#### Attention-deficit/hyperactivity disorder (ADHD) and the choice of small immediate over larger delayed rewards. A comparative meta-analysis of performance on simple choice-delay and temporal discounting paradigms

Abstract

*Objective*: Impulsive choices can lead to sub-optimal decision making, a tendency which is especially marked in individuals with ADHD. We compared two different paradigms assessing impulsive choice, the simple choice paradigm (SCP) and the temporal discounting paradigm (TDP). *Methods*: Random effects meta-analyses on thirty-seven group comparisons (22 SCP; 15 TDP) consisting of 3.763 subjects (53% ADHD). *Results*: Small to medium effect sizes emerged for both paradigms, confirming that subjects with ADHD choose small immediate over large delayed rewards more frequently than controls. Moderation analyses show that offering real rewards in the SCP almost doubled the odds ratio for subjects with ADHD. *Conclusion*: We suggest that a stronger than normal aversion towards delay interacts with a demotivating effect of hypothetical rewards, both factors promoting impulsive choice in subjects with ADHD. Further, we suggest the SCP as the paradigm of choice due to its larger ecological validity, contextual sensitivity, and reliability.

Key words: ADHD, Impulsive Choice, Delay Aversion, Delay Discounting, Meta-Analysis

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#### Introduction

#### Both human and animal choice behavior is characterized by the tendency to prefer immediate over delayed rewards – all else being equal. Under certain circumstances this impulsive pattern of choice can lead to sub-optimal decision making, where more valuable rewards available only in the future are sacrificed for less valuable rewards that can be gained without waiting. Such intertemporal decision making is underpinned by the complex interaction between cognitive and motivational processes (Sonuga-Barke, Cortese, Fairchild, & Stringaris, 2016). That this tendency seems especially marked in individuals with attention-deficit/hyperactivity disorder (ADHD) is supported by data from two different experimental paradigms that appear to tap different aspects of intertemporal decision processes (Scheres, Sumiya, & Thoeny, 2010). In one (simple choice paradigm: SCP) individuals are presented with repeated trials incorporating the same basic choice between two options differing in reward size and delay to delivery. On these tasks delays are typically in the seconds-range and the actual delay is experienced by the participants. Two specific variants have been employed most often in ADHD studies. In the Choice Delay Task (CDT; Sonuga-Barke, Taylor, Sembi, & Smith, 1992), the options are nearly always 1 unit of reward after 2 seconds and 2 units after 30 seconds. Here the decision point comes at the beginning of the trial and once the choice is made the participant is committed to the chosen outcome. In the Maudsley Index of Delay Aversion (MIDA; Kuntsi, Oosterlaan, & Stevenson, 2001; Marco et al., 2009) the reward and delay parameters are usually the same as in the CDT but the choice is presented in a computer game-based format. Participants operate a spaceship which moves across the screen during each trial at a fixed rate and have to choose between either destroying one spaceship after a short delay (2 secs) and two spaceships after a longer delay (30 secs). This means that the key choice point comes during the trial when the first enemy spaceship appears and the participant decides where to shoot it or not. Both paradigms were originally designed to test the specific predictions of the delay aversion hypothesis – that choice of small immediate rewards is motivated by desire to reduce delay. Thus they originally compared the choice between the rewards in two settings. In both settings there were usually a fixed number of trials so that choosing the large reward maximized rewards over time. In one, however, there was no post reward delay after the small reward and choosing that reward reduced the overall delay on the task. The other when a post reward delay equalised the length of the trials delivering the different options where choosing the small reward did not reduce delay. However, most studies have only included the no post-reward delay condition of either task.

#### The second commonly used approach is called the temporal discounting paradigm (TDP). Here participants are presented with multiple trials offering different combinations of delay and reward. For instance, a small reward of €0, €5, €10, €20, or €30 delivered immediately might be contrasted with a large constant reward (e.g. €30) delivered after a variable delay (e.g. now, tomorrow, one week, one month). In this kind of task, delay length and reward size are varied systematically across trials in order to establish the function according to which they are traded-off against each other. In these paradigms choice options are often hypothetical – with the participants not actually experiencing delay or receiving the chosen rewards – and delays to the large reward are typically in the range of days and weeks. A more detailed description of delay discounting paradigms is provided by da Matta, Gonçalves, and Bizarro (2012).

