in accordance with the ethical standards prescribed in the 1964 Declaration of Helsinki.

1.2. Apparatus and procedure

Participants engaged in a "virtual maze" decision making task in which they navigated a simple maze to gain rewards (further details of which will be presented elsewhere, Baker & Holroyd, in preparation; see also Baker et al., 2007). In brief, at the start of each trial participants were presented with an image of the base arm of a "T-Maze" showing the length of the arm and two alleys projecting to the left and to the right from its far end (1000 ms), followed by a green double arrow appearing against the far wall at the maze intersect; together these stimuli remained on the screen until the participant made their alley selection. Participants were instructed to press button 1 with their left index finger to select the left alley, or to press button 2 with their right index finger to select the right alley. At the time of their response, the image of the selected alley appeared for a duration of 500 ms. Then, an apple image or an orange image appeared in the center of the image, against the far wall of the alley. Together, the alley and fruit images remained on the screen for 1000 ms. Participants were told that presentation of one type of fruit indicated that the alley they selected contained 5 cents (reward feedback), and that the presentation of the other type of fruit indicated that the alley they selected was empty (no-reward feedback); the mappings between feedback stimuli and reward types were counterbalanced across participants. Participants were further told that on each trial they should chose the alley where they believed the reward would be, and that they would be given all of the money they found. Unbeknownst to the participants, on each trial the type of feedback stimulus was selected at random (50% probability for each feedback type, which is a standard probability used to elicit a robust feedback ERN; Nieuwenhuis, Holroyd, et al., 2004). The feedback was followed by a blank screen delay for 1000 ms and then the next trial began. The experiment consisted of 4 blocks of 50 trials each separated by self-paced rest periods. Critically, participants were given their accumulated winnings twice during the experiment, first midway through the task and second at the end of the experiment (CAN\$ 5.00 total). Note that we adopted the child-friendly, virtual maze guessing task because we expected it to engage children more than the guessing tasks commonly used with adults to elicit the feedback ERN (Nieuwenhuis, Holroyd, et al., 2004).

1.3. Data acquisition and analysis

Data acquisition and analysis followed our standard procedures for recording and analyzing the feedback ERN (see also Baker & Holroyd, in preparation; Holroyd & Krigolson, 2007). The electroencephalogram (EEG) was recorded using a montage of 19 electrode sites in accordance to the extended international 10–20 system. Signals were acquired using Ag/AgCl ring electrodes mounted in a nylon electrode cap with an abrasive, conductive gel (Falk Minow Services, Herrsching). Signals were amplified by low-noise electrode differential amplifiers with a frequency response of dc 0.017–67.5 Hz (90 dB octave roll off) and digitized at a rate of 250 samples/s. Digitized signals were recorded to disk using Brain Vision Recorder software (Brain Products GmbH, Munich). Inter-electrode impedances were maintained below 10 Ω . Two electrodes were also placed on the left and right mastoids. The EEG was recorded using the average reference. The electrooculogram (EOG) was recorded for the purpose of artifact correction; horizontal EOG was recorded from the external canthi of both eyes, and vertical EOG was recorded from the suborbit of the right eye and electrode channel Fp2.

Post-processing was performed using Brain Vision Analyzer software (Brain Products GmbH). The digitized signals were filtered using a 4th order digital Butterworth filter with a passband of .10–20 Hz. An 800 ms epoch of data extending from 200 ms prior to 600 ms following the onset of each feedback stimulus was extracted from the continuous data file for analysis. Ocular artifacts were corrected using the eye movement correction algorithm described by Gratton, Coles, and Donchin (1983). The EEG data were re-referenced to linked mastoids electrodes. The data were baseline corrected by subtracting from each sample the mean voltage associated with that electrode during the 200 ms interval preceding stimulus onset. Muscular and other artifacts were removed using a $\pm 200 \mu\text{V}$ level threshold and a $\pm 50 \mu\text{V}$ step threshold as rejection criteria. ERPs were then created for each electrode and participant by averaging the single-trial EEG according to feedback type (reward, no-reward).

