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Decision-Making Deficits in Adolescent Boys with and without Attention-Deficit/Hyperactivity Disorder (ADHD): an Experimental Assessment of Associated Mechanisms

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Abstract

Adolescents with Attention-Deficit/Hyperactivity Disorder (ADHD) demonstrate increased levels of real-life risk-taking behavior like substance abuse and reckless behavior in traffic, which potentially originates in decision-making deficits. Using experimental gambling tasks, the current study investigated three potential underlying mechanisms: (1) risky vs. suboptimal decision making, (2) the complexity of decision-making strategies and (3) the influence of feedback. Participants were 181 male adolescents (81 ADHD, 100 Typically Developing (TD); $M_{age} = 15.1$ years). First, we addressed a common confound in many gambling tasks by disentangling risk seeking from suboptimal decision making, and found that ADHD-related decision-making deficits do not originate in increased risk seeking but in suboptimal decision making. Second, we assessed decision-making strategies with a Bayesian latent mixture analysis and found that ADHD-related decision-making deficits are characterized by the use of less complex strategies. That is, adolescent boys with ADHD, relative to TD adolescent boys, less often adopted strategies in which all characteristics relevant to make an optimal decision were integrated. Third, we administered two gambling task conditions with feedback in which adolescents experience the outcomes of their decisions and found that adolescents with ADHD performed worse relative to TD adolescents on both conditions. Altogether, this set of studies demonstrated consistent decision-making deficits in adolescent boys with ADHD: The use of less complex decision-making strategies may cause suboptimal decision making, both in situations with and without direct feedback on performance.

Keywords Attention-deficit/hyperactivity disorder (ADHD) · Decision making · Adolescence · Risk taking · Strategies

Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is a heritable neurodevelopmental disorder characterized by excessive inattention, impulsivity and hyperactivity, causing clinically significant impairment across settings (American Psychiatric Association 2013). For example, many adverse health outcomes are related to ADHD (Nigg 2013), and many of these

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pertain to risk-taking behavior (RTB). ADHD is associated with many forms of RTB, such as risky driving, substance abuse, gambling, criminal behavior and sexual RTB (see Pollak et al. 2019, for a review). Estimated life expectancy is lower in individuals with ADHD relative to individuals without ADHD (Barkley and Fischer 2018), which can be partly explained by these increased levels of RTB. Additionally, ADHD and related problems put a high financial burden on society (Zhao et al. 2019). For these reasons, it is of pivotal importance to elucidate underlying mechanisms of ADHD-related RTB, to better understand causes of RTB and ultimately improve interventions targeting RTB. As suggested by Pollak et al. (2019), a decision-theory framework may be fruitful to achieve these goals.

Experimental gambling task paradigms are often used to assess risk taking. The advantage of these tasks, in comparison to real-life risk-taking measures, is the possibility to isolate and assess underlying mechanisms. A recent meta-analysis aggregating all studies that compared individuals with ADHD to controls on gambling tasks revealed that ADHD groups engaged in more risky decision making than control groups (Dekkers et al. 2016), which aligns with real-life findings.

Various mechanisms are presumed to explain this risky decision making in ADHD. In the current study we investigate three mechanisms of special interest: (1) risk seeking vs. suboptimal decision making, (2) the complexity of decision-making strategies and (3) the influence of feedback. For each of these mechanisms, we use several new versions of a well-established gambling task (i.e., Gambling Machine Task (GMT); Jansen et al. 2012; see Fig. 1).

1. Risky Vs. Suboptimal Decision Making

Risk taking is defined as "engagement in behaviors that are associated with some probability of undesirable results" (Boyer 2006). In decision making literature, choosing the option with the highest range of outcomes (i.e., the highest standard deviation of expected outcomes) is considered risky. In many gambling tasks, the risky option is also the suboptimal option in terms of mean expected outcomes (i.e., expected value).[1] It is therefore impossible to determine whether a risky decision reflects risk seeking or a suboptimal decision (see Schonberg et al. 2011, for a comprehensive review on different definitions of risk). This distinction is important: Many real-life examples exist in which risk and EV are negatively related (e.g., reckless behavior in traffic may result in a higher range of outcomes than cautious behavior, and is most probably also related to a lower EV as for most people the costs of a serious traffic accident outweigh the joy of speeding), but in some cases the risky alternative may be the optimal alternative (e.g., investing money instead of saving; Dekkers et al. 2018). Because of this confound, characterizing individuals with ADHD as risk *seeking* may be premature, as they may also be suboptimal decision makers.[2] Three previous efforts to, indirectly, test the difference between risky and suboptimal decision making in ADHD are worth mentioning.

First, a meta-analysis showed that groups with ADHD only engaged in more risk taking than controls on tasks where the risky option was also the suboptimal option. On tasks where risk taking was optimal, groups did not differ (Dekkers et al. 2018). Second, in an empirical study, adults with ADHD did not differ from controls when risk taking was suboptimal but, crucially, showed less risk taking than controls in a condition where risk taking was optimal (Dekkers et al. 2018). Third, adolescents with ADHD did not choose the risky option more often than controls if the risky and safe option had equal expected value (Pollak et al. 2016). These three studies, albeit indirectly, suggest that ADHD is related to suboptimal decision making, and not to risk seeking.

However, the most conclusive way to test the hypothesis that adolescents with ADHD are characterized by suboptimal, and not by risky decision making, is by adopting a task paradigm in which (1) risky vs. safe decisions are measured keeping the expected value of the options constant (as was done in earlier studies) and (2) optimal vs. suboptimal decisions are measured keeping risk constant. This second manipulation, which is crucial to disentangle risky from suboptimal decision making, has never been used in ADHD literature before. In the current study, we therefore designed a new version of the GMT. In the GMT, participants repeatedly have to make a decision between two gambling machines. To test potential differences in risk seeking, we constructed items in which two gambling machines were characterized by equal expected values and different levels of risk. To test potential differences in suboptimal decision making, we also constructed items in which the two gambling machines were characterized by equal risk but different expected values. We hypothesize (H1) that decision making in adolescents with ADHD is suboptimal but not risky (cf. Dekkers et al. 2018; Pollak et al. 2016).

2. Decision-Making Strategies

Disentangling suboptimal from risky decision making in adolescents with ADHD is an important first step in understanding their decision-making deficits. However, to better understand *why* adolescents with ADHD demonstrate problems in decision-making, it is crucial to identify mechanisms that

[1] **Expected Value (EV)** = (gain probability × gain amount) – (loss probability × loss amount). **Risk** = $\sqrt{}$(gain probability × (gain amount - EV)^2 + loss probability × (loss amount - EV)^2). Note: loss amount is an absolute value.

[2] Throughout this study, "optimal" describes the decision for the option with the highest EV.

