

**NO EVIDENCE FOR INHIBITORY DEFICITS OR ALTERED REWARD PROCESSING IN  
ADHD: DATA FROM A NEW INTEGRATED MONETARY INCENTIVE DELAY  
GO/NO-GO TASK**

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**Acknowledgements:** We would like to thank all the participating children and adolescents, their parents and teachers. This research was supported by a grant from the Fund for Scientific Research – Flanders (Belgium) (FWO), awarded to the first author.

## ABSTRACT

**Objective:** Cognitive and motivational factors differentially affect individuals with mental health problems such as attention-deficit/hyperactivity disorder (ADHD). Here we introduce a new task to disentangle the relative contribution of inhibitory control and reward anticipation on task performance in children with ADHD and/or autism spectrum disorders (ASD).

**Methods:** Typically developing children, children with ADHD, ASD or both disorders worked during separate sessions for monetary or social rewards in go/no-go tasks with varying inhibitory load levels. Participants also completed a monetary temporal discounting (TD) task.

**Results:** As predicted task performance was sensitive to both the effects of anticipated reward amount and inhibitory load. Reward amount had different effects depending on inhibitory load level. TD correlated with inhibitory control in the ADHD group.

**Discussion:** The integration of the monetary incentive delay and go/no-go paradigms was successful. Surprisingly there was no evidence of inhibitory control deficits or altered reward anticipation in the clinical groups.

**Keywords:** Attention-Deficit/Hyperactivity Disorder, Autism Spectrum Disorder, Reward processing, Response inhibition

## INTRODUCTION

Consistent with a number of theories (e.g., Barkley, 1997; Nigg, 2001) studies with both children and adults provide evidence for a link between attention-deficit/hyperactivity disorder (ADHD) and inhibitory dysfunction (Boonstra, Kooij, Oosterlaan, Sergeant, & Buitelaar, 2010; Lijffijt, Kenemans, Verbaten, & van Engeland, 2005; Oosterlaan, Logan, & Sergeant, 1998). Barkley (1997) argued that a deficit in behavioural response inhibition is the core deficit in ADHD and is specifically related to the disorder. Others see deficient inhibitory performance in ADHD rather as a consequence of a non-optimal energetic state (Sergeant, Oosterlaan, & Van der Meere, 1999). However, there are also studies that do not find these inhibitory problems in ADHD (Daugherty, Quay, & Ramos, 1993; Jennings, van der Molen, Pelham, Debski, & Hoza, 1997; Raymaekers, Antrop, van der Meere, Wiersema, & Roeyers, 2007; Scheres, Oosterlaan, & Sergeant, 2001). One possible explanation is that variations in cognitive and motivational characteristics of tasks can impact on ADHD children's performance (Johnson, Wiersema, & Kuntsi, 2009; Luman, Oosterlaan, & Sergeant, 2005; Scheres et al., 2001). Worse task performance in ADHD might be due to cognitive factors other than inhibitory load (Banaschewski et al., 2004; Lijffijt et al., 2005; Rommelse et al., 2007). This has been investigated by manipulating inhibitory load within the same task (e.g., Van De Voorde, Roeyers, Verté, & Wiersema, 2010) by altering the ratio of no-go versus go trials (Ciesielski, Harris, & Cofer, 2004). In general, participants make more commission errors in a high (e.g., 75-25 go/no-go) versus low (e.g., 25-75 go/no-go) inhibitory task condition (Braver, Barch, Gray, Molfese, & Snyder, 2001; Ciesielski et al., 2004). Van De Voorde et al. (2010) found increased inaccuracy in ADHD in both a high (80-20 go/no-go) and low inhibitory load condition (50-50 go/no-go). However, this group effect was not related to inhibitory load (as reflected in the absence of a group by inhibitory load interaction effect), indicating that inaccuracy in ADHD may be due to other factors, which is

inconsistent with the inhibitory deficit view. Rommelse et al. (2007) concluded that poor performance of children with ADHD on inhibition measures may result from deficiencies in lower order cognitive processes and not only from executive functioning deficits.

Furthermore besides the impact of task characteristics, some have argued that deficits seen in ADHD on inhibitory control tasks may be due not to problems with dealing with inhibitory tasks but rather to a general lack of motivation, which can be addressed by adding rewards. There is some evidence to support this: children with ADHD can perform well on inhibition tasks when properly motivated. For instance, Slusarek, Velling, Bunk, and Eggers (2001) found that ADHD children's inhibitory performance on a stop-signal task was only worse than typically developing controls under a low reward condition. However, when given high levels of reward, children with ADHD performed as well as controls. Also, Konrad, Gauggel, Manz, and Schöll (2000) found that inhibitory control deficits in children with ADHD during a Stop Signal Task could be normalised through non-social incentives. Kohls, Herpertz-Dahlmann, and Konrad (2009) found that both money and social reward (smiling faces) improved inhibitory performance of children with ADHD and controls, although monetary incentives had a substantially stronger effect than social incentives. For the ADHD sample however, social rewards had a stronger effect on improving response inhibition compared to the control group, an effect interpreted as consistent with a hypersensitivity to social rewards in children with ADHD. However, there are also negative results. Oosterlaan and Sergeant (1998) found that impairments in children with ADHD were present despite the delivery of rewards or escape from response cost for correct inhibitions. They concluded that ADHD involves a fundamental deficit in response inhibition. However, Slusarek et al. (2001) argued that Oosterlaan and Sergeant (1998) did not use different intensities of the incentives and that their design was not able to adequately measure differences in motivational dispositions. Despite the arguments of Slusarek et al. (2001) some more recent studies using

either a stop task (Shanahan, Pennington, & Willcutt, 2008) or go/no-go task (Desman, Petermann, & Hampel, 2008; Wodka et al., 2007) have also failed to find motivational modulation of inhibition in ADHD.

When interpreting these inconsistent results, one should take into account the finding that individuals with ADHD process cues of upcoming rewards differently from typically developing peers (e.g., Haenlein & Caul, 1987; Sagvolden, Johansen, Aase, & Russell, 2005; Sonuga-Barke & Fairchild, 2012). For instance, children with ADHD have an unusually strong preference for immediate reward, even if they have the opportunity to choose a larger delayed reward. This characteristic plays a central role in the delay aversion theory of Sonuga-Barke, Taylor, Sembi, and Smith (1992) and the steeper and shorter delay-of-gratification gradient as hypothesized by Sagvolden, Aase, Zeiner, and Berger (1998). A second line of motivational research in ADHD shows that reward and response cost have a positive effect on task performance and motivation of children (controls and ADHD), with sometimes a normalization of the performance of children with ADHD (Luman et al., 2005). The positive effect of reinforcement on cognitive skills seems to be larger for children with ADHD than for typically developing controls (Luman et al., 2005; Luman, Tripp, & Scheres, 2010). However other researchers suggest a hyposensitivity to reward cues in ADHD (Haenlein & Caul, 1987). Evidence from functional magnetic resonance imaging (fMRI) studies is more consistent, showing a reduced activation in the ventral striatum of adolescents and adults with ADHD during reward anticipation (Scheres, Milham, Knutson, & Castellanos, 2007; Ströhle et al., 2008).

