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Time Perception Deficits in Children and Adolescents with ADHD: A Meta-analysis

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Abstract

Objective: Prior studies have reported time perception impairment in children and adolescents with ADHD but the results were inconsistent. **Method:** The current meta-analysis reviews 27 empirical studies published in English after year 2000 that compared time perception competence among children and adolescents with and without ADHD. **Results:** Results from 1620 participants with ADHD and 1249 healthy controls showed significant timing deficits in ADHD. Children/adolescents with ADHD perceived time less accurately (Hedges' $g > 0.40$), less precisely (Hedges' $g = 0.66$) and had higher tendency to overestimate time than their healthy counterparts. Moderator analyses indicated that the discrepancy of time perception between groups was not affected by the type of timing tasks nor the modality of stimuli used in the tasks. Nonetheless, results were moderated by age and gender. **Conclusion:** These findings may update current understanding of the underlying neuropsychological deficits in ADHD and provide insight for future research in clinical assessments and treatments for ADHD.

Keywords

ADHD, meta-analysis, time perception, neuropsychological deficits

Introduction

ADHD and Time Perception Deficits

Attention-deficit/hyperactivity disorder (ADHD) is a neurodevelopmental disorder with persistent patterns of inattentiveness and/or hyperactivity-impulsivity that interfere with normal functioning (American Psychiatric Association, 2013). The world-wide estimated prevalence of ADHD is between 2% and 7%, with an average of around 5% (Sayal et al., 2018) and it is more commonly observed in males than females (Ramtekkar et al., 2010). Apart from deficits in executive function (Barkley, 1997) and aversion to delay (Sonuga-barke et al., 2008), which are commonly found deficits in individuals with ADHD, time perception deficit has been hypothesized as another neuropsychological impairment in ADHD (Sonuga-Barke et al., 2010).

Time perception refers to an individual's subjective experience of event durations and the passage of time. Studies on time perception have shown that children with ADHD in general show lower accuracy in time perception tasks (Hurks & Hendriksen, 2010; Hwang-Gu & Gau, 2015; Smith et al., 2002). In line with earlier findings in adults (Pollak et al., 2009), Walg et al. (2017) showed that children with ADHD perceived time as longer than their typically developing peers, which suggests the presence of a faster internal clock among individuals with ADHD.

As suggested by the Scalar Expectancy Theory (SET) and the Dynamic Attending Theory (DAT), an internal timing mechanism referred to as "the internal clock" is essential to the experience of time. According to the SET, there is a "pacemaker-counter" within an individual which generates temporal pulses that are counted by an accumulator. The registered counts are then compared against stored information in the long-term memory to enable one's judgment on the length of time (e.g. Gibbon et al.,1984; Pöppel, 1989). As the SET suggests, working memory plays a crucial role in time perception, as sufficient working memory capacity is required to register the pulses accurately in the timing process. However, working memory impairment is

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common among individuals with ADHD (Barkley, 1997), and this may have contributed to their poorer time perception abilities.

The DAT highlights the importance of attention in the timing process (Jones & Boltz, 1989). It postulates that the emission of temporal pulses from the internal clock can be influenced by external stimuli in the environment. When one attends to external cues in the surroundings, such as musical rhythm or visual pattern, the speed of the internal clock may vary accordingly and lead to a distortion of the subjective perception of time (e.g. Hammerschmidt & Woellner, 2019). As suggested by the DAT, individuals with ADHD who have attention problems might be more susceptible to the influence of external stimuli in time perception.

The two theories provide plausible explanations for the timing deficits observed in ADHD. However, not all studies comparing time perception between individuals with and without ADHD showed consistent findings. Inconsistencies in results may be attributed to the use of different task paradigms and parameters of measurement to assess time perception in prior studies, as well as the application of different modalities in stimulus presentation during time perception tasks. For instance, Barkley et al. (2001), Bauermeister et al. (2005), and Meaux and Chelonis (2003) found significant differences between ADHD and healthy controls in absolute discrepancy scores in time reproduction tasks but not in time estimation tasks. Hwang-Gu and Gau (2015) and Meaux and Chelonis (2003) found significant group differences in time reproduction when measuring absolute discrepancy, but not when measuring accuracy coefficient. Besides task paradigm and parameter of measurement, the modality of stimulus also appears to matter in the measurement of time perception. Plummer and Humphrey (2009) reported more accurate responses in time reproduction tasks for both the ADHD and control groups when stimuli were presented in dual modality (visual and auditory) in contrast to auditory, or worse still, visual modality. However, Toplak and Tannock (2005) revealed no significant effects of stimulus modality on the difference in time discrimination between ADHD and healthy controls. Although prior studies provided supportive evidence for time perception deficits in ADHD when compared with healthy controls, whether and to what extent such between-group differences in time perception were influenced by differing measuring factors remains unknown.

Measuring Accuracy and Precision in Time Perception

Empirical studies often used two parameters to measure timing performance: (1) accuracy—indicated by the deviation of a temporal judgment from the veridical value; and (2) precision—indicated by the variability across temporal judgments (Thoenes & Oberfeld, 2017).

Measures of accuracy include coefficient of accuracy, bisection point, and absolute error/discrepancy. The *coefficient of accuracy* is a signed magnitude of error commonly used for measuring accuracy. It is calculated by dividing each temporal judgment response by the actual duration. A score that is higher than 1.00 reflects overestimation, while a score lower than 1.00 indicates underestimation (Mullins et al., 2005). The *bisection point* is another signed measure of accuracy which indicates the point of subjective perception of equality when judging two time intervals (Walg et al., 2015). *Absolute error/discrepancy* indicates the extent to which a temporal judgement deviates from the actual duration, but does not reflect the direction of deviation (Bauermeister et al., 2005).

Commonly used measures of precision include: (1) the *standard deviation of the estimates of time* across various presentations of the same interval; (2) the *difference limen*, that is, the threshold for the minimal difference in duration between two time intervals below which the time intervals cannot be discriminated (Allman & Meck, 2012); and (3) the *coefficient of variation*, that is, the ratio of the standard deviation of temporal estimates to the mean estimate of time interval (Zelaznik et al., 2012).

Nevertheless, results are mixed when the parameters of time perception measures were considered. For instance, Meaux and colleagues (2003) reported significant differences between ADHD and controls in time reproduction tasks based on absolute error (accuracy), whereas Hurks and Hendriksen (2010) reported no significant differences between groups in time reproduction tasks based on the coefficient of accuracy. Using the standard deviation of mean production time as a measure of precision, Smith et al. (2002) reported no significant differences between ADHD and the controls. However, when using the difference limen instead, Toplak and Tannock (2005) revealed significant differences between ADHD and controls in time perception tasks. To understand whether and to what extent individuals with ADHD differ from healthy groups in time perception performance, more systematic analysis is required to account for the effect of using different measures on time perception tasks.

Task Paradigm and Stimulus Modality in Time Perception Studies

Prior studies used mainly four types of task paradigms to measure time perception, namely, (1) time estimation, (2) time production, (3) time reproduction, and (4) time discrimination.

In *time estimation* tasks, participants are asked to verbally estimate the duration of temporal intervals (Barkley et al., 2001). In *time production* tasks, participants have to produce specific temporal intervals (e.g., 5 seconds) by indicating the start and end of the target intervals. In *time* *reproduction* tasks, specific time intervals are presented to participants using visual or auditory formats, after which participants were asked to reproduce the same target interval as the one they have just seen/heard. In *time discrimination* tasks, participants are presented with two or three temporal stimuli in visual or auditory format, and asked to indicate which one is shorter/the shortest (or longer/the longest), or whether the stimuli last for the same duration (Huang et al., 2012).

In prior studies, group differences between individuals with and without ADHD were not consistently observed across tasks paradigms. For instance, Smith et al. (2002) found significant difference between ADHD and control groups in time discrimination tasks, but not in verbal estimation or time reproduction tasks. Yet Hwang-Gu and Gau (2015) reported more overestimation of time in youths with ADHD than their typically developing peers in verbal estimation tasks, and Bauermeister et al. (2005) found significant group differences in time reproduction tasks.

Modality of the stimuli may also affect time perception. As the DAT suggests, external environment can affect one's temporal judgment. The modality of stimuli may play a role in timing performance especially in time reproduction and time discrimination tasks. Ashcraft (2002) found that auditory information was reportedly available in short-term memory for 4 seconds, while visual information was only available for about 0.5 seconds. As such, information is likely to be more easily recalled in the auditory rather than the visual format. In line with this argument, Plummer and Humphrey (2009) reported that children responded more accurately in auditory condition than in visual condition in time reproduction task. However, Toplak and Tannock (2005) found no significant effect of stimuli modality on the difference in time perception between the ADHD and control groups. It remains unclear whether stimuli modality has a real effect on timing performance in children and adolescents with ADHD.