#### Recently, two meta-analyses have addressed the issue of impulsive choice in ADHD, analysing data from simple choice delay and TD paradigms (Patros et al., 2016; Pauli-Pott & Becker, 2015). However, these studies suffer from several methodological shortcomings, as they (i) include studies that duplicate data from overlapping data sets in different papers, (ii) omit key papers during the study period and (iii) fail to take account of (a) different study designs (i.e. repeated measures designs) and significant variations in task designs and (b) whether just a subset of trials were included in the analysis. These latter limitations are problematic as they affect estimates of performance variance which will affect experimental effect calculations (Borenstein, Hedges, Higgins, & Rothstein, 2009; Dunlap, Cortina, Vaslow, & Burke, 1996). For instance, in repeated measures designs, even if task order is randomized or counterbalanced to minimize carryover effects (Park, Bose, Notz, & Dean, 2011), the total time on task is increased when compared with non-repeated measures designs. This might have different implications for task performance in the involved experimental groups. In this sense, boredom and fatigue might increase much more in subjects with ADHD than in controls with increasing experimental duration, differentially affecting performance quality in both groups. As a result, the mean group effect averaged across different task conditions might overestimate the true population effect when compared with non-repeated measures designs.

#### We performed an up to date meta-analysis to address these methodological considerations incorporating data from both the SCP and TDP paradigms. Our prediction was that effects would be larger in SCPs than TDPs. First, the repetitive character of choice presentation in the SCP may exacerbate delay intolerance compared to the larger variation of task parameters across trials in the TDP. Second, trial density, i.e. the number of choices during the complete experiment, is typically greater in the TDP than in the SCP. This may mean that the negative power of overall experienced delay might be larger in the SCP. Third, whereas participants actually experience delays in the SCP, they are mostly hypothetical in the TDP. Thus SCP will elicit more delay aversion than TDP exacerbating the tendency to choose the immediate over the delayed reward.

#### Further, we addressed the impact of variation in specific task characteristics to further our understanding of the mechanisms underlying ADHD-related delay intolerance and impulsive choice in ADHD, as well as methodological differences between studies in terms of study design. First, we examined the effect of session length differences as characterised by the number of choice trials in the SCP studies and the number of choices given with a specific combination of delay and reward in the TDP studies. We hypothesized that preference for the small immediate reward would be greater the longer the sessions/the greater the number of trials on the basis that the negative affective power of delay would increase the more time that delay was experienced. Second, we examined the effects of reward type. We hypothesized the preference for the immediate small option would be greater when choice outcomes were of low incentive value (i.e., points rather than real rewards like money or sweets) on the grounds that the lack of willingness of ADHD individuals to wait for delayed outcomes may be a task specific expression of a deficit in intrinsic motivation seen in other contexts. For the TDP, we also expected larger group differences to emerge in low incentive conditions (discounting of hypothetical rewards) when compared with high incentive conditions (discounting of real rewards). Third, we examined the effect of compensation for task completion as a whole as a motivational factor, as adding incentives has been shown to improve performance on a whole host of settings (Konrad, Gauggel, Manz, & Scholl, 2000; Marx, Höpcke, Berger, Wandschneider, & Herpertz, 2013; Scheres, Oosterlaan, & Sergeant, 2001; McInerney & Kerns, 2003; see Luman, Oosterlaan, & Sergeant, 2005, for a review). Fourth, we analysed the impact of study design (single measures vs. repeated measures) on group differences for the above mentioned reasons.

#### Method

#### *Literature search*

#### Studies were identified by searching the following electronic databases: Pubmed (Medline), OVID databases (PsychInfo, EMBASE, EMBASE classic, and OVID Medline), WEB OF KNOWLEDGE (Web of Science, Biological abstracts, Biosis, and Food science and technology abstracts) from inception to September 16th, 2016. The following ADHD-related key words were employed : *ADHD*, *ADD*, *attention deficit* *disorder with hyperactivity*, *syndrome hyperkinetic*, *hyperkinetic syndrome*, *hyperactivity* *disorder*, *hyperactive child syndrome*, childhood hyperkinetic syndrome, *attention deficit hyperactivity disorders, attention deficit hyperactivity disorder, attention deficit hyperactivity disorder, overactive child syndrome, attention deficit hyperkinetic disorder, hyperkinetic disorder*, *attention* *deficit* *disorder* *hyperactivity*, *attention* *deficit* *disorders* *hyperactivity*, *child* *attention* *deficit* *disorder*, *hyperkinetic* *syndromes*, *syndromes* *hyperkinetic*, *hyperkinetic* *syndrome* *childhood*, and these were combined with the following terms impulsive choice-related terms: *delay*, *delay* *aversion*, *delay of gratification*, *delay intolerance*, *choice delay*, *impulsive choice*, *Choice* *Delay Task*, *CDT*, *Maudsley Index of Delay Aversion*, *MIDA*, *reward*, waiting, *delay discounting*, *temporal discounting*, *single-choice task*. Search terms and syntax were adapted for each database.