In trying to reconcile the contradictory results of the impact of these two factors (inhibitory load and reward processing) it becomes essential to be able to disentangle their specific effects from one another within the same task. In this paper we introduce a new task designed to study the interaction between the effects of inhibitory control and reward

anticipation on task performance. Most studies of reward and response inhibition in ADHD focus on the receipt of a specific reward, but do not specifically investigate the potential impact of reward anticipation. The monetary incentive delay (MID) task of Knutson, Fong, Adams, Varner, and Hommer (2001) was designed to distinguish the phase of reward anticipation and receipt of the outcome for use in fMRI research. A cue at the beginning of each trial denotes the magnitude of the reward that can be received at the end of the trial after a correct response. The MID task can also be used to tap behavioural effects (Demurie, Roeyers, Baeyens, & Sonuga-Barke, 2011). Spreckelmeyer et al. (2009) and Rademacher et al. (2010) adapted the original MID task by adding different monetary and social reward intensities. Three types of smiling faces with increasing happiness intensity were used as social rewards. Reaction times (RT) decreased with increasing level of anticipated reward (Rademacher et al., 2010; Spreckelmeyer et al., 2009). A similar task design was used by Demurie et al. (2011). They operationalized social reward as a pictogram of a person approving the performance of another person with thumbs up and a compliment in a text balloon combined with points. Similar to Rademacher et al. (2010) they found a linear effect of monetary and social reward intensity on the accuracy and RT of children with ADHD, autism spectrum disorder (ASD) and typically developing controls. Both clinical groups, but not controls, responded faster to monetary than social rewards. There was thus no evidence for a hypersensitivity to social rewards in ADHD (Demurie et al., 2011).

In the current study the MID task, as the initial concept, was adapted and integrated into a go/no-go paradigm in which the frequency of go and no-go trials was varied to produce settings with high (i.e., a low proportion of no-go trials) and low inhibitory load (i.e., a low proportion of go trials). Several aspects of the task design are noteworthy. First, in many of the aforementioned studies on motivational effects on response inhibition, the stop task (Logan, 1994) was used as the inhibition measure. However, researchers have expressed

reservations with regard to the appropriateness of the stop task as a measure of inhibition in ADHD. Stop-signal reaction time differences are suggested to reflect a more generalized deficit in attention or cognitive processing in ADHD, rather than behavioural inhibition problems (Alderson, Rapport, & Kofler, 2007). Therefore, we wanted to replicate prior findings with a go/no-go task. Second, the effects of monetary and social reward anticipation were compared. Finally, both correct go- and no-go-responses were rewarded to reduce the chance that differences between individuals in terms of the strategies adopted could explain the results. Scheres et al. (2001) found that reward improved overall task performance of both children with ADHD and typically developing children during a stop task where reward was only given after successful inhibition, and not after fast response execution. However, children with ADHD slowed down more in the reward condition than in the non-reward condition compared to controls. This has been interpreted as a strategy effect and thus a stronger tendency to seek reward in children with ADHD.

Usually reward processing and inhibitory abilities are investigated in both a sample of children with ADHD and a control group of typically developing children (Luman et al., 2005). However, children with ASD also show problems with response inhibition (Bishop & Norbury, 2005; Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2004; Verté, Geurts, Roeyers, Oosterlaan, & Sergeant, 2005) and differences in reward processing (Dawson, Osterling, Rinaldi, Carver, & McPartland, 2001), mainly with regard to social rewards (Chevallier, Kohls, Troiani, Brodtkin, & Schultz, 2012; Demurie et al., 2011; Garretson, Fein & Waterhouse, 1990; Geurts, Luman, & van Meel, 2008; Schultz, 2005; Scott-Van Zeeland et al., 2010; but see Dichter, Richey, Rittenberg, Sabatino, & Bodfish, 2012; Kohls et al., 2012). In order to examine to what extent abnormal reward processing and inhibition problems in ADHD are disorder-specific, this study also included a group of children with ASD and a group of children with a comorbid diagnosis of ADHD and ASD.

The main goal of this study was to develop a new paradigm that integrated the MID task with a go/no-go paradigm. We had a number of research questions. First we tested whether the task could demonstrate the effects of reward anticipation, inhibitory demands and their interaction. We predicted (1) a main effect of inhibitory load, with more commission errors in the high inhibitory load condition, (2) a main effect of reward amount, with better performance with increasing rewards and (3) an interaction between reward amount and inhibitory load - with the effects of reward amount being most pronounced under the low inhibitory load conditions (Leotti & Wager, 2010). Second, we looked at the effects of reward type (money versus social rewards). We predicted stronger effects of monetary as opposed to social rewards (Kohls et al., 2009). Third, we explored the effects of psychopathology on the effects of the relevant task parameters. To do this we compared a group of children with ADHD with a typically developing control group, a group of children with ASD and one with both ADHD and ASD. On the basis of prior work we predicted (1) worse inhibitory performance in all clinical groups especially in the high inhibitory load condition and (2) a greater effect of reward amount on the children with ADHD. Since this is the first study to investigate the effects of reward on inhibition in an ASD group and a comorbid group (ADHD+ASD), we had no clear predictions for these groups. (3) In line with Demurie et al. (2011) we expected a stronger effect of monetary rewards in the clinical groups. Our final aim addressed Mischel et al.'s (2011) suggestion of an interrelation between executive control and delay-of-gratification. However, Solanto et al. (2001) and Karalunas and Huang-Pollock (2011) found that deficits in inhibition (as measured by stop-signal RT) were uncorrelated to the tendency to choose a smaller immediate reward rather than a larger delayed reward, which suggests that inhibitory deficits and delay aversion are independent characteristics. Moreover both characteristics were strongly and independently associated with ADHD (Solanto et al., 2001). In their studies response inhibition was measured with the Stop Signal Task (Logan,

1994) and delay aversion with the Choice Delay Task (CDT; Sonuga-Barke et al., 1992). The CDT uses a fixed-choice design that does not give insight into how trade-offs are made between reward magnitude and delay duration before reward delivery. One of the main advantages of temporal discounting (TD) tasks is that they allow for measuring this trade-off (Scheres et al., 2006). The subjects in the current study performed a monetary TD task and different go/no-go tasks, which gave us the opportunity to investigate the association between TD and inhibitory performance. In line with the suggestion of Mischel et al. (2011) we expected significant associations between TD and number of commission errors in the go/no-go tasks.