Effects of Gender and Age on Time Perception

Gender difference has been a constant theme in time perception research. MacDougall (1904) reported gender difference in time discrimination in a non-clinical sample more than a century ago, and this result has been replicated in later research (Eisler & Eisler, 1992; Hancock et al., 1992; Hancock et al., 1994; Hancock & Rausch, 2010; Rammsayer & Lustnauer, 1989; Schiff & Oldak, 1990). However, some studies did not observe any gender effects on time perception (e.g., Baldwin et al., 1966). In a meta-analysis of gender differences in time perception among healthy individuals, Block et al. (2000) found a small effect of gender on time perception accuracy which was moderated by task design. Specifically, gender effects have been indicated for retrospective tasks (i.e., tasks in which participants were not informed to make temporal judgment before the presentation of the stimuli), favoring males over females, but not for prospective ones (i.e., tasks in which participants were informed to make temporal judgment in advance). Sanders and Sinclair (2011) also found that men performed better than women in time perception accuracy, but this was not observed for the precision of timing. In sum, previous findings provided evidence for gender differences in time perception in non-clinical populations, although the gender effects were small and likely affected by the design of the timing tasks and other factors.

While most research in this area has been conducted among healthy populations, there are a limited number of studies that have investigated gender effects on time perception in individuals with ADHD, the samples of which were often over-represented by males (Ramtekkar et al., 2010). The majority of these studies typically found no significant gender effects. For instance, Himpel et al. (2009), Toplak and Tonnock (2005), and Walg et al. (2015) revealed no effects of gender on time discrimination in either the ADHD or control group. These findings are dissimilar to those obtained from healthy participants. Whether the discrepancy in results between ADHD and non-ADHD individuals signifies real differences between them or relates to the gender imbalance in the research samples awaits further investigation.

Apart from gender, age is often considered an influential factor that may affect time perception. The perceived passage of time has been shown to be faster with the increase of age in the general population (Wittmann & Lehnhoff, 2005). Espinosa-Fernández et al. (2003) showed that the underproduction of time intervals increases when age advances. Age also appears to affect temporal sensitivity, as supported by a systematic review indicating substantial age-related differences in time estimation and time production in adults (Block et al., 1998). Despite the salient effects of age on time perception observed in adults, there is much less evidence in the existing literature pertaining to age effects on time perception in children, not to mention those with ADHD. Among the few studies that have examined age effects on time perception in children, Droit-Volet et al. (2007) observed an increase in sensitivity to time in children from age 5 to 8, while Neufang et al. (2008) did not find age effects on time discrimination among children. It will be of value to evaluate whether age differentially affects time perception in children with ADHD versus their typically developing peers.

The Current Study

Given the perplexing findings on time perception difference between individuals with and without ADHD, the current study aimed to address three questions: (1) whether children and adolescents with ADHD demonstrated time perception deficit compared to their typically developing peers; (2) if yes, in which aspect of time perception, namely,

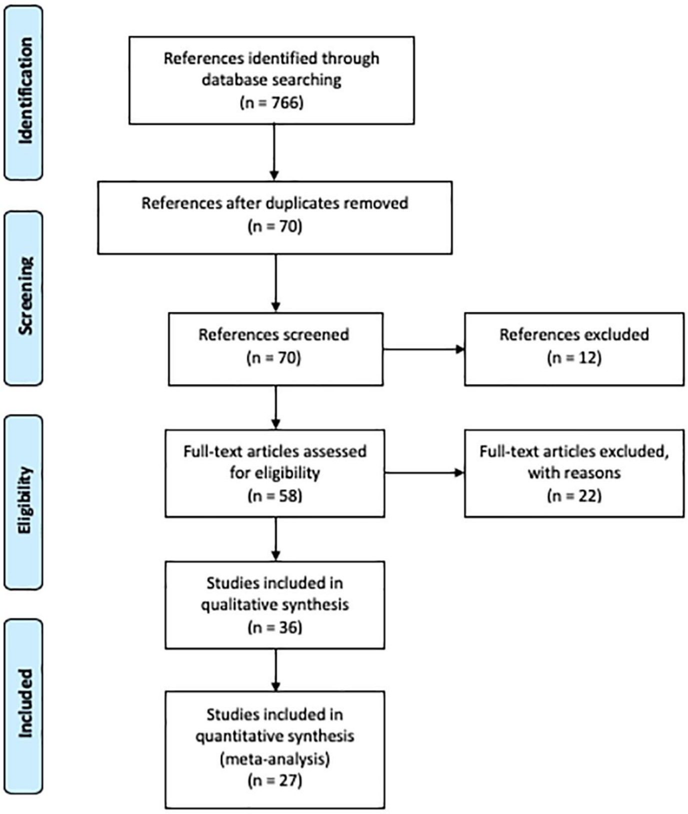

Figure 1. Flow chart of study selection procedure.

accuracy or precision, did the ADHD groups differ from the control groups; (3) whether task paradigm and stimulus modality affected the difference in time perception between the groups; and (4) whether such between-group differences in time perception, if observed, were influenced by age and gender. A meta-analysis was conducted to answer these questions.

Method

This meta-analysis review was conducted according to the standard guidelines for conducting and reporting systematic review studies (PRISMA; Moher et al., 2009).

Identification of Studies

Studies were identified in several databases, including Web of Science, PsycInfo, PsycARTICLES, and Google Scholar. The key words used in the search were "ADHD" and "child*" along with "time perception," "temporal," "timing*," "time reproduction," "time production," or "time discrimination." The last search date was August 14, 2019. References appeared in the identified articles were further screened to examine their eligibility for inclusion by the first and second authors independently using identical selection criteria. Figure 1 presents a flow chart to illustrate the study selection process.

Inclusion Criteria

Studies that met the following criteria were included in the meta-analysis: (1) empirical study with a between-group design, and inclusion of at least one group of individuals with ADHD and one group of matched healthy controls; (2) the sample consisted of children/adolescents (up to 19 years old); (3) inclusion of at least one time perception task; (4) published in English after year 2000; (5) results on the participants' accuracy or precision of time perception were reported; and (6) sample sizes, means, standard deviations of the measures, or relevant statistics (e.g., t or F-values) were reported, to allow calculation of the effect size estimates.

Description of the Included Studies and Data Extraction

Based on the criteria described earlier, 27 studies met the inclusion criteria (Figure 1), and together provided data from a total of 2869 participants. Among them, there were

1620 children/adolescents with ADHD (83% male) and 1249 healthy controls (57% male). Mioni et al. (2019) did not provide the gender ratio and therefore was not included in the gender ratio calculation. The mean age (weighted by sample size) of the participants with ADHD was 11.31 years (*SD*=2.72 years), and that of the healthy controls was 10.78 years (*SD*=2.75 years) while the overall mean age was 11.08 years (*SD*=2.74 years). Note that McInerney and Kerns (2003) and Plummer and Humphrey (2009) did not provide SD and hence the weighted calculation of SD did not include these two studies. Regarding task paradigm, time reproduction was assessed in most studies (TR; 22 studies), followed by time discrimination (TD; 8 studies), and subsequently, time estimation (TE; 5 studies) and time production (TP; 3 studies). Table 1 presents the descriptive summary of the included studies.

The required information from each study was extracted and coded based on the PRISMA Checklist for meta-analysis (Moher et al., 2009). Relevant data were extracted by the first and third authors independently. After the selection process, each researcher reviewed the articles and completed a data extraction form specifically designed for this meta-analysis with the following information extracted from the selected studies: bibliographic information, diagnostic assessment (i.e., DSM-IV), age, gender ratio, sample size, IQ, medication condition, type of time perception tasks (time reproduction, time estimation, time production, and time discrimination), stimulus modality (visual, auditory, or both), length of interval, and findings. After extracting the data independently, the first and third authors examined and compared the information and finalized the content on the data extraction form.

Quality Assessment

Since there are limited standardized tools for quality assessment for non-intervention group comparison studies, risk of bias of individual studies was assessed independently by the first and second authors using the Joanna Briggs Institute (JBI) critical appraisal checklist for cross sectional studies (Moola et al., 2020). The JBI checklist was utilized to make the final decision on whether a study should be included. Initial agreement between the ratings of the two reviewers on quality assessment was 89% and any disagreement was resolved through discussion to reach consensus.

Coding Procedures

Processing effect sizes. This study aimed to investigate the group differences between the ADHD and healthy control samples. The Hedges' *g* (Hedges, 1981)—an estimate of the standardized mean difference between groups—was used as the effect size metric in this analysis. Key statistics such as means, standard deviations, sample sizes, effect sizes (if any) and other statistics were obtained from the original published papers. For studies in which the relevant statistics needed for the meta-analysis were not fully presented, their authors were contacted through email for more information.

Based on the sample sizes and all the key statistics mentioned above, a Hedges' g was calculated for each task performance, based on the equations listed in Appendix 1. For studies that have reported the means, SD, and sample sizes (i.e., Barkley et al., 2001; Choi, 2012; González-Garrido et al.,2008), *g* was calculated as shown in equation (1) (Appendix 1), where *s* is the pooled sample standard deviation (see equation (2)). Five studies reported two samples of patients with ADHD (Bauermeister et al., 2005; Huang et al., 2012; Marx et al., 2010; Mullins et al., 2005; Toplak et` al., 2003). For these studies, we averaged the reported data (means and standard deviations weighted by sample size) across the two patient samples. A summary of the effect sizes (Hedges' *g*) and relevant statistics are presented in Table 2.