#### *Eligibility criteria*

#### Articles that met the following criteria were included: (i) were peer reviewed and included original data; (ii) examined human subjects; (iii) employed SCPs (CDT, MIDA or close variants) or TDPs; (iv) incorporated a control group; (v) diagnosis of ADHD was validated using standard research diagnostic instruments (i.e. structured or semi-structured interviews) in case of clinical trials, or validated diagnostic screening instruments (i.e. ADHD-specific questionnaires) in population-based trials, and the paper clearly describes the diagnostic procedure and the sources of cases and controls; (vi) tasks only included certain rewards – not variable or uncertain delays or outcomes. If more than one article was published based on the same data set, we selected the study with the larger sample size or, in case of equal sample sizes, the study which was published earlier. Two reviewers (I.M. and X.Y.) independently assessed the eligibility of all studies.

#### *Data extraction*

#### On the SCP the main outcome variable were the choices for the large delayed reward. As some studies reported absolute numbers whereas others reported the percentage of choices, percentages were transformed into absolute numbers. For the TDP it was *k* (the individuals’ discounting rate) and the area under the curve (AUC) of the discounting function. In the TDP, larger *k* values and smaller AUC values indicate steeper devaluation of the delayed reward (Peters & Büchel, 2011). Furthermore, the following variables were extracted as factors of interest for the meta-regression analyses: the number of trials scheduled in the SCPs and the number of choices given with a particular set of parameters in TDPs as indicators of session length; reward type (real vs. hypothetical); general compensation for task completion (yes, no). The authors of selected articles were contacted via e-mail, and information on the variables of interest was gathered if not contained in the article, including the question whether the data stem from the same data pool as other published studies.

#### *Meta-analytic approach*

#### The principal meta-analyses were performed using effect size estimates derived from random effects models. Independent meta-analyses were conducted for both the SCP and TDPs to conform to the assumption of independent effect sizes that underline meta-analytic procedures (Borenstein et al., 2009). Moreover, for studies reporting several relevant dependent outcome variables (i.e. repeated measures designs), the condition which was presented first was chosen if the conditions were presented consecutively. In the case of counterbalanced designs, an aggregate statistic was computed using Borenstein’s method (Borenstein et al., 2009). This method was chosen as it was found to be the least biased and most precise (Hoyt and Del Re, 2015). The default correlation between outcome measures was set at .50 (Wampold et al., 1997). Studies with sufficiently long “wash-out periods” (Hedayat & Stufken, 2003), i.e. studies with a period of several days between the measurements, were treated like non-repeated measures designs. Odds ratios (Cornfield, 1951) and standardized mean differences (Hedges and Olkin, 1985) were computed for the SCP and the TDP, respectively. We computed odds ratios based on the total event rate per study, i.e. total number of choices per cohort. Odds ratios were transformed to standardized mean differences for comparability using the following formula:

#### $$d=LogOddsRatio\* \frac{\sqrt{3}}{π}$$

#### $$V\_{d}=V\_{LogOddsRatio}\*\frac{3}{π^{2}}$$

This method was originally proposed by Hasselblad and Hedges (1995). Standardized mean differences were assessed as low (d = .2), moderate (d = .5), and high (d = .8), according to the Cohen (1992) convention. All meta-analytic procedures were conducted using the R-software package ‘metafor’ (Viechtbauer, 2010). Restricted maximum-likelihood estimation (REML) was used by to estimate τ2 which are approximately unbiased (Viechtbauer, 2005). To assess between-trial heterogeneity, we computed Q and I2 statistics. When interpreting I2 values, we followed general conventions of .25, .50, and .75 corresponding to low, moderate, and high between-trial heterogeneity, respectively. Funnel plots, fail-safe N (Rosenthal, 1993), and rank tests for funnel plots (Begg and Mazumdar, 1994) were used to assess publication bias. Additionally, we conducted meta-regression analyses to explore moderating effects of task parameters (session length; reward type; general compensation for task completion) and study design (single measures vs. repeated measures) using mixed effect regression models (Viechtbauer, 2010). It is noteworthy that the dummy coded age variable was created to enable pragmatic comparisons (i.e. children vs. adolescents and adults in the SCPs and adults vs. children and adolescents in the TDPs). Finally, sensitivity analyses were conducted for several methodological reasons.

#### Results

#### *Study inclusion*

#### The flow diagram describing study selection is depicted in Figure 1. Discrepancies between raters’ judgement of whether a paper met inclusion criteria occurred in 39 cases, and the respective articles were sent to SC for moderation. The studies were then discussed between all three authors until a consensus was reached. From the remaining 64 studies that were included in qualitative synthesis, 32 used the SCP and 31 used TDP, and one study incorporated both paradigms.