The feedback ERN was measured at channel FCz, where it typically reaches maximum amplitude (Holroyd, Larsen, & Cohen, 2004; Holroyd & Krigolson, 2007; Nieuwenhuis, Holroyd, et al., 2004; Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004). Following our standard procedure, for each participant the feedback ERN was determined by subtracting the average ERP elicited by reward feedback from the average ERP elicited by no-reward feedback (Holroyd & Coles, 2002;

Holroyd & Krigolson, 2007). The peak amplitude of this difference wave was obtained by averaging the difference wave within a 200–300 ms window following feedback onset; this method is appropriate for special populations as it is less sensitive to EEG artifact than the peak-picking method is (DeBoer, Scott, & Nelson, 2005). ERPs and associated differences waves were obtained for trials averaged across the entire experiment, and separately for trials averaged across the first (blocks 1 and 2) and second (blocks 3 and 4) halves of the experiment. Finally, for the purpose of comparison, we also evaluated the amplitude of the P300 by identifying its maximum voltage at channel Pz (where this ERP component reaches maximum amplitude) within a 300–600 ms window following feedback onset (for a review of the P300, see Donchin & Coles, 1988). For each participant, the P300 amplitudes were then averaged by experiment half (first, second) and feedback type (reward, no-reward).

2. Results

Fig. 1 illustrates the ERPs associated with feedback indicating reward and no-reward, recorded at channel FCz. The data were relatively free of artifact, as the artifact rejection procedure discarded an average of 1.1 and 0.8% trials for the children with ADHD and control children, respectively, although an additional 28 and 25% of the trials were respectively corrected for the two populations by the eyeblink correction algorithm. For both groups of participants, the feedback ERN was significantly different from zero (controls: $-1.8 \mu\text{V}$, $t[12] = -2.50$, $p < .01$, confidence interval = $[-2.9 \mu\text{V}, -0.6 \mu\text{V}]$; ADHD: $-2.0 \mu\text{V}$, $t[13] = -2.39$, $p = .01$, confidence interval = $[-3.5 \mu\text{V}, -0.5 \mu\text{V}]$) and exhibited a frontal–central scalp distribution with a maximum at channel FCz. These results indicate that the T-Maze task successfully elicited the feedback ERN in both populations. However, contrary to our expectation, the amplitude of the feedback ERN was not significantly different between groups, $t(25) = 0.33$, $p = .74$, Cohen's $D = .12$. To analyze this result further, we averaged the feedback ERN accord-

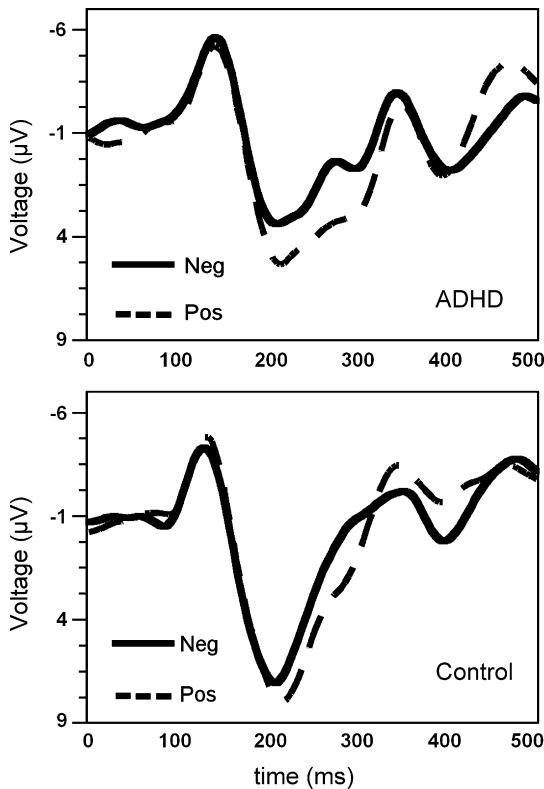


Fig. 1. Event-related brain potentials elicited by reward (“pos”) feedback and no-reward (“neg”) feedback, for children with ADHD (top) and control children (bottom). Feedback onset occurs at 0 ms. Data recorded at channel FCz. Note that negative is plotted up by convention.

