



The interplay of delay aversion, timing skills, and impulsivity in children experiencing attention-deficit/hyperactivity disorder (ADHD) symptoms

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Abstract

Impulsive behaviours occurring as a central deficit in connection with attention-deficit/hyperactivity disorder (ADHD) are associated with social and academic impairment in children. Whereas impulsivity was shown to be related to both delay aversion and deficient timing skills, the mutual relation between the latter two has hardly been investigated. The present study therefore examined the interplay of delay aversion, timing skills, and impulsivity in a sample of eighty-eight children aged between seven and fourteen, twenty-one of them diagnosed with ADHD. Children participated in a delay aversion and a tapping task, while parents reported about their impulsiveness. The results showed that both delay aversion and deficient timing skills were related to impulsivity. Contrasting prior assumptions, delay aversion and timing skills were also shown to be related, even when controlling for impulsivity. Implications for interventions aiming to reduce children's impulsivity as well as methodological considerations regarding whether to view ADHD as a category or a continuum are discussed.

Keywords ADHD symptoms · Dimensionality · Delay aversion · Timing skills · Impulsivity

Introduction

Children who are impulsive as part of attention-deficit/hyperactivity disorder (ADHD) symptoms are generally described to experience difficulties with waiting their turn in

conversations or games, are prone to losing temper in conflicts or when frustrated, often interrupt or intrude others, and talk excessively (American Psychiatric Association (APA) 2013; Barkley 2006; World Health Organization (WHO) 1992). Additionally, their attentional focus constantly shifts

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from one to other novel or more salient stimuli, thus causing a lack in sustained attention (Martel et al. 2008). As a consequence, children described to be impulsive experience substantial difficulties effectively interacting within social relationships with peers, family members, and adults (Barkley 2002; Huang-Pollock et al. 2009). Moreover, their academic performance is impaired, which is reflected by an overall poorer school performance, an increased risk for grade retention, and an enhanced demand for supportive after-school programmes, for instance (Barkley 2006; Biederman et al. 1996; Jensen et al. 2004; LeFever et al. 2002).

Nevertheless, to assume that only individuals diagnosed with ADHD are impulsive and hence experience associated functional difficulties is a misconception. Substantial empirical evidence converges on the idea that ADHD should best be described as a continuum ranging from very low to very intense symptomatology, hence affecting all individuals to a certain degree (Coghill and Sonuga-Barke 2012; Haslam et al. 2006; Levy et al. 1997; Marcus and Barry 2011; Salum et al. 2014; Shaw et al. 2011). In accordance with these findings, functional impairments were shown to be associated with ADHD symptoms across this continuum (DeYoung and Rueter 2017; Levy et al. 1997; Polderman et al. 2010).

Results of cross-sectional studies suggest that impulsivity is, in addition to a deficit in inhibitory control, associated with a motivational style termed delay aversion as well as with deficient timing skills (Coghill et al. 2014; Noreika et al. 2013; Rubia et al. 2009; Sonuga-Barke 2002; Sonuga-Barke et al. 2010). *Delay aversion* denotes a motivationally driven tendency to avoid or escape waiting or delay, which is particularly prevalent in children experiencing ADHD symptoms, especially when the duration of the delay is unclear (Antrop et al. 2006; Bitsakou et al. 2006, 2009; Tripp and Alsop 2001). Sonuga-Barke (2002) hypothesised that delay aversion might initially result from fundamental alterations in neuronal reward circuits leading to a shortened delay of reward gradient. These children would thus generally devalue future events at higher rates than other children, hence developing a preference for immediacy, which manifests itself in behavioural impulsivity. From a very early age on, children are thus assumed to respond impulsively in situations characterised by waiting and delay, hence failing to meet culturally shaped expectations of other children, their own parents, and other adults. Over time, situations in which delays are to be expected then become associated with the expectation of failure so that affected children develop a generalised aversion against situations characterised by waiting and delay, that is delay aversion. As a consequence, delay aversion is thus considered to manifest as a behavioural trait and is hence found to be associated with impulsivity (Solanto et al. 2001; Sonuga-Barke et al. 2010).