There were seven studies that did not provide sufficient details on the means and SDs for the ADHD and control groups. Among them, two studies have reported the effect sizes in Cohen's *d* (McInerney & Kerns, 2003; West et al., 2000). For these two studies, *g*, variances of *g*, and standard errors of *g* were calculated from Cohen's *d* according to Hedges (1981; see equations (7)–(11)). For the five other studies in which no effect sizes were reported, *g* was calculated from the *F* statistics and sample sizes (see equation (3); Hurks & Hendriksen, 2010; Khoshnoud et al., 2018; Meaux & Chelonis, 2003; Mioni et al., 2019; Walg et al., 2015). The interpretation of the magnitude of effect sizes was based on the conventional standard, that is, an effect size of 0.8 is considered as a large effect, 0.5 is considered as moderate, and 0.2 is considered a small effect (Cohen, 1988). There might be more than one between-group comparison in a selected study, as different types of tasks were employed to assess participants' temporal processing. Based on *g* and the reported sample sizes, we calculated the variances of *g* (equation (4)) according to Borenstein et al. (2009). One value of *g* and V_g were produced for each pair of comparison in each selected study. Once the *g* value was obtained for each comparison, the lower and upper limits of the confidence interval of *g* were calculated according to equations (5) and (6).

Two major measures indicated accuracy in time perception, namely, absolute error and signed accuracy. Absolute error reflects how accurately the individual perceived time, but cannot provide information on the direction of deviation (i.e., overestimation versus underestimation). A positive value of *g* for absolute error indicated a larger error of estimation for the ADHD group than the control group, and thus implied a lower accuracy for the ADHD group. Coefficient accuracy (CA) and

Table 1. Characteristics of Studies Included in the Meta-Analysis.

		ADHD				Control						
Study	Diagnostics criteria	Group/subtype	Mean age (SD)	Male (%)	N	Mean age (SD)	Male (%)	N	Task	Accuracy measure	Precision measure	Modality
Barkley et al. (2001)	DSM-IV		14.7 (1.5)	88	101	14.8 (1.6)	85	39	TETR	Abs.errorAbs.error		NA
Bauermeister et al. (2005)	DSM-IV	Combined	8.4 (1.4)	63.6	33	8.8 (1.5)	52	25	TETR	Abs.errorAbs.error		Visual
		Inattentive	9.1 (1.1)	71.2	54							
Choi (2012) (thesis)	Not mentioned		9.2 (1.5)	75	20	9.5 (1.0)	78	23	TETR	Abs.errorCAAbs. errorCA		NAVisual
González-Garrido et al. (2008)	DSM-IV		8.8 (1.5)	100	16	8.9 (1.4)	100	16	TR	Signed estimation accuracy		Visual
Gooch et al. (2011)	DSM-IV		9.5 (1.5)	65	17	10.3 (2.6)	45.2	42	TR	Abs.error		Visual
Himpel et al., (2009)	Not mentioned		11.3 (2.3)	92	63	11.3 (2.2)	63	40	TD		DL	Auditory
Huang et al. (2012)	ICD-10	With ADHD family history	8.3 (1.5)	94	42	8.5 (1.6)	89	100	TPTRTD	Abs.errorCAAbs. errorCA	DL	NA Visual auditory
		Without ADHD family history	8.5 (1.5)	94	52							
Hwang et al., (2010)	DSM-IV		12.8 (1.5)	87	168	13.2 (1.8)	81	90	TR	Abs.error		Visual
Hwang-Gu & Gau (2015)	DSM-IV & The Chinese K-SADS-E		12.3 (1.6)	87	223	12.7 (1.9)	81	84	TETR	Abs.errorCAAbs. errorCA		Visual
Kerns et al. (2001)	DSM-IV		9.4 (1.8)	67	21	9.3 (1.8)	67	21	TR	Abs.error		Visual
Khoshnoud et al. (2018)	DSM-IV		9.5 (1.7)	53	15	9.4 (1.3)	47	19	TR		CV	Visual
Marx et al. (2010)	DSM-IV & German version of K-SADS-PL	Children sample	9.8 (1.8)	100	20	9.8 (1.6)	100	20	TPTRTD	Abs.errorAbs.error	DL	Visual
		Adolescent sample	14.3 (1.2)	100	20	14.3 (1.2)	100	20				
Marx et al. (2017)	K-SADS-PL		10.6 (1.6)	100	17	9.5 (1.5)	100	18	TETPTR	Abs.errorCAAbs. errorCAAbs. errorCA		Visual
Meaux and Chelonis (2003)	DICA-IV DSM-IV		10.5 (0.9)	67	30	10.4 (0.8)	47	30	TR	Abs.errorCA		Visual
McInerney and Kerns (2003)	DICA-IV		10.1	90	30	10.1	90	30	TR	Abs.error		Visual
Mioni et al. (2017)	DSM-IV		10.9 (1.0)	78	23	10.9 (0.9)	71	24	TR	CA	CV	Visual
Mioni et al., (2019)	SDAI		8.8 (1.3)	NA	91	8.8 (1.3)	NA	91	TR	Abs.errorCA		Visual
Mullins et al. (2005)	DSM-IV	Combined subtype	9.3 (1.8)	84	20	10.1 (1.2)	80	64	TR	Abs.errorCA		Visual
		Inattentive subtype	10.4 (2.0)	80	19							
Plummer and Humphrey (2009)	DSM-IV-TR		12.8	65	20	12.8	65	20	TR	Abs.errorCA		Visual auditoryVisual + Auditory
Radonovich and Mostofsky (2004)	DSM-IV & DICA-IV		9.9 (1.5)	82	27	10.0 (1.2)	80	15	TD		DL	Auditory
Rommelse et al. (2007)	Not mentioned		11.9 (2.9)	81	226	11.4 (3.2)	40	162	TR	Abs.error		Visual + auditory
Smith et al. (2002)	ICD-10 or DSM-IV		11.3 (2.3)	86	22	11.2 (1.7)	91	22	TDTR	BP	Mean variability	Visual
Toplak and Tannock (2005)	DSM-IV		15.6 (1.4)	87	46	15.3 (1.4)	46	44	TD		DL	Visual auditory
Toplak et al. (2003)	DSM-IV	Children	8.9 (1.3)	78	31	9.3 (1.3)	60	50	TD		DL	Auditory
		Adolescent	15.2 (1.4)	59	35	15 (1.2)	46	39				
Valko et al. (2010)	DSM-IV		11 (2.1)	60	33	11 (2.1)	60	33	TR	Abs.error	SD of mean reproduction time	Visual
West et al. (2000)	DSM-IV	Inattentive subtype	10.7 (1.1)	100	14	10.1 (1.6)	100	44	TR	Abs.error		Visual auditory
		Combined subtype	9.9 (1.7)	100	30							
Yang et al. (2007)	DSM-IV		8.5 (1.6)	80	40	8.6 (1.4)	85	40	TD		DL	Visual

Note. DSM: Diagnostic and Statistics Manual; ICD: International Statistical Classification of Diseases and Related Health Problems; K-SADS: The Kiddie Schedule for Affective Disorders and Schizophrenia; K-SADS-PL: Kiddie-SADS-Present and Lifetime Version; K-SADS-E: Kiddie epidemiologic version of the Schedule for Affective Disorders and Schizophrenia; DICA-IV: The Diagnostic Interview for Children and Adolescents IV; SD = Standard deviation; N= sample size; Abs.error = absolute error; BP = Bisection point (Point of subjective equality); DL = Difference limen; CV = Coefficient of variation; CA = coefficient of accuracy; NA = not applicable.
Empty cells represent missing information in studies.

Table 2. Standardized Mean Differences (Hedge's *g*) Between ADHD and Control Groups for Accuracy and Precision of Time Perception.

	Study *N*	Trial *n*	Hedge's *g*	CI_L, CI_U	*t*	*p*	*Tau*^{2}	I^2(%)	*Q*	Df	P_Q
Absolute error in accuracy											
Outliers included	18	29	0.65	[0.39, 0.90]	5.22	<.001	0.31	80.8	146.00	28	<.001
Outlier-corrected	16	26	0.46	[0.36, 0.56]	9.52	<.001	0.01	23.5	32.66	25	.14
Signed accuracy											
Outliers included	9	16	−0.38	[−0.68, −0.09]	−2.79	.01	0.21	72.0	53.64	15	<.001
Outlier-corrected	8	13	−0.44	[−0.58, −0.30]	−6.76	<.001	0.01	12.0	13.64	12	.32
Precision											
(No outliers)	11	13	0.66	[0.50, 0.81]	9.34	<.001	0.02	13.7	13.91	12	.31

Note. *N*: number of studies; *n*: number of trials included in the model; *g*: pooled effect size estimate; CI_L: the lower bound of the 95% confidence interval; CI_U: the upper bound of the 95% confidence interval; Tau^2: between-study variance; I^2: percentage of variability in the effect sizes; *Q*: Cochran's *Q* (between-group heterogeneity); P_Q: the *p* value of Cochran's Q.

bisection point (BP) represent another type of indicator that provides information on the direction of estimation, that is, signed accuracy. For TE and bisection tasks (one type of TD tasks that use BP as a measure), a positive *g* indicated a larger overestimation of the target time interval for the ADHD group, whereas for the other two task paradigms (TR and TP), a positive *g* indicated a larger underestimation of duration for the ADHD group than the control group. Hence, we reversed the sign of *g* for the TE and bisection tasks, so that the effect sizes across all four task types were comparable. After reversing the sign for *g* for TE and bisection tasks, a positive value of *g* indicated an underestimation of duration for the ADHD group relative to the healthy control group while a negative value of *g* showed vice versa. Similarly, for the measures of precision (difference limen, coefficient variation, standard deviation of time production), a positive value of *g* indicated a lower precision of time judgment for individuals with ADHD compared to their typically developing peers.