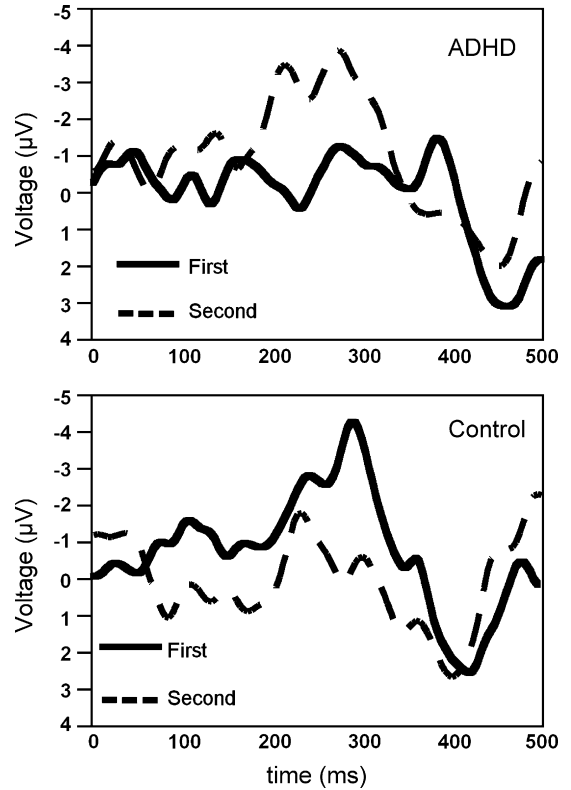


Fig. 2. Feedback error-related negativity difference waves as a function of the first (solid lines) and second (dashed lines) halves of the task, for children with ADHD (top) and control children (bottom). Feedback onset occurs at 0 ms. Data recorded at channel FCz. Note that negative is plotted up by convention.

ing to the first and second half of the experiment, before and after the participants received their first bonus payment (Fig. 2; average number of trials per condition: children with ADHD = 49, typical children = 49; minimum number of trials per ERP = 40). A two-way ANOVA with group (control, ADHD) and time (pre-payment, post-payment) as factors indicated an interaction between group and time, $F(1, 25) = 8.49$, $p < .01$, $ES = .25$ (Fig. 3). Post hoc analysis indicated that, for typical children, feedback ERN amplitude tended to decrease from the beginning to the end of the experiment, $t(12) = -2.03$, $p = .06$, Cohen's $D = .61$. In contrast, for children with ADHD, feedback ERN amplitude increased from the beginning to the end of the experiment, $t(13) = 2.16$, $p = .05$, Cohen's $D = .73$.

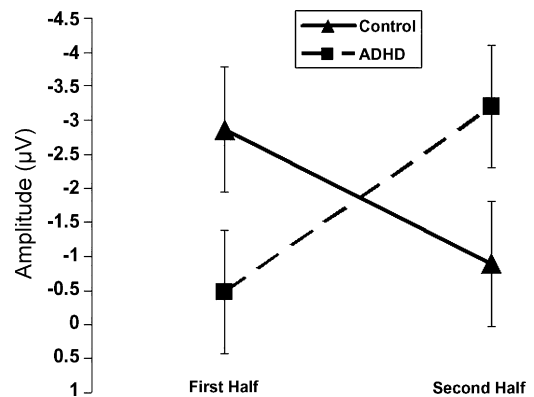


Fig. 3. Feedback error-related negativity amplitude as a function of the first and second halves of the task, for children with ADHD (dashed line) and control children (solid line). Data recorded at channel FCz. Note that negative is plotted up by convention. Error bars indicate standard errors of the mean.

Table 1
Response time data

	Control	ADHD
Reward		
First	604 ± 84	791 ± 80
Second	508 ± 87	646 ± 84
No-reward		
First	532 ± 89	793 ± 86
Second	440 ± 86	655 ± 83

Note: Control, control participants; ADHD, children with attention-deficit hyperactivity disorder; reward, trials following reward feedback; no-reward, trials following no-reward feedback; first, first half of experiment; second, second half of experiment. Values are given in ms; error values indicate standard errors.

For the purpose of comparison, we also analyzed the amplitude of the P300 across groups. A three-way ANOVA on P300 amplitude as a function of group (ADHD, control), experiment half (first, second), and feedback type (reward, no-reward) indicated that the P300 was larger following reward feedback (13.7 μ V) than following no-reward feedback (12.0 μ V), $F(1, 25) = 4.89$, $p < .05$, $ES = .16$; all other main effects and interactions were not significant, $p > .05$. Further, the difference in P300 amplitude between reward and no-reward trials was not significantly larger at channel Pz than at channel FCz, $t(26) = -.99$, $p = .33$, Cohen's $D = .23$, suggesting that the effect could be due either to actual variation in P300 amplitude or to component overlap with the tail of the feedback ERN (Holroyd & Krigolson, 2007).

