The relationship between responsiveness to social and monetary rewards and ADHD symptoms

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Abstract

Alterations in reward processing are frequently reported in attention deficit hyperactivity disorder (ADHD). One important factor affecting reward processing is the quality of reward as social and monetary rewards are processed by different neural networks. However, the effect of reward type on reward processing in ADHD has not been extensively studied. Hence, in the current study, an exploratory research was conducted to investigate the effect of reward type (i.e., social or monetary) on different phases of reward processing. We recorded event-related potentials (ERPs) during a spatial attention paradigm in which cues heralded availability and type of the upcoming reward and feedbacks informed about the reward earned. Thirty-nine (19 males) healthy individuals (age range: 19–27 years) participated in the study. ADHD symptoms were assessed by using ADHD self-report scale (ASRS). Our results revealed a consistent negative correlation between the hyperactivity subscale of ASRS and almost all social-feedback related ERPs (P2, P3, and FRN). ERP amplitudes after social feedbacks were less positive for P2 and P3 and more negative for FRN for individuals with greater hyperactivity levels. Our findings suggest that hyporesponsiveness to social feedbacks may be associated with hyperactivity. However, the results have to be confirmed with clinical populations.

Keywords Attention-deficit/hyperactivity disorder · Event-related potentials · FRN · P2 · P3 · Reward processing

Introduction

Humans have a tendency to maximize rewards and avoid nonrewarded situations. These rewards may be in the form of primary rewards, such as food, water, and sexual stimuli (Berns et al., 2001), or secondary rewards, such as social approval or money (Korn et al., 2012). Studies on secondary rewards indicated that social and monetary rewards could be processed differently at neural level (Gozales-Gadea et al., 2016; Rademacher et al., 2010). However, despite several functional magnetic resonance imaging (fMRI) studies in this field, differentiation in the processing of social and monetary rewards,

underlying mechanisms and behavioral outcomes of such processes are not entirely addressed yet (Izuma et al., 2008; Lin et al., 2012; Rademacher et al., 2010; Spreckelmeyer et al., 2009; Zink et al., 2008). Individual differences in ADHD symptomatology also can be an important factor, because attention deficit hyperactivity disorder (ADHD) is directly associated with impairments and unusual functioning of reward-related processes (Plichta & Scheres, 2014; Tripp & Wickens, 2009).

Neural networks involved in reward processing have been extensively studied using fMRI both in clinical and healthy populations (Hayes et al., 2014; Plichta & Scheres, 2014; Radua et al., 2015). The paradigms used in these studies generally included cues as predictors of rewards. Results of these studies indicated that rewards or reward-predicting cues have a potential to activate a brain network including ventral tegmental area, anterior striatum, and ventromedial prefrontal cortex.

Type of rewards (i.e., social or monetary) can be a crucial factor influencing the neural basis of reward processing. For instance, social rewards often imply a positive evaluation of self by others, and these type of rewards can greatly contribute to one's perception of own social status. Therefore, social reward is an immensely important concept for understanding human behaviour, because social relations often are formed

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after evaluation of costs and rewards of social interactions (see social exchange theory; Homans, 1958; Emerson, 1976). Monetary rewards are more psychical, and such rewards are associated with the material (financial) gain.

Processing of social and monetary rewards also can be related to different neural networks. However, several studies investigating this difference reported mixed and inconsistent results (Izuma et al., 2008; Lin et al., 2012; Rademacher et al., 2010; Spreckelmeyer et al., 2009; Zink et al., 2008). While some of these studies showed that a substantial overlap between the neural representation of social and monetary rewards (Chib et al., 2009; Izuma et al., 2008; Lebreton et al., 2009; Lin et al., 2012; Zink et al., 2008), others reported that social and monetary rewards lead to different neural activations (Rademacher et al., 2010; Spreckelmeyer et al., 2009). Studies supporting overlapping networks hypothesis report that a single area (ventromedial prefrontal cortex, Chib et al., 2009) or a circuit (limbic fronto-striatal, Lebreton et al., 2009) is responsible for general evaluation of all categories of goods. Also, Izuma et al. (2008) showed that the striatum showed greater activity in response to both monetary rewards and social reward. However, Rademacher et al. (2010) found that social rewards are rather associated with amygdala activation, whereas monetary rewards are strongly related to the thalamus activation. Hence, the underlying neural mechanisms of reward processing in social and monetary rewards are yet to be elucidated and individual differences, such as psychological disorders, can potentially moderate reward processing.