The second construct shown to be associated with impulsive behaviours independent from delay aversion is a *deficit in timing skills* (Coghill et al. 2014; Sonuga-Barke

et al. 2010; Toplak and Tannock 2005a; Valera et al. 2010; Walg et al. 2012). Timing skills denote different timing abilities such as motor timing, which characterises the temporal organisation of motor behaviour, perceptual timing, which denotes the ability to estimate explicitly attended temporal intervals, and temporal foresight, which refers to the ability to consider the future consequences of one's decisions or actions (for an overview see, e.g., Noreika et al. 2013). Most robust evidence for an association between impulsivity and deficient timing skills stems from studies assessing motor timing skills using sensorimotor synchronisation and continuation tasks, such as tapping tasks (Rubia et al. 2003; Toplak and Tannock 2005a; Zelaznik et al. 2012). Tapping tasks require participants to synchronise their finger tapping rhythm with an external stimulus and to keep this rhythm when the stimulus is removed (Noreika et al. 2013). Studies examining the relation between impulsivity and deficient timing skills in children found support for a general decrease in inter-tapping intervals, hence indicating deficits in time perception (Huang et al. 2012; Rubia et al. 1999, 2003; Toplak and Tannock 2005a; Zelaznik et al. 2012). Deficient timing skills are considered to be related to a faster internal clock (Rubia et al. 1999, 2007; Sonuga-Barke et al. 1998; Toplak and Tannock 2005b). Time intervals are thus perceived to be longer than they have actually been, thus explaining impulsive reactions. Consequently, current evidence supports the idea that impulsive behaviour shown by children with ADHD symptoms is associated with either delay aversion *or* deficient timing skills, while the latter two were shown to be unrelated (cf. Sonuga-Barke et al. 2010).

However, although empirical evidence supports the assumption that delay aversion and deficient timing skills are unrelated while both are associated with impulsivity (Sonuga-Barke et al. 2010), the idea that they comprise two strictly separate functional deficits does not seem totally clear yet: Theoretical considerations suggest that not only deficits in reward mechanisms, but also deficient timing skills might be associated with delay aversion and thus also with impulsivity (cf. Rubia et al. 2009), hence suggesting that delay aversion comprises a motivational deficit associated with both deficits in reward mechanisms and deficient timing skills. These theoretical considerations are underpinned by results from neuroimaging studies supporting the assumption that delay aversion and deficits in temporal processing seem to share neuronal alterations (Castellanos and Tannock 2002; Shih et al. 2009; Teicher et al. 2000).

In sum, although the relation between impulsivity occurring in the context of ADHD symptoms and delay aversion as well as deficits in timing skills is well established and consistently supported by prior research, both theoretical considerations and implications derived from neuroimaging studies indicate that the relation between delay aversion

and timing skills requires further investigation. Additionally, such investigations should acknowledge that impulsivity may best be described as a continuum ranging from very low to very intense. Beyond theoretical implications, the results derived from such studies will have important ramifications for the planning of training programmes aiming to reduce impulsive behaviour and associated functional impairment.

The present study therefore aimed to examine the interplay between impulsivity, delay aversion, and timing skills in a sample of children experiencing different levels of impulsivity. It was first hypothesised that impulsivity and delay aversion would be positively related (Hypothesis 1), and second, that impulsivity and timing skills would be negatively related (Hypothesis 2). Finally, it was hypothesised that timing skills and delay aversion would be negatively related (Hypothesis 3a) and that this relation would also hold when controlling for the influence of impulsivity on both timing skills and delay aversion (Hypothesis 3b).

Methods

Participants

Data were collected within the scope of a larger project aiming to examine different aspects of decision-making in children with and without ADHD. The study was approved by local ethics committees, and all procedures performed were in accordance with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Written informed consent for participation was obtained from parents or legal guardians, and children consented verbally.

Children with and without a prior clinical diagnosis of ADHD were eligible for participation. Further inclusion criteria were an $IQ \geq 70$ as measured with the Culture Fair Test (CFT 20-R; Weiß and Weiß 2006) and a birth weight of ≥ 2500 g. Children were not eligible for participation in case their parents reported about a pervasive developmental disorder, autism spectrum disorder, or psychotic disorder. They were recruited from schools, local child psychiatric outpatient centres, and a clinic for child and adolescent psychiatry, psychosomatics, and psychotherapy. The total sample comprised $N = 115$ children (28 female) aged between 7 years and 3 months and 13 years and 8 months ($M_{age} = 10.1$ years, $SD_{age} = 1.60$ years). Out of the total sample, $n = 46$ children reported a prior ADHD diagnosis. One parent of each child (eleven fathers) was also recruited.