#### Five SCP studies were excluded for the use of duplicate data (studies presented in italics met inclusion criteria): Banaschewski et al. (2012), Bitsakou, Psychogiou, Thompson, & Sonuga-Barke (2009), Marco et al. (2009), and Wood et al. (2011) overlap with *Kuntsi et al. (2010)* (the data stem from the International Multi-Center ADHD genetics (IMAGE) project (Kuntsi, Neale, Chen, Faraone, & Asherson, 2006), and Sjöwall & Thorell (2014) overlaps with *Sjöwall, Roth, Lindqvist, & Thorell (2013)*. Five SCP studies were excluded because of variations in task design (no trials constraint condition was implemented: Patros, Alderson, Lea, & Tarle, 2017; a pre-reward delay was imposed before response selection, and variable delays were used: Gawrilow, Gollwitzer, & Oettingen, 2011; variable long delays were used, and no control group design was implemented: Potter & Newhouse, 2008; Potter, Ryan, & Newhouse, 2009; no condition without post-reward delay was implemented: Schweitzer & Sulzer-Azaroff, 1995). Finally, one study was excluded due to methodological considerations (no independent control group was implemented, and data stem from the IMAGE project: Sonuga-Barke et al., 2011). Three of the remaining studies reported ADHD subtype data but provided combined data for the whole clinical sample upon request (Lambek et al., 2010; Solanto et al., 2007; Wahlstedt, Thorell, & Bohlin, 2009) and one study reported data for a subset of trials but sent the complete data upon request (Sjöwall, Roth, Lindqvist, & Thorell, 2013), such that we were able to include these studies in our meta-analysis. Wilhelm et al. (2010) incorporated two versions of the SCP (“sweets” and “money” condition) within one study, but the (“sweets”) condition was always presented first. Likewise, Solanto et al. (2001) presented two blocks of 20 trials each and rewards were delivered after each block. As the conditions in both studies were not randomised or balanced but were presented consecutively, we decided to use only the first condition from each study in order to avoid the inclusion of potential carryover effects. Altogether, we were able to include 22 SCP studies in our meta-analysis (see Table 1).

#### From the TDP studies, nine studies were excluded for the use of duplicate data (Costa Dias et al. (2013; 2015) and Wilson, Mitchell, Musser, Schmitt, & Nigg (2011) overlap with *Mitchell, Wilson, & Karalunas (2015)*; Demurie, Roeyers, Baeyens, & Sonuga-Barke (2013) overlap with *Demurie, Roeyers, Baeyens, & Sonuga-Barke (2012)* and *Demurie, Roeyers, Wiersema, & Sonuga-Barke (2016)*; Hoogman et al. (2011), Mostert et al. (2015a) and Onnink et al. (2015) overlap with *Mostert et al. (2015b)*, which are all based on the IMpACT study (Franke, Vasquez, Johansson, Hoogman, Romanos, & Boreatti-Hümmer, 2010); Scheres, Tontsch, & Thoeny (2013) overlaps with *Scheres, Tontsch, Thoeny, & Kaczkurkin (2010)*; Wilbertz, Trueg, Sonuga-Barke, Blechert, Philipsen, & Tebartz van Elst (2013) overlap with *Wilbertz et al. (2012)*. One study displayed significant variations in task design and was therefore excluded (implemented post-reward delays: Rosch & Mostofsky, 2016). Finally, seven studies were excluded due to methodological considerations (the diagnostic procedure was not explained: Fassbender et al., 2014; authors failed to respond to our request for missing relevant information: Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Dai, Harrow, Song, Rucklidge, & Grace, 2013; Li et al., 2008; Plichta et al., 2009; Scheres, Tontsch, Thoeny, & Kaczkurkin, 2010; Scheres et al., 2006). In three studies, the DDT was performed in the fMRI scanner (Carlisi et al., 2015; Chantiluke et al., 2014; Ortiz et al., 2015). However, as stress induction was not found to affect TDP task performance in ADHD subjects in a recently conducted study (Krause-Utz et al., 2016), we decided to include these studies in our meta-analysis. Finally, we were able to include 15 TDP studies in our meta-analysis (see Table 2).