## METHODS

### Participants

41 typically developing children, 34 children with ADHD, 36 with ASD and 16 with a comorbid diagnosis of ADHD and ASD took part. Each (8-16 years old) had an IQ of 80 or more, measured on 4 subscales of the Wechsler Intelligence Scale for Children - 3<sup>rd</sup> edition (Wechsler, 1991; similarities, vocabulary, block design and picture arrangement). The sum of these subtest scores gives a reliable estimate of the FSIQ (Grégoire, 2005). Groups did not differ in age ( $p = .86$ ), IQ ( $p = .12$ ), sex ratio ( $p = .22$ ; see Table 1) or distribution over the five social classes as measured by the Hollingshead Index ( $\chi^2(9) = 8.63$ ,  $p = .47$ ).

Control children were recruited through letters to local elementary and secondary schools and targeted advertisements in magazines. All control children were nominated by their parents as not displaying behaviour problems. The participants with ADHD and/or ASD were all outpatients, recruited through rehabilitation centres, special school services, and other agencies specialized in the care of children with developmental disorders. All had previously been diagnosed with ADHD and/or ASD by a multidisciplinary team according to DSM-IV-TR (American Psychiatric Association, 2000) criteria. Clinical diagnoses were confirmed

with a validated measure: the Autism Diagnostic Interview, Revised (ADI-R; Lord, Rutter, & Lecouteur, 1994), Autism Diagnostic Observational Schedule, Generic (ADOS-G; Lord et al., 2004) or Childhood Autism Rating Scale (CARS; Schopler, Reichler, Devellis, & Daly, 1980) for ASD. The ADHD diagnosis was verified using the disruptive behaviour module (ADHD, oppositional defiant disorder, conduct disorder) of the Diagnostic Interview Scale for Children for DSM-IV (Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000). In the ADHD sample, 10 participants met the criteria for the inattentive subtype, 4 for the hyperactive subtype and 20 for the combined subtype. Furthermore, 16 participants also fulfilled the diagnostic criteria of ODD, but none of the participants with ADHD had comorbid CD. In the comorbid sample, 7 participants met the criteria for the inattentive subtype, 2 for the hyperactive subtype and 7 for the combined subtype. 6 participants with a comorbid diagnosis also showed the diagnostic criteria of ODD, but none had comorbid CD. Participants on stimulant medication were asked to discontinue their medication at least 24 hours prior to testing. 22 participants with ADHD were medicated with methylphenidate (MPH), 4 participants with ASD and 11 participants with ADHD and ASD.

Parents and teachers completed questionnaires to obtain a broad view of the child's overall functioning and possible comorbid symptoms. Parents completed the Disruptive Behavior Disorder rating scale (DBDRS; Pelham, Gnagy, Greenslade, & Milich, 1992) and Social Communication Questionnaire (SCQ; Rutter, Bailey, & Lord, 2003). Teachers completed the DBDRS.

### **Monetary and Social Incentive Delay (MID and SID) go/no-go tasks**

The tasks were based on Knutson's MID task (Knutson et al., 2001). A cue at the start of each trial indicated the motivational consequences of good performance. In the current version an empty circle indicated no reward, one with one line a medium reward and one with three lines a high reward for good performance. In the MID/SID go/no-go tasks children were

told that they could earn money (MID) or points (SID) during the task. The investigator told them that they would see a cue at the start of each trial that would show how much they could win during that specific trial. Furthermore, the meaning of the cues was explained and the children were told how to react to the target stimuli. It was stressed that they had to react as quickly as possible, but also had to try to be as accurate as possible. These instructions were illustrated with pictures of the cues and targets and presented in four different instruction windows. The instructions were then followed by ten target trials.

The classic MID task was adapted in three ways. First of all, the simple target detection task typically used was replaced by a rewarded go/no-go task. The go/no-go paradigm is one of the most frequently used response inhibition measures (Simmonds, Pekar, & Mostofsky, 2008). In this paradigm either a go (square) or a no-go stimulus (triangle) is presented on the screen in each trial. Children have to press a button when they see a go-stimulus but avoid responding when they see a no-go stimulus. By adding this go/no-go aspect to the MID task, we wanted to measure the interaction between reward anticipation and response inhibition processes. To do this we compared conditions with different inhibitory load levels: a 75-25 go/no-go condition, which loaded high on inhibitory demands, and a 25-75 go/no-go condition with low inhibitory demands. In the 75-25 condition, there were 81 go and 27 no-go trials. In the 25-75 condition, there were 27 go-trials and 81 no-go trials. Second, in the original MID task difficulty was set such that participants would succeed on approximately 66% of all trials, based on RTs collected during a practice session. In our adaptation performance level was not individually tailored, as we wanted to be able to investigate group differences in both RT and task accuracy as well as in total amount of gain. Third, we compared the effects of monetary and social rewards. In the monetary (MID) conditions, participants could win eurocents for a fast and correct reaction. A cue presented at the start of each trial signalled the size of the reward to be delivered. Three reward intensities were

possible: no reward (0 eurocent), medium reward or high reward. Rewards for correct inhibitions and correct go-responses were in proportion with the go/no-go rate, thus the 25% reactions were rewarded 3 times as high as the 75% reactions. By doing so, alternative strategies, such as always or never pressing the button, could be discouraged. A fast and/or correct reaction was rewarded 4 (75 % reaction) or 12 eurocents (25% reaction) after a medium reward cue and 10 or 30 eurocents respectively after a high reward cue (see Figure 1 for an overview of the meaning of the cues in the 75-25 monetary task). All participants correctly believed that they would receive the obtained amount of money at the end of the testing. During the social (SID) conditions, reward was operationalized as 0, 4, 12, 10 or 30 points, in combination with a pictogram of an interaction between two persons. One person in the pictogram approves the performance of the other person with thumbs up and a compliment in a text balloon. The compliments were different in each block, to avoid habituation. Examples are 'Ok' as a 0 points compliment, 'Well done' for a medium reward and 'You're a champion!' for a high reward. Figure 2 shows an example trial of each task.

Each child performed under two conditions (high versus low inhibitory load), so that there were in total 4 conditions: monetary-high inhibition load (MID-High), monetary-low inhibition load (MID-Low), social-high inhibition load (SID-High) and social-low inhibition load (SID-Low). In each condition there were 10 practice trials and three blocks of 36, 6 sec trials, yielding a total of 118 trials. During each trial, participants saw one of three cue shapes (500 msec), followed by a black screen (pre-target delay, random variable duration: 2000-2500 msec) and the target stimulus (triangle or square, 260 msec). During go-trials participants had to react within a 500 msec response window to be rewarded. During no-go trials, a button press during the post-target delay was considered incorrect. After the post-target delay (variable duration dependent of pre-target delay duration: 1000-1500 msec), a feedback screen (1740 msec) notified participants of whether they had won money (monetary

task) or points (social task) during that trial and indicated their cumulative total at that point. The order of the four conditions was counterbalanced among the participants.

### **Monetary temporal discounting task**

Participants also performed a computerized monetary TD task. They were instructed to make repeated choices between (hypothetical) small variable rewards delivered immediately and a large constant reward (30€) delivered after a variable delay (now, tomorrow, the day after tomorrow, 1 week, 2 weeks) (see Figure 3). Reward magnitudes were 0€, 5€, 10€, 20€ and 30€, visualized as euro notes. Each small immediate reward was paired four times with every delay for the large reward, resulting in a total of 100 choice trials. Trials were administered in the same pseudo-random order to all participants. Left or right position of the delayed reward was balanced over trials.