In clinical populations, reward processing has been most extensively studied in ADHD, because impairments in reward processing is strongly related to ADHD symptomatology (Plichta & Scheres, 2014; Tripp & Wickens, 2009). For instance, Sonuga-Barke et al. (2010) showed that children and adolescents with ADHD prefer immediate rewards even if they are smaller in quantity. Several studies also investigated the influence of reward type in ADHD; these studies yielded conflicting results, making it difficult to understand clearly the ADHD-related impairments in reward processing (Demurie et al., 2011 in adolescents; Kohls et al., 2009 and Vloet et al., 2011 in children). For example, Kohls et al. (2009) reported improvements in the performance in relation to social rewards; others showed that monetary rewards led to enhanced performance compared with social rewards in children with ADHD (Demurie et al., 2011; Vloet et al., 2011). Furthermore, the majority of the fMRI studies using reward-processing tasks consistently showed that ADHD is associated with reduced neural activation in the ventral striatum especially during the reward anticipation phase (Plichta & Scheres, 2014 for review), and there is a positive relationship between impulsivity-related traits and ventral-striatum activity. However, a number of recent studies (von Rhein et al., 2015) reported an increased ventral striatal and prefrontal responsiveness during rewards anticipation in ADHD (Ma et al., 2016; von Rhein et al., 2015).

Furthermore, Kappel et al. (2014) reported a decreased ventral-striatal responsiveness during reward anticipation in adults but not in children with ADHD. Another study (Furukawa et al., 2014) showed that hyperactivity and impulsivity symptoms of ADHD were negatively associated with ventral striatal responses during reward anticipation, yet positively related to responses to reward. Moreover, during losses, individuals with ADHD had increased amygdala activation, which also was correlated with negative affective symptoms (Wilbertz et al., 2015).

The above-mentioned fMRI studies help to understand the brain regions being activated during reward processing in ADHD yet with several limitations. First, fMRI has very well-known shortcomings, such as low temporal resolution. Moreover, the slow characteristic of the hemodynamic response may not be enough for examining sequential steps occurring during the course of reward processing. In this respect, studies utilizing event-related potentials (ERPs) can potentially provide more information.

Several ERP studies also have addressed reward processing. These studies demonstrated a negative deflection at frontocentral sites with a peak at around 250 ms after the feedback presentation (Gehring & Willoughby, 2002; Holroyd & Coles, 2002; Miltner et al., 1997; Walsch & Anderson, 2012). This deflection is called feedback-related negativity (FRN). The FRN is thought to reflect dopaminergic signals on neurons of the anterior cingulate cortex, which is a crucial area for reward processing (Ibanez et al., 2012), motivation in social interactions (Lavin et al., 2013), and social rejection (Sun & Yu, 2014). In ADHD, Thoma et al. (2015) and Holroyd et al. (2008) reported enhanced FRN response in children and adults with ADHD. A series of studies found that the FRN amplitudes are greater following rewarded trials compared with nonrewarded trials (Bellebaum & Daum, 2008; Ferdinand et al., 2012; Hajcak et al., 2007). Furthermore, Flores et al. (2015) compared FRN amplitudes in response to social and monetary incentives. The authors reported that the amplitude of FRN was larger following the rewarded trials compared to the nonrewarded trials only when the incentive is monetary, yet no difference was observed in the condition with social incentives. Another ERP component that seems to play a major role in reward processing is P300, a positive wave that usually peaks between 300 and 600 ms after reward presentation with a greater positive deflection at centroparietal scalp sites (Sutton et al., 1965). P300 can be influenced several characteristics of incentives, such as availability, valence, and task relevance (Johnson, 1988; Squires et al., 1977; Picton, 1992; Pritchard, 1981). While the FRN is sensitive to the valence of the feedback, the P300 amplitude often is responsive to the magnitude of a reward (Sato et al., 2005; Yeung et al., 2005). Despite these valuable findings, it is noteworthy to mention that most of these ERP studies focused on the monetary rewards exclusively. However, the type of a reward is an important determinant of underlying neurocognitive processing and ADHD

symptomatology can be closely associated with specific problems in the processing of social or monetary rewards.