Parents of children who were treated with methylphenidate or amphetamines were asked to wash out medication for 24 h before the study. However, not all parents adhered to this instruction. Numerically, children with ADHD medicated during the test session showed reduced delay

Table 1 Descriptive characteristics of the sample

Variable	<i>M</i>	<i>SD</i>	Empirical range (min–max) [Possible range (min–max)]
ADHD symptoms	0.81	0.69	0.00–2.79 [0.00–3.00]
Inattention	0.99	0.81	0.00–3.00 [0.00–3.00]
Hyperactivity	0.54	0.66	0.00–2.71 [0.00–3.00]
Impulsivity	0.89	0.85	0.00–3.00 [0.00–3.00]
Delay aversion	213.65	129.07	25.12–503.90
Timing skills (in ms)	–122.91	153.69	–574.97–164.57
Age (in years)	9.94	1.59	7.33–13.67
IQ	109.91	14.47	76.00–149.00 [54.00–160.00]
Socioeconomic status	15.34	3.59	6.70–21.00 [3.00–21.00]

ADHD symptoms, inattention, hyperactivity, and impulsivity were measured using an external rating scale for ADHD (FBB-ADHS; Döpfner and Görtz-Dorten 2008); delay aversion was assessed using the Delay Frustration Task (DeFT; Bitsakou et al. 2006); timing skills were assessed using a tapping task; IQ was assessed using the Culture Fair Intelligence Test 20-R (CFT 20-R; Weiß and Weiß 2006); the families' socioeconomic status (SES) was assessed using the IDEAS Social Background Inventory (ISBI; Körner and Betz 2012)

aversion ($M_{medicated} = 191.39$,¹ $M_{without\ medication} = 198.21$) and improved timing skills (i.e., smaller deviations from the rhythm they were instructed to keep while tapping; $M_{medicated} = -181.19$, $M_{without\ medication} = -141.33$) compared to children with ADHD not medicated, hence indicating that medical treatment was effective. As parents were additionally instructed to report about their child's ADHD symptoms as if unmedicated, thus leading to incongruent information from task measures (child medicated) and parents (child unmedicated), all children medicated during the second test session, during which the data for the present analysis were collected, were excluded from the sample ($n = 26$; all diagnosed with ADHD). In addition, one participant diagnosed with a learning disability and an $IQ < 70$ was excluded ($n = 1$). The final sample for the present investigation thus comprised $N = 88$ children (26 female; $M_{age} = 9.94$ years, $SD_{age} = 1.59$ years). Of those children, $n = 21$ reported a prior diagnosis of ADHD (seven female; five medicated with methylphenidate). Table 1 presents the descriptive characteristics of the whole sample.

¹ To measure *delay aversion*, participants were instructed to indicate answers to simple math tasks with a button press. The computer accepted the answer with varying delay. During the delay, the number of button presses and their mean duration was recorded. An index calculated as the product of the number of button presses and their duration indicated delay aversion.

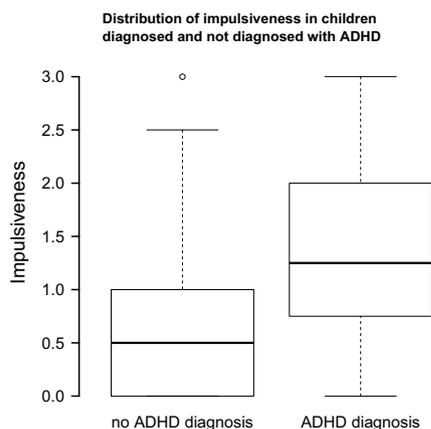


Fig. 1 Boxplot showing the distribution of impulsiveness as reported by parents for children with ($n=21$) and without ($n=67$) ADHD diagnosis

In acknowledging empirical data showing that ADHD should rather be viewed as a continuum than as a category (Coghill and Sonuga-Barke 2012; Haslam et al. 2006; Levy et al. 1997; Marcus and Barry 2011; Salum et al. 2014; Shaw et al. 2011), the present study did not differentiate between children with and without a clinical diagnosis of ADHD. The distribution of individual impulsivity levels covered the whole range from no or very low to very intense symptoms of impulsivity (Fig. 1).