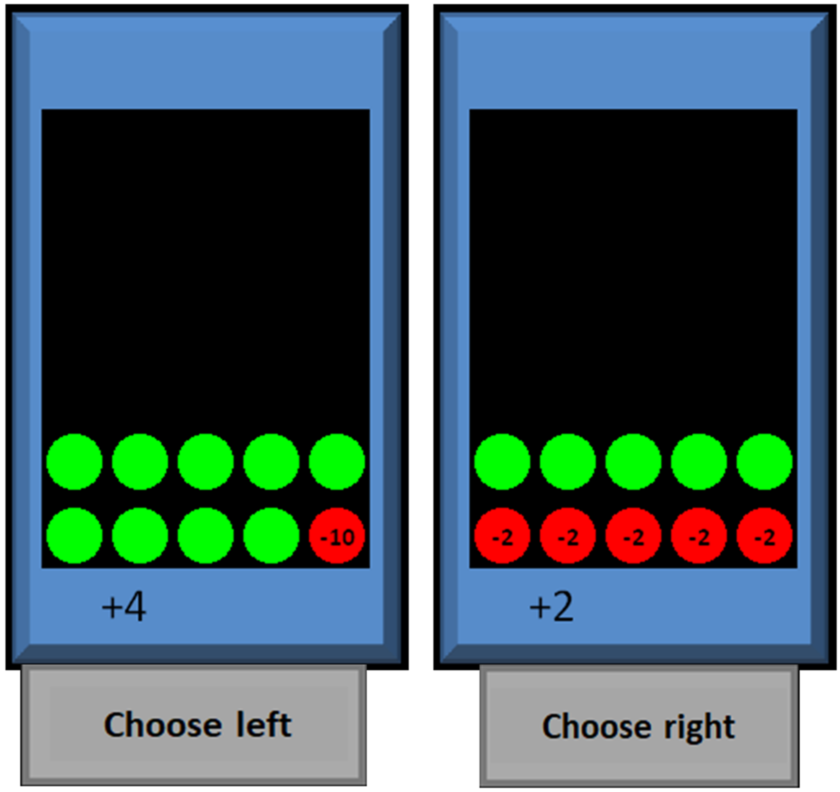

Fig. 1 Example of a Gambling Machine Task (GMT) item. Participants choose between two gambling machines. A "loss probability" item is depicted: both gambling machines have a certain gain and probabilistic losses. Participants always receive the certain gain on the gambling machine, and additionally receive a probabilistic loss based upon a random selection by the computer of one of the ten balls in the gambling machine

drive their decision-making deficits. In the second part of this study, we therefore assessed the strategies that adolescents use in their decision making. A decision-making strategy is an information-processing approach to make a decision (Payne 1976). Decision-making strategies may vary in their complexity. Complete integration of the amounts and probabilities related to both gains and losses (e.g., "I'll balance the almost certain joy of a beer against the probable costs of not performing optimally in school tomorrow vs. less joy with more optimal school performance") is considered the optimal and also the most complex decision-making strategy (Von Neumann and Morgenstern 1944). However, other strategies are often observed (e.g., heuristic lexicographic strategies), in which information is considered sequentially (Kahneman and Tversky 1972). Attention is directed to the most salient characteristic, and if options differ on this characteristic, a decision is made (e.g., "I'll take a beer, because that'll be most fun"). However, if options are similar on this characteristic, individuals consider another characteristic (e.g., "The party is equally fun with or without a beer, so I'll choose for a soda because then I'll perform better at school tomorrow"). Sequential decision-making strategies can vary in complexity depending on the number of characteristics considered.

Executive functions (EF) like inhibition and working memory are crucial in decision making (Bexkens et al. 2016; DeStefano and LeFevre 2004; Stewart 2009). That is, a lack of inhibition may lead to impulsively choosing an option based on one particular characteristic while ignoring potentially relevant information. Moreover, working memory is required to calculate the option with the highest expected value (Brand et al. 2007). As ADHD is consistently associated with deficits in both inhibition (Barkley 1997; Lijffijt et al. 2005; Willcutt et al. 2005) and working memory (Kasper et al. 2012; Martinussen et al. 2005; Willcutt et al. 2005), the complexity of decision making may be affected.

In the second part of the current study, using another version of the GMT, we compare decision-making strategies of adolescents with and without ADHD. We hypothesize that (H2) adolescents with ADHD use less complex, less integrative decision-making strategies than TD adolescents.

3. Influence of Feedback

The first two parts of this study are focused on situations in which participants do not experience consequences of their decision. However, in real life decisions are often followed by immediate experience of the consequences (henceforth referred to as feedback). Feedback may be processed differentially in adolescents with ADHD relative to TD adolescents. One recent study comparing adolescents with and without ADHD on a gambling task with and without feedback revealed that poorer decision making was observed in adolescents with ADHD as compared to TD controls, but only if feedback was provided (Pollak and Shoham 2015). This finding resembles literature demonstrating differential feedback processing in ADHD (Crone et al. 2003; Luman et al. 2010; Sonuga-Barke and Fairchild 2012).

In gambling tasks feedback is often delivered on both gains and losses. However, for a large proportion of real-life risk-taking behaviors (e.g., substance use, unsafe sex), positive and negative feedback are delivered at different moments, with positive feedback often manifesting earlier and negative feedback only being present on the long-term. In this respect, a gambling task with only direct feedback on gains has higher ecological validity. In the current study, we therefore administered a gambling task with full feedback on both gains and on losses and a gambling task with partial feedback, only on gains. Adolescents with ADHD may be particularly sensitive to the latter manipulation, given two lines of evidence. First, ADHD may be characterized by an enhanced focus on gains: individuals with ADHD showed a diminished neural response when anticipating gains (Scheres et al. 2007; Ströhle et al. 2008), which may lead to compensatory gain seeking behavior. Second, ADHD is characterized by delay aversion, meaning that small immediate gains are preferred over larger delayed gains (Jackson and MacKillop 2016; Solanto et al. 2001). Offering immediate feedback only on gains may therefore guide adolescents with ADHD towards focusing on the immediate gain. For these two reasons, we hypothesize that (H3) the difference in performance between adolescents with ADHD and TD adolescents is larger in the gambling task with partial feedback (i.e., only feedback on gains) than in the gambling task with full feedback. To test this hypothesis, a new version of the GMT is used.

In all studies, we test the influence of age, intelligence and SES, and we perform different subgroup analyses for comorbid Disruptive Behavior Disorders (DBD), and for different ADHD presentations. Age is relevant because decision making may improve across development (Jansen et al. 2012). Similarly, higher intelligence and SES are related to decision making quality (Bexkens et al. 2016; Jansen et al. 2013). Comorbid DBD is assessed to investigate if potential group differences are not merely driven by comorbid behavioral disorders, as these are also implicated with decision-making deficits (Dekkers et al. 2016), and different ADHD presentations are assessed to establish to what extent potential group differences apply to all ADHD presentations.