We also examined the behavioral data for evidence of whether the participants used information in the feedback to alter their behavior, whether such behavior changed across the course of the experiment, and most importantly, whether it differed across groups. A three-way ANOVA on response time (RT) data as a function of group (ADHD, control), experiment half (first, second), and feedback type on the previous trial (reward, no-reward) indicated that participants responded faster in the second half of the experiment (575 ms) compared to the first (676 ms), $F(1, 25) = 9.01$, $p < .01$, $ES = .27$. However, all other main effects and interactions were not significant, $p > .05$, although there was a trend for typical children to respond faster than children with ADHD, $p = .07$ (Table 1). Likewise, a three-way ANOVA on the number of trials in which participants switched to a new alley compared to that chosen on the previous trial, as a function of group (ADHD, control), experiment half (first, second), and feedback type on the previous trial (reward, no-reward), indicated that participants tended to switch alleys more frequently following no-reward feedback (61 trials) than following reward feedback (43 trials), $F(1, 25) = 21.00$, $p < .001$, $ES = .46$. However, all other main effects and interactions were not significant, $p > .05$ (Table 2). These results suggest that although both groups used the feed-

Table 2
Switch data

	Control	ADHD
Reward		
First	21.4 ± 2.7	22.8 ± 2.6
Second	18.1 ± 3.8	23.6 ± 3.7
No-reward		
First	31.1 ± 1.6	31.8 ± 1.6
Second	30.5 ± 2.1	28.6 ± 2.1

Note: Control, control participants; ADHD, children with attention-deficit hyperactivity disorder; reward, trials following reward feedback; no-reward, trials following no-reward feedback; first, first half of experiment; second, second half of experiment. Values are total number of switches in each condition; error values indicate standard errors.

back to guide their behavior, the strategies did not differ between groups.

3. Discussion

We predicted that disruption of the reward prediction error signals carried by the midbrain dopamine system would manifest in the ERP of medication-free children with ADHD as an abnormal feedback ERN. Instead, we found that the size of the feedback ERN was about as large in children with ADHD as in typical children. Nevertheless, a closer examination revealed an interaction of feedback ERN amplitude with group and time. For typical children, feedback ERN amplitude decreased somewhat from the first to the second half of the experiment, whereas the opposite was true for children with ADHD (Fig. 3). Critically, the increase in feedback ERN amplitude for the children with ADHD appears to have resulted from delivery of the bonus payment midway through the experiment. Given that feedback ERN amplitude is correlated with the degree of task engagement (Yeung, Holroyd, & Cohen, 2005), the ERP results could suggest that children with ADHD were not initially motivated by the abstract performance feedback. Only once the significance of the performance feedback was made salient to the children by giving them a physical monetary reward did the performance feedback elicit a large feedback ERN. Conversely, the apparent decrease in feedback ERN amplitude across the experiment in typical children might have resulted from increased disengagement by that group as the task progressed. These results are consistent with studies showing that children with ADHD are especially sensitive to and motivated by the saliency of the reward (Barkley, 1997b; McInerney & Kerns, 2003; Michel, Kerns, & Mateer, 2005; Slusarek, Velling, Bunk, & Eggers, 2001), as well as with an extensive literature implicating abnormal reward processing in ADHD (Luman et al., 2005). It also seems consistent with observations of a steep delay-of-reinforcement gradient in ADHD, such that children with ADHD are relatively more sensitive than typical children to the temporal proximity of the reward (Sagvolden et al., 2005).

One might ask whether this result stemmed from a general difference related to the motivational states of the two populations as opposed to a specific difference associated with the feedback ERN: If the children with ADHD were more or less motivated than the control children to find the rewards, then such a difference could manifest in the amplitudes of any number of ERP components, not just the feedback ERN. Militating against this possibility is the fact that a group effect was not observed for the amplitude of the P300, suggesting that the effect of motivation on the ERP was specific to feedback ERN amplitude. Furthermore, both groups tended to switch to the alternate alley following no-reward feedback about equally often, suggesting that they were about equally motivated to carry out the task. A non-significant trend in RT was observed between the two groups, such that the children with ADHD tended to respond more slowly than the control children did, but this effect did not interact with block half in parallel with feedback ERN amplitude. Nevertheless, we caution against pressing this line of reasoning too far: It is our position that the feedback ERN indexes the activity of a neural mechanism that actually determines the motivational state of the participants. The amplitude of the feedback ERN is thought to indicate whether or not a goal has been met (Holroyd, Hajcak, & Larsen, 2006), is sensitive to the context in which rewards are delivered (Holroyd et al., 2004; Nieuwenhuis, Yeung, et al., 2004), and is correlated with the degree of interest in the outcome (Yeung et al., 2005). By extension, the feedback ERN is largest in contexts that motivate participants to pursue the task goal actively. By this view, the feedback ERN indexes a causal mechanism underlying different motivational/goal

states, as opposed to simply being an epiphenomenon of those states.