Procedure

Children and parents attended two test sessions taking place at different days in the laboratory. Including breaks, Session 1 lasted about 2.5 h, Session 2 about 2.0 h. Two experimenters welcomed children and parents upon their arrival. One experimenter was then assigned to the parent and one to the child. Parent and child were both assessed and interviewed separately. Different experimenters conducted Sessions 1 and 2. The data analysed in the present study were collected in Session 2.

Measures

ADHD symptoms

ADHD symptoms were measured using an external rating questionnaire for ADHD (FBB-ADHS; Döpfner and Görtz-Dorten 2008). The FBB-ADHS is a German rating scale addressing ADHD symptom criteria according to the DSM-IV-TR (APA 2000) and the ICD-10 (WHO 1992) on the three symptom scales: inattention (nine items), hyperactivity (seven items), and impulsivity (four items). All items were answered on a four-point rating scale ranging from 0 (not at all) to 3 (in particular). In case the child was usually

medicated, parents were instructed to report about their child as if unmedicated. A mean ADHD symptom score was calculated as the mean of all item scores from all symptom scales. Specific symptom scores for inattention, hyperactivity, and impulsivity were calculated as the mean of all item scores of the respective symptom scales. Parents needed approximately ten minutes to fill in this questionnaire.

Timing skills

A tapping task was used to assess each participant's timing skills. Children were first instructed to tap along the pace of a given auditory tone that was presented every 1200 ms in 15 cued trials. In 41 uncued trials, the cue tone was not present anymore and children were instructed to keep on tapping in the same pace as the cued tone had appeared. The participants' tapping was recorded as the children had to tap by pressing a response button on a response box. The relative mean deviance (in ms) from each inter-tap-interval (1200 ms) in uncued trials, calculated on a trial-to-trial basis, comprised the variable derived from this task. We hereby deviate from approaches of prior studies that used within-subject standard deviations (Sonuga-Barke et al. 2010) or mean reaction times (Coghill et al. 2014), for instance, as we consider the information whether participants tapped faster or slower than the expected rhythm (i.e., the tap that is expected if the participant followed the rhythm of the cued trials in uncued trials exactly) important. Especially individuals high in impulsivity, and hence those with a faster internal clock, are assumed to tap faster than individuals lower in impulsivity. Children completed the tapping task in about 12 min.

Delay aversion

It is assumed that delay averse individuals become frustrated when they encounter a situation characterised by delay that cannot be escaped. This frustration, assumed to correspond to delay aversion, was assessed using the Delay Frustration Task (DeFT; Bitsakou et al. 2006). As this task does not assess children's ability to tolerate reward-related delay, like choice tasks usually employed do (i.e., tasks in which children have to decide between a small immediate and a large delayed reward; Douglas and Parry 1983; Kuntsi et al. 2001), the DeFT is expected to overcome shortcomings of choice tasks viewed to decrease the comparability of results across age groups. This decrease is expected to be attributable to the notion that rewards offered in the scope of choice tasks become far less salient as children mature and access to rewards increases enormously (Bitsakou et al. 2006). Additionally, children's ability to tolerate reward-related delay is expected to substantially increase as children grow older, hence causing potential ceiling effects (Bitsakou et al. 2006).

For the DeFT, every participant was instructed to answer 55 simple math tasks. Every task was presented separately together with four possible answers. Participants were asked to select one answer by pressing a button from a four-button response box. In 39 trials, the programme moved to the next trial as soon as the participant responded (no post-response delay). In 16 trials, however, the access to the next question was delayed by either three, four, five, six, seven, eight, nine, or ten seconds (two trials each), or by 20 s (eight trials), that is, the response button was ‘inactive’ during the delay period, while the next task was not yet presented (post-response delay). Nevertheless, all responses, also those entered during the delay, were recorded. At the end of the delay period, the response box was ‘reactivated’. All post-response delay trials were presented in a pseudo-randomized order. At the beginning of the task, nine trials were always without post-response delay. The placement of the 16 post-response delay trials was therefore randomized across the remaining 46 trials. The number of responses and their average duration were recorded for each trial separately and for time periods within the post-reward delay periods. The total duration of responses (i.e., the product of number of button presses and their average duration) in those trials with 20 s delay constituted the variable calculated from this task (cf. Bitsakou et al. 2006; Sonuga-Barke et al. 2010). The DeFT took approximately 10 min.