We have chosen to use hypothetical rewards and delays in this study, thus the children did not actually receive the rewards, neither did they experience real delays, but they had to imagine that they would receive these rewards after a given delay. Results from TD tasks with real rewards and delay intervals have previously been shown to be highly correlated with those of hypothetical TD tasks (Johnson & Bickel, 2002; Scheres, Sumiya, & Thoeny, 2010), which suggests that there is congruency between what participants believe they would choose and what they actually choose. Both real and hypothetical TD tasks are thus reliable measures of TD and give similar results.

### **Data preprocessing of the TD task**

Preprocessing of TD data was based on procedures described by Critchfield and Kollins (2001) and Scheres et al. (2006) and has been explained into detail in Demurie, Roeyers, Baeyens, and Sonuga-Barke (2012). First, subjective values of the delayed reward were determined for each delay by two independent raters. The subjective value of the delayed reward was estimated by averaging the switch points in the ascending and descending choice

sequences (Critchfield & Kollins, 2001). These switch points are defined as the magnitudes of the small immediate reward for which the participant shows indifference in a choice against the large delayed reward (Scheres et al., 2006). The second step in the preprocessing of the data was to calculate the area under the curve (AUC) for the TD functions according to the procedure described by Myerson, Green, and Warusawitharana (2001). The steeper the discounting function, the smaller the AUC will be.

## **Procedure**

Children and their parents were invited to the Faculty of Psychology and Educational Sciences. All participants and parents signed an informed consent form prior to testing. At the beginning of the test session we verified whether participants on methylphenidate were really off medication for at least 24 hours by asking when they had taken their last dose of methylphenidate. The study was approved by the Ethical Committee of the Faculty of Psychology and Educational Sciences of Ghent University.

## **Dependent measures and data analysis**

The AUC reflects the steepness of the TD slopes. Percentage of commission errors (pressing the button after a no-go target) has been used as a measure of response inhibition, with more errors reflecting more deficient response inhibition. Other dependent measures were percentage of omission errors (not pressing the button after a go target), mean reaction time of go-responses (RT) and within-subject variability, operationalized as within-subject standard deviation of RTs of go-responses (SD-RT). Responses faster than 150 msec were considered to be premature responses and excluded from the analyses.

A 4 ('Group': controls vs. ADHD vs. ASD vs. ADHD+ASD) x 2 ('Inhibitory load': high inhibitory load - 75/25 go/no-go task vs. low inhibitory load - 25/75 go/no-go task) x 2 ('Reward type': monetary vs. social reward) x 3 ('Reward amount': no reward vs. medium reward vs. high reward) design was used in repeated measures analyses. To answer the

research questions, the focus was on the main and two-way interaction effects. Furthermore, correlations between AUC and number of commission errors have been calculated.

## RESULTS

### I. Are the manipulations of inhibitory load and reward amount successful?

**Was there a main effect of inhibitory load?** There were main effects of inhibitory load on all dependent variables. A higher percentage of commission errors was seen in the high inhibitory load condition ( $F(1,122) = 641.87, p < .001$ ). Omission errors on the other hand were more frequent in the low inhibitory load condition ( $F(1,122) = 133.62, p < .001$ ). Participants responded faster ( $F(1,116) = 119.70, p < .001$ ), but with more intra-subject variability ( $F(1,98) = 16.58, p < .001$ ) in the high inhibitory load condition.

**Was there a main effect of reward amount?** Main effects of reward amount were found for all go-response related measures, but not for commission errors. For omission errors ( $F(2,121) = 60.91, p < .001$ ) and RT of correct go-responses ( $F(2,115) = 30.89, p < .001$ ) performance improved for each increase in anticipated reward (Om/RT no reward > Om/RT medium reward > Om/RT high reward). Furthermore, participants' RTs became less variable in the high reward trials compared to the medium reward trials ( $F(2,97) = 4.43, p < .05$ ).

**Was there an interaction between inhibitory load and reward amount?** For commission errors, an interaction between inhibitory load and reward amount ( $F(2,121) = 8.68, p < .001$ ) was found (see Figure 4). In the high inhibitory load condition, there was an effect of reward amount ( $F(2,122) = 4.06, p < .05$ ), showing a lower percentage of commission errors in the high reward trials compared to the medium reward trials (comm 12 > comm 30;  $p < .05$ ). In the low inhibitory load condition, the effect of reward intensity ( $F(2,121) = 8.25, p < .001$ ) showed the reversed pattern: surprisingly participants made most errors in the high reward condition (comm 0 = comm 4 < comm 10;  $p = .34, p < .001$  and  $p < .01$  respectively).

For omission errors the interaction between inhibitory load and reward amount ( $F(2,121) = 12.18, p < .001$ , see Figure 5) pointed out that greater effects of reward amount could be found in the low compared to the high inhibitory load conditions ( $F(1,125) = 4.77, p < .05$  for medium versus no reward;  $F(1,125) = 27.85, p < .001$  for high versus no reward;  $F(1,125) = 11.56, p < .01$  for high versus medium reward).

For RT of correct go-responses, the interaction between inhibitory load and reward amount ( $F(2,115) = 15.92, p < .001$ ) showed that there was a greater decline in RTs with increasing reward in the low inhibitory load condition (RT 0 > RT 12 > RT 30) compared to the high inhibitory load condition (RT 0 = RT 4 > RT 10). Finally for SD-RT, the interaction between inhibitory load and reward amount was not significant ( $F(2,97) = 2.48, p = .09$ ).

## **II. Is there a different effect of monetary versus social reward anticipation?**

Reward type effects were only found for the go-response variables. For omission errors a main effect of reward type ( $F(1,122) = 25.81, p < .001$ ) was found, with a lower percentage of omission errors in the monetary conditions. An interaction between reward type and amount ( $F(2,121) = 3.53, p < .05$ ) showed that this effect could only be seen in the rewarded trials. Furthermore, an interaction between inhibitory load and reward type ( $F(1,122) = 3.75, p = .055$ ) demonstrated that greater differences between monetary and social rewards ( $F(1,125) = 3.97, p < .05$ ) could be found in the low compared to the high inhibitory load conditions. Furthermore, RT of correct go-responses were faster when money could be won ( $F(1,116) = 4.20, p < .05$ ). Finally, an interaction effect between inhibitory load and reward type ( $F(1,98) = 5.65, p < .05$ ) was found for SD-RT: only in the high inhibitory load condition less variable RTs were observed when money compared to social rewards could be won ( $p < .01$ ).