Most studies reported more than one pair of comparison due to the inclusion of various time length intervals in a particular task in those studies. In this case, we averaged the values of *g* across the same task and computed V_g according to equation (4). The average effect sizes (see Appendix 2) were used to measure the potential effect of ADHD on the accuracy and precision in time perception, and whether the effect would differ across different task paradigms and modalities of stimuli.

Moderator variables. As the age range involved in this meta-analysis was broad (i.e., from 6 to 19), we included the mean age of the sample in each study as a moderator to account for the effect of age. Furthermore, as ADHD is found to be more prevalent in boys, the gender ratio (i.e., the percentage of boys in each study) was also incorporated as another moderator variable to account for the gender effect.

Analyses

All the analyses were conducted using R (R Core Team, 2019), with the packages of "meta" (Balduzzi et al., 2019), "metafor" (Viechtbauer, 2010), "tidyverse" (Wickham et al., 2019), and "dmetar" (Harrer et al., 2019). Random-effect-models were used to estimate the pooled effect sizes. The effects of moderators, including age, gender, task paradigm, and stimulus modality were evaluated using random-effects meta-regression models. Outliers were identified by the "find.outlier" function in the "dmetar" package in R. The heterogeneity was assessed by Cochran's *Q*—the difference between the observed effect sizes and the fixed-effect model estimate; Tau-squared—the between-study variance; and I^2—the percentage of variability in the effect sizes (Higgins & Thompson 2002). The interpretation of I^2 was based on the "rule of thumb" proposed by Higgins et al. (2003), which suggests that low, moderate, and substantial heterogeneities should correspond to the values of 25%, 50%, and 75% respectively. The possibility of publication bias was indicated by the asymmetry of funnel plots tested using the Egger's test (Egger et al., 1997). A significant result of Egger's test denotes substantial asymmetry in the funnel plot, which suggests possibility of publication bias. In such cases, the trim-and-fill procedure (Duval & Tweedie, 2000) would be adopted to estimate the actual effect sizes. Furthermore, the fail-safe N calculation (Rosenthal, 1979) would be used to evaluate the publication bias.

Results

Accuracy and Precision in Time Perception

A random-effects-model was used to estimate the pooled effect sizes. The standardized mean differences (Hedges' *g*) between the ADHD and the control groups in the 27 studies are presented in Table 2 and Figure 2.

Using the function of "find.outliers" in "dmetar" package in R, studies with confidence intervals (CI) of effect

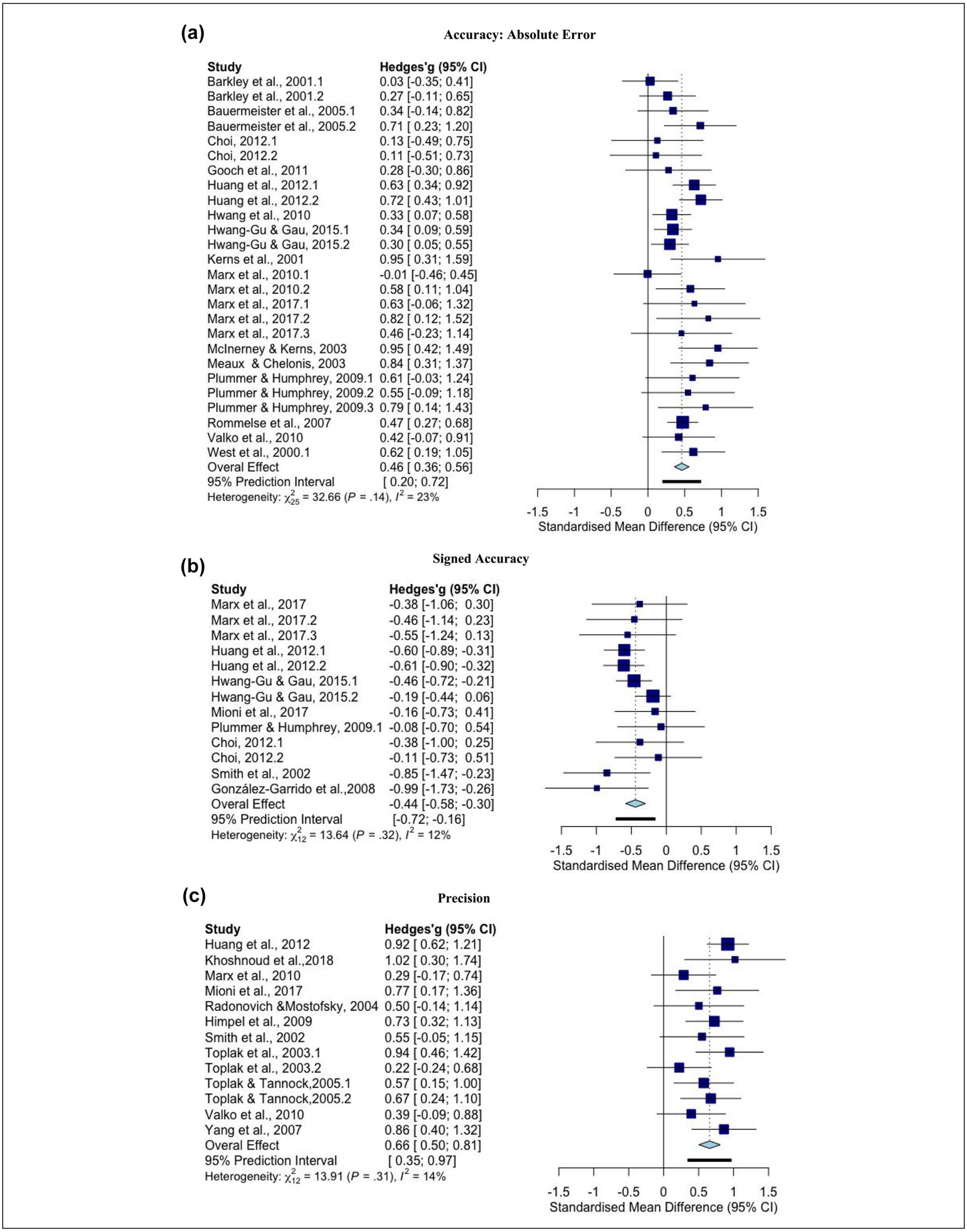

Figure 2. Forest plots showing standardized mean differences (Hedges' *g*) and the corresponding 95% confidence intervals (CI) for: (a) accuracy: absolute error, (b) signed accuracy, and (c) precision across included samples.

sizes outside the limits of the 95% CI of the pooled effect size were excluded. For absolute error in accuracy, Mioni et al. (2019), Mullins et al. (2005), and West et al. (2002) were identified as outliers. After excluding these outliers, the estimated standardized mean difference (Hedges' *g*) for absolute error was .46 (95% CI = [0.36, 0.56], $p < .001$), suggesting that a significantly larger absolute error in accuracy was displayed by the ADHD group when compared to the control group. The overall pooled effect size was nearly moderate. The inter-study heterogeneity was not significant, $Q(25) = 23.5$, $p = .14$, and corresponded to an I^2 of 23.5%. Thus, the studies were overall consistent, with low heterogeneity ($I^2 < 25\%$). The Egger's test (Egger et al., 1997) indicated an insignificant asymmetry in the funnel plot, $t = 1.06$, $p = .30$, suggesting a low risk of publication bias. As such, no studies were trimmed. The fail-safe N calculation revealed that an additional 2337 trials ($p < .001$) were required before the cumulative effect became statistically nonsignificant.

For signed accuracy, as the direction of deviation was indicated by the sign of *g*, those studies that did not provide sufficient information for calculating the sign of *g* were excluded. Mullins et al. (2005) and Plummer and Humphrey (2009) were identified as outliers and further excluded from the analyses. As a result, only 13 trials from 8 studies were included in the analysis. The estimated effect size for signed accuracy was −0.44 (95% CI = [−0.58, −0.30], $p < .001$), suggesting that children with ADHD overestimated time more than their typically developing peers. The inter-study heterogeneity was not significant after excluding the outliers, $Q(12) = 13.64$, $p = .32$, and corresponded to an I^2 of 12.0%. The Egger's test revealed an insignificant asymmetry in the funnel plot, $t = -0.15$, $p = .88$, suggesting a low risk of publication bias. The fail-safe N calculation showed that an additional 218 trials ($p < .001$) were required before the cumulative effect became statistically nonsignificant.

