

Prevalence and diagnostic validity of motivational impairments and deficits in visuospatial short-term memory and working memory in ADHD subtypes

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Abstract Deficits in working memory (WM) and reinforcement sensitivity are thought to give rise to symptoms in the combined (ADHD-C) and inattentive subtype (ADHD-I) of ADHD. Children with ADHD are especially impaired on visuospatial WM, which is composed of short-term memory (STM) and a central executive. Although deficits in visuospatial WM and reinforcement sensitivity appear characteristic of children with ADHD on a group-level, the prevalence and diagnostic validity of these impairments is still largely unknown. Moreover, studies investigating this did not control for the interaction between motivational impairments and cognitive performance in children with ADHD, and did not differentiate between ADHD subtypes. Visuospatial WM and STM tasks were administered in a standard (feedback-only) and a high-reinforcement (feedback + 10 euros) condition, to 86 children with ADHD-C, 27 children with ADHD-I (restrictive subtype), and 62 typically developing controls (aged 8–12). Reinforcement sensitivity was indexed as the difference in performance between the reinforcement conditions. WM and STM impairments were most prevalent in ADHD-C. In ADHD-I, only WM impairments, not STM impairments, were more prevalent than in controls. Motivational impairments were not common (22 %

impaired) and equally prevalent in both subtypes. Memory and motivation were found to represent independent neuropsychological domains. Impairment on WM, STM, and/or motivation was associated with more inattention symptoms, medication-use, and lower IQ scores. Similar results were found for analyses of diagnostic validity. The majority of children with ADHD-C is impaired on visuospatial WM. In ADHD-I, STM impairments are not more common than in controls. Within both ADHD subtypes only a minority has an abnormal sensitivity to reinforcement.

Keywords ADHD subtypes · Working memory · Reinforcement · Reward

Introduction

Deficits in executive functioning are proposed to play a pivotal role in explaining the problems individuals with ADHD encounter in daily life [1, 2]. Executive functions allow individuals to regulate their behavior, thoughts and emotions, and thereby enable self-control. Working memory (WM) is considered a core causal executive process in ADHD [3], and is described as the ability to maintain, control and manipulate goal-relevant information [4, 5]. Research indeed suggests that WM is one of the most impaired executive functions in ADHD [6, 7, 63], and that WM impairments in children with ADHD may account for their deficits in attention [8, 9], hyperactivity [10], and impulsivity [11].

According to Baddeley [4] WM is a multicomponent system consisting of two storage subsystems and a central executive. The storage subsystems—phonological and visuospatial short-term memory (STM)—are dedicated to

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the short-term storage of modality (phonological or visuospatial) specific information. The central executive is a mental control system with limited attentional resources that is responsible for supervising, controlling and manipulating information in the STM systems. Studies investigating WM components in children with ADHD indicate that, on a group-level, both their STM and central executive are impaired [e.g., 12–15]. Furthermore, meta-analytic findings suggest that children with ADHD show more impairment on tasks measuring visuospatial WM than on tasks measuring phonological WM [e.g., 2, 6].

Although impaired visuospatial WM appears characteristic of children with ADHD on a group-level, recent findings suggest that ADHD is a neuropsychologically heterogeneous disorder that probably is not characterized by any single core dysfunction [16–19]. Given that only a subset of children with ADHD meets criteria for an executive function deficit [16–23], visuospatial WM deficits on group-level are probably carried by only a subset of children with ADHD [16]. However, despite its obvious significance for assessment and treatment, only two studies (Holmes et al. [24]; Lambek et al. [25]) have attempted to demarcate this WM-impaired subset within the ADHD population. These studies found visuospatial WM impairments in 29–47 % of the children with ADHD [25],¹ and an overall diagnostic hit rate (overall correct classification of children with and without ADHD) based on visuospatial WM measures of about 75 % (correctly identifying 84.3 % of the children with ADHD and 58 % of typically developing (TD) children [24]). In addition, even less is known about the individual differences within the ADHD population on the components of visuospatial WM: only Holmes et al. investigated the diagnostic validity of a visuospatial STM measure. They found this measure to be less accurate in discriminating between children with and without ADHD (correctly identifying 81.9 % of the children with ADHD, but only 12 % of TD children) than their measure of visuospatial WM.