Regarding social-monetary comparison, one study (Gonzalez-Gadea et al., 2016) investigated the influence of ADHD comparing social and monetary reward processing. In that study, the authors observed that children with ADHD had altered reward processing of both social and monetary rewards. However, up to date, no study systematically has investigated the relationship between ADHD symptoms and neural responses to different types of rewards. Because ADHD can be a prolonged disorder over the lifespan (Cubillo et al., 2012 for review), it is important to investigate ADHD-related impairments and how they are altered through the lifespan. Furthermore, ADHD has two main components: impulsivity and hyperactivity (Sagvolden et al., 2005). However, many studies focusing on ADHD and reward sensitivity did not particularly focus on any of these subtypes. Exceptionally, Stark et al. (2011) investigated whether impulsivity or hyperactivity is associated with altered reward processes in ADHD. They observed that both subtypes of ADHD are associated with altered reward processing; social rewards were not specifically targeted in that study. They mainly focused on monetary rewards.

Based on the previous literature, the current exploratory study was designed to investigate the modulation effect of ADHD symptoms on different phases of social and monetary reward processing. For this purpose, we used a spatial attention paradigm (Krebs et al., 2012) with cues indicating availability and the type of rewards and feedback informing about the reward acquired (monetary-reward, social-reward, monetary nonreward and social-nonreward conditions). We explored the modulation of cue and feedback related ERPs with reward availability and type of reward considering ADHD scores. We primarily investigated how ADHD symptoms (hyperactivity, impulsiveness) are associated with feedback and cue-related ERP components in different reward types (social vs. monetary).

Materials and Methods

Participants

Thirty-nine (19 males), right-handed (mean age: 22.06 ± 1.94 years, age range: 19–27) participants were recruited with no history of any neurological and psychiatric disease. Participants were university students from different majors (e.g., engineering, international relations, and psychology) in Istanbul. The study protocol was approved by the local Ethics Committee and was performed in accordance with the Declaration of Helsinki. All the participants were informed about the study procedures and provided written, informed consent.

Psychological Assessments

While screening for the ADHD symptoms of participants, Turkish versions of the adult ADHD self-report scale (ASRS) were utilized (Adler et al., 2006; Doğan et al., 2009; Kessler et al., 2005). Moreover, UPPS Impulsive Behavior Scale (UPPS) (Whiteside & Lynam, 2001; Yargıç et al., 2011), Barratt Impulsiveness Scale (BIS) (Barratt, 1959; Güleç et al., 2008; Patton & Stanford, 1995), and Wender Utah Rating Scale (WURS) (Oncu et al., 2005; Ward, 1993) were used to capture impulsiveness and childhood ADHD symptoms for exploratory reasons. Hence, the results of the scales other than ASRS are only provided in supplementary material (see Supplementary Text 1). All participants filled in all of the indicated self-report questionnaires.

The ASRS consists of 18 DSM-IV items rated on a five-point, Likert-type, self-assessment scale. Half of the items assess hyperactivity/impulsivity, and the other half assess inattention symptoms. The internal consistency of ASRS was high (Cronbach's $\alpha = 0.88$; for inattention subscale, Cronbach's $\alpha = 0.82$; for hyperactivity/impulsivity subscale, Cronbach's $\alpha = 0.78$). Additionally, test-retest reliability after 2 weeks was high (for total score $r = 0.85$; for inattention and hyperactivity/impulsivity subscales scores respectively; $r = 0.73$ – 0.89).

Procedure

The experiment paradigm was created based on earlier fMRI (Krebs et al., 2012) and EEG (Schevernels et al., 2014) studies (Figure 1). Each trial started with a central gray fixation square (0.5°), two placeholder frames (6° lateral from fixation and 6° below fixation), and an arrow cue on a black screen (800 ms). The arrow cue appeared indicating target location (left or right) and reward availability (plus, reward or minus, no-reward). Furthermore, the color (white or black) of the squares in the center of the arrows indicated the type of reward (social or monetary). Reward-predicting signs and colors were always correct and counterbalanced across participants. After the arrows, the interstimulus interval screen was presented and included a central gray fixation square (0.5°) and two placeholder frames (600 ms). Next, two circles were presented in the placeholder frames for 200 ms as a target. The circles (1°) had two gaps opposite from one another. The participants were instructed to attend only to the cued side and indicate which gap was larger by pressing right index finger for “top gap” and right middle finger for “bottom gap.” Participants could respond immediately after the appearance of the target stimuli and during the fixed ISI (1,000 ms). Therefore, the total response window was 1,200 ms.