#### *Overall effect sizes*

#### *Single Choice Paradigm*

#### Based on the initial funnel plot, two extreme outliers were identified. Whereas Gupta et al. (2009) reported an effect size outside the bounds of the confidence interval, Yang et al. (2011) reported a standard error approximately three times the size of other studies (figure available upon request from the authors). These studies were excluded from all further calculations. Thus, the final sample included 22 independent trials from 20 studies, including four trials from within-study designs (Antrop et al., 2006; Metin et al., 2016; Wahlstedt, 2009; Yu et al., 2015). The total participant sample in this quantitative review was *n* = 2.666 (1.425 of which with a diagnosis of ADHD). The sample size per trial varied between *n* = 27 (Sonuga-Barke et al., 1992) and *n* = 809 (Kuntsi et al., 2010). The estimated log odds ratio for the SCP was 0.65 (95% CI: .47 – .83, *p* < .0001) which corresponds to an OR of 1.9, suggesting that the ratio between the shorter and the longer delay is approximately doubled in the population with a diagnosis with ADHD compared to the control group. The transformed log odds ratio corresponds to a standardized mean difference of *d* =.36 (*SDd*=.003).[[1]](#footnote-1) Despite removing the above studies we still observed significant inter-study heterogeneity, *Q*(21) = 384.29, *p* < .0001, corresponding to an *I*2 of 95.44% (95% CI: 92.20 – 97.87), thus supporting further moderation analysis. A forest plot of the log odds ratios for the SCP is presented in Figure 2. A funnel plot for the reduced sample is depicted in Figure 3. A rank correlation test of the funnel plot asymmetry was significant suggesting that a publication bias might be present (Kendall’s tau = -.39, *p* = .01). Fail-safe *N* calculation revealed that an additional 6.892 trials would be required to reduce the observed significance level to .05.

#### *Temporal Discounting Paradigm*

#### The total participant sample in this quantitative review was *n* = 1.097 (561 of which with a diagnosis of ADHD). The sample size per trial varied between *n* = 21 (Ortiz et al., 2015) and *n* = 232 (Mostert et al., 2015a). The final sample included *k* = 15 independent trials from 15 studies, including three trials from within-study designs (Paloyelis et al., 2010; Yu et al., 2015; Yu & Sonuga-Barke, 2016). The estimated standardized mean difference for the TDP was 0.43 (95% CI: .29 – .57, *p* < .0001) suggesting a small to medium sized effect size. We observed no significant inter-study heterogeneity, *Q*(14) = 17.02, *p* =.26, *ns*), corresponding to an *I*2 of 18.59% (95% CI: 0 – 70.74). A forest plot of the standardized mean differences for the TDP is presented in Figure 4. A rank correlation test of the funnel plot asymmetry (Figure 5) was not significant suggesting no publication bias was present (Kendall’s tau = .12, *p* = .56). Fail-safe *N* calculation revealed that an additional 245 trials would be required to reduce the observed significance level to .05.

#### Given age was confounded with the dependent measure used (eight out of nine studies that were conducted with children or adolescents reported AUC; five out of six studies that were conducted in adults reported *k*), we repeated the meta-analysis for *k* and AUC estimators separately. For the *k*-trials, the estimated standardized mean difference was 0.45 (95% CI: .22 – .67, *p* = .0001). In turn, the estimated standardized mean difference for the AUC trials was .43 (95% CI: .24 – .62, *p* <.001).

#### *Moderation analyses*

#### *Single Choice Paradigm*

#### Fitting a mixed effects model including the number of choices, reward type (hypothetical vs. real), and general compensation for task completion (yes, no) as moderators revealed a significant result, *Q*(3) = 8.12, *p* = .04. Further analysis revealed reward as a significant moderator *Q*(1) = 7.52, *p* = .01. Offering a reward significantly decreased the log odds ratio from 1.11 to .53 for subjects with ADHD compared to controls, meaning that anticipation of real rewards nearly halved choice impulsivity in subjects with ADHD. Reward accounted for 27.60% of the between-study variance, but residual inter-study heterogeneity was still significant, *Q*(19) = 226.92, *p* < .0001. A mixed effects model including study design as a dummy coded factor revealed a statistically non-significant result, *Q*(1) = .21, *p* = .65. An additional analysis including only age group (children only vs. rest) as a moderator revealed a non-significant result, *Q*(1) = 0.003, *p* = .96.

#### *Temporal Discounting Paradigm*

#### The same analysis as above revealed non-significant results, *Q*(3) = 1.67, *p* = .64. A mixed effects model including study design as a dummy coded factor revealed a statistically non-significant result, *Q*(1) = .07; *p* = .79. An additional analysis including only age group (adults vs. rest) as a moderator revealed a non-significant result, *Q*(1) = .96, *p* = .33.