Moreover, the results of these prevalence- and diagnostic validity studies [24, 25] may be confounded by motivational deficits. Motivational models propose that children with ADHD are less stimulated by reinforcement (i.e., reward) than typically developing children (probably due to a dopaminergic deficit) and therefore require higher amounts of reward in order to perform optimally [28–32]. Research indeed shows that children with ADHD, in contrast to their TD peers, show suboptimal performance on

visuospatial WM- and visuospatial STM tasks under regular reinforcement conditions (e.g., feedback-only), and require relatively high incentives (e.g., feedback + 10 euros) to perform to their full abilities [13, 33, 34]. Holmes et al. and Lambek et al. did not control for these motivational deficits in children with ADHD (both studies used only regular reinforcement conditions), which may have resulted in an overestimation of the prevalence and diagnostic validity of WM and STM impairments in their ADHD samples.

Furthermore, ADHD can be divided into multiple subtypes (American Psychiatric Association [43]). The two most prevalent and valid diagnostic subtypes of ADHD are the combined subtype (ADHD-C) and the predominantly inattentive subtype (ADHD-I; [7, 64, 65]). ADHD-C and ADHD-I are characterized by distinct patterns of symptomatic behavior, associated features and demographics [e.g., see 47]. Nevertheless, the studies of Holmes et al. [24] and Lambek et al. [25] included both children with ADHD-C and ADHD-I, but did not differentiate between these subtypes. Moreover, although (on a group level) both subtypes appear to have equally pronounced motivational deficits (i.e., abnormal reinforcement sensitivity), evidence suggests that children with ADHD-I are less impaired on visuospatial WM than children with ADHD-C and, in contrast to children with ADHD-C, seem unimpaired on visuospatial STM (at least when motivational deficits are taken into account; [30, 35–37]; also see [7, 38, 66]). Therefore, the findings of Holmes et al. and Lambek et al. may be neither representative of children with ADHD-C, nor of children with ADHD-I.

Finally, although an abnormal sensitivity to reinforcement (as defined by Haenlein and Caul [28]) might be characteristic for children with ADHD on a group-level (for reviews [39, 40]; see also [13, 33, 34]), the prevalence and diagnostic validity of this motivational deficit within the ADHD population is largely unknown. Only one recent study (de Zeeuw et al. [23]) investigated its prevalence in children with ADHD, and found that <8 % of these children could be classified as having an abnormal sensitivity to reinforcement. However, de Zeeuw et al. used a small ADHD sample ($n = 26$) which included all ADHD subtypes (obviously, subtype comparisons were not possible), and concluded that the low prevalence rate (e.g., prevalence in TD controls was 10 %) was probably related to the high frequency of positive feedback that was applied during their motivation task (80 % of the trials were rewarded), which may have attenuated the impact of the motivational deficits in their ADHD sample [23]. To our knowledge, no studies investigated the diagnostic validity of abnormal reinforcement sensitivity in ADHD.

The current study therefore investigated: (1) the prevalence and diagnostic validity of visuospatial WM impairments and

¹ Loo et al. [26] (in adolescents), Sjöwall et al. [22] and Wahlstedt et al. [27] generally find a somewhat lower prevalence of working memory deficits in the ADHD population than Lambek et al. [25]. However, this lower prevalence might be explained by the fact that these three studies only use a composite score of both visuospatial and phonological working memory measures.

visuospatial STM impairments in children with ADHD, taking their motivational deficits into account; (2) the prevalence and diagnostic validity of these motivational deficits in children with ADHD; and (3) whether the prevalence and diagnostic validity of these impairments differ between ADHD subtypes. Exploratively, we examined the differences between the neuropsychologically/motivationally impaired and unimpaired children with ADHD-C and ADHD-I on behavioral symptoms and other demographic variables (e.g., medication use, gender, IQ, etc.).