After a fixed ISI (1,000 ms), the target stimuli were followed by a visual feedback stimulus for 800 ms, indicating whether the response was correct. If participants responded

Fig 1. In the experimental paradigm, the direction of arrow cues indicated the target location (left or right); the color of the squares embedded arrow showed reward types (social or monetary); the signs in the squares (minus or plus) indicated reward availability

correctly, a happy smiling face (social reward) or 10 TRY (monetary reward, Turkish Liras = 2.82 USD, 2.39 EUR) note followed the correct response. If participants made a mistake or did not respond in 1200 ms, they were shown a sad face (social) or an empty wallet (monetary). In no-reward condition, a neutral face or 1 piaster on the screen was presented regardless of the accuracy. Finally, a blank screen appeared during the intertrial interval (1,200 ms).

Reaction time and accuracy were recorded during the task in all conditions. The reward type was counterbalanced across trials. However, the amount of rewards did not change across trials. Participants knew how much they had earned at a given trial, because it was always the same amount of reward (10 TRY or 0 TRY for monetary and smiley face or neutral face for social reward). However, the participants were not shown the cumulative reward amount that they earned until the end of the task. Moreover, the social and monetary rewards in the experiment were not only the feedback participant received after each trial, they also were a promised real social event invitation (in social reward condition) and a certain amount of money (in monetary reward condition) that participants could receive depending on their performance at the end of the experiment. Participants were told that they would receive a fraction of the money that they collected during the experiment, and if they could collect a certain amount of happy faces, they would be invited to a real social event. At the end, all participants received 20 TRY (5.65 USD, 4.78 EUR) and were all invited to the social event.

Participants were first prepared for EEG recording. Then, they went through a practice session of the experimental paradigm. After the practice, participants continued with the main

paradigm, which contained two blocks of 160 trials (320 total trials). Each trial type (social reward, monetary reward, social no-reward, and monetary no-reward) was equally distributed throughout the task. Participants were informed to perform the task quickly and accurately. The main task was completed between 20 and 30 minutes based on participants' performances. The experimental paradigm was designed and run by an open source experimental design software (Opensesame V3.0; Mathôt et al., 2012). At the end of the experimental session, participants were asked to fill out the questionnaires in random order. One experimental session did not exceed 75 minutes.

EEG acquisition and analyses

EEG activity was recorded at a sampling rate of 1,024 Hz (Pycorder 1.9) using a Brain Products Actichamp 32 channel system with active electrodes. All electrode impedances were reduced to less than 10 k Ω . The EEG was recorded using the average reference. The EEG data were processed using BrainVision Analyzer 2.0 software (Brain Products GmbH, Munich, Germany). The data were digitally filtered with a 40/0.01-Hz low-pass and high-pass filter and 50-Hz notch filter. Trials with eye blink artefacts were detected with independent component analyses and corrected. Epochs were created within the time window -200 and $+1,400$ ms relative to the onset of the relevant stimulus (cue or feedback), including a 200-ms prestimulus period for baseline correction. Trials with overt movement artefacts were excluded using the semi-automatic artefact rejection features. We rejected trials with above 60 μ V in a time window of 400 ms (200 ms before

and after stimulus) and drifts larger than $\pm 200 \mu\text{V}$ in any scalp electrodes. After artefact rejection, the number of trials per condition were listed in supplementary Table S1. Then, EEG epochs were averaged for each participant across trials for each condition. Mean amplitudes were selected for cue-related N100 and P200 following cue stimuli and for feedback-related N100, P200, FRN, P300 following feedback stimuli across electrodes. A cue-related N100 was detected at the same brain area from 140 to 180 ms. A P200 with a fronto-central positive deflection (F3, F4, F7, F8, FC1, FC2, Cz, C3, C4) was observed between 140 and 280 ms.

A feedback-related N100 was quantified at fronto-central electrode sites (Fz, F3, F4, F7, F8, FC1, FC2, CP1, CP2, Cz, C3, C4) from 100 to 150 ms. A P200 with a positive deflection at frontocentral electrode sites (Fz, Fp1, Fp2, F3, F4, F7, F8, FC1, FC2, FC5, FC6, CP1, CP2, CP5, CP6, Cz, C3, C4) was detected between 175 and 250 ms time window. A FRN component was observed at the same area (Fz, Fp1, Fp2, F3, F4, FC1, FC2, CP1, CP2, Cz, C3, C4) from 250- to 350-ms time window and calculated based on the procedure of previous studies (Potts et al., 2006). Lastly, a feedback-related P300 was quantified in a large number of electrodes (Fz, Fp1, Fp2, F3, F4, F7, F8, FC1, FC2, FC5, FC6, FT9, FT10, CP1, CP2, CP5, CP6, Cz, C3, C4) between 350 and 450 ms. Mean amplitudes for each ERPs were averaged across selected electrodes according to the different conditions.