## **III. What are the effects of psychopathology on the effects of the relevant task parameters?**

**Was there a group difference in overall task performance?** No group differences in percentage of commission errors ( $F(3,122) = 1.32, p = .27$ ), RT ( $F(3,116) = .41, p = .75$ ) and SD-RT of correct go-responses ( $F(3,98) = 1.60, p = .19$ ) were found. For omission errors ( $F(3,122) = 3.36, p < .05$ ) on the other hand, a difference between the controls and the comorbid group could be observed, with the latter ones making more errors.

**Were there group differences in the impact of anticipated rewards?** An interaction between reward amount and group ( $F(6,242) = 2.52, p < .05$ ; see Figure 6) for omission errors demonstrated that a group difference could be observed in the no-reward trials only: participants with a combined diagnosis of ADHD+ASD had a higher percentage of omission errors than controls and participants with ASD (with the ADHD participants in between). Performance of the participants with ADHD+ASD thus normalized in the rewarded trials. For the other variables, no interactions between reward amount and group were found.

**Was there a different effect of monetary versus social reward anticipation in the participating groups?** No interaction effects between group and reward type were found for any of the dependent variables.

#### **IV. Is there an association between TD and inhibitory performance?**

Correlations between the AUC for money and the percentage of commission errors in the go/no-go tasks were calculated for the four participating groups. Only in the ADHD sample, significant correlations between monetary AUC on the one hand and the percentage of commission errors in the MID-High condition ( $r(32) = -.41, p < .05$ ) and the percentage of commission errors in the SID-High condition ( $r(32) = -.52, p < .01$ ) on the other hand have been found. These correlations remained significant if IQ was controlled for.

## **DISCUSSION**

In the current study, we successfully adapted the MID task (Knutson et al., 2001) to investigate the interaction between reward anticipation and inhibitory control. We did this by integrating this task into a go/no-go paradigm to compare two levels of inhibitory load and three amounts of reward. We were able to formulate answers to the four sets of predictions. The first set of predictions related to the task manipulations, which were successful: we observed the predicted effects of inhibitory load and reward amount, as well as interactions between both factors. This interaction showed that anticipated rewards differentially affected task performance in the two inhibition conditions. With regard to commission errors, we found a positive effect of reward anticipation on inhibitory performance in the high inhibitory load condition: fewer errors were made in the high-reward trials compared to the medium reward trials. Inhibitory performance can thus be influenced by reward anticipation, irrespective of group. These results are in line with previous reports of improved inhibitory performance due to reward (e.g., Kohls et al., 2009; Luman et al., 2005). Surprisingly, in the low inhibitory load condition the percentage of commission errors increased in the highest reward condition. This was possibly due to the fact that the reward for correct go-trials was three times higher than for no-go-trials (30 versus 10 points/eurocents) in the low inhibitory load condition which made ‘pressing the button’ a more prepotent response in the high-reward trials, although this was not expected given the low frequency of go-trials (25%). The cue for a high reward seemed to be a salient cue that made suppressing the go-response harder in these trials. Thus our effort to avoid the strategy of ‘always pressing the button’ in the high inhibitory load condition seems to have had the opposite effect in the low inhibitory load condition. Another possible explanation is that our manipulation evoked a response bias towards or response strategy of always reacting to the high reward predicting cues (to maximize the chance of winning the high go-related reward). Unequal distribution of rewards between two types of correct response produces a systematic preference for the response

producing the larger reward (Tripp & Alsop, 1999). Although the overall size of reward was equal for the go and no-go responses, it is possible that participants saw the reward amounts as imbalanced, causing a response bias for the go-response. In any case, with regard to commission errors our results clearly suggest that the effects of reward anticipation on performance are sensitive to variation in inhibitory load. For omission errors and RT of correct go-responses, we found that the effects of anticipated rewards were stronger in the low compared to the high inhibitory load condition. One may argue that there was more room for improvement in the low inhibitory load condition, but there was no evidence for a ceiling effect in the high inhibitory load condition. Leotti and Wager (2010) also found that performance improvement induced by changes in motivational context were less extreme when inhibitory demands were higher. Thus also for the go-responses differential effects of neuropsychological load could be observed. Kohls et al. (2012) suggested that findings of aberrant reward sensitivity should be considered in the context of the cognitive demands required for a task, since subjective reward value varies inversely with the effort necessary to obtain the reward (Botvinick, Huffstetler, & McGuire, 2009). Krebs, Boehler, Roberts, Song, and Woldorff (2012) showed that the anticipation of both varying reward magnitudes and varying degrees of task difficulty evoked interacting brain activations in the dopaminergic midbrain and cortico-striatal-thalamic circuits, contributing to the modulation of resource recruitment in order to facilitate task performance when it is particularly worthwhile. In line with this, we found that task demands indeed seem to alter sensitivity to anticipated rewards and consequently the selection of task strategies.

Our second set of predictions related to the type of reward employed. Reward type had an impact on all go-response related measures: omission errors and RT in all four tasks and on SD-RT in the high inhibitory load condition. The results are in line with those of Demurie et al. (2011) and Kohls et al. (2009): although both monetary and social reward improved task

performance of all participants, performance was better when monetary rewards compared to social rewards could be won. For omission errors, an interaction between reward type and reward intensity was found: the main effect of reward type could only be observed in the rewarded trials. These results emphasize the power of money as a reinforcer, both in daily life and in research.

Our third set of predictions related to the comparison of the effects of reward anticipation and inhibitory load in ADHD and/or ASD. Against our predictions and in contrast to a great deal of the existing literature we found very little evidence for differential effects of reward amount or inhibitory load in these groups. First, we found no differences in the percentage of commission errors (both on rewarded and unrewarded trials) in the ADHD or the ASD groups. Nigg (2001) hypothesized that children with ADHD manifest deficits with effortful or controlled inhibition ('executive inhibition') but that inhibition of behaviours or cognitions associated with reward or punishment ('motivational inhibition') is intact. One possible explanation is that the motivational effects of reward anticipation extended to the non-rewarded trials, normalizing inhibitory performance in the clinical groups throughout the entire task. Given the positive influence of motivational variables on effort allocation (Sanders, 1983; Sergeant et al., 1999), reward anticipation might have elevated the energetic state of the children with ADHD to a more optimal level leading to a better inhibitory performance. On the other hand, others have also previously failed to find evidence for impaired inhibitory performance in ADHD or ASD (Daugherty et al., 1993; Ozonoff & Jensen, 1999; Raymaekers et al., 2007; Van De Voorde et al., 2010). The current results appear to support theoretical accounts questioning the fundamental and unique causal role of executive function deficits in ADHD and ASD (Sergeant, 2000; Sonuga-Barke et al., 1992). Banaschewski et al. (2004) suggested that the occurrence of inhibition problems in ADHD might depend on which tasks are used to measure inhibition. Furthermore go/no-go tasks do