IQ

Intelligence was measured using the Culture Fair Intelligence Test 20-R (CFT 20-R; Weiß and Weiß 2006). The CFT 20-R is a non-verbal and non-numeric intelligence test assessing skills of completing series, classifications, matrices, and topological reasoning, and is often employed with children with ADHD who are known to experience difficulties with reading, writing, and arithmetic (e.g., Biederman et al. 1996; Monuteaux et al. 2005). Its results are reported to be comparable to those of other IQ tests including verbal and numerical subtests (Downing 1965; Hays and Smith 1980). Children needed approximately 25 min to complete the CFT 20-R.

Socioeconomic status

The families’ socioeconomic status (SES) was measured using the Center for Individual Development and Adaptive Education of Children at Risk (IDeA) Social Background Inventory (ISBI; Körner and Betz 2012). The ISBI was filled in by one parent of each participant and asked about the family’s (potential) migration background, the language spoken in the family, and other social aspects (e.g., the parental education, profession, income, cultural capital). An SES index that could range between a minimum of 3.0, indicating low

SES, and a maximum of 21.0, indicating high SES, was calculated as a sum score from three dimensions: income, occupational status, and educational and professional training (cf. Lampert et al. 2013). Parents needed about 30 min to complete the ISBI.

Analyses

Data preparation

After deleting the first trial of the experimental block of uncued trials, data of the tapping task were controlled for outliers on a within-subjects level (i.e., values below or above three interquartile ranges from the median). Outliers were removed, and the mean deviance from the expected taps (i.e., the tap that is expected if the participant followed the rhythm in uncued trials exactly) was calculated. On a between-subjects level, data were again screened for outliers defined as values below or above three standard deviations from the mean. No outliers were detected. Data from the delay frustration task were screened for outliers (i.e., values below or above three standard deviations from the mean on an interindividual level), and no outliers were detected.

Statistical analyses

To test whether impulsivity and delay aversion were positively related (Hypothesis 1), whether impulsivity and timing skills were negatively related (Hypothesis 2), and whether timing skills and delay aversion were negatively related (Hypothesis 3a), partial correlation analyses, controlling for age and ADHD diagnosis, were conducted. Both age and ADHD diagnosis were shown to be significantly related to variables of interest (see Table 2). To test Hypothesis 3b, partial correlation analyses correlating timing skills and delay aversion while controlling for age, ADHD diagnosis, and impulsivity were conducted. Using correlation analyses, it was first acknowledged that associations between variables should be examined and second, that no causal interpretation of the results was possible due to a cross-sectional and non-experimental study

Table 2 Correlations between variables

Variable	1	2	3	4	5
1. Impulsivity	–				
2. Delay aversion	.23*	–			
3. Timing skills	–.23*	–.27*	–		
4. Age	–.19	–.25*	.15	–	
5. IQ	–.13	–.25*	.11	–.03	–
6. SES	–.20	–.02	–.04	–.10	.41*

Pearson’s correlation (2-tailed); * $p < .05$

design. As all hypotheses had a direction derived from the literature, and as the reverse direction could be excluded, they were tested one-tailed.

Results

Table 2 presents the correlations of delay aversion, deficient timing skills, and impulsivity with covariates. Two-tailed statistics are reported as not all variables should be expected to be interrelated.

The partial correlation analysis testing Hypothesis 1 showed that impulsivity and delay aversion were significantly positively related ($r = .24, p = .016$) when controlling for age and ADHD diagnosis. Controlling for age, but not ADHD diagnosis, only marginally affected the strength of this relation ($r = .20, p = .34$). Figure 2 shows how impulsivity and delay aversion are related.

Additionally, impulsivity and timing skills were significantly negatively related ($r = -.20, p = .041$; Hypothesis 2) when age and ADHD diagnosis were controlled for. Controlling only for age only marginally altered the relation's strength ($r = -.24, p = .026$). The relation between impulsivity and timing skills can be seen from Fig. 3.

Finally, timing skills were significantly negatively related to delay aversion ($r = -.24, p = .020$; Hypothesis 3a) when controlling for age and ADHD diagnosis, and also when impulsivity was additionally controlled for ($r = -.20, p = .045$; Hypothesis 3b). Controlling for age ($r = -.23, p = .021$) or age and impulsivity ($r = -.20, p = .044$) only, only marginally altered the strength of the relation between timing skills and delay aversion. The relation between timing skills and delay aversion can be seen from Fig. 4.