#### *Sensitivity analyses*

#### A sensitivity analysis revealed that for the SCP trials, excluding the Sonuga-Barke et al. (1992) study which reported data from only a subset of trials only marginally reduced the estimated log odds ratio from .65 to .62 (95% CI: .45 – .79, p < .001). For the TDP trials, excluding the Stevens et al. (2015) study in which all ADHD subjects additionally suffered from cocaine dependence did not alter the estimated standardized mean difference, *d* = 0.43 (95% CI: .28 – .58, *p* < .0001).

#### Discussion

#### In this meta-analysis, we aimed to compare the simple choice (SCP) and the temporal discounting (TDP) paradigms in their ability to differentiate ADHD subjects from controls with respect to their tendency to prefer immediate over delayed rewards, i.e., impulsive choice. We predicted that effects would be larger in the SCP than in the TDP due to an expected greater salience of the negative power of experienced delay as generated by the repetitive character of choice presentation, lower trial density, and the experience of real (vs. hypothetical) delays. We further predicted that session length (i.e. the number of trials), incentive value (i.e. hypothetical vs. real rewards), and general compensation for task completion may moderate the magnitude of experimental group differences in both paradigms. Our meta-analyses on 22 SCP trials and 15 TDP trials revealed that both paradigms showed small to medium effect sizes (SCP: *d* = 0.36; TDP: *d* = 0.43), confirming that subjects with ADHD are apt to choose small immediate over large delayed rewards more frequently when compared with controls. In the TDP, only marginal effect size differences emerged when analysing the two available dependent measures (*k*, *AUC*) separately. These effect sizes are slightly smaller than those ones identified in previous meta-analyses which might be attributed to our stricter methodological approach. Contrary to our expectations, we did not find larger effect sizes in the SCP. One explanation might be that the SCPs mostly uses real rewards (which seem to reduce the effect sizes) whereas the TDPs mostly use hypothetical rewards, and thus the lack of differences may primarily be due to methodological confounds. Alternatively, both tasks might test different aspects of the underlying choice decision processes. In this sense, the integrated neuroeconomic model of decision making (Sonuga-Barke, Cortese, Fairchild, & Stringaris, 2016) specifies a three-stage decision making process, comprising reward evaluation (assessment of the utility of potential choice outcomes based on parameters such as valence, magnitude, timing, and probability), decision and management (comparison of the subjective value of choice alternatives; choice of the most preferred option; choice implementation), and appraisal and accommodation (comparison of the expected and derived choice utility, generation of a prediction error; update of the initial utility evaluation; reinforcement learning). This decision making process is informed and guided by three distributed and interacting brain systems, i.e. self-referential processes, executive control, and reinforcement learning and emotion processing. Thus, the SCP might predominantly address emotion processing (negative feelings due to low-frequent trial succession and the experience of real, immediate delays), whereas the TDP, especially when using long temporal delays, might put more emphasis on executive aspects (e.g., decisions must be made for longer periods of time; future consequences must be weighed against each other). As it is impossible to disentangle these explanatory approaches at the moment, we put them up as possible hypotheses to be tested in future head-to-head studies.

#### In line with our hypotheses, we were able to show that offering a reward almost doubled the odds ratio for subjects with ADHD compared to controls in the SCP, suggesting that those with ADHD were much more likely to choose the large delayed reward in relation to controls when they anticipated real rewards. Delay in and of itself (separated from rewards) seemed to exacerbate impulsive choice – a finding consistent with the delay aversion model. However, as eighteen rewarded studies were contrasted against only four non-rewarded studies, this finding should be interpreted with caution. In contrast, we were not able to detect an effect of reward on the TDP effect sizes. Again, the analysis was not balanced in this paradigm, only three out of all included studies used a condition with reward in terms of chance payoff (Ortiz et al., 2015; Paloyelis et al., 2010) or real money (Yu et al., 2015), whereas all other studies used hypothetical rewards. Additionally, a lower motivational power of chance payoff compared with certain rewards might have additionally contributed to these zero findings. In line with this assumption, no differences are commonly observed in the discounting functions for hypothetical rewards vs. chance payoff in healthy subjects (Johnson & Bickel, 2002; Lawyer, Schoepflin, Green, & Jenks, 2011; Madden, Begotka, Raiff, & Kastern, 2003; Madden et al., 2004), questioning the motivational power of this reward condition. Another factor that complicates a direct comparison of the reward effect in both experimental designs is an imbalance of the nature of the delays, i.e. delays are always experienced in the SCP whereas they are almost exclusively hypothetical in the TDP. As a result, delay type and compensation strategy are confounded, i.e. SCPs typically implemented real delays and rewards whereas TDPs typically implemented hypothetical delays and rewards.