Statistical Analyses

In addition to the behavioral data, we analysed cue-related and feedback related ERPs. For the feedback related phase, we only included correct trials and ignored incorrect trials, because there were not enough data for incorrect trials to conduct reliable ERP analyses. After the multivariate normality analyses, data of one participant was excluded due to extreme values as identified by multivariate outlier analysis (based on Mahalanobis distance). For the further analyses, we used a repeated-measures analysis of variance (rANOVA) with two factors: availability of reward (reward, no-reward) and reward type (social, monetary). The correlations between the mean amplitude of the ERPs and ADHD scale (ASRS) were calculated. Additionally, the correlations between the reaction time/accuracy of the participants and the scores of the ADHD were analysed and presented in the supplementary material. In both correlation analyses, Spearman nonparametric correlation coefficient was used, because the scores of ADHD scale were not normally distributed. After excluding the extreme scores, correlation analyses were repeated, but the results remained the same. The results are reported without Bonferroni correction for multiple testing. However, to avoid false-positive results, we also are referring to the Bonferroni corrected p values when interpreting the results (Schevernels et al., 2014). Bonferroni corrected p values are as follows: $p < 0.025$ for

the cue phase (N1 and P2) and $p < 0.017$ for the feedback phase (N1, P2, and P3). Reaction time (ms) and accuracy also were analysed across all subjects using a repeated-measures 2×2 ANOVA: reward type and reward availability.

Results

Behavioral Results

Table 1 demonstrates the means and standard deviations for all scales. Table 2 demonstrates the behavioral performance of participants, and the results indicate that the difficulty level of the task was well adjusted.

rANOVA results for the accuracy indicated there was a significant main effect of reward availability (reward vs. no-reward, $F(1,37) = 10.967$, $p < 0.01$), and participants were more accurate in the rewarded trials ($M = 93\%$, standard deviation $[SD] = 9\%$) compared with nonrewarded trials ($M = 88\%$, $SD = 14\%$). No significant main effect of reward type ($F(1,37) = 1.883$, $p = 0.18$) or interaction between the reward type and reward availability was found ($F(1,37) = 0.653$, $p = 0.45$). Similarly, rANOVA for response times showed that there was a significant main effect of reward availability (reward vs. no-reward), and participants were faster while responding in reward availability ($M = 524.68$ ms, $SD = 78.94$ ms; $F(1,37) = 13.429$, $p = 0.001$) compared with the no-reward condition ($M = 532.96$ ms, $SD = 81.51$ ms). Furthermore, there was a significant main effect of reward type ($F(1,37) = 9.567$, $p < 0.01$). During the social reward trials ($M = 526.54$ ms, $SD = 79.76$ ms), participants responded faster compared with the monetary reward trials ($M = 531.1$

Table 1. The mean and standard deviations for all psychological assessments and subscales

Scales	Mean	S.D.	Min	Max
WURS	28,32	16,760	5	90
ASRS total	31,19	8,797	16	61
ASRS hyperactivity	15,27	4,992	9	34
ASRS inattention	15,92	5,937	5	28
UPPS premeditation	35,35	4,283	27	44
UPPS urgency	24,42	5,613	13	38
UPPS sensation seeking	32,19	8,451	14	47
UPPS perseverance	31,11	4,892	22	39
BIS total	63,78	10,255	38	96

Note. WURS: Wender Utah Rating Scale (Oncu et al., 2005; Ward, 1993); ASRS: Adult ADHD self-report scale (Adler et al., 2006; Doğan et al., 2009; Kessler et al., 2005); UPPS: UPPS Impulsive Behavior Scale (Whiteside & Lynam, 2001; Yargıç et al., 2011); BIS: Barratt Impulsiveness Scale (Barratt, 1959; Güleç et al., 2008; Patton & Stanford, 1995).