The estimated standardized mean difference for precision was .66 (95% CI = [0.50, 0.81], $p < .001$), suggesting that participants with diagnosis of ADHD perceived time less precisely than their typically developing peers. No outliers were detected among the 11 studies that reported measures of precision. The interstudy heterogeneity was not significant, $Q(12) = 13.91$, $p = .31$, and corresponded to an I^2 of 13.7%. The Egger's test reported an insignificant asymmetry in the funnel plot, $t = -0.84$, $p = .42$, which signified a low risk of publication bias. The fail-safe *N* calculation showed that an additional 446 trials ($p < .001$) were required before the cumulative effect became statistically nonsignificant.

Moderator Analyses

Results of the meta-regression analyses with age, gender, task paradigm, and stimulus modality as moderators are summarized in Table 3. For absolute error in accuracy, age served as a significant moderator of the time perception difference between ADHD and control groups ($\beta = -0.07$, 95% CI = [−0.11, −0.03], $t = 3.66$, $p = .001$), suggesting that the older the participants in the studies, the smaller the between-group difference obtained. For gender, male ratio in each group was coded as a moderator, and between-group difference in gender ratio was dummy-coded as a binary factor to indicate whether the ratio of male in each group was the same. Results showed that neither the gender ratio in each group (ADHD: $\beta = -0.13$, 95% CI = [−0.99, 0.74], $t = -0.30$, $p = .77$; Control: $\beta = -0.09$, 95% CI = [−0.62, 0.44], $t = -0.35$, $p = .73$) nor the difference in gender ratio between groups ($\beta = -0.16$, 95% CI = [−0.38, 0.05], $t = -1.60$, $p = .12$) affected the between-group difference in time perception. Furthermore, task paradigm ($\beta = 0.13$, 95% CI = [−0.04, 0.30], $t = 1.57$, $p = .13$) and stimulus modality ($\beta = 0.04$, 95% CI = [−0.08, 0.16], $t = 0.66$, $p = .51$) both did not affect the between-group difference as shown by the meta-regression analyses.

For signed accuracy, there was a significant effect of age on between-group difference in time perception ($\beta = 0.07$, 95% CI = [0.006, 0.14], $t = 2.42$, $p = .03$), indicating that the older the participants, the less overestimation of time revealed in the ADHD group in contrast to the control group. For gender, both the male ratios in the ADHD group ($\beta = -1.79$, 95% CI = [−3.19, −0.39], $t = -2.81$, $p = .02$) and the control group ($\beta = -1.95$, 95% CI = [−3.23, −0.67], $t = -3.35$, $p = .006$) significantly affected the time perception group difference, meaning that the more males there were in either group, the more overestimation of time observed in the ADHD group in comparison with the control group. However, gender ratio difference between groups did not moderate the between-group difference in time perception ($\beta = 0.03$, 95% CI = [−0.36, 0.42], $t = 0.16$, $p = .88$). Both task paradigm ($\beta = 0.002$, 95% CI = [−0.16, 0.17], $t = 0.03$, $p = .98$) and stimulus modality ($\beta = 0.22$, 95% CI = [−0.10, 0.53], $t = 1.52$, $p = .16$) did not affect the between-group difference in signed accuracy of time perception.

For precision in time perception, the effect of age on between-group difference was significant ($\beta = -0.06$, 95% CI = [−0.11, −0.01], $t = -2.79$, $p = .02$). The male ratios in the ADHD group ($\beta = 0.04$, 95% CI = [−0.05, 0.14], $t = 1.03$, $p = 0.32$) and the control group ($\beta = 0.04$, 95% CI = [−0.05, 0.14], $t = 1.02$, $p = .33$), and the gender ratio difference between groups ($\beta = 0.26$, 95% CI = [−0.13, 0.64], $t = 1.45$, $p = 0.17$) did not affect the group difference in time perception precision. Moreover, both task paradigm ($\beta = -0.04$, 95% CI = [−0.44, 0.36], $t = -0.21$, $p = .84$) and stimulus modality ($\beta = -0.12$, 95% CI = [−0.44, 0.20], $t = -0.84$, $p = .42$) did not significantly affect the between-group difference in time perception precision.

Discussion

Based on a total sample of 1620 children and adolescents with ADHD and 1249 healthy controls from 27 studies, this

Table 3. Meta-regression analyses with age, gender, task paradigm, and stimulus modality as moderators.

Moderator	β	SE	CI_L, CI_U	*t*	*p*
Accuracy (absolute error)					
Mean age	−0.07	0.02	[−0.11, −0.03]	−3.66	.001**
% of male in ADHD group	−0.13	0.42	[−0.99, 0.74]	−0.30	.77
% of male in control group	−0.09	0.26	[−0.62, 0.44]	−0.35	.73
Gender ratio difference between groups	−0.16	0.10	[−0.38, 0.05]	−1.60	.12
Task paradigm	0.13	0.08	[−0.04, 0.30]	1.57	.13
Stimuli modality	0.04	0.06	[−0.08, 0.16]	0.66	.51
Signed accuracy					
Mean age	0.07	0.03	[0.006, 0.14]	2.42	.03*
% of male in ADHD group	−1.79	0.64	[−3.19, −0.39]	−2.81	.02*
% of male in control group	−1.95	0.58	[−3.23, −0.67]	−3.35	.006**
Gender ratio difference between groups	0.03	0.18	[−0.36, 0.42]	0.16	.88
Task paradigm	0.002	0.07	[−0.16, 0.17]	0.03	.98
Stimuli modality	0.22	0.14	[−0.10, 0.53]	1.52	.16
Precision					
Mean age	−0.06	0.02	[−0.11, −0.01]	−2.79	.02*
% of male in ADHD group	0.04	0.04	[−0.05, 0.14]	1.03	.32
% of male in control group	0.04	0.04	[−0.05, 0.14]	1.02	.33
Gender ratio difference between groups	0.26	0.18	[−0.13, 0.64]	1.45	.17
Task paradigm	−0.04	0.18	[−0.44, 0.36]	−0.21	.84
Stimuli modality	−0.12	0.14	[−0.44, 0.20]	−0.84	.42

Note. $^{**}p < .01$, $^{*}p < .05$.

meta-analysis examined whether there were significant differences in time perception between ADHD and control groups among participants aged 6 to 19.

Accuracy and Precision in Time Perception

Overall, children and adolescents with ADHD showed lower accuracy in judging the duration of time compared to their typically developing peers and the overall pooled effect size was moderate. The results of the signed accuracy analysis indicated that children with ADHD displayed stronger tendencies than the healthy controls to overestimate time across all types of tasks.

These findings are in line with the hypothesis of a "faster internal clock" that prevails in individuals with ADHD (Walg et al., 2017). The faster-running internal clock might cause the individuals with ADHD to perceive time intervals as longer than actual, and hence more likely to overestimate time. Deficits in working memory and attention, which are pervasive in ADHD, are found to be associated with the timing functions among individuals with ADHD (Noreika et al., 2013). According to the pacemaker-counter model (Treisman, 1963), a reference duration is held in the long-term memory for comparison with the currently timed duration. Working memory plays a crucial role in accurately registering the temporal pulses emitted by the pacemaker in the timing process. Hence, working memory deficits obstructing the registration of counts might lead to lower temporal sensitivity in the ADHD group (Toplak et al., 2003).

Alternatively, the tendency to overestimate time among individuals with ADHD may also be explained by the DAT, which posits that the allocation of attention to more stimulating—rather than boring—events might lead to duration overestimation (Tse et al., 2010). Individuals with ADHD may likely be constantly shifting their focus of attention and searching for more stimulating objects and events in the surroundings, therefore registering more attentional pulses and consequently perceiving time as longer. In fact, it has been pointed out that the lack of sustained attention to temporal intervals might have contributed to the poor performance of individuals with ADHD in time perception tasks (Noreika et al., 2013). For instance, lower attentiveness in children diagnosed with ADHD has been shown to relate to their subpar performance in time discrimination tasks in contrast to typically developing children (Rubia et al., 2007).

For precision in time perception, children/adolescents with ADHD made more variable judgments of time relative to the healthy controls. This difference was consistently observed across all task paradigms and stimulus modalities. The SET postulates that a constant ratio exists between the variability of duration judgment and the mean of the objective duration, known as the Weber's ratio (Gibbon, 1977). Timing performance of typically developing individuals, despite fluctuations observed in the Weber's ratio (for review, see Grondin, 2010), generally follows the scalar property presumed by the SET. Our results indicated lower precision and higher variability in time perception for children and adolescents with ADHD. The lack of precision in duration judgments may reflect a violation of the scalar property of the Weber's ratio in individuals with ADHD. This violation is often considered as an indicator of pathological conditions (Buhusi & Meck, 2005).

Moreover, lower timing precision in the ADHD children/adolescents might also be due to unrefined motor timing skills. A case study in which a 9-year-old boy diagnosed with ADHD was reported to improve in timing accuracy after 7 weeks of metronomic limb movement training demonstrated the importance of motor skills to timing functions (Bartscherer et al., 2005). Children with ADHD have been found to demonstrate a higher reaction time variability (Kofler et al., 2013) as well as slower and more variable motor outputs than their non-affected siblings, and the variability in motor timing was found to be associated with ADHD (Rommelse et al., 2007). Hence, the higher variability in motor processing and motor timing in ADHD might provide a plausible explanation for the lower precision in timing observed in children and adolescents with ADHD in the current study.