Methods

Participants

Participants were 81 adolescents with ADHD and 100 typically developing (TD) adolescents (all boys[3]), 12–19 years old ($M = 15.07$, $SD = 1.57$). Participants with ADHD were included when meeting the following criteria: (a) a previous (lifetime) ADHD classification by a licensed psychologist or psychiatrist and (b) an ADHD diagnosis (all presentations) based on the Diagnostic Interview Schedule for Children (DISC; Shaffer et al. 2000), a structured DSM-based interview that was administered to one of the parents. ADHD participants were recruited via mental healthcare institutions (62%), special education (4%), the Dutch parents' association for ADHD (21%) and regular education (13%); all TD adolescents were recruited via regular education. The majority of the ADHD group (72%) was taking stimulant medication at the time of the investigation. ADHD participants using methylphenidate discontinued medication 24 hours before testing to reach total wash-out (Greenhill and Ford 1998). For participants using dexamphetamine, the required wash-out period was 48 hours (Wong and Stevens 2012). Adolescents using atomoxetine, clonidine or antipsychotics were excluded. For the TD group, participants were included when (a) no past ADHD, ODD or CD diagnosis was reported by parents/caretakers and (b) participants had normal range scores on the Inattention, Hyperactivity/Impulsivity, ODD and CD scales of the parent-report DBDRS. In both groups, participants were excluded when their estimated IQ was below 80. Informed consent was provided by the participants and their legal caretakers, and the study was approved by the institutional review board of the University of Amsterdam, department of psychology.

Measures

Gambling Machine Task (GMT)

The GMT (Jansen et al. 2012) is a computerized gambling task, in which participants choose the one of two gambling machines they think is more advantageous. The two gambling machines can differ in probabilities and amounts of gains and losses. It is explained to the participant that the amount of gain that is depicted on the gambling machine is certain, and that one of the ten balls inside the machine will be randomly drawn, some of which will result in a loss (see Supplementary Materials 1 for full instructions). In this study, several versions of the GMT were used depending on the three main research questions. Differences between these versions are explained below; specific instructions can be found in Supplementary Materials 1, item characteristics in Table S1 in Supplementary Materials 2, and more detailed graphical examples of all GMT versions in Supplementary Materials 3.

1. Risky Vs. Suboptimal Decision Making GMT First, to investigate *risky* decision making without the confounding influence of EV differences between options, we created 15 items in which both options had identical EV's, but different levels

[3] Adolescents took part in a multi-experiment study. For another, yet unpublished part of this study, we measured salivary hormone levels (among which testosterone), and recruiting girls would have required a substantially larger sample size.

of riskiness (see Table S1, block I for item characteristics). The proportion of risky choices was used as outcome measure. Second, to investigate *(sub)optimal* decision making without the confounding influence of differences in riskiness, we created 10 items in which both options differed in EV, but had identical levels of riskiness (see Table S1, block II for item characteristics). The proportion of optimal choices was used as outcome measure.

These 25 items were presented both in a loss-probability version and a gain-probability version. In the loss-probability version each gambling machine is associated with a certain gain, and losses are probabilistic (as in Fig. 1). The gain-probability version is mirrored to the loss-probability version: loss is certain, gains are probabilistic. Participants were forced to choose one of the two gambling machines and they did not experience outcomes of their decisions. The order of the versions of the GMT was counterbalanced, and the order of the 25 items within each version and the positioning of the response options (i.e., right or left) were randomized over all participants.

2. Decision-Strategy GMT To test whether adolescents with ADHD use less complex decision-making strategies relative to TD adolescents, a decision-strategy GMT was used (Bexkens et al. 2016; Jansen et al. 2012; see Table S1, Block III for all item characteristics). The 40 items were constructed in such a way that 18 potential decision-making strategies (see Table 1) could be derived from the response patterns, as all strategies yielded unique response patterns. The strategies varied in complexity. Simple strategies focus only on one characteristic, more complex strategies focus on several characteristics sequentially (e.g., focus on gain amount first, if equal across machines then focus on loss amount). The most complex strategies involve partial or total integration. Participants showing partial integration use the semi-integrative decision-making strategy: multiplying the amount and frequency of loss, and only if this is equal across machines consider amount of gains next (for gain-probability items this is mirrored: multiply amount and frequency of gains, if equal across machines then consider amount of loss). Total integration is established if participants choose according to the EV: frequency of gain × amount of gain - frequency of loss × amount of loss. Because of the low frequency of occurrence of the simple strategies in the data, the three most simple decision-making strategies (i.e., guessing, one-dimensional and two-dimensional) were merged into one complexity level, resulting in four different complexity levels (Table 1).

Different to the first part of the study, participants now had three response options (machine A, machine B and doesn't matter). The 'doesn't matter' option was required to assess strategy use, as it would be selected when participants perceived both options in an item as equally advantageous. Again, both a loss-probability and a gain-probability version were administered, and adolescents did not experience feedback on their decisions. The order of the versions of the GMT was counterbalanced and the order in which the items were administered was identical for all participants.

Psychometric properties of both versions of the decision-strategy GMT were reasonable: internal consistency was moderate ($\alpha = .74$ and .75 for the loss- and gain-probability version, respectively), and the split-half reliability was good ($r_{sh} = .84$ and .82 for the loss- and gain-probability version, respectively).

3. Feedback GMT To test whether the difference in performance between adolescents with ADHD and TD adolescents is larger with partial feedback (i.e., only feedback on gains) than with full feedback, two different GMT conditions were used: one with full feedback, and one with partial feedback. In the *full-feedback condition*, the balls were shuffled after the participant made his decision. One of the ten balls was randomly selected (i.e., participants could see the shuffling of the balls), and the corresponding outcome was presented to the participant. In this condition, the full outcome (i.e., the gain and the potential loss) was presented: gains were presented by golden coins that appeared on screen, losses by red coins. Second, in the *partial-feedback condition*, the selected gambling machine was covered once the balls were shuffled. Then, participants were only presented with the gains associated with their decision (i.e., the certain gain that was associated with their selection), indicated by golden coins that appeared on their screen after making a decision. However, participants were instructed that the computer would remember their decision, and that it was possible that a red ball had been selected, which was associated with a loss that was not immediately shown to the participant.

Because the assessment of the influence of feedback on decision making requires a substantial larger number of items than the GMT versions used in the first two parts of this study (Jansen et al. 2013), these GMT conditions with feedback were only administered using the loss-probability version of the task. In both feedback conditions, participants were forced to choose between the left and right gambling machine. Four different items were all presented 30 times in succession (cf. Jansen et al. 2013), resulting in 120 items in total (see Table S1, Block IV for all item characteristics). The order in which the four blocks of 30 items were presented and the order of the full vs. partial feedback condition was counterbalanced over all participants. The outcome variable was the number of optimal choices (i.e., choosing the option with the highest EV), potentially ranging from 0 to 120.

Disruptive Behavior Disorder Rating Scale (DBDRS)

The Dutch translation of the parent-report version of the DBDRS (Oosterlaan et al. 2000; Pelham et al. 1992) was used to screen for ADHD, ODD (Oppositional Defiant Disorder)

Table 1 Possible decision strategies on the Gambling Machine Task (GMT; Jansen et al. 2012).