Table 2. The descriptive statistics of behavioral measures per conditions

	Minimum	Maximum	Mean	S.D.
<i>Mean RT</i>	436,91	851,85	528,82	79,93
<i>SR RT</i>	428,09	849,65	522,41	78,04
<i>SNR RT</i>	442,06	852,08	530,67	82,17
<i>MR RT</i>	436,24	850,54	526,94	80,36
<i>MNR RT</i>	434,62	855,15	535,25	81,34
<i>Mean ACC</i>	0,48	0,99	0,90	0,11
<i>SR ACC</i>	0,44	1,00	0,92	0,10
<i>SNR ACC</i>	0,43	0,99	0,88	0,14
<i>MR ACC</i>	0,54	1,00	0,93	0,09
<i>MNR ACC</i>	0,42	1,00	0,88	0,14

Note. RT: reaction time; ACC: accuracy; SR: social reward; SNR: social non-reward MR: monetary reward; MNR: monetary non-reward.

ms, SD = 80.36 ms). However, the interaction of reward type and reward availability was not significant ($F < 1$, NS).

ERP Results

The cue-related N1 amplitude was larger for reward cues ($M = 0.30$, $SD = 0.28$) compared with nonreward cues ($M = 0.10$, $SD = 0.28$), as indicated by a main effect of reward ($F(1,37) = 4.423$, $p = 0.042$, $\eta_p^2 = 0.107$). The type of rewards did not influence the amplitude of this component ($F < 1$, NS), and there was no significant interaction ($F < 1$, NS). The cue-related P2 had a larger amplitude for nonreward cues ($M = 2.15$, $SD = 0.27$) than reward cues ($M = 1.88$, $SD = 0.26$; $F(1,37) = 6.091$, $p = 0.018$, $\eta_p^2 = 0.141$; Figure S1 in supplementary). No significant main effect of reward type ($F < 1$, NS) or an interaction ($F < 1$, NS) were found for the P2 component.

There was not any interaction or main effects for the feedback-related N1 component (reward type: $F(1,37) = 3.652$, $p = 0.064$, $\eta_p^2 = 0.090$; availability of reward: $F < 1$, NS; interaction: $F(1,37) = 2.812$, $p = 0.102$, $\eta_p^2 = 0.071$). The feedback-related P2 had a larger amplitude for reward feedbacks ($M = 4.18$, $SD = 0.44$) than nonreward feedbacks ($M = 3.87$, $SD = 0.40$; $F(1,37) = 5.317$, $p = 0.027$, $\eta_p^2 = 0.126$; Figure 2) and significantly larger amplitude for social rewards ($M = 4.56$, $SD = 0.48$) than for monetary rewards ($M = 3.49$, $SD = 0.40$; $F(1,37) = 13.636$, $p = 0.001$, $\eta_p^2 = 0.269$), as indicated by the main effect. There was no significant interaction effect for this component either ($F < 1$, NS). The FRN component amplitude was significantly larger (more negative) for the monetary reward feedbacks ($M = 1.55$, $SD = 0.62$) compared with the social reward ($M = 4.68$, $SD = 0.64$; $F(1,37) = 69.767$, $p = 0.000$, $\eta_p^2 = 0.653$). Furthermore, there was a significant interaction between the reward type and availability of reward ($F(1,37) = 14.674$, $p = 0.000$, $\eta_p^2 = 0.284$; Figure 3), indicating more negative FRN with no

reward compared with reward in the social condition and more negative FRN with reward compared with no reward in the monetary condition. The availability of rewards did not influence the amplitude of FRN ($F < 1$, NS). The feedback-related P3 component had significantly larger amplitude for social reward feedbacks ($M = 3.06$, $SD = 0.43$) compared with monetary rewards ($M = 1.12$, $SD = 0.46$; $F(1,37) = 56.141$, $p = 0.000$, $\eta_p^2 = 0.603$). This main effect was modulated by an interaction between the reward type and availability of reward ($F(1,37) = 5.012$, $p = 0.031$, $\eta_p^2 = 0.119$; Figure 4), indicating greater P3 in the reward condition compared with the no reward condition when the reward type is social; yet, no such clear difference can be observed between conditions when the reward type is monetary. No main effect of the availability of rewards was observed ($F < 1$, NS).

Correlation results

The correlational analyses between ASRS and feedback related ERPs showed a negative correlation between the hyperactivity subscale of ASRS and feedback-related P2, P3, and FRN when the feedback was social (Table 3; Supplementary Figures S2, S3, and S4). Larger P2 and P3 amplitude were found in social feedback condition in relation to reduced hyperactivity scores of ASRS. Considering that the FRN is a negative deflection, higher scores for hyperactivity were associated with more negative FRN amplitudes in social reward condition. No other significant correlations were found for the other scales.