The deficits in accuracy and precision in time perception might partially explain why children with ADHD often show weaker time management skills (Abikoff et al., 2013; Barkley, 1997). Time management involves higher cognitive processes that comprise the abilities to estimate time, order events chronologically, and allocate appropriate amount of time to different activities (Abikoff et al., 2013). A lower precision in time perception might likely imply more significant problems in planning and managing time encountered in everyday life. This knowledge regarding time perception deficits in children and adolescents with ADHD may inform future directions of interventions for children with ADHD.

Effects of Moderators on Time Perception

Results from the meta-regression analyses showed no significant effects of task paradigm and stimulus modality on the difference in timing performance between individuals with and without ADHD. The invariance of between-group differences across task paradigms suggested an overall timing deficit in ADHD, regardless of the presentation of timing tasks. The insignificant effect of stimulus modality provides evidence against the contention that stimuli presented visually in time perception tasks are less accurately perceived by children/adolescents than auditory stimuli.

As hypothesized, age is a significant moderator of group differences in time perception accuracy between individuals with and without ADHD. Our results demonstrated that older children with ADHD were more aligned with their healthy counterparts in time perception accuracy than did the younger children—that is, their time perception became more accurate, and they were less likely to overestimate temporal durations with increasing age. Furthermore, our results revealed a significant effect of age on the between-group difference in time perception precision, showing that the difference in the precision of timing between ADHD and non-ADHD groups also reduced as age increased. In sum, our findings suggested that as children with ADHD grow up, their time perception abilities improve in terms of both accuracy and precision, and become more comparable to their typically developing peers. Hence, although the between-group differences in time perception remain significant, children with ADHD are apparently catching up with their typically developing peers as they age, similar to the situation for other ADHD symptoms which are observed to lessen with age due to maturation (Berger et al., 2013; Faraone et al., 2006; Hart et al., 1995).

Gender appears to affect the between-group discrepancies in time perception as well. When there were more males in the study samples, larger overestimation of time in the ADHD group was observed in comparison with the control group. Such results could indicate two possibilities. First, males tend to overestimate time more than females in general, which is unlikely as a prior meta-analysis found a small but significant effect of gender favoring the males (Block et al., 2000). Second, it may suggest that ADHD has a larger impact on time perception in males than in females. Our results showed that a higher ratio of males in the ADHD group was associated with a larger overestimation of time in this group, suggesting that time perception in boys might be more affected by the ADHD condition than girls. This finding is in line with the results from a prior study which showed that girls with ADHD were more accurate than boys with ADHD in time reproduction (Plummer & Humphrey, 2009).

Limitations of the Study

First, the number of studies found and included in this meta-analysis is relatively small, which might induce biases in the meta-analytical results. Furthermore, the current study did not investigate the diversity of time perception across different ADHD subtypes, mainly due to the lack of subtype information reported in the original studies. Previous findings showed that more severe symptoms of inattention were associated with less accurate timed responses only in the inattentive subtype but not in the combined subtype (Bluschke et al., 2018). Future studies may examine the diverse patterns of time perception performance across different ADHD subtypes in time perception. Lastly, medication status was not taken into account in the meta-analysis. If more studies can provide information about the medication status of their participants, it will be of high value to examine whether medication may affect the difference in time perception abilities between children with and without ADHD.

Conclusion

To summarize, results of our meta-analysis showed that children and adolescents with ADHD performed substantially worse than their typically developing peers in both accuracy and precision in time perception. Young individuals with ADHD seemed to overestimate time intervals and sense time as dragging more than their healthy counterparts. Our findings concur with the proposition of a “faster internal clock” in individuals with ADHD. Age and gender have significant effects on group differences in time perception between ADHD and control groups. Although the difference in time perception remained significant, children with ADHD become more comparable to their healthy counterparts as they grow up. The male ratios in both ADHD and control groups have significant effects on group comparison in time perception. However, the difference in time perception abilities did not significantly depend on task paradigm or stimulus modality.

The meta-analyses results revealed a salient impairment in time perception among young individuals with ADHD compared to their healthy counterparts. With reference to the current findings, time perception deficit may be considered as another important neuropsychological manifestation of ADHD, apart from executive dysfunction and delay aversion. Hence, clinical assessment of ADHD may try to include measures of time perception as markers of timing deficits in ADHD. This might contribute to providing a more comprehensive profile of the functioning of the individuals and inform treatment plans. We also recommend that interventions for children/adolescents with ADHD may incorporate training to enhance time perception competence of the individuals to facilitate better planning and time management in their everyday life.

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References

(References marked with an asterisk indicate studies included in the meta-analysis)

Abikoff, H., Gallagher, R., Wells, K. C., Murray, D. W., Huang, L., Lu, F., & Petkova, E. (2013). Remediating organizational functioning in children with ADHD: Immediate and long-term effects from a randomized controlled trial. *Journal of Consulting and Clinical Psychology*, *81*(1), 113–128. https://doi.org/10.1037/a0029648

Allman, M. J., & Meck, W. H. (2012). Pathophysiological distortions in time perception and timed performance. *Brain*, *135*(3), 656–677. https://doi.org/10.1093/brain/awr210

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (DSM-5®)*. American Psychiatric Pub.

Ashcraft, M. H. (2002). *Cognition* (3rd ed.). Prentice Hall.

Balduzzi, S., Rücker, G., & Schwarzer, G. (2019). How to perform a meta-analysis with R: A practical tutorial. *Evidence-Based Mental Health*, *22*(4).

Baldwin, R. O., Thor, D. H., & Wright, D. E. (1966). Sex differences in the sense of time: Failure to replicate a 1904 study. *Perceptual and Motor Skills*, *22*(2), 398. https://doi.org/10.2466/pms.1966.22.2.398

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*(1): 65–94. https://doi.org/10.1037/0033-2909.121.1.65

*Barkley, R. A., Edwards, G., Laneri, M., Fletcher, K., & Metevia, L. (2001). Executive functioning, temporal discounting, and sense of time in adolescents with attention deficit hyperactivity disorder (ADHD) and oppositional defiant disorder (ODD). *Journal of Abnormal Child Psychology*, *29*(6), 541–556. https://doi.org/10.1023/a:1012233310098

Bartscherer, M. L., Bartscherer, M. L., & Dole, R. L. (2005). Interactive Metronome® training for a 9-year-old boy with attention and motor coordination difficulties. *Physiotherapy Theory and Practice*, *21*(4), 257–269. https://doi.org/10.1080/09593980500321085

*Bauermeister, J. J., Barkley, R. A., Martinez, J. V, Cumba, E., Ramirez, R. R., Reina, G., Matos M Salas, C. C. (2005). Time estimation and performance on reproduction tasks in subtypes of children with attention deficit hyperactivity disorder. *Journal of Clinical Child and Adolescent Psychology*, *34*(1). https://doi.org/10.1207/s15374424jccp3401_14

Berger, I., Slobodin, O., Aboud, M., Melamed, J., & Cassuto, H. (2013). Maturational delay in ADHD: evidence from CPT. *Frontiers in Human Neuroscience*,*7*. https://doi.org/10.3389/fnhum.2013.00691

Block, R. A., Hancock, P. A., & Zakay, D. (2000). Sex differences in duration judgments: A meta-analytic review. *Memory & Cognition*, *28*(8), 1333–1346. https://doi.org/10.3758/bf03211834

Block, R. A., Zakay, D., & Hancock, P. A. (1998). Human aging and duration judgments: A meta-analytic review. *Psychology and Aging*, *13*(4), 584–596. https://doi.org/10.1037/0882-7974.13.4.584

Bluschke, A., Schuster, J., Roessner, V., & Beste, C. (2018). Neurophysiological mechanisms of interval timing dissociate inattentive and combined ADHD subtypes. *Scientific Reports*. https://doi.org/10.1038/s41598-018-20484-0

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2009). *Introduction to Meta-Analysis. Introduction to Meta-Analysis*. John Wiley & Sons, Ltd.

Buhusi, C. V., & Meck, W. H. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews Neuroscience*, *6*(10), 755–765. https://doi.org/10.1038/nrn1764

*Choi, P. K. (2012). The role of divided attention and selective attention in time perception deficit of children with attention deficit hyperactivity disorder (Doctoral dissertation, The University of Hong Kong, Hong Kong).

Cohen, J. (1988). *Statistical power analysis for the behavioural sciences*. Lawrence Earlbaum Associates.

Droit-Volet, S., Meck, W. H., & Penney, T. B. (2007). Sensory modality and time perception in children and adults. *Behavioural Processes*, *74*(2), 244–250. https://doi.org/10.1016/j.beproc.2006.09.012

Duval, S., & Tweedie, R. (2000). Trim and fill: A simple funnel-plot–based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*, *56*(2), 455–463.http://www.jstor.org/stable/2676988.