We investigated these questions by using the task scores of children with ADHD-C, ADHD-I and TD children on the visuospatial WM- and STM version of the Chessboard task [13, 33]. To account for, and investigate, the motivational deficits in the ADHD samples we presented these tasks in two reinforcement conditions: a feedback-only condition and a condition with feedback and a large monetary incentive (10 euros). This 10 euros condition was previously found to optimize task performance in children with ADHD-C [33]. The change in performance between the feedback-only and 10 euros condition was considered the measure of sensitivity to reinforcement (the reinforcement sensitivity index; see Footnote 3).

We predicted that: (1) visuospatial WM and reinforcement sensitivity would significantly discriminate children with ADHD (of both subtypes) from TD children, and that related impairments would be more prevalent in children with ADHD-C and ADHD-I than in TD children [21, 24, 30, 33]; (2) visuospatial STM would only discriminate children with ADHD-C, but not children with ADHD-I, from TD children [30], and (3) children with ADHD-C and ADHD-I who were classified as impaired on WM, STM and/or reinforcement sensitivity would have more behavioral problems and less favorable demographic characteristics than their unimpaired ADHD-C or ADHD-I peers [7].

Method

Participants

A total of 175 children participated: 86 children with ADHD-C (aged 8–12 years), 27 children with ADHD-I (aged 9–12 years), and 62 TD children (aged 8–12 years). Children with ADHD were recruited from outpatient mental-health-care centers, TD children through elementary schools. Portions of the data were presented elsewhere [13, 35].

Inclusion criteria

For all groups: (a) an IQ score ≥ 80 established by the short version of the Dutch Wechsler Intelligence Scale for Children (WISC-III [41]). Two subtests, Vocabulary and

Block Design, were administered to estimate Full Scale IQ (FSIQ). This composite score has satisfactory reliability and correlates highly with FSIQ [42]; (b) absence of any neurological disorder, sensory (color blindness, vision) or motor impairment as stated by the parents; (c) not taking any medication other than methylphenidate.

For the ADHD-C group: (a) a prior DSM-IV-TR [43] diagnosis of ADHD combined-type and absence of any autism spectrum disorder (ASD) according to a child psychologist or psychiatrist; (b) a score within the clinical range (95th–100th percentile) on the ADHD scales of both the parent and teacher version of the Disruptive Behavior Disorder Rating Scale (DBDRS [44, Dutch translation: 45]). The DBDRS contains four DSM-IV scales; Inattention, Hyperactivity/Impulsivity, Oppositional Defiant Disorder (ODD), and Conduct Disorder (CD). Adequate psychometric properties are reported [45]; (c) meeting criteria for ADHD combined-type on the ADHD section of the Diagnostic Interview Schedule for Children, parent version (PDISC-IV [46]). The PDISC-IV is a structured diagnostic interview based on the DSM-IV, with adequate psychometric properties; (d) absence of CD based on the CD sections of the PDISC-IV.

For the ADHD-I group: (a) a prior DSM-IV-TR diagnosis of ADHD inattentive-type and absence of any ASD according to a child psychologist or psychiatrist; (b) a score within the clinical range on the Inattention scale and a score below the clinical range on the Hyperactivity/Impulsivity scale of both the parent and teacher version of the DBDRS; (c) to ensure that the ADHD-I group did not include any children with subthreshold ADHD-C, we followed recommendations made in the benchmark review of Milich et al. [47, see also 1, 30]: children in the ADHD-I group not only had to meet criteria for ADHD inattentive-type on the ADHD section of the PDISC-IV, but also had to have <4 hyperactivity/impulsivity symptoms; (d) no CD based on the CD sections of the PDISC-IV.