We also check whether the variance in the inattention domain was different from the hyperactivity domain; the variance in these subscales was not significantly different from each other ($F < 1$, NS). Furthermore, these subscales were not closely associated, because the correlation between the hyperactivity and inattention scales was only marginally significant ($r = 0.29$, $p = 0.08$).

Additionally, the correlational analyses between the reaction times and accuracy rates of participants and ASRS scores showed that there was a negative correlation between the hyperactivity subscale, total score of ASRS, and mean reaction times of participants (Supplementary Table S2). Besides, there were not any correlations between accuracy rates of participants and ASRS scale scores.

Discussion

An exploratory study was conducted among normal participants to investigate social and monetary reward processes in relation to ADHD symptoms. As expected, participants were more accurate and faster in rewarded trials regardless of the ADHD symptoms. EEG results showed that the reward type did not modulate the cue-related ERP components. However, the feedback-related P2, P3, and FRN had larger amplitudes

Fig 2. The feedback related potentials in different reward conditions. The mean amplitudes of the N1, FRN, P2 and P3 for social rewards (black), monetary rewards (red), social non-rewards (blue) and monetary non-

rewards (green) in left frontal area (a), right frontal (b), central (c) and middle frontal area (d)

for social rewards. More importantly, we observed a relationship between hyperactivity symptoms and feedback-related ERP components as such increased hyperactivity was associated with decreased P2 and P3 amplitudes and increased FRN in response to social feedbacks. These findings are further discussed below.

The main goal of the current study was to explore the effects of ADHD symptoms on different phases of reward processing and to explore whether this effect was different for social and

monetary rewards. Our results showed that social-feedback related ERPs were associated with ADHD symptoms, particularly with hyperactivity. There was a significant negative correlation between hyperactivity symptoms and P2, P3, FRN amplitudes in the social feedback condition. As hyperactivity scores increased, the P2 and P3 amplitudes in response to social feedbacks decreased, and FRN amplitudes increased. The FRN was thought to reflect a reward prediction error, and it is expected to be greater when the difference between the expected and the

Fig 3. The mean amplitude of FRN in different reward conditions

received reward is larger (Holroyd et al., 2003; Yasuda et al., 2004; Huang & Yu, 2014). According to our correlational results for FRN amplitude, one can speculate that individuals with lower hyperactivity scores considered social rewards as satisfactory, so the prediction error and FRN amplitude were smaller. On the other hand, individuals with greater hyperactivity scores found social rewards less satisfactory, and this prediction error created greater FRN negativity. However, this explanation can be tested only in future studies including affective response to different types of reward. Together, these results may indicate that lack of responsiveness for social feedback can play a role in the pathogenesis of ADHD. It is well known that children with ADHD have problems in social functioning (Landau & Moore, 1991), and social dysfunction has a major role in the prognosis of ADHD (Greene et al., 1997). In addition, the theory of mind and emotion recognition literature suggests that children with ADHD are lacking awareness of others' feelings (Buitelaar et al., 1999; Yuill & Lyon, 2007), and similar to individuals with

autism spectrum disorder (ASD), individuals with ADHD have difficulties in understanding social cues (Nijmeijer et al., 2008). Although individuals with elevated ADHD have social interest, they often have difficulties in evaluating social feedback (Bora & Pantellis, 2016). This similarity between ADHD and ASD also was demonstrated previously by Gonzalez-Gadea et al. (2016). The authors showed no FRN modulation during social decisions in children with ADHD and ASD. Due to the difficulties in understanding social cues, individuals with ADHD may not be responsive to social rewards as efficiently as healthy people. Nevertheless, some caution is warranted while interpreting the connection between social dysfunction in ADHD in real life and hyposensitivity to social rewards, because understanding the social cues in real life can be quite different and more complex.

An important clinical implication of current findings can be the use of social cognition training and social feedback-based learning to improve the social functioning of individuals with

Fig 4. The mean amplitude of feedback related P300 in different reward conditions

Table 3. Correlations between the amplitude of feedback related ERPs and hyperactivity, inattention subscale and total scores of the ASRS.