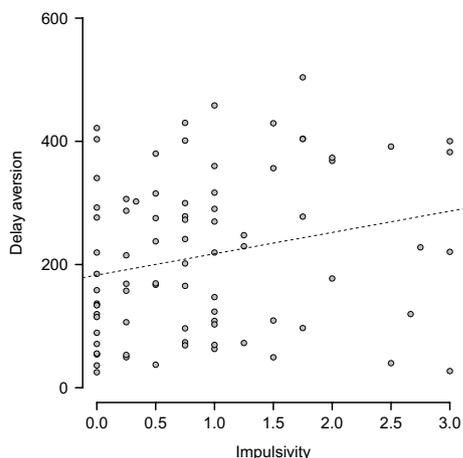


Fig. 2 Scatterplot indicating the relation between impulsivity and delay aversion

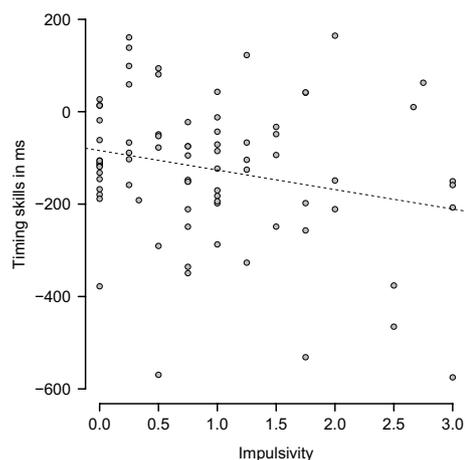


Fig. 3 Scatterplot indicating the relation between impulsivity and timing skills

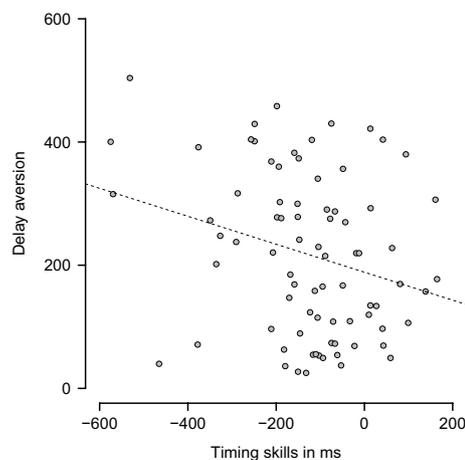


Fig. 4 Scatterplot indicating the relation between timing skills and delay aversion

Discussion

The present study aimed to examine the interplay between delay aversion, timing skills, and impulsivity in children with varying degrees of impulsivity. The results provided support for our hypotheses, showing that impulsivity was positively related to delay aversion (Hypothesis 1). Second, the results demonstrated that impulsivity was negatively related to timing skills (Hypothesis 2). Third, timing skills were shown to be negatively related to delay aversion (Hypothesis 3a), even when the influence of impulsivity was controlled for (Hypothesis 3b).

The findings that impulsivity was positively related to delay aversion and negatively related to timing skills in a sample of children experiencing varying degrees of impulsivity were in accordance with existing research in samples

of children with clinically diagnosed ADHD (Huang et al. 2012; Rubia et al. 2003, 2009; Sonuga-Barke 2002; Toplak and Tannock 2005a; Zelaznik et al. 2012). Our results thus support the assumption that both delay aversion and deficient timing skills are associated with impulsive behaviour.

Beyond prior research, our findings corroborate theoretical considerations, suggesting that a relation between deficient timing skills and delay aversion exists in children experiencing ADHD symptoms (Rubia et al. 2009), thereby partially contrasting the results presented by Sonuga-Barke and colleagues (2010). This contrast might be attributable to several differences between the two studies. First, the present study investigated the interplay between delay aversion, timing skills, and impulsivity in a sample of children with varying degrees of impulsivity (i.e., viewing impulsivity as a continuum), whereas Sonuga-Barke and colleagues (2010) examined children with a clinical diagnosis of ADHD only. Hence, the variance of impulsivity levels might have been larger, thus covering a wider range, in the present study. Second, whereas the present study viewed delay aversion, timing skills, and impulsivity as continuous variables, Sonuga-Barke and colleagues (2010) selected arbitrary cut-off values to determine whether children had deficient timing skills or not and whether they showed delay aversion or not (i.e., dichotomous variables). Hence, also the variance of timing skills and delay aversion should have been larger in the present study. Consequently, with viewing delay aversion, timing skills, and impulsivity as continua, thus refraining from establishing arbitrary categories, and with furthermore refraining from recruiting children with diagnosed ADHD only, we assumed meaningful variance to remain in the data, thus allowing them to explain more of the variance found while at the same time increasing the power of the analyses conducted. Differing results between the present study and the one conducted by Sonuga-Barke and colleagues (2010) may hence be attributable to these differences.