For the control group: (a) a score within the normal range (<80 th percentile) on all scales of both the parent and teacher version of the DBDRS; (b) absence of a prior DSM-IV-TR diagnosis of ASD or any other psychiatric disorder (apart from a mathematics disorder or reading disorder) as stated by the parents.

Group differences in demographics and characteristics and are listed in Table 1 (including the presence of a DSM-IV-TR diagnosis of a mathematics disorder or reading disorder as stated by the parents). Eight children in the ADHD-I group (30 %) and 61 children in the ADHD-C group (71 %) were taking methylphenidate,² but discontinued medication at

² This relative difference between the ADHD groups in medication-use was significant, $\chi^2(1) = 13.814$, $p < 0.001$. However, including medication-use as a covariate in analyses where the ADHD groups were compared (and covariation was possible) did not change the pattern of the results.

Table 1 Group demographics, parent and teacher ratings and mean performance differences

Measure	Group						F/χ^2	η_p^2	Group comparison ^{a, b}
	ADHD-C		ADHD-I		TD children				
	$(n = 86)$		$(n = 27)$		$(n = 62)$				
	M	SD	M	SD	M	SD			
Gender (M:F)	70:16	—	18:9	—	27:35	—	22.9		C = I; TD \neq C, I
Age (years)	10.4	1.3	11.1	1.1	10.1	1.2	6.9		I > C, TD; C = TD
FSIQ	101	11.2	106	10.5	110	12.6	11.6		I = C, TD; C < TD
DBDRS parent									
Inattention	21.6	4.0	19.0	4.5	2.5	2.4	538.3		TD < I < C
Hyperactivity/impulsivity	20.7	4.6	7.0	3.4	2.2	2.3	476.4		TD < I < C
ODD	12.4	5.3	5.5	4.4	1.9	2.2	158.1		TD < I < C
CD	2.6	2.3	0.9	1.4	0.1	0.3	41.2		TD = I; C > TD, I
DBDRS teacher									
Inattention	17.2	5.0	15.7	4.9	1.6	1.8	307.5		TD < I, C; I = C
Hyperactivity/impulsivity	15.6	5.7	2.9	2.5	1.0	1.5	261.0		TD = I; C > TD, I
ODD	9.9	5.8	3.9	2.8	0.7	0.9	93.0		TD < I < C
CD	1.6	2.2	0.3	0.8	0.1	0.2	20.4		TD = I; C > TD, I
Weekly spendable income (in euros)	2.5	2.7	2.3	1.6	1.7	1.1	3.1		I = C, TD; C > TD
Mathematics disorder (yes:no)	0:86	—	0:27	—	0:62	—	—		—
Reading disorder (yes:no)	6:80	—	0:27	—	2:60	—	2.7		ns ($p = 0.260$)
Medication-use (yes:no)	61:25	—	8:19	—	—	—	13.8		I \neq C
Working memory (age adjusted)									
Feedback-only	5	1.0	5.5	1.0	6.3	0.8	22.4	0.21	C < I < TD
10 euros	5.5	0.8	6	0.8	6.5	0.7	17.4	0.17	C < I < TD
Short-term memory (age adjusted)									
Feedback-only	5.3	1.0	5.8	0.9	6.3	0.8	13.0	0.13	TD > C, I; C = I;
10 euros	5.7	0.8	6.2	0.8	6.4	0.6	8.6	0.09	C < TD, I; TD = I
Reinforcement sensitivity index	7.4 %	11.1 %	6.7 %	11.7 %	2.2 %	9.5 %	3.9	0.05	TD < C, I; C = I

I ADHD-I, C ADHD-C, TD typically developing children, CD Conduct Disorder, DBDRS Disruptive Behavior Disorder Rating Scale, FSIQ Full Scale IQ, M:F male:female, ODD Oppositional Defiant Disorder