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *Bmj*, *315*(7109), 629–634. https://doi.org/10.1136/bmj.315.7109.629

Eisler, H., & Eisler, A. D. (1992). Time perception: Effects of sex and sound intensity on scales of subjective duration. *Scandinavian Journal of Psychology*, *33*(4), 339–358. https://doi.org/10.1111/j.1467-9450.1992.tb00923.x

Espinosa-Fernández, L., Miró, E., Cano, M., & Buela-Casal, G. (2003). Age-related changes and gender differences in time estimation. *Acta Psychologica*, *112*(3), 221–232. https://doi.org/10.1016/s0001-6918(02)00093-8

Faraone, S. V., Biederman, J., & Mick, E. (2006). The age-dependent decline of attention deficit hyperactivity disorder: a meta-analysis of follow-up studies. *Psychological Medicine*, *36*(2), 159. https://doi.org/10.1017/s003329170500471x

Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review*, *84*(3), 279–325. https://doi.org/10.1037/0033-295x.84.3.279

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of sciences*, *423*(1), 52–77. https://doi.org/10.1111/j.1749-6632.1984.tb23417.x

*González-Garrido, A. A., Gómez-Velázquez, F. R., Zarabozo, D., López-Elizalde, R., Ontiveros, A., Madera-Carrillo, H., Vega, O. L., Alba, O. D. J. L., & Tuya, J. D. L. S. (2008). Time reproduction disturbances in ADHD children: An ERP study. *International Journal of Neuroscience*, *118*(1), 119–135. https://doi.org/10.1080/00207450601042177

*Gooch, D., Snowling, M., & Hulme, C. (2011). Time perception, phonological skills and executive function in children with dyslexia and/or ADHD symptoms. *Journal of Child Psychology and Psychiatry*, *52*(2), 195–203. https://doi.org/10.1111/j.1469-7610.2010.02312.x

Grondin, S. (2010). Timing and time perception: a review of recent behavioral and neuroscience findings and theoretical directions. *Attention, Perception, & Psychophysics*, *72*(3), 561–582. https://doi.org/10.3758/app.72.3.561

Hammerschmidt, D., & Woellner, C. (2019). Sensorimotor Synchronization with higher metrical levels in music shortens perceived time. *Music Perception*, 263–277. https://doi.org/10.1525/mp.2020.37.4.263

Hancock, P. A., Arthur, E. J., Chrysler, S. T., & Lee, J. (1994). The effects of sex, target duration, and illumination on the production of time intervals. *Acta Psychologica*, *86*(1), 57–67. https://doi.org/10.1016/0001-6918(94)90011-6

Hancock, P. A., & Rausch, R. (2010). The effects of sex, age, and interval duration on the perception of time. *Acta Psychologica*, *133*(2), 170–179. https://doi.org/10.1016/j.actpsy.2009.11.005

Hancock, P. A., Vercruyssen, M., & Rodenburg, G. J. (1992). The effect of gender and time-of-day on time perception and mental workload. *Current Psychology*, *11*(3), 203–225. https://doi.org/10.1007/bf02686841

Harrer, M., Cuijpers, P., Furukawa, T., & Ebert, D. D. (2019). dmetar: Companion R Package For The Guide 'Doing Meta-Analysis in R'. R package version 0.*0*.9000.

Hart, E. L., Lahey, B. B., Loeber, R., Applegate, B., & Frick, P. J. (1995). Developmental change in attention-deficit hyperactivity disorder in boys: A four-year longitudinal study. *Journal of Abnormal Child Psychology*, *23*(6), 729–749. https://doi.org/10.1007/bf01447474

Hedges, L. (1981). Distribution theory for Glass's estimator of effect size and related estimators. *Journal of Educational Statistics*, *6*, 107–128. https://doi.org/10.3102/10769986006002107

Higgins, J. P., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in medicine*, *21*(11), 1539–1558. https://doi.org/10.1002/sim.1186

Higgins, J. P. T., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. *British Medical Journal*, *327*(7414): 557–560. https://doi.org/10.1136/bmj.327.7414.557

*Himpel, S., Banaschewski, T., Grüttner, A., Becker, A., Heise, A., Uebel, H., Albrecht, B., Rothenberger, A., & Rammsayer, T. (2009). Duration discrimination in the range of milliseconds and seconds in children with ADHD and their unaffected siblings. *Psychological Medicine*, *39*(10), 1745–1751. https://doi.org/10.1017/s003329170900542x

*Huang, J., Yang, B. rang, Zou, X. bing, Jing, J., Pen, G., McAlonan, G. M., & Chan, R. C. K. (2012). Temporal processing impairment in children with attention-deficit-hyperactivity disorder. *Research in Developmental Disabilities*, *33*(2), 538–548. https://doi.org/10.1016/j.ridd.2011.10.021

Hurks, P. P. M., & Hendriksen, J. G. M. (2010). Retrospective and prospective time deficits in childhood ADHD: The effects of task modality, duration, and symptom dimensions. *Child Neuropsychology*, *17*(1), 34–50. https://doi.org/10.1080/09297049.2010.514403

*Hwang, S. L., Gau, S. S. F., Hsu, W. Y., & Wu, Y. Y. (2010). Deficits in interval timing measured by the dual-task paradigm among children and adolescents with attention-deficit/hyperactivity disorder. *Journal of Child Psychology and Psychiatry*, *51*(3), 223–232. https://doi.org/10.1111/j.1469-7610.2009.02163.x

*Hwang-Gu, S. L., & Gau, S. S. F. (2015). Interval timing deficits assessed by time reproduction dual tasks as cognitive endophenotypes for attention-deficit/hyperactivity disorder. *PloS one*, *10*(5). https://doi.org/10.1371/journal.pone.0127157

Jones, M. R., & Boltz, M. (1989). Dynamic Attending and Responses to Time. *Psychological Review*, *96*(3), 459–491. https://doi.org/10.1037/0033-295x.96.3.459

*Kerns, K. A., McInerney, R. J., & Wilde, N. J. (2001). Time reproduction, working memory, and behavioral inhibition in children with ADHD. *Child Neuropsychology*, *7*(1), 21–31. https://doi.org/10.1076/chin.7.1.21.3149

*Khoshnoud, S., Shamsi, M., Nazari, M. A., & Makeig, S. (2018). Different cortical source activation patterns in children with attention deficit hyperactivity disorder during a time reproduction task. *Journal of Clinical and Experimental Neuropsychology*, *40*(7), 633–649. https://doi.org/10.1080/13803395.2017.1406897

Kofler, M. J., Rapport, M. D., Sarver, D. E., Raiker, J. S., Orban, S. A., Friedman, L. M., & Kolomeyer, E. G. (2013). Reaction time variability in ADHD: A meta-analytic review of 319 studies. *Clinical Psychology Review*, *33*(6), 795–811. https://doi.org/10.1016/j.cpr.2013.06.001

MacDougall, R. (1904). Sex differences in the sense of time. *Science*, *19*, 707–708. https://doi.org/10.1126/science.19.487.707

*Marx, I., Hübner, T., Herpertz, S. C., Berger, C., Reuter, E., Kircher, T., Herpertz-Dahlmann, B., & Konrad, K. (2010). Cross-sectional evaluation of cognitive functioning in children, adolescents and young adults with ADHD. *Journal of Neural Transmission*, *117*(3), 403–419. https://doi.org/10.1007/s00702-009-0345-3

*Marx, I., Weirich, S., Berger, C., Herpertz, S. C., Cohrs, S., Wandschneider, R., Höppner, J., & Häßler, F. (2017). Living in the fast lane: Evidence for a global perceptual timing deficit in childhood adhd caused by distinct but partially overlapping task-dependent cognitive mechanisms. *Frontiers in Human Neuroscience*, *11*, 122. https://doi.org/10.3389/fnhum.2017.00122

*McInerney, R. J., & Kerns, K. A. (2003). Time reproduction in children with ADHD: Motivation matters. *Child Neuropsychology : A Journal on Normal and Abnormal Development in Childhood and Adolescence*, *9*(2), 91–108. https://doi.org/10.1076/chin.9.2.91.14506

*Meaux, J. B., & Chelonis, J. J. (2003). Time perception differences in children with and without ADHD. *Journal of Pediatric Health Care*, *17*(2), 64–71. https://doi.org/10.1016/s0891-5245(02)88326-2

*Mioni, G., Capodieci, A., Biffi, V., Porcelli, F., & Cornoldi, C. (2019). Difficulties of children with symptoms of attention-deficit/hyperactivity disorder in processing temporal information concerning everyday life events. *Journal of Experimental Child Psychology*, *182*, 86–101. https://doi.org/10.1016/j.jecp.2019.01.018

*Mioni, G., Santon, S., Stablum, F., & Cornoldi, C. (2017). Time-based prospective memory difficulties in children with ADHD and the role of time perception and working memory. *Child Neuropsychology*, *23*(5), 588–608. https://doi.org/10.1080/09297049.2016.1172561

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G., The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Med 6*(7): e1000097. https://doi.org/10.1371/journal.pmed1000097