	Strategy Type (complexity level)	Characteristics	Description: decisions are made based on…
1	Guessing (1)	–	Randomly selecting choice options
2	Simple (1)	FL	Frequency of loss
3	Simple (1)	AL	Amount of loss
4	Simple (1)	CG	Amount of certain gain
5	Sequential (1)	FL > AL	Frequency of loss, if equal consider amount of loss
6	Sequential (1)	FL > CG	Frequency of loss, if equal amount of certain gain
7	Sequential (1)	AL > FL	Amount of loss, if equal frequency of loss
8	Sequential (1)	AL > CG	Amount of loss, if equal amount of certain gain
9	Sequential (1)	CG > FL	Amount of certain gain, if equal frequency of loss
10	Sequential (1)	CG > AL	Amount of certain gain, if equal amount of loss
11	Sequential (2)	FL > AL > CG	Frequency of loss, if equal amount of loss, if equal amount of certain gain
12	Sequential (2)	FL > CG > AL	Frequency of loss, if equal amount of certain gain, if equal amount of loss
13	Sequential (2)	AL > FL > CG	Amount of loss, if equal frequency of loss, if equal amount of certain gain
14	Sequential (2)	AL > CG > FL	Amount of loss, if equal amount of certain gain, if equal frequency of loss
15	Sequential (2)	CG > FL > AL	Amount of certain gain, if equal frequency of loss, if equal amount of loss
16	Sequential (2)	CG > AL > FL	Amount of certain gain, if equal amount of loss, if equal frequency of loss
17	Semi-integrative (3)	(FL*AL) > CG	Expected value of loss, if equal use gain amount
18	Integrative (4)	CG - (FL*AL)	Expected value

Strategies range from the most basic (i.e., guessing) to simple (i.e., considering one characteristic only), to sequential (i.e., considering several characteristics sequentially), to semi-integrative (i.e., sequentially considering expected loss, then certain gain), to integrative (i.e., considering expected value). Considered characteristics are shown; CG = certain gain, AL = amount loss, FL = frequency loss (i.e., probability of loss). Note that the characteristics are based on the loss-probability version of the GMT, but these apply to the gain-probability items in a similar way (FL becomes FG, CG becomes CL, AL becomes AG). Complexity is indicated in parentheses

and CD (Conduct Disorder) symptoms. The DBDRS has 42 items which are answered on a 4-point Likert-scale and consists of 4 subscales: inattention, hyperactivity/impulsivity, ODD and CD. The DBDRS scores on these subscales were classified as normal, subclinical (80th – 95th percentile) or clinical (95th – 100th percentile). Adequate psychometric properties are reported in Dutch and Flemish populations (Oosterlaan et al. 2000), and in the current study internal consistency was excellent ($\alpha = .95$ for the inattention subscale, $\alpha = .94$ for the hyperactivity/impulsivity subscale). In case adolescents used medication, parents were asked to report the behavior of their child off-medication.

Diagnostic Interview Schedule for Children (DISC-IV)

For diagnostic assessment of the ADHD group, the Dutch translation of the DISC-IV (Ferdinand and van der Ende 1998; Shaffer et al. 2000) was administered in one of the parents/caretakers. The DISC-IV is a DSM-IV based structured diagnostic interview, consisting of six sections: disruptive behavioral disorders, anxiety disorders, mood disorders, schizophrenia, substance use disorders, and miscellaneous disorders. Psychometric properties of the DISC-IV are good (e.g., agreement between DISC and clinicians ratings, test-retest reliability) and parent report was preferred over child-report as it has superior test-retest reliability and sensitivity (Shaffer et al. 2000). Administration of the DISC-IV took approximately 4 h. Again, in case adolescents used medication, parents were asked to report the behavior of their child off-medication.

Intelligence

To estimate intelligence in adolescents 12 to 16 years old, a short version of the Dutch Wechsler Intelligence Scale for Children-III (WISC-III-NL; Kort et al. 2002; Wechsler 1991) was used, consisting of subtests Block Design and Vocabulary. For adolescents older than 16 years, subtests Vocabulary and Matrix Reasoning of the Dutch Wechsler Adult Intelligence Scale-IV (WAIS-IV; Wechsler 2008) were used. In both cases, these short forms are reliable and correlate highly with total intelligence (Pierson et al. 2012; Sattler 2001).

Socio-Economic Status

Socio-economic status (SES) was based on the educational level of both parents, using Verhage's seven-point classification schedule (Verhage 1964). Higher scores indicate higher SES: A score of 1 indicated that a parent received a maximum of 6 years of primary education, a score of 7 indicated that a parent received scientific education (master or doctoral university degree).

Procedure

Participants were tested during three sessions. Parents filled out the DBDRS and answered questions about SES and ethnicity online before the first session. In the first session, participants performed the intelligence tests and parallel to this session, in the ADHD group, the DISC was administered to one of the parents. In the second and third session, three different GMT's were administered per session, along with several other cognitive tasks and questionnaires, which were irrelevant for the current study. The order of the GMT's was counterbalanced. Participants were explicitly instructed that one of their decisions on each GMT would be selected afterwards to determine their reward (also see task instructions in Supplementary Materials 1). On average, participants received 40 euros for their participation in the three test sessions.

Data-Analysis

To test the first hypothesis (risky vs. suboptimal decision making), bootstrapped regression analyses were used to assess whether group (ADHD versus TD) predicted risky/suboptimal decision making. Intelligence, age and SES were all included in these models as covariates (main effects only), as these variables have been shown to influence decision making (e.g., Bexkens et al. 2016; Jansen et al. 2013). Separate analyses were performed for the loss- and gain-probability versions of the GMT.

To test the second hypothesis (decision-making strategies), a model-based latent-mixture analysis using Bayesian inference was used to assign strategies to participants' response patterns. This method assumes that participants' responses to the items are reflected by a decision-making strategy predicting a specific item-response pattern. The number of strategies in the data and the number of adolescents assigned to these strategies were derived simultaneously, and adolescents were assigned to the strategy that predicted their response pattern best (see Steingroever et al. 2019 for more details on this procedure; R-code on https://osf.io/84uf2/). Next, these strategies were categorized into 4 levels of complexity. Using ordinal logistic regression, we tested whether groups differed in terms of complexity of their decision-making strategy. Again, main effects of intelligence, age and SES were included in the models. Correlation analyses between strategy complexity and reaction times were performed as validity check.

To test the third hypothesis (influence of feedback), a repeated measures ANOVA was performed on the number of optimal decisions, with GMT condition as within-subjects independent variable (full vs. partial feedback), group as independent variable and intelligence, age and SES as covariates.

Scores on outcome variables deviating more than three SD's from the mean were defined as outliers (Howell 1998). In case of outliers, both analyses with and without outliers were reported. A power analysis indicated that for regression analyses with 4 predictors, an estimated medium effect size, power of .80 and $\alpha = .05$, a sample size of 85 is sufficient. Power analysis for ordinal regression is complicated: according to guidelines on power for logistic regression (Peduzzi et al. 1996), 160 participants are required for our analysis with 4 predictors and assuming an even distribution of participants over the 4 categories of decision-making complexity. A sample size of 34 is sufficient for the repeated measures ANOVA.

Results

Participant Characteristics

Participants were 181 adolescent boys between 12 and 19 years old, 81 with ADHD and 100 TD controls (see Table 2 for sample characteristics). Groups did not differ on age, IQ, SES and ethnicity. Scores on all DBDRS subscales were significantly higher for the ADHD group relative to the TD control group. Comorbidity was frequently observed in the ADHD group: 31% of the adolescents met criteria for either ODD and/or CD, 30% for at least one anxiety disorder, and 16% for a tic disorder (see Table 2 for more details on comorbidity).