^a MAN(C)OVAs were performed. If the overall group-effect was significant ($p < 0.05$), additional post hoc Tukey tests or additional MANCOVAs were performed to clarify the group differences (for all significant differences p values were < 0.01). Nominal data were analyzed with Chi square tests

^b If an independent measure (i.e., gender, age, FSIQ, parent and teacher ratings, weekly spendable income, or medication use) differed between certain groups (e.g., ADHD-C vs. TD group) it was subsequently used as covariate in the matching group comparison of the performance indices (i.e., the working memory, short-term memory, and reinforcement sensitivity index). Therefore, in analyses of the performance indices, IQ, weekly spendable income and gender were used as covariates when all groups were compared and when ADHD-C was compared to controls; gender was used as covariate when ADHD-I was compared to controls; and parent-rated inattention, ODD, CD and medication-use were used as covariates when the ADHD groups were compared. Covarying for these independent measures did not change the pattern of the results

least 24 h before the test-session, allowing a complete wash-out [48].

The Chessboard task: WM and STM

The WM version of the Chessboard task [33] is a visuospatial WM performance measure based on two WM tasks: the Corsi Block Tapping Task [49] and the subtest Letter–Number Sequencing from the Wechsler Adult Intelligence Scale (WAIS-III [50]). The WM task taps the ability to

both maintain and reorganize visuospatial information that is relevant for the task at hand (see Fig. 1). To ensure that every presented sequence of stimuli has to be reorganized (and the central executive is tapped), the order of stimuli presentation is random with the restriction that in every sequence at least one blue stimulus is presented before the last green stimulus.

The STM version of the Chessboard task [13] is a visuospatial STM performance measure tapping the ability to maintain visuospatial information relevant for the task at

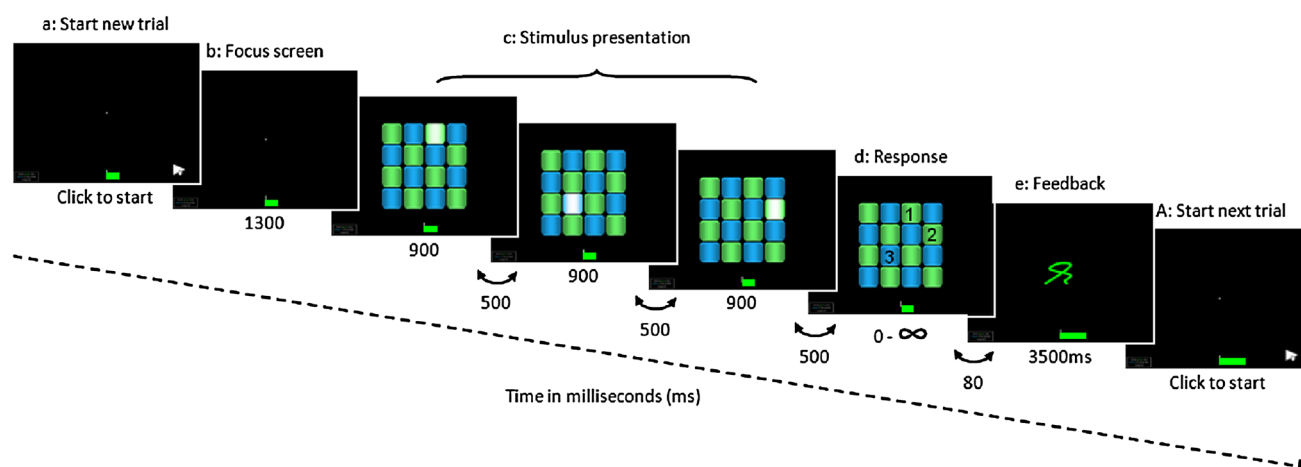


Fig. 1 A trial on the working memory version of the Chessboard task. *a* To start a trial the arrowhead button in the bottom-right corner of the screen has to be clicked. *b* Then the focus screen (a black screen with a little white cross) is presented. *c* Subsequently, a sequence of stimuli (squares that light up) is presented 1 × 1 on a 4 × 4 grid with green and blue squares ordered in a chessboard formation. Each stimulus lights up for 900 ms and is followed by an inter-stimulus interval of 500 ms. *d* After the stimulus-sequence is presented the participant responds by mouse-clicking on the squares. To respond correctly the presented stimuli have to be reproduced in a reorganized way: the green stimuli have to be reproduced before the