It should be noted that this study has several limitations. First, on the basis of these data alone we cannot rule out the possibility that the change in feedback ERN amplitude associated with the children with ADHD would have occurred even without the mid-experiment bonus; it remains possible that feedback ERN amplitude would have increased in children with ADHD for reasons other than the salience of the reward. Second, because this finding was post hoc, it is somewhat more likely to have resulted from a statistical fluke than a predicted effect would have been. Third, we did not assess children for their overall intelligence, so these results could reflect differences in I.Q. rather than ADHD *per se*. Fourth, our ADHD sample included children with comorbid disorders, namely CD and GAD, which may likewise have confounded the results. All of these factors provide cause for replicating and extending these findings in a future experiment.

The ERP has been studied extensively in children with ADHD (Barry, Johnstone, & Clarke, 2003), but to our knowledge only one ERP study has examined reward processing in this population (Van Meel et al., 2006; see also Van Meel, 2005). In contrast to our results, Van Meel et al. found that the feedback ERN was relatively larger for medication-free, 8–12-year-old children with ADHD compared to age-matched typical children. However, the ERPs in their study did not display a typical feedback ERN for either the ADHD or control groups (see their Fig. 2), at least as compared to adults (cf. Miltner et al., 1997; Nieuwenhuis, Holroyd, et al., 2004), so it is unclear whether what they measured was in fact a feedback ERN. A possible confounding factor in that study was that the feedback stimuli (visual images of a bomb and a treasure chest) were not counterbalanced across participants, which was not true in the present experiment. Unfortunately, as of yet no developmental study of the feedback ERN in typical children has been published, so no standard exists with which these results can be compared.

The dopamine theory of the ERN holds that, like phasic decreases of midbrain dopamine activity, the ERN should be elicited by the first indication that ongoing events are worse than expected. According to this position, when participants rely on external feedback stimuli in trial-and-error learning tasks to determine the correctness of the response, the feedback elicits the ERN, but when they have internalized the appropriate stimulus response mapping yet nevertheless make an error, the response elicits the ERN (Holroyd & Coles, 2002). Such a “response ERN” is commonly elicited by errors in speeded RT tasks (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990; Gehring, Goss, Coles, Meyer, & Donchin, 1993). Notably, children with ADHD produce relatively small response ERNs on error trials in speeded RT tasks (Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005; but see Burgio-Murphy et al., 2007; Jonkman, van Melis, Kemner, & Markus, 2007; Van Meel, Heslenfeld, Oosterlaan, & Sergeant, 2007; Wiersma, Van der Meere, & Roeyers, 2005) and make relatively small RT adjustments following those errors (Schachar et al., 2004; Sergeant & van der Meere, 1988; Wiersma et al., 2005), which are considered to be a signature of an error-sensitive control process (Laming, 1979; Rabbitt, 1966). This failure to slow their responses following errors is reversed with administration of methylphenidate (Krusch et al., 1996). Interestingly, Sagvolden et al.’s Dynamic Developmental Theory has been criticized on the grounds that it cannot account for post-error slowing because it lacks an error detection mechanism (Sergeant, 2005). However, we have demonstrated with a computational simulation that phasic dopamine signals can in principle do exactly this, at least when their impact on anterior cingulate cortex is considered (Holroyd, Yeung, Coles, & Cohen, 2005). The results of the present study suggest that the response ERN might

be modulated by the reward context, perhaps differently for children with ADHD compared to typical children. In particular, the response ERN, like the feedback ERN, might be relatively larger for children with ADHD in tasks where correct responses are financially rewarded on each trial (cf. Hajcak, Moser, Yeung, & Simons, 2005).

In retrospect, it is perhaps not surprising that the reward processes of typical children and children with ADHD do not reflect static properties of their respective dopamine systems. Rather, the reward process mediated by the dopamine system and its frontal–striatal targets appears to be sensitive to the context in which the task is carried out (Holroyd et al., 2004; Nieuwenhuis, Yeung, et al., 2004). According to the reinforcement learning theory of the ERN, the observed insensitivity of the feedback ERN in ADHD to abstract feedback, compared to when those same feedback stimuli indicate a concrete reward, should be paralleled by equivalent changes in the phasic activity of the midbrain dopamine system (Holroyd & Coles, 2002). Sagvolden et al. (2005) proposed that the reward prediction error signal is reduced in children with ADHD, whereas Grace (2001) proposed the opposite. Our results suggest that both positions may be correct: In children with ADHD, the reward prediction error signals may be smaller when the abstract performance feedback is not immediately associated with reward, but larger when the abstract performance feedback is immediately associated with reward. Such context-dependent activity of the midbrain dopamine system may be revealed by functional magnetic resonance imaging (Aron et al., 2004), especially given recent advances improving the ability of this method to reveal activity of the midbrain dopamine nuclei (D’Ardenne, McClure, Nystrom, & Cohen, 2008).

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