Inter-Correlations

Correlations between all variables that are included in the analyses can be found in Table 3.

Hypothesis I: Risky Vs. Suboptimal Decision Making

Figure 2 shows the percentage of risky choices on the items with different riskiness and equal expected values across options, as well as the percentage of optimal choices on the items with equal riskiness but different expected values across options.

Table 2 Sample characteristics.

	ADHD ($N = 81$)	TD ($N = 100$)	
Age (SD)	14.99 (1.79)	15.14 (1.38)	$t(147.96) = .63$, *n.s.*
IQ (SD)	103.38 (13.70)	101.92 (12.92)	$U = 4276.0$, *n.s.*
SES (SD)	5.70 (.79)	5.72 (.84)	$U = 3876.5$, *n.s.*
Ethnicity			$\chi^2(2) = .15$, *n.s.*
Dutch	76.5%	77.0%	
Western	4.9%	6.0%	
Non-western	18.5%	17.0%	
DBDRS Inattention	16.07 (1.41)	10.90 (1.21)	$U = 8031.5$, $p < .001$
DBDRS Hyp./Imp.	15.19 (1.85)	10.58 (1.13)	$U = 7815.0$, $p < .001$
DBDRS ODD	13.56 (2.24)	10.84 (1.24)	$U = 6804.0$, $p < .001$
DBDRS CD	13.65 (2.65)	11.29 (1.23)	$U = 6179.0$, $p < .001$
DISC ADHD Presentation (C/I/H)	40/39/2	–	–
DISC Disruptive Behavioral Disorders	31%	–	–
DISC Substance Use Disorder	3%	–	–
DISC Anxiety Disorder	30%	–	–
DISC Mood Disorder	6%	–	–
DISC Tic Disorder	16%	–	–
DISC Enuresis/Encopresis	1%	–	–
DISC Eating Disorder	1%	–	–

Note: non-parametric tests were used when assumptions were violated. DISC was only administered in the ADHD group.

Abbreviations: TD Typically Developing, SD Standard Deviation, n.s. not significant, SES Socio-Economic Status, DBDRS Disruptive Behavior Disorder Rating Scale, Hyp. Hyperactivity, Imp. Impulsivity, ODD Oppositional Defiant Disorder, CD Conduct Disorder, DISC Diagnostic Interview Schedule for Children, C Combined presentation, I Inattentive presentation, H Hyperactive/impulsive presentation

As hypothesized, on items in which the risky and the safe option were equally advantageous, there was no difference in risky decision making between adolescents with and without ADHD (see Table 4 for test statistics). There was also no effect of age, IQ and SES on risky decision making. These patterns were similar for both loss- and gain-probability GMT versions. Dividing the ADHD group into subgroups with and without comorbid DBD (i.e., ODD and/or CD) revealed more risky decision making in adolescents with ADHD and comorbid DBD than in adolescents with only ADHD on the loss-probability GMT, but not on the gain-probability GMT, $t(77) = -2.14$, $p = .04$, $d = .57$, and $t(78) = -.38$, $p = .70$, $d = .09$, respectively. Adolescents with the combined ADHD presentation did not perform different from adolescents with the inattentive ADHD presentation on both GMT's.

No outliers were detected on the loss-probability GMT items, and one outlier was detected on the gain-probability GMT. After excluding this outlier, results were highly similar and none of the effects changed in terms of significance.

In line with our expectations, on the items where options differed in expected value but not in riskiness, adolescents with ADHD gave the optimal response less often. Also, the number of optimal responses increased with age and IQ. There was no effect of SES (see Table 4 for test statistics). Again, these patterns were similar for both loss- and gain-probability GMT items. No differences were observed between ADHD-subgroups with and without comorbid DBD and adolescents with the combined ADHD presentation did not perform different from adolescents with the inattentive ADHD presentation.

One outlier was detected on the loss-probability items, and two outliers were detected on the gain-probability items. On the loss-probability items, the effect of group no longer reached significance after excluding this outlier ($\beta = -.13$, bootstrapped 95% CI [−.08, .00], $p = .061$), other effects were highly similar. On the gain-probability items, results were highly similar after excluding the two outliers, that is, none of the effects changed in terms of significance.

Hypothesis II: Decision-Making Strategies

A model-based latent-mixture analysis using Bayesian inference (Steingroever et al. 2019) was used to assign strategies to participants' response patterns. Strategies were assigned to participants, based on the correspondence between the participants' specific GMT response pattern and the response pattern predicted by the strategy. Strategies were clustered based on complexity: complexity level 1: simple (guessing, one- and

Table 3 Correlations (Pearson's r) between all variables included in subsequent analyses. Group is coded as 0 for TD boys and 1 for boys with ADHD. H1/2/3 refers to the hypothesis of interest.

	1	2	3	4	5	6	7	8	9	10	11	12
1. Group												
2. Age	−.05											
3. IQ	.06	.23*										
4. SES	−.01	.12	.25**									
5. Risky (LP) H1	.01	−.02	.06	.16*								
6. Risky (GP) H1	−.02	−.01	−.04	.01	.10							
7. Opt. (LP) H1	−.14#	.26**	.29***	.20**	.08	.02						
8. Opt. (GP) H1	−.16*	.25**	.37***	.12	−.01	.01	.31***					
9. Comp. (LP) H2	−.20**	.25**	.22**	.21**	.10	.12	.41***	.24**				
10. Comp. (GP) H2	−.10	.12	.16*	.17*	.15#	.06	.36***	.31**	.37***			
11. Full Fb. H3	−.15*	.20**	.37***	.15*	−.01	−.05	.34***	.43**	.25**	.24**		
12. Partial Fb. H3	−.18*	.31***	.31***	.20**	−.04	−.04	.30***	.45**	.19*	.13#	.53***	

# $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$.

Abbreviations: Comp. Complexity of the decision-making strategy, Fb. Feedback, GP Gain Probability, LP Loss Probability, Opt. Optimal choices

two-dimensional sequential), complexity level 2: three-dimensional sequential, complexity level 3: semi-integrative, and complexity level 4: integrative. Specific assignment per group can be found in Supplementary Materials 4. Figure 3 illustrates differences in the complexity of decision-making strategies between the ADHD group and the TD group, which were studied using ordinal logistic regression models.

Loss-Probability GMT

The overall fit of the ordinal logistic regression model was acceptable, $\chi^2(521) = 559.13$, $p = .12$, Nagelkerke's pseudo $R^2 = .18$. Group predicted the complexity of the decision-making strategy, $\beta = .82$, Wald $(1) = 7.69$, $p = .006$: adolescents with ADHD demonstrated less complex decision-making strategies than controls. In the same model, IQ ($\beta = .03$, Wald $(1) = 5.99$, $p = .014$) and age ($\beta = .28$, Wald $(1) = 8.82$, $p = .003$) also predicted decision making complexity: more intelligent and older adolescents showed more complex decision making. Socio-economic status did not significantly predict decision-making complexity, $\beta = .35$, Wald $(1) = 3.50$, $p = .061$.