			Hyperactivity	Inattention	Total
Feedback related P3	Social reward	C.C.	-0,415*	0,08	-0,08
		Sig.	0,01	0,65	0,63
	Monetary reward	C.C.	-0,23	0,05	-0,01
		Sig.	0,18	0,77	0,97
	Social non-reward	C.C.	-0,502*	0,06	-0,15
		Sig.	0,00	0,73	0,38
	Monetary non-reward	C.C.	-0,17	0,00	-0,01
		Sig.	0,32	0,99	0,95
Feedback related P2	Social reward	C.C.	-0,31	0,09	-0,08
		Sig.	0,06	0,60	0,65
	Monetary reward	C.C.	-0,28	0,13	0,02
		Sig.	0,10	0,43	0,91
	Social non-reward	C.C.	-0,420*	0,17	-0,06
		Sig.	0,01	0,32	0,72
	Monetary non-reward	C.C.	-0,17	0,13	0,07
		Sig.	0,32	0,46	0,68
Feedback related negativity	Social reward	C.C.	-0,404*	0,10	-0,11
		Sig.	0,01	0,55	0,51
	Monetary reward	C.C.	-0,28	-0,06	-0,16
		Sig.	0,09	0,72	0,35
	Social non-reward	C.C.	-0,436*	0,11	-0,09
		Sig.	0,01	0,51	0,59
	Monetary non-reward	C.C.	-0,18	0,04	-0,02
		Sig.	0,28	0,81	0,88

Note. C.C.: Correlation coefficient; *Bonferroni corrected $p > 0.017$.

ADHD. Nevertheless, future studies designed to investigate difficulty in reward-cue understanding in clinical population are highly recommended.

It is worth mentioning that we did not find a relationship between inattention subtype of ADHD and feedback-related ERP components even though the variance in hyperactivity subscale was not significantly different from the variance in the inattention subscale. Relatedly, there is an abundance of evidence showing that higher levels of impulsivity, whether related to ADHD or not, affect perception and processing of rewards (Beck et al., 2009; Bickel et al., 1999; Galtress & Kirkpatrick, 2010; Kirby et al., 1999; Martin & Potts, 2004; Ripke et al., 2012). Therefore, the significant correlations we found are likely to be associated with impulsivity rather than hyperactivity. Hence, a conclusion to be drawn from these results is as follows: the individuals with lower impulsivity have greater neural responsivity to social feedbacks than individuals with higher levels of impulsivity. The current study also had several limitations. First, only healthy individuals without a prior ADHD diagnosis participated. Therefore, the results have to be confirmed in clinical populations with similar reward-related ERP paradigms. Second, the study was

conducted with young adults. However, comparing children with and without ADHD may also provide stronger evidence in terms of the role of reward type on ADHD symptoms. Third, in the current study 2D smiley images were used to provide information whether they received social incentive or not. The rationale for this is eliminating potential confounding effects, such as gender or race, of the real faces. Thus, by using 2D smiley images, we aimed to eliminate the possible biases that may arise due to inter-individual differences. However, we acknowledge the fact that using real human faces (Ding et al., 2017) also could have benefits in terms of greater ecological validity. Hence, it is recommended for future studies to compare 2D smiley faces with real human faces to decide on the most appropriate set of stimuli for providing social feedback. Fourth, a negative correlation was found between the reaction times and hyperactivity subscale and total ASRS score. If this finding had been accompanied by a negative correlation between the accuracy rates and symptom scores, we could have speculated that higher hyperactivity tendency led to premature responses with mistakes, which is considered as the speed-accuracy trade-off (Heitz, 2014). Some studies report that this trade-off is altered in individuals

with ADHD (Mulder et al., 2010). However, we could not find any correlation between accuracy and ASRS scores and could not actually calculate the speed-accuracy trade-off due to high accuracy levels (~90%). One plausible explanation for this can be that the task used was relatively easy as reflected the mean accuracy and therefore faster reaction times did not necessarily led to create lower accuracy. Furthermore, lack of speed-accuracy trade off also may be due to the sample characteristics. Because we tested healthy individuals only, it is possible that we did not observe ADHD-related speed-accuracy trade off changes. Fifth, with the task we used in present study, we could not make a distinction between positive and negative prediction errors as usually made in the reinforcement literature, because the accuracy rates of participants were sufficient for behavioural evaluation but not for electrophysiological data. Future studies should be designed with higher difficulty levels to be able to evaluate positive and negative prediction errors at the same time.

To conclude, our findings suggest a link between hyperactivity and processing of social rewards, yet a similar link cannot be observed for the monetary rewards. This finding contributes to understanding of impairments in social functioning in relation to elevated ADHD levels, more specifically ADHD-related impulsivity. Future studies should explore the effect of reward type on reward processing in clinical populations with known reward processing deficits.

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