#### Taken together, an imbalance between compensation strategies (real vs. hypothetical), a somewhat weaker motivational power of rewards (chance payoff vs. certain rewards) and a confounding between compensation strategies and the nature of delays (real vs. hypothetical) in published studies that have been conducted so far necessitate further systematic research in order to determine how both factors – delay and reward valence – independently from each other contribute to impulsive choice in ADHD. On one hand, our findings argue for a motivational value of real rewards or, the other way around, for a demotivating effect of hypothetical rewards in the context of delay, manifesting itself in more pronounced impulsive choice. On the other hand, recent neuroimaging findings argue for the negative emotional power of experienced delays in terms of aymygdala-striatal hyperactivation to trigger impulsive choice, irrespective of the nature of the rewards (chance payoff: Plichta et al., 2009; hypothetical rewards: Lemiere et al., 2012; Wilbertz et al., 2013), although no study using certain rewards instead of chance payoff has been conducted so far. A previously conducted study directly comparing temporal discounting in anticipation of real vs. hypothetical rewards in adults with ADHD does not resolve these uncertainties (Paloyelis et al., 2010). Although subjects with ADHD showed steeper discounting when compared with controls in anticipation of hypothetical delays and rewards but equal performance in anticipation of real delays and rewards (Paloyelis et al., 2010), it remains unclear from this study if the real experience of the delays or the prospect of real rewards or both factors may explain these findings.

#### Contrary to our expectations, we were not able to identify a moderation effect of general compensation for task completion on the effect sizes which might have several reasons: (i) compensation might not have influenced the behaviour of the subjects during the experiment as it was not contingent on task performance; (ii) the subjects, at least the children, might not have been aware of the compensation in advance; (iii) at least the children might not have been compensated directly but the compensation might have been given to their parents. Likewise, session length did not turn out to be a significant moderator variable. This was probably due to restricted variance in the SCP and limited practical relevance in the TDP. More precisely, almost all SCP studies incorporated 20 trials, whereas one study that used 30 trials (Gupta et al., 2009) reported a very large effect size outside the bounds of the confidence interval of all other studies and another study that used only 10 trials (Yang et al., 2011) reported a standard error approximately three times the size of other studies such that both studies were excluded as outliers. These studies provide valuable information in that impulsive choice might increase with overall experimental session length (Gupta et al., 2009) according to the delay aversion hypothesis (Sonuga-Barke et al., 1992) and in that substantial inter-individual heterogeneity exists, with some of the subjects with ADHD being impaired already at very early stages of their performance whereas others still behave in a functional manner (Yang et al., 2011). With regard to the TDP, even though the number of experimental trials is more heterogeneous between studies, no real delays are imposed after the decisions such that the pure number of trials had only little impact on overall experimental length when compared with the SCP. To sum up, more studies are needed in order to examine how session length affects impulsive choice in subjects with ADHD.

#### Across both paradigms, Pauli-Pott & Becker (2015) found, in their meta-analysis, an age-dependent decrease of impulsive choice in the sense that children with ADHD (< 12 years) were more strongly impaired than adolescents (13–16 years). Likewise, Patros et al. (2016) showed that preschool-aged children with ADHD (< 8 years) were more strongly impaired than school-aged children (8–12 years) and adolescents (13–18 years). In contrast, we were not able to identify task-specific age effects in our meta-analysis. Methodological reasons might have contributed to these negative findings: (i) the sample composition in our study differs from previously conducted meta-analyses according to the methodological considerations outlined in the introduction section. As a result, 40% of the SCP studies and about 30% of the TDP studies did not examine “pure” age groups of children, adolescents, and adults according to the neurocognitive developmental stages outlined by Casey, Tottenham, Liston, & Durston (2005) which were also used in the previous meta-analyses, but they used combined age groups. Rather than excluding these studies from the analyses, we resolved this problem by flexibly contrasting the age groups based upon the data available (SCP: children vs. “rest”; TDP: adults vs. “rest”). This might have masked true population effects, especially in the TDP analyses. (ii) The TDP studies incorporated a larger proportion of adults than the SCP studies, thus making it necessary to analyze both tasks separately in order to avoid biased results in terms of paradigm by age interaction effects. Accordingly, the statistical power to detect age effects was presumably restricted. Despite the lack of age effects in our meta-analysis, there is evidence that delay discounting generally improves with age (Green, Fry, & Myerson, 1994; Scheres et al., 2006), depending on maturation processes within the limbic-fronto-striatal circuitry (Demurie et al., 2012) which are associated with improving top-down regulation of motivational tendencies in healthy subjects. Likewise, recent meta-analyses (Pauli-Pott & Becker, 2015; Patros et al., 2016) point to an age-dependent decrease of choice impulsivity in subjects with ADHD, although this phenomenon seems to persist and might even play a role in affected adults (Marx et al., 2010). Taken together, more cross-sectional studies using the pre-defined age groups according to Casey et al. (2005) or longitudinal studies are needed in order to track the developmental pathway of impulsive choice in ADHD.