As a validity check, we found that decision-making complexity and reaction time were correlated, $r_s = .50$, $p < .001$, indicating that more complex strategies were associated with slower response times. Additional analyses showed no differences between ADHD-subgroups with and without comorbid DBD in decision-making strategy

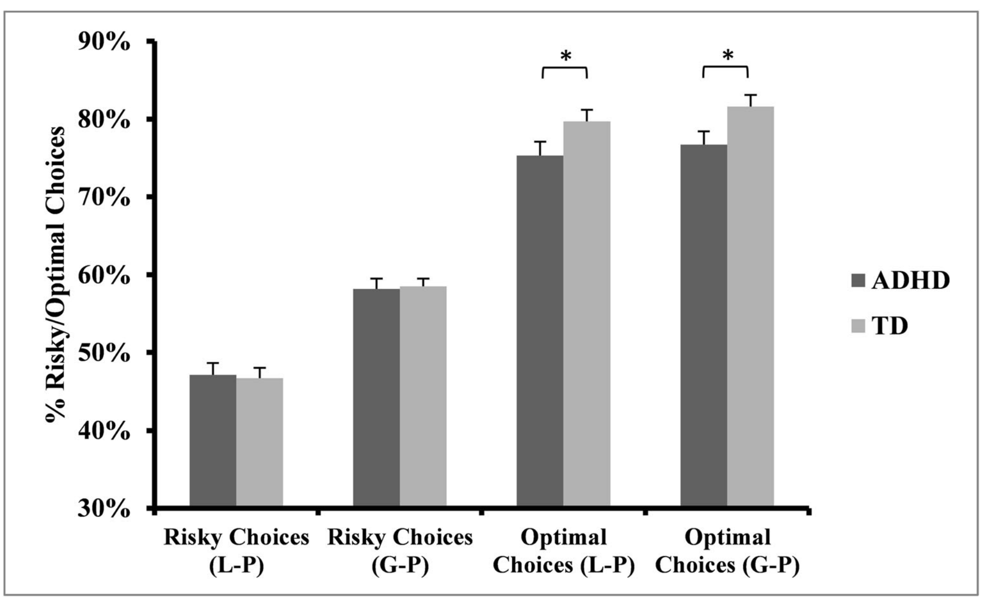

Fig. 2 Percentages of risky and optimal decision making, on loss- and gain-probability versions of the GMT (L-P and G-P, respectively). Note: The percentage of risky choices reflects performance on GMT items with equal expected values and different riskiness between options. The percentage of optimal choices reflects performance on GMT items with equal riskiness and different expected values between options. *$p < .05$ Abbreviations: ADHD Attention-Deficit/Hyperactivity Disorder, GMT Gambling Machine Task, TD Typically Developing

Table 4 Bootstrapped regression models for the prediction of the number of risky and the number of optimal choices.

	Standardized β	Bootstrapped 95% CI	*p* value	R^2
Loss-probability GMT - risky choices				.029
Group	.01	−.04, .05	.901	
IQ	.03	−.00, −00	.737	
SES	.16	.00, .06	.058	
Age	−.05	−.02, .01	.547	
Gain-probability GMT - risky choices				.003
Group	−.01	−.04, .03	.894	
IQ	−.05	−.00, .00	.519	
SES	.02	−.01, .02	.717	
Age	−.00	−.01, .01	.942	
Loss-probability GMT – optimal choices				.161
Group	−.15	−.09, −.01	.038#	
IQ	.23	.00, .00	.003	
SES	.12	−.00, .05	.076	
Age	.19	.00, .03	.013	
Gain-probability GMT – optimal choices				.192
Group	−.17	−.09, −.01	.013	
IQ	.34	.00, .01	.001	
SES	.01	−.02, .03	.865	
Age	.16	.00, .03	.019	

Note: group was dummy coded: 0 = TD and 1 = ADHD.

# indicates that this effect is no longer significant after excluding an outlier

complexity, $\chi^2(3) = .06$, $p = .996$, and no differences between adolescents with the combined and the inattentive ADHD presentation, $\chi^2(3) = 5.20$, $p = .158$.

Gain-Probability GMT

On the gain-probability version of the GMT the same ordinal logistic regression model yielded no significant effects, i.e., group, age, IQ and SES did not predict decision making complexity. The overall fit of the ordinal logistic regression model was acceptable, $\chi^2(533) = 548.34$, $p = .31$, Nagelkerke's pseudo $R^2 = .07$. Again, as a validity check, we found that decision-making complexity and reaction time were correlated, $r_s = .40$, $p < .001$, indicating that more complex strategies were associated with slower response times. Additional analyses showed no differences between ADHD-subgroups with and without comorbid DBD in decision-making strategy complexity, $\chi^2(3) = 2.97$, $p = .396$, and no differences between adolescents with the combined and the inattentive ADHD presentation, $\chi^2(3) = 1.02$, $p = .796$.

Hypothesis III: Full Vs. Partial Feedback

GMT conditions with full and partial feedback were administered to establish the influence of feedback (Fig. 4).

A repeated measures ANOVA with the number of optimal responses as dependent variable and GMT condition (full vs. partial feedback) as within-subjects variable, group (ADHD vs. TD) as between-subjects variable, the interaction between the two, and intelligence, age and SES as covariates revealed (1) a main effect of GMT condition, $F(1,174) = 4.01$, $p = .047$, $\eta_p^2 = .023$, indicating that participants performed better with full feedback than with partial feedback; (2) a main effect of group, $F(1,174) = 8.51$, $p < .01$, $\eta_p^2 = .047$, indicating that adolescents with ADHD gave less optimal responses than TD adolescents, and (3) no interaction between GMT condition and group, $F(1,174) = .45$, $p = .51$, $\eta_p^2 = .003$, indicating that the difference between the two GMT conditions was similar for both groups. Furthermore, significant effects of intelligence and age were found, indicating that more intelligent and older participants made more optimal decisions. There was no effect of SES.

Additional analyses revealed that no differences were observed between ADHD-subgroups with and without comorbid DBD and between adolescents with the combined and the inattentive ADHD presentation on both feedback conditions. Three outliers were identified on the GMT with full feedback (none on the GMT with partial feedback). After excluding these outliers, results were highly similar and none of the effects changes in terms of significance.

Discussion

This study investigated underlying mechanisms of decision-making problems in adolescent boys with ADHD. Elucidating these mechanisms is important to better understand why adolescents with ADHD are often involved in real-life risk-taking behavior like substance abuse, reckless behavior in traffic, criminal behavior and risky sexual behavior (Nigg 2013; Pollak et al. 2019), and to ultimately develop interventions that may guide adolescents towards better decision making.