not tap all aspects of inhibitory performance (Nigg, 2000). We can thus not exclude the possibility that our go/no-go tasks were not sensitive enough to find group differences in inhibitory performance. Future studies should check the baseline sensitivity of tasks in discriminating children with ADHD and typically developing children. Second, except for the omission errors, there were no differential effects of reward amount on performance across the groups: no interactions between group and reward amount were found for commission errors, RT and SD-RT. The current results are in line with the unexpected findings of Demurie et al. (2011), showing no evidence for the predicted hyposensitivity to changes in reward amount in ADHD. Reward anticipation seems to have a general effect on task performance over and above any specific reward or group effects on cognitive control (Geurts et al., 2008). Barkley (1997) postulated that children with ADHD are not more or less sensitive to rewards, but suggested that their behaviour is more influenced by immediate events and their consequences than by experiences more distal in time. In the current adaptation of the MID task, the participants were rewarded immediately after each correct response. As children with ADHD might perform similar to controls under schedules of continuous and immediate reinforcement (e.g., Barber, Milich, & Welsh, 1996; Parry & Douglas, 1983), the chosen reinforcement schedule might be the reason why we did not find any differential reward effects in the ADHD sample. However, for omission errors we did find an interaction between group and reward intensity. Only in the no-reward trials, children with a combined diagnosis of ADHD and ASD made more omission errors compared to controls and children with ASD, but this group difference disappeared in the rewarded trials. Given that omission errors have been linked to attentional problems and lapses of attention during response execution (Bezdjian, Baker, Lozano, & Raine, 2009), our results suggest that attention problems in children with ADHD+ASD are worse compared to controls and children with ASD when they are not rewarded, but normalize when rewards are expected.

These attention problems in the comorbid group were not reflected in the inattention scores on the questionnaires rated by parents and teachers, as these were not higher compared to the other clinical groups. Is it possible that parents and teachers of children with a comorbid diagnosis of ADHD and ASD in our sample reinforce these kids more systematically in daily life, as learnt in certain parent training courses? Third, against our expectations, the effects of reward type did not interact with group and we did not find evidence for a smaller effect of social as opposed to monetary rewards in the clinical groups (Chevallier et al., 2012; Demurie et al., 2011).

Finally, with regard to our last prediction, evidence for a link between response inhibition and temporal discounting in the ADHD sample was found, since monetary TD correlated negatively with the percentage of commission errors in both the monetary and social high inhibitory load condition, but not with those of the low inhibitory load condition. The steeper the TD slope, the more commission errors were made, suggesting that poor response inhibition and steep TD indeed are associated. Our results are thus in line with the predictions of Mischel et al. (2011). Previous studies, making use of the stop signal task and CDT, found no correlation between delay aversion and inhibitory deficits in ADHD (Karalunas & Huang-Pollock, 2011; Solanto et al., 2001). In the current study inhibition was measured with go/no-go tasks and a hypothetical TD task was used to tap delay averse response style. The use of these tasks may have been decisive for finding the association. However, based on the current results nothing can be concluded with regard to the underlying causality of this association. Future studies might further investigate the strength and causal mechanisms of the possible association between temporal discounting and inhibition.

Some limitations should be acknowledged as well. First, we wanted to vary the inhibitory load of the go/no-go tasks, by using both 75-25 and 25-75 go/no-go tasks. However, if we compared task performance on the two tasks, there were not only more commission errors in

the high inhibitory load condition, but also less omission errors and faster, but more variable responses. As percentage of commission errors is supposed to reflect a measure of inhibitory difficulties and impulsivity, while omission errors have been linked to attentional problems (Bezdjian et al., 2009), this result suggests that the two tasks might tap different cognitive processes, with the high inhibitory load condition tasks focusing mainly on response inhibition and the low inhibitory load condition also measuring attention and target detection. The design of the low inhibitory load condition is in fact that of an oddball task, where subjects are instructed to generate a response to infrequent targets (Braver et al., 2001). These differences in inhibitory and attentional demands may have confounded our results. Second, the sample size of the comorbid group was rather low, which might have had an impact on the power of the effects. On the other hand, this was the only group where we found a group difference in the percentage of omission errors. Third, some evidence for a link between inhibition and TD in the ADHD sample could be found, since monetary TD correlated negatively with the number of commission errors in the high inhibitory load condition. However, these go/no-go tasks also had a reward processing aspect, which may have had a confounding effect on our results, especially if we take abnormal reward processing in ADHD (Luman et al., 2005) into account. Future research should thus make use of ‘pure’ go/no-go tasks to investigate the association between TD and inhibition performance on go/no-go tasks.

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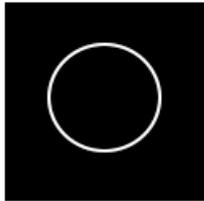
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**Table 1** *Descriptive characteristics of the sample*

	Controls n = 41		ADHD n = 34		ASD n = 36		ADHD+ASD n = 16		
	<b>M</b>	<b>SD</b>	<b>M</b>	<b>M</b>	<b>SD</b>	<b>SD</b>	<b>M</b>	<b>SD</b>	
<b>Sex</b>									
Male	30		28		33		13		$\chi^2(3) = 4.43, p = .22$
Female	11		6		3		3		
<b>Age in months</b>	137.39	22.23	137.41	22.14	136.42	26.31	131.56	28.10	F(3,123) = .26, p = .86
<b>Estimated FSIQ</b>	105.95	8.84	101.76	11.62	105.08	12.96	99.13	11.07	F(3,123) = 1.98, p = .12
<b>SCQ</b>	4.10	3.12	5.71	3.00	13.58	5.56	17.63	5.98	F(3,123) = 58.70, p < .001 Controls = ADHD < ASD < ADHD+ASD
<b>Parent DBDRS</b>									
<b>IA</b>	4.32	3.27	15.29	5.72	13.31	6.13	14.13	5.75	F(3,123) = 34.63, p < .001 Controls < ADHD = ASD = ADHD+ASD
<b>H/I</b>	2.34	2.72	12.99	5.24	9.53	4.87	13.44	6.41	F(3,123) = 41.31, p < .001 Controls < ASD < ADHD = ADHD+ASD
<b>Teacher DBDRS</b>									
<b>IA</b>	2.86	3.39	10.23	6.11	8.41	6.38	10.44	6.11	F(3,102) = 12.63, p < .001 Controls < ADHD = ASD = ADHD+ASD
<b>H/I</b>	1.69	2.67	8.53	5.79	4.45	5.21	7.42	6.08	F(3,102) = 11.80, p < .001 Controls = ASD < ADHD; ADHD = ADHD+ASD; ASD = ADHD+ASD

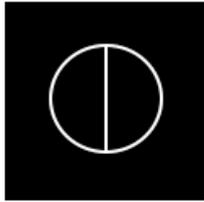
*Note:* FSIQ: full scale intelligence quotient, SCQ: Social Communication Questionnaire, DBDRS: Disruptive Behavior Disorder rating scale, IA: inattention subscale scores, H/I: hyperactive/impulsive subscale scores

**For the 75-25 monetary go/no-go task**



no reward

No reward cue: - go: - reaction: +0  
 - no reaction: 0  
 - no-go: - reaction: 0  
 - no reaction: +0



medium reward

Medium reward cue: - go: - reaction: + 4 eurocent  
 - no reaction: 0  
 - no-go: - reaction: 0  
 - no reaction: +12 eurocent