Practical and methodological implications

Our findings that timing skills are related to delay aversion and that both timing skills and delay aversion are related to impulsivity may have important practical implications for training programmes aiming to reduce children's impulsive behaviours. Such training programmes should be considered important as impulsive behaviours are associated with substantial social and academic difficulties (Barkley 2002, 2006; Biederman et al. 1996; Huang-Pollock et al. 2009; Jensen et al. 2004; LeFever et al. 2002). Specifically, our findings first reinforce that programmes aiming to train the ability to endure delay and programmes targeting to train timing skills, such as cognitive trainings, for instance, should reduce impulsivity. Additionally, however, as results of the present study support the assumption of a relation

between delay aversion and deficient timing skills, they implicitly suggest that impulsivity may also be reduced with programmes targeting both delay aversion and timing skills at the same time. One may furthermore assume the efficacy of such complex intervention programmes to increase when two instead of only one underlying risk processes are reduced (i.e., the programme's goal is targeted from two directions at the same time; cf. Cortese et al. 2015). Hence, future studies should first aim at designing complex training programmes aiming to reduce both deficits in timing and delay aversion concurrently. Subsequent studies should then aim to evaluate these training programmes' efficiency with a special focus on their capability to reduce deficits in timing skills, delay aversion, and impulsivity.

Moreover, as our results showing that delay aversion, timing skills, and impulsivity are interrelated were derived from a sample of children showing the full range of impulsivity symptoms from no or very low to intense symptomatology, it should be expected that programmes training timing skills and/or aiming to reduce delay aversion should also be beneficial for children experiencing impairment due to subthreshold levels of impulsivity, that is, children who are impaired, but do not experience enough impairment to be diagnosed with ADHD. These children are generally not eligible to participate in intervention programmes due to financial caveats of healthcare providers. Other programme formats that can be administered more cost-efficiently in the form of computer- or tablet-based games or as part of music lessons at schools (e.g., clapping and stomping games), for instance, should therefore be developed.

From a methodological standpoint, the replication of findings from prior studies examining children with clinical diagnoses of ADHD only in a sample of children showing the full range of impulsivity symptoms (i.e. from no/very low to intense symptomatology), viewing these constructs as continua, may be assumed to further support the assumption that ADHD symptoms and associated impairments should be viewed as dimensions. Hence, as results seem to hold independent from the sample assessed, it might not necessarily be vital for future research to recruit children with clinical diagnoses of ADHD only, but population samples representing the natural distribution of ADHD symptoms might be recruited instead. As population samples are generally easier to recruit than clinical samples, larger sample sizes might thus be achieved, hence further increasing statistical power.

Finally, the results of this present study provide additional evidence for the idea that timing skills constitute an important factor that should be taken into consideration when examining impulsivity, delay aversion, or ADHD symptoms in general. Future research should therefore more consistently acknowledge timing skills as covariates or outcome variables, thereby contributing to a more thorough understanding of the aetiology of ADHD.

Limitations and implications for further research

To the best of our knowledge, the present study provided the first investigation of the interplay of delay aversion, timing skills, and impulsivity, viewing these latter constructs as continua. Future studies aiming to further examine these relations should be aware of its following limitations and weaknesses. First, excluding participants medicated during the test session from analyses could have limited the generalizability of the results as we might have excluded especially those children showing substantial ADHD symptoms (i.e., they showed such intense ADHD symptoms that their parents could not take them off medication for the day of the test session), thereby introducing systematic bias into the data. Hence, future studies should aim at recruiting larger numbers of both children with ADHD usually medicated and unmedicated, while all of them are off medication during the test session.