First, we addressed a confound observed in most gambling task paradigms in ADHD literature: the risky option (i.e., the option that is associated with the widest range of possible outcomes) is often also the suboptimal option in terms of expected value (see Dekkers et al. 2018 for an overview on the correlation between risk and expected value in the most commonly used gambling tasks). This makes it impossible to establish which specific mechanism (i.e., risk seeking or suboptimal decision making) drives decision-making deficits. In the current study, risk seeking and suboptimal decision making were disentangled using an innovative version of the Gambling Machine Task (GMT). As expected, adolescent boys with ADHD demonstrated more suboptimal (i.e., more often favoring the option with the lowest expected value), but not more risky decision making relative to TD adolescent boys. This result aligns earlier studies that partly disentangled

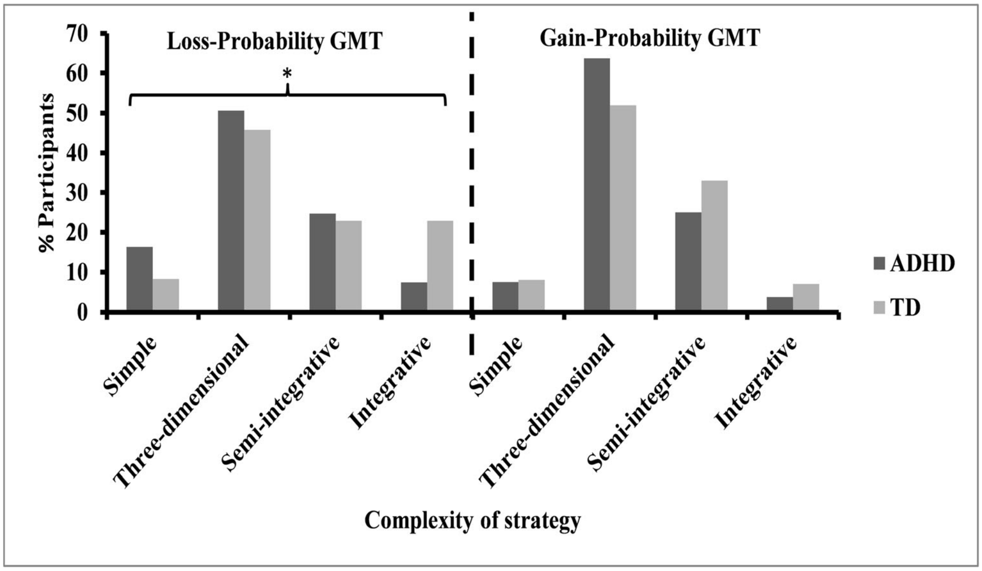

Fig. 3 Percentage of participants applying decision-making strategies ordered by complexity (from least to most complex; left to right) within the groups with and without ADHD, for both the loss-probability GMT (left) and the gain-probability GMT (right). * indicates that in the overall model, the ADHD group used less complex strategies than the TD group

risky from suboptimal decision making (Dekkers et al. 2018; Pollak et al. 2016). However, the current study was the first to fully disentangle risk and expected value, as our task not only contained items with equal expected values and different risks (as was done in earlier studies), but, crucially, also contained items with different expected values and equal riskiness. The results reinforce the conclusion that risk seeking is not the mechanism behind ADHD-related decision-making problems. Accordingly, real-life risk-taking behavior observed in adolescents with ADHD may be caused by the inability to make the most optimal decision, instead of having an intrinsic preference for behavior with a wide range of potential outcomes.

Although the finding that adolescent boys with ADHD are characterized by suboptimal decision making instead of risk seeking is relevant in itself, it does not indicate what factors may contribute to this. Therefore, in the second part, we investigated strategies that adolescent boys with and without ADHD used on the GMT. Boys with ADHD used less complex decision-making strategies than TD boys, although only in the loss-probability GMT. More specifically, relative to TD adolescent boys, adolescent boys with ADHD showed less integration of the characteristics of the decision but instead approached characteristics separately. In real life, not paying attention to all characteristics may lead to more risky decision making, especially if information about potential losses (e.g., negative consequences of substance abuse, unsafe sex, gambling addiction) is ignored. Considering parts of information regarding a decision separately, instead of integrating them, may potentially originate in executive functioning deficits (Martinussen et al. 2005; Willcutt et al. 2005). For example, inhibition problems may guide adolescents with ADHD towards suboptimal decision making, failing to inhibit a response based on one particular characteristic of an option.

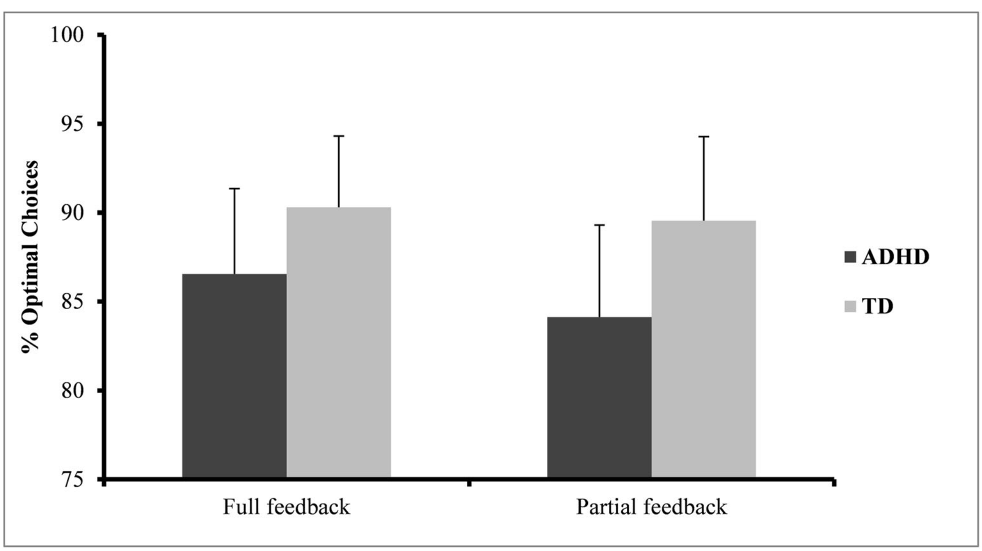

Fig. 4 Mean percentage of optimal choices (i.e., choosing the highest EV), as a function of group and feedback condition

This is in line with the current findings that reaction times were faster for those adolescents using less complex strategies. Working memory deficits in ADHD (Kasper et al. 2012) may cause difficulties in calculating the expected value of the gambling machines, which may explain why adolescents with ADHD utilize strategies of lower complexity more often. Future studies should test this hypothesized link between less complex decision making and executive dysfunctioning directly.

However, we only observed group differences in strategies on the loss-probability GMT version. On the gain-probability GMT version, with a certain loss and probabilistic gains, no differences were found. Inspection of the strategies used by the participants (see Table S2 in Supplementary Materials 4) reveals that a relatively large proportion of the TD boys used the less complex semi-integrative strategy in the gain-probability version of the GMT, whereas they used the more complex integrative strategy more often in the loss-probability version. Potentially, the design of the gain-probability version of the GMT guides all adolescents towards a slightly less complex, and possibly more impulsive decision-making style. The probabilistic gains in this version may attract disproportionate attention from the adolescents, thereby ignoring the constant loss. This explanation is congruent with our observation that many boys used the semi-integrative strategy on the gain-probability GMT version in particular, a strategy that mainly focuses on integration of amount and probability of gain.