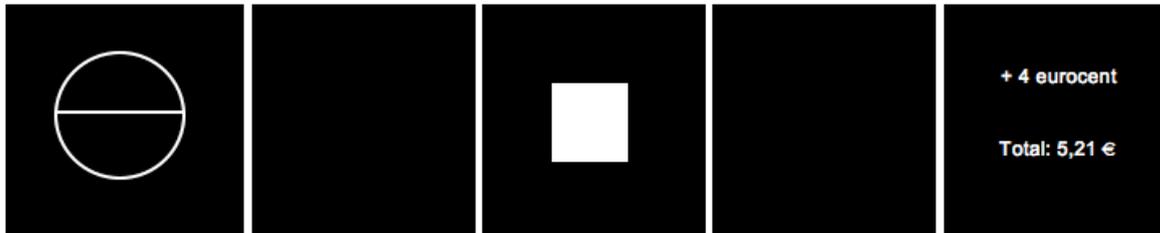


high reward

High reward cue: - go: - reaction: + 10 eurocent  
 - no reaction: 0  
 - no-go: - reaction: 0  
 - no reaction: + 30 eurocent

**Figure 1.** *Reward cues in the 75-25 monetary task*

**Go-trial in the MID tasks:**



500 ms

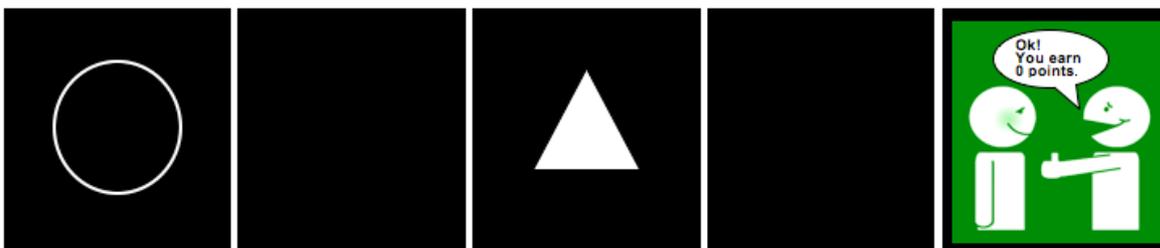
2000-2500 ms

260 ms  
(response window:  
500 ms)

1000-1500 ms

1740 ms

**No-go trial in the SID tasks:**



500 ms

2000-2500 ms

260 ms  
(response window:  
500 ms)

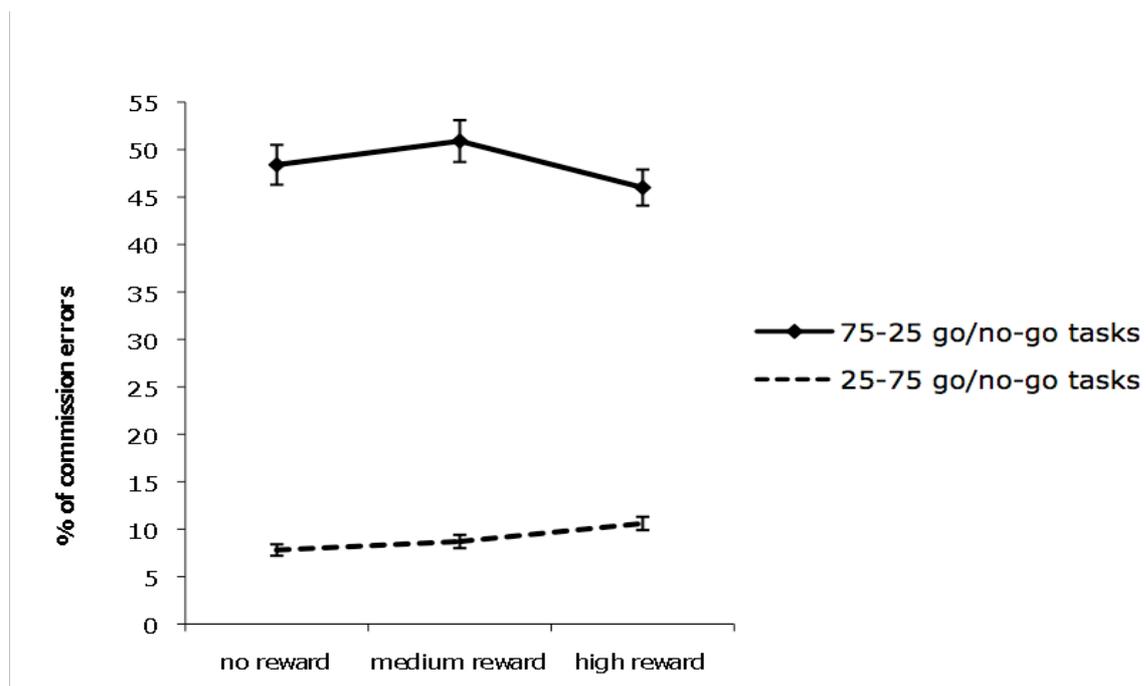
1000-1500 ms

1740 ms

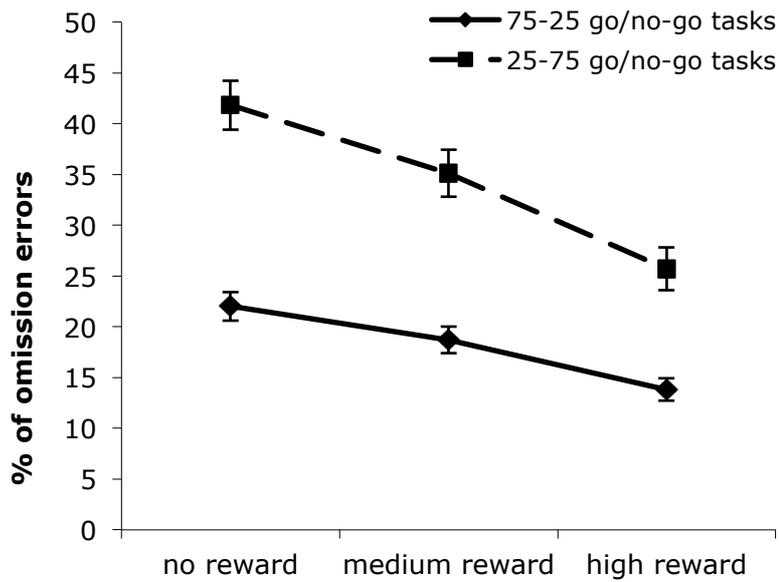
**Figure 2.** *A trial of the monetary and social tasks*