Additionally, with examining children aged between seven and fourteen ($M_{\text{age}} = 9$ years and 11 months, $SD = 1$ year and 7 months) the results of the present study can only hardly be generalised to samples of younger and older children. This can especially be assumed as timing skills should improve, while impulsivity should reduce with age (Biederman et al. 2000; Block et al. 1999; Drake et al. 2000; Fischer and Hartnegg 2004; McAuley et al. 2006). In this sense, delay aversion may be theorised to develop in early childhood, at least partly driven by deficient timing skills, thus resulting in a true association of the two constructs. In situations characterised by waiting or delay, impulsive behaviours would then constitute a strategy to avoid or escape delay, manifesting itself as a trait over time. As children mature and timing skills improve, the strength of the relation between delay aversion and timing skills as well as impulsivity and timing skills would then attenuate, while the relation between delay aversion and impulsivity would remain stable or increase. Future studies should examine whether such considerations can be supported by empirical evidence. Such studies might do so using longitudinal designs such as, for instance, measurement burst designs (e.g., Stawski et al. 2015). They might furthermore wish to do so using ambulatory assessment, thus allowing to examine these latter interrelations in ecologically valid settings, such as at school or at work and in real time (Fahrenberg and Myrtek 1996; Fahrenberg et al. 2007; Trull and Ebner-Priemer 2013). Thus, they would allow to investigate whether the interrelations between delay aversion, timing skills, and impulsivity change with development and maturation and whether they impair functioning in real life.

Moreover, as none of the studies concerned with delay aversion, timing skills, and impulsivity was able to derive causal implications yet (e.g., Noreika et al. 2013; Rubia et al. 2009; Solanto et al. 2001; Sonuga-Barke et al. 2010; Toplak

and Tannock 2005a; Valera et al. 2010; Walg et al. 2012) future studies should aim to inform about potential causal interrelations between these constructs. This might be realised by a series of studies specifically manipulating one of the constructs each, for instance, by altering timing skills, response inhibition, or delay tolerance on behavioural (e.g., through cognitive trainings) or neurophysiological levels (e.g., through non-invasive neuromodulation and training approaches such as transcranial direct current stimulation (tDCS), transcranial magnetic stimulation (TMS), or neurofeedback). Thus, theoretical considerations regarding the different causal functions of delay aversion, timing skills, and impulsivity could be substantiated. Such studies should additionally be substantially powered, thus allowing to examine the—potentially causal—differential contributions of timing skills and delay aversion to impulsivity using multiple regression analysis, for instance.

Finally, due to the wealth of measures and paradigms that may be used to assess delay aversion, timing skills, and impulsivity, further research investigating the interplay of these three constructs using additional measures is required to obtain a more thorough understanding of the subject matter. New methodological approaches, such as latent variable analysis in combination with a well-conceived theory-driven design of studies could furthermore help to investigate the relations examined in the present study. Such approaches could additionally help to characterise differences and similarities between tasks in terms of what they measure. As such, they might, for instance, clarify whether measures of impulsivity and timing skills actually measure different constructs or whether both measure impulsivity, whether the delay frustration task and choice tasks actually both measure delay aversion, or whether the delay frustration and the tapping task share a common underlying construct such as motor impulsivity.

Conclusion

To the best of our knowledge, the present study was the first to investigate the interplay of delay aversion, timing skills, and impulsivity in a sample of children experiencing varying degrees of ADHD symptoms and thus impulsivity. Beyond replicating the finding that delay aversion and deficient timing skills are related, the results showed that delay aversion and timing skills are related, even when the influence of impulsivity is controlled for, thereby challenging the results of prior studies (cf. Sonuga-Barke et al. 2010). Consequently, the findings from the present investigation question aetiological conclusions derived from prior studies, thus furthermore emphasising the need for further studies aiming to clarify the aetiology of ADHD symptoms and impulsive behaviours.

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Compliance with ethical standards

Conflict of interest There are no conflicts of interest to be declared by any author.

Appendix: Supplementary analyses

Interplay of delay aversion, timing skills and other ADHD symptoms

To test whether inattention and hyperactivity were related to delay aversion and timing skills, additional two-tailed partial correlation analyses were calculated. Controlling for age and ADHD diagnosis, the analyses showed that inattention and delay aversion were unrelated ($r = .14$, $p = .23$), while hyperactivity and delay aversion were related ($r = .22$, $p = .049$). Additionally, controlling for age and ADHD diagnosis, inattention and timing skills were unrelated ($r = -.068$, $p = .55$), while also hyperactivity and timing skills were ($r = -.093$, $p = .42$). Finally, delay aversion and timing skills were related when controlling for inattention, age, and ADHD diagnosis ($r = -.23$, $p = .045$), while they were not when controlling for hyperactivity, age, and ADHD diagnosis ($r = -.21$, $p = .66$).

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