The paradigms that are employed in the first two parts were so-called cool decision-making tasks, without feedback on decisions (Castellanos et al. 2006; Skogli et al. 2014). This enables a precise examination of different cognitive processes, but also limits ecological validity, as almost all decisions in daily life involve some form of feedback. Pollak and Shoham (2015) suggested that experiencing feedback harms decision making in adolescents with ADHD. To investigate whether adolescents with ADHD also demonstrated decision-making deficits on hot decision-making paradigms, and more specifically whether these deficits differ in conditions of full vs. partial feedback, we administered two conditions of the GMT with feedback (i.e., full feedback, and partial feedback on gains only). Boys with ADHD made less optimal decisions relative to controls on the GMT condition with full feedback (i.e., feedback on both gains and losses), as well as on the GMT condition with partial feedback (i.e., only feedback on gains). This adds to the evidence from the first two parts of this study, claiming that adolescent boys with ADHD demonstrate decision-making deficits. Potentially, the use of less complex decision-making strategies by boys with ADHD – as established in the second part of this study – also impacts their performance on decision-making tasks with feedback (part three). This hypothesis has at least some plausibility, as correlations between the complexity of the decision-making strategy (part two) and performance on the tasks with feedback (part three) were significant and in the expected direction: The higher the complexity of the strategy, the higher the performance on the tasks with feedback.

Against expectation, all adolescents, irrespective of their diagnostic status, made less optimal responses when they only received partial feedback on gains than when they received feedback on gains and losses. The partial feedback potentially guided all adolescents towards paying more attention to gains, and therefore caused them to make less optimal decisions. This mechanism may be of importance in several manifestations of real-life risk-taking behavior. For example, many forms of substance abuse and sexual risk-taking behavior are characterized by instantly experiencing gains, and involve losses that only become manifest later in time (Boyer 2006).

Taken together, we conclude that ADHD is characterized by suboptimal decision making, and not by risk seeking. Potentially, this could be explained by the use of faster, less complex decision-making strategies. Furthermore, we found that boys with ADHD also perform worse relative to TD boys on gambling tasks with feedback, although not disproportionally so in a task with partial feedback.

The decision-making deficits in adolescent boys with ADHD observed throughout all parts of the current study are unlikely to be explained by comorbid behavioral disorders. A substantial proportion of the ADHD group (31%) met criteria for a comorbid Disruptive Behavior Disorder (DBD; i.e., ODD and/or CD), and this subgroup did not differ from the subgroup with ADHD without DBD on any of the domains where ADHD-related decision-making deficits were found (i.e., suboptimal decision making, lower complexity of decision-making strategies, poor decision making while experiencing feedback). The only significant difference between these subgroups was found on the gambling task where options differed in riskiness while keeping EV constant: Boys with ADHD and DBD were more risk seeking than boys with ADHD without DBD. This may imply that DBD's are particularly associated with risk seeking, which aligns several studies demonstrating increased levels of risky decision making in both gambling tasks and real life in ADHD samples with comorbid DBD's (Dekkers et al. 2016; Pollak et al. 2019; Ramos Olazagasti et al. 2013; Sarver et al. 2014).

The current set of studies has several strengths and limitations. A major strength is that we administered different gambling task paradigms, ranging from cognitive (i.e., "cool") tasks towards affective (i.e., "hot") tasks. On all tasks we found ADHD related decision-making deficits. These findings are robust, as no differences were found between adolescents with and without comorbid DBD, and between adolescents with the combined and the inattentive ADHD presentation. The large sample size and the similarity of the groups on all demographic characteristics add to the confidence in the findings. Despite these strengths, several caveats warrant consideration. First, our sample consisted of only boys, which limits the generalizability of the findings. Previous studies found that women are more sensitive to feedback (Jansen et al. 2013; Moeller and Robinson 2010), have a higher punishment sensitivity (Cross et al. 2011) and are less risk seeking (Powell and Ansic 1997) than men, and future studies should investigate these sex-related decision-making differences in ADHD samples. Second, although we used both cool and hot decision-making tasks, the ecological validity may be limited as testing adolescents in controlled scientific settings is not particularly reflective of real life (Pollak et al. 2018). As risk-taking behavior in adolescence often occurs in a peer context (Steinberg and Morris 2001) and peer presence generally increases risk-taking behavior (Chein et al. 2011; van Hoorn et al. 2017), the addition of social feedback to hot decision-making paradigms may be a potential solution to increase the ecological validity of decision-making paradigms (cf. Albert et al. 2013). Third, no diagnostic interview was administered in parents of the adolescents in the TD group, and therefore potential comorbidity is unknown. Differences in for example anxiety, mood and tic disorders between groups could confound the current findings. For example, internalizing disorders have been related to avoidance of high loss options (Garon et al. 2006; Peters and Slovic 2000), which could lead to a more cautious decision-making style. Therefore, future studies should ideally also assess the full range of psychopathology in the control group.

Fourth, in all three studies positive effects of age on decision making were observed. As ADHD has often been associated with maturational delays (Shaw et al. 2007) and the relationship between ADHD symptoms and cognitive processes like decision making may vary over development (Brocki and Bohlin 2006), future studies should investigate whether decision-making deficits are also related to ADHD later in development, to rule out the explanation that the group differences as observed in the current study are not only a consequence of maturational differences. However, several meta-analytic findings on ADHD and decision making indicate that decision-making deficits are linked to ADHD regardless of age (Dekkers et al. 2016; Mowinckel et al. 2015), which indicates that decision-making deficits are related to ADHD regardless of developmental stage.

Altogether, the three studies demonstrate a consistent pattern of decision-making deficits in adolescent boys with ADHD relative to their typically developing peers. Future studies should (1) independently replicate the finding that ADHD is related to decision-making deficits (cf. Pollak et al. 2016); (2) examine whether these findings also generalize to girls with ADHD, and to ADHD populations at different developmental stages and (3) develop psychometrically sound measures to assess decision-making deficits in clinical practice. Although these steps still need to be undertaken, the current results do have some tentative clinical implications. Clinicians working with adolescents with ADHD should be aware that suboptimal decision-making strategies potentially cause the real-life risk-taking behavior that these adolescents often present when seeking help. Assisting adolescents in making optimal decisions could follow the lines of normative decision-making models (Furby and Beyth-Marom 1992): identification of options, establishment of consequences of all options, weighting of different consequences in terms of likelihood and desirability, and finally integration of all information to make the optimal decision (similar to the integrative strategy on the gambling task). For example, visual aids increased integration of information (Bailey et al. 2011). However, full integration may not be a feasible aim for all adolescents with ADHD, and may also not be the most handy strategy when executive resources are limited. In these cases, faster and efficient heuristics (Payne et al. 1988) may be a better treatment aim.

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Compliance with Ethical Standards

Procedures were conform ethical standards of the institutional review board of the University of Amsterdam and were in accordance with the 1964 Helsinki declaration and later amendments. All participants and one of their parents/caretakers provided active informed consent.

Conflicts of interest All authors declare no conflicts of interest.

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