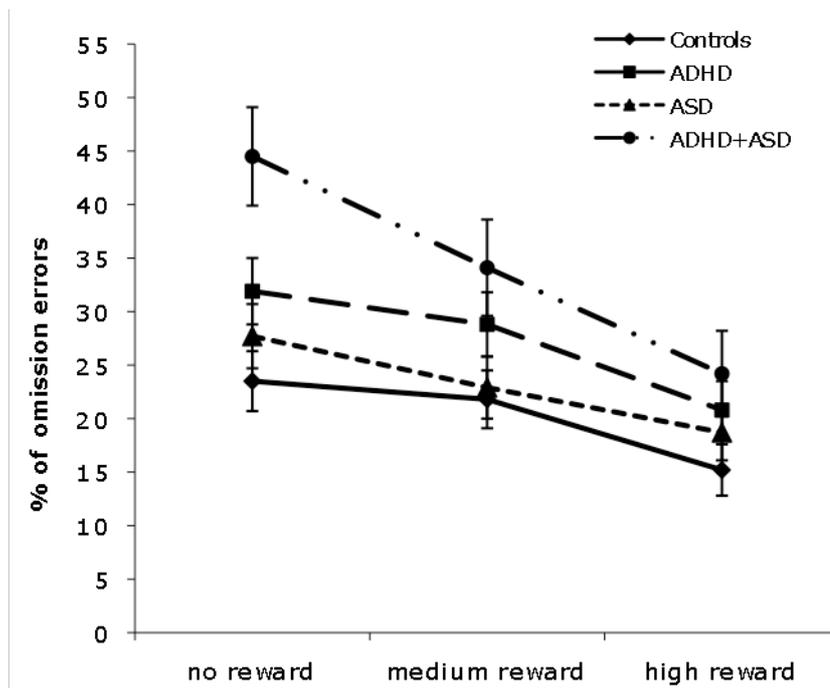
**Figure 3.** *Trial of the monetary temporal discounting task. Instruction: Which reward do you prefer, taking the delay into account?*



**Figure 4.** *Interaction between inhibitory load and reward amount for commission errors (error bars refer to standard errors)*



**Figure 5.** *Interaction between inhibitory load and reward amount for omission errors (error bars refer to standard errors)*



**Figure 6.** *Interaction between group and reward intensity for omission errors (error bars refer to standard errors)*

**Table S1.** Group means and standard deviations per condition for the four dependent variables

High inhibitory load	MID task								SID task								
	Controls		ADHD		ASD		ADHD+ASD		Controls		ADHD		ASD		ADHD+ASD		
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	
<b>Commission errors</b>																	
0 eurocent	0,45	0,27	0,45	0,25	0,49	0,29	0,56	0,26	0,46	0,25	0,43	0,23	0,50	0,28	0,51	0,20	
12 eurocent	0,47	0,29	0,47	0,24	0,49	0,27	0,57	0,22	0,50	0,24	0,55	0,25	0,49	0,29	0,53	0,22	
30 eurocent	0,41	0,24	0,44	0,24	0,41	0,24	0,51	0,24	0,46	0,21	0,46	0,20	0,46	0,28	0,53	0,15	
<b>Omission errors</b>																	
0 eurocent	0,15	0,16	0,22	0,16	0,19	0,15	0,32	0,17	0,15	0,13	0,22	0,17	0,18	0,15	0,33	0,16	
4 eurocent	0,14	0,16	0,18	0,16	0,14	0,14	0,18	0,17	0,17	0,11	0,22	0,15	0,17	0,15	0,30	0,20	
10 eurocent	0,10	0,10	0,15	0,17	0,11	0,11	0,14	0,13	0,13	0,11	0,16	0,13	0,14	0,14	0,18	0,16	
<b>RT</b>																	
0 eurocent	330,37	32,21	339,81	32,89	331,52	34,60	330,84	34,55	337,25	31,41	337,47	34,42	323,90	32,92	346,86	37,66	
4 eurocent	333,09	34,29	340,79	36,10	329,61	37,41	329,93	38,56	336,94	34,47	335,05	31,72	327,23	34,70	351,84	33,79	
10 eurocent	332,46	30,47	329,99	34,48	330,71	41,15	324,95	33,81	330,04	32,55	327,09	32,06	324,77	37,51	337,53	32,05	
<b>SD-RT</b>																	
0 eurocent	63,63	10,91	72,39	10,83	67,29	14,40	72,06	9,54	68,60	10,46	73,16	12,85	70,90	17,00	72,00	13,49	
4 eurocent	65,50	12,55	74,55	12,21	62,04	14,17	69,75	15,41	69,13	14,50	74,13	9,94	66,66	13,80	70,26	13,84	
10 eurocent	65,76	11,50	68,32	10,99	62,56	8,94	66,25	16,28	67,65	12,65	70,80	13,70	64,92	14,02	71,55	12,88	
Low inhibitory load	Controls		ADHD		ASD		ADHD+ASD		Controls		ADHD		ASD		ADHD+ASD		
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	
<b>Commission errors</b>																	
0 eurocent	0,06	0,08	0,07	0,07	0,06	0,06	0,11	0,08	0,07	0,06	0,08	0,08	0,07	0,07	0,12	0,17	
4 eurocent	0,08	0,08	0,08	0,07	0,08	0,08	0,12	0,09	0,07	0,07	0,09	0,09	0,08	0,10	0,10	0,09	
10 eurocent	0,08	0,09	0,09	0,07	0,11	0,10	0,15	0,09	0,08	0,08	0,09	0,06	0,09	0,08	0,17	0,11	
<b>Omission errors</b>																	

0 eurocent	0,31	0,27	0,38	0,28	0,36	0,30	0,54	0,32	0,33	0,27	0,45	0,26	0,38	0,27	0,59	0,23
12 eurocent	0,27	0,24	0,35	0,30	0,26	0,24	0,41	0,25	0,29	0,27	0,40	0,26	0,35	0,27	0,48	0,25
30 eurocent	0,19	0,20	0,22	0,25	0,21	0,26	0,24	0,26	0,20	0,23	0,30	0,24	0,29	0,26	0,41	0,27

#### RT

0 eurocent	384,43	46,15	376,60	35,42	371,18	47,03	378,15	44,86	372,53	42,76	394,78	52,53	383,68	42,20	370,81	42,69
12 eurocent	375,70	39,97	365,47	39,86	361,00	36,14	359,65	38,76	368,52	41,52	368,88	36,23	362,77	45,79	363,09	44,24
30 eurocent	347,07	44,55	345,19	44,22	339,66	50,10	332,18	35,85	348,23	43,37	359,21	42,03	354,09	46,26	363,18	46,02

#### SD-RT

0 eurocent	57,41	19,31	61,95	20,86	60,71	22,71	74,01	28,38	64,68	18,54	54,19	23,96	63,61	18,46	62,28	39,05
12 eurocent	65,74	18,14	71,46	27,92	63,76	19,42	76,23	16,91	62,67	21,65	66,24	16,01	62,80	17,84	64,44	18,16
30 eurocent	62,35	17,43	60,95	18,94	62,67	21,74	62,97	26,63	62,00	18,38	64,81	21,62	60,91	17,09	60,67	32,54

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