Moola, S., Munn, Z., Tufanaru, C., Aromataris, E., Sears, K., Sfetcu, R., Currie, M., Qureshi, R., Mattis, P., Lisy, K., & Mu, P-F. Chapter 7: Systematic reviews of etiology and risk. In: Aromataris E, Munn Z (Editors). *For Evidence Synthesis*. JBI, 2020. https://synthesismanual.jbi.global

*Mullins, C., Bellgrove, M. A., Gill, M., & Robertson, I. H. (2005). Variability in time reproduction: Difference in ADHD combined and inattentive subtypes. *Journal of the American Academy of Child and Adolescent Psychiatry*, *44*(2), 169–176. https://doi.org/10.1097/00004583-200502000-00009

Neufang, S., Fink, G. R., Herpertz-Dahlmann, B., Willmes, K., & Konrad, K. (2008). Developmental changes in neural activation and psychophysiological interaction patterns of brain regions associated with interference control and time perception. *NeuroImage*, *43*(2), 399–409. https://doi.org/10.1016/j.neuroimage.2008.07.039

Noreika, V., Falter, C. M., & Rubia, K. (2013). Timing deficits in attention-deficit/hyperactivity disorder (ADHD): Evidence from neurocognitive and neuroimaging studies. *Neuropsychologia*, *51*(2), 235–266. https://doi.org/10.1016/j.neuropsychologia.2012.09.036

*Plummer, C., & Humphrey, N. (2009). Time perception in children with ADHD: The effects of task modality and duration. *Child Neuropsychology*, *15*(2), 147–162. https://doi.org/10.1080/09297040802403690

Pollak, Y., Kroyzer, N., Yakir, A., & Friedler, M. (2009). Testing possible mechanisms of deficient supra-second time estimation in adults with attention-deficit/hyperactivity disorder. *Neuropsychology*, *23*(5), 679. https://doi.org/10.1037/a0016281

Pöppel, E. (1989). The measurement of music and the cerebral clock: A new theory. *Leonardo*, *22*(1), 83. https://doi.org/10.2307/1575145

R Core Team (2019). R: A language and environment for statistical computing. *R Foundation for Statistical Computing, Vienna, Austria*.

*Radonovich, K. J., & Mostofsky, S. H. (2004). Duration judgments in children with ADHD suggest deficient utilization of temporal information rather than general impairment in timing. *Child Neuropsychology*, *10*(3), 162-172. https://doi.org/10.1080/09297040409609807

Rammsayer, T., & Lustnauer, S. (1989). Sex differences in time perception. *Perceptual and Motor Skills*, *68*(1), 195–198. https://doi.org/10.2466/pms.1989.68.1.195

Ramtekkar, U. P., Reiersen, A. M., Todorov, A. A., & Todd, R. D. (2010). Sex and age differences in attention-deficit/hyperactivity disorder symptoms and diagnoses: implications for DSM-V and ICD-11. *Journal of the American Academy of Child & Adolescent Psychiatry*, *49*(3), 217–228. https://doi.org/10.1016/j.jaac.2009.11.011

Rosenthal, R. (1979). The file drawer problem and tolerance for null results. *Psychological Bulletin*, *86*(3), 638. https://doi.org/10.1037/0033-2909.86.3.638

Rommelse, N. N. J., Altink, M. E., Oosterlaan, J., Beem, L., Buschgens, C. J. M., Buitelaar, J., & Sergeant, J. A. (2007). Speed, variability, and timing of motor output in ADHD: Which measures are useful for endophenotypic research? *Behavior Genetics*, *38*(2), 121–132. https://doi.org/10.1007/s10519-007-9186-8

*Rommelse, N. N., Oosterlaan, J., Buitelaar, J., Faraone, S. V., & Sergeant, J. A. (2007). Time reproduction in children with ADHD and their nonaffected siblings. *Journal of the American Academy of Child & Adolescent Psychiatry*, *46*(5), 582–590. https://doi.org/10.1097/chi.0b013e3180335af7

Rubia, K., Smith, A., & Taylor, E. (2007). Performance of children with attention deficit hyperactivity disorder (ADHD) on a test battery of impulsiveness. *Child Neuropsychology*, *13*(3), 276–304. https://doi.org/10.1080/09297040600770761

Sayal, K., Prasad, V., Daley, D., Ford, T., & Coghill, D. (2018). ADHD in children and young people: prevalence, care pathways, and service provision. *The Lancet Psychiatry*, *5*(2), 175–186. https://doi.org/10.1016/s2215-0366(17)30167-0

Sanders, G., & Sinclair, K. (2011). Sex differences in accuracy and precision when judging time to arrival: data from two internet studies. *Archives of Sexual Behavior*, *40*(6), 1189-1198. https://doi.org/10.1007/s10508-010-9704-2

Schiff, W., & Oldak, R. (1990). Accuracy of judging time to arrival: effects of modality, trajectory, and gender. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(2), 303. https://doi.org/10.1037/0096-1523.16.2.303

*Smith, A., Taylor, E., Warner Rogers, J., Newman, S., & Rubia, K. (2002). Evidence for a pure time perception deficit in children with ADHD. *Journal of Child Psychology and Psychiatry*, *43*(4), 529–542. https://doi.org/10.1111/1469-7610.00043

Sonuga-Barke, E., Bitsakou, P., & Thompson, M. (2010). Beyond the dual pathway model: evidence for the dissociation of timing, inhibitory, and delay-related impairments in attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry*, *49*(4), 345–355. https://doi.org/10.1016/j.jaac.2009.12.018

Sonuga-Barke, E. J., Sergeant, J. A., Nigg, J., & Willcutt, E. (2008). Executive dysfunction and delay aversion in attention deficit hyperactivity disorder: nosologic and diagnostic implications. *Child and Adolescent Psychiatric Clinics of North America*, *17*(2), 367–384. https://doi.org/10.1016/j.chc.2007.11.008

Thoenes, S., & Oberfeld, D. (2017). Meta-analysis of time perception and temporal processing in schizophrenia: Differential effects on precision and accuracy. *Clinical Psychology Review*, *54*, 44–64. https://doi.org/10.1016/j.cpr.2017.03.007

*Toplak, M. E., Rucklidge, J. J., Hetherington, R., John, S. C. F., & Tannock, R. (2003). Time perception deficits in attention-deficit/hyperactivity disorder and comorbid reading difficulties in child and adolescent samples. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *44*(6), 888–903.

*Toplak, M. E., & Tannock, R. (2005). Time Perception: Modality and Duration Effects in Attention-Deficit/Hyperactivity Disorder (ADHD). *Journal of Abnormal Child Psychology*, *33*(5), 639–654.

Treisman, M. (1963). Temporal discrimination and the indifference interval. Implications for a model of the "internal clock". *Psychological Monographs*, *77*(13), 1–31. https://doi.org/10.1037/h0093864

Tse, P. U., Nobre, A., & Coull, J. (2010). Attention underlies subjective temporal expansion. *Attention and Time*, 137–150.

*Valko, L., Schneider, G., Doehnert, M., Müller, U., Brandeis, D., Steinhausen, H. C., & Drechsler, R. (2010). Time processing in children and adults with ADHD. *Journal of Neural Transmission*, *117*(10), 1213–1228. https://doi.org/10.1007/s00702-010-0473-9

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*(3), 1–48. https://doi.org/10.18637/jss.v036.i03

Walg, M., Hapfelmeier, G., El-Wahsch, D., & Prior, H. (2017). The faster internal clock in ADHD is related to lower processing speed: WISC-IV profile analyses and time estimation tasks facilitate the distinction between real ADHD and pseudo-ADHD. *European Child and Adolescent Psychiatry*, *26*(10), 1177–1186. https://doi.org/10.1007/s00787-017-0971-5

Walg, M., Oepen, J., & Prior, H. (2015). Adjustment of Time Perception in the Range of Seconds and Milliseconds. *Journal of Attention Disorders*, *19*(9), 755–763. https://doi.org/10.1177/1087054712454570

*West, J., Douglas, G., Houghton, S., Lawrence, V., Whiting, K., & Glasgow, K. (2000). Time perception in boys with attention-deficit/hyperactivity disorder according to time duration, distraction and mode of presentation. *Child Neuropsychology*, *6*(4), 241–250. https://doi.org/10.1076/chin.6.4.241.3140

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T. L., Miller, E., Bache, S. M., Müller, K., Ooms, J., Robinson, D., Seidel, D. P., Spinu, V., . . . Yutani, H. (2019). Welcome to the tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wittmann, M., & Lehnhoff, S. (2005). Age effects in perception of time. *Psychological Reports*. https://doi.org/10.2466/pr0.97.3.921-935

*Yang, B., Chan, R. C., Zou, X., Jing, J., Mai, J., & Li, J. (2007). Time perception deficit in children with ADHD. *Brain Research*, *1170*, 90–96. https://doi.org/10.1016/j.brainres.2007.07.021

Zelaznik, H. N., Vaughn, A. J., Green, J. T., Smith, A. L., Hoza, B., & Linnea, K. (2012). Motor timing deficits in children with Attention-Deficit/Hyperactivity disorder. *Human Movement Science*, *31*(1), 255–265. https://doi.org/10.1016/j.humov.2011.05.003

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