#### Finally, some statistical considerations should be discussed. The SCP displays larger between-study heterogeneity when compared with the TDP which might be due to several factors. First, the variance criterion is sensitive to the number of studies, and the SCP sample contains a larger number of studies when compared with the TDP. Second, SCP analyses are based on the number of choices in the sample instead of aggregated data and therefore show larger reliability, i.e. smaller confidence intervals. Third, the SCP might be more sensitive to contextual variables such as experimental length and the provision of real vs. hypothetical rewards.

#### Conclusions

#### The strengths of our study lie (i) in the rigor of study selection according to methodological aspects, especially the exclusion of overlapping data sets and the systematic assessment of further factors that might inflate the effect sizes, (ii) the larger content-validity due to exclusion of studies with significant variations in task design (e.g. choice impulsivity did not reduce overall delay length; delay was not a consequence of choice but preceded choice), and (iii) the separate estimation of effect sizes and moderation effects for both paradigms in order to avoid biased results due to confounding delay x reward effects. However, methodological difficulties that have emerged from the published literature such as an imbalance of compensation strategies in both paradigms (real vs. hypothetical), a confounding between compensation strategies and the nature of delays (predominantly real delays and rewards in the SCP; predominantly hypothetical delays and rewards in the TDP), restricted variability in the number of trials in the SCP, and weak motivational power of rewards in the TDP (e.g. chance payoff vs. certain rewards) make it difficult to describe – at the moment – the interplay between the determinants of impulsive choice. However, it seems reasonable to believe that a stronger than normal aversion towards delay (Sonuga-Barke et al., 1992) interacts with a demotivating effect of hypothetical instead of real rewards, both factors promoting impulsive choice in subjects with ADHD. This view is well supported by recent research demonstrating that the prospect of significant reward, along with valid trial-to-trial feedback, largely normalized the formerly altered brain activity patterns and associated task performance deficits in children with ADHD (Hammer et al., 2015; Hammer, Cooke, Stein, & Booth, 2015), putting up to discussion reward feedback immediacy as a further potential moderator of ADHD-related delay intolerance and impulsive choice in ADHD.

#### Our finding that both the SCP and the TDP obtain comparable effect sizes raises the question whether or not researchers should implement both paradigms in studies on impulsive choice in ADHD. Due to its larger ecological validity (delays are really experienced), its larger contextual sensitivity (sensitive to real vs. hypothetical rewards) and as it is the more precise performance estimator (in terms of reliability), we would suggest the SCP as the paradigm of choice, merely limited by the need for identification of further moderators of task performance due to the large residual heterogeneity and the outstanding investigation whether or not both paradigms tap the same or different aspects of impulsive choice.

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Figure Captions

*Figure 1*. Flow chart of study selection procedure (PRISMA).

*Figure 2*. Forest plot of the effect sizes (Log Odds Ratios) and 95% confidence intervals for comparisons of subjects with ADHD vs. controls (SCP). The size of the symbols reflects study sample size. Positive values indicate larger choice impulsivity (i.e., the less frequent choice of the large delayed reward) in the ADHD group when compared with the control group.

*Figure 3*. Funnel plot visualizing the relationship between effect sizes (Log Odds Ratios) and standard errors (SCP). Outliers are excluded. Data were adjusted in order for the bounds of the pseudo confidence interval region are equal to *± 1.96 √(SE² + τ²)*, where *τ²* is the amount of heterogeneity as estimated by the model.

*Figure 4*. Forest plot of the effect sizes (standardized mean differences, *d*) and 95% confidence intervals for comparisons of subjects with ADHD vs. controls (TDP). The size of the symbols reflects study sample size. Positive values indicate larger choice impulsivity (i.e., steeper delay discounting) in the ADHD group when compared with the control group.

*Figure 5*. Funnel plot visualizing the relationship between effect sizes (d) and standard errors (TDP). Data were adjusted in order for the bounds of the pseudo confidence interval region are equal to *± 1.96 √(SE² + τ²)*, where *τ²* is the amount of heterogeneity as estimated by the model.

1. ####  The estimated log odds ratio with outliers included was OR = .75 (95% CI: 0.53 – 0.98), *p* < .0001) which corresponds to an OR of 2.12, which is equivalent to a standardized mean difference of d = .42 (*SDd*=.004).

 [↑](#footnote-ref-1)