blue stimuli; both in the same order as presented (the numbers in picture *d* show an example of a correct reorganization). *e* After a response feedback is presented. *A* After feedback-presentation, the participant can start the next trial by clicking on the arrowhead button [13]. Dimensions of the task (height × width): 4 × 4 grid (14 × 13.9 cm), individual stimuli (3.4 × 3.2 cm); distances between adjacent stimuli: 0.3 cm between horizontally adjacent stimuli and 0.2 cm between vertically adjacent stimuli (differences between the height and the width were the result of a small 3D-effect in the stimuli)

hand. The STM version is an STM analogue of the WM task: the stimuli have to be reproduced in the same way as on the WM task; green stimuli have to be reproduced before the blue stimuli (see Fig. 1). However, in contrast to the WM task, on each trial of the STM task all the green stimuli are presented before the blue stimuli. Therefore, none of the presented sequences on the STM task have to be reorganized (and only the storage component is tapped; for more details see [13]).

The difficulty level of both tasks is adaptive; after two consecutive correct or incorrect reproductions, the sequence is increased or shortened by one stimulus. Minimal sequence length is two stimuli and there is no maximum sequence length. Because the difficulty level adapts to individual performance, the amount of positive and negative feedback is approximately the same (55 % reward, 45 % response-cost) for each child and in both task versions and both reinforcement conditions. Each task consists of ~5 practice trials followed by 30 experimental trials, and takes about 10 min to complete (for more details [13]).

Reinforcement conditions

Each participant completed both reinforcement conditions, and each reinforcement condition contained both the STM and WM task (see orders of presentation used in counterbalancing below). In the feedback-only condition, children

were instructed to do their best and respond as accurately as possible. In the 10 euros condition, children were told that they could earn 10 euros if they performed well enough on the task. In both reinforcement conditions, participants received immediate visual and auditory feedback and could monitor their overall performance by means of a 'performance bar' (for a detailed description see [13] or ESM Appendix 1).

Dependent measures

On both task versions, the first 12 trials are required to reach the child's optimal difficulty level and were therefore excluded from analysis [13, 33], and see ESM Appendix 2. Thus, performance on each task was measured by the mean sequence length of the last 18 trials. The reinforcement sensitivity index was defined as the relative difference in mean (STM and WM) performance between the 10 euros condition and the feedback-only condition (i.e., the percentage difference in mean performance as a result of extra reinforcement).³

³ Reinforcement sensitivity index = [(WM + STM 10 euros) – (WM + STM FO)] × [100/(WM + STM 10 euros)]. WM = age-corrected mean score on WM task; STM = age-corrected mean score on STM task; FO = feedback-only condition.

Procedure

The study was approved by the faculty's IRB. The participating mental-healthcare centers sent recruitment letters to the parents of all children aged 8–12 years with a DSM-IV-TR diagnosis of ADHD (all subtypes). The participating elementary schools sent recruitment letters to the parents of all children aged 8–12 years (no matching procedure was applied). If parents were interested in participating they could contact the researchers for more information and to sign up for the study. After obtaining informed consent from the parents (on behalf of the participating children), parents and teachers completed the DBDRS. If DBDRS inclusion criteria were met, participants were invited to one 100-min test-session. During this session's first hour the two reinforcement conditions (feedback-only and 10 euros), each containing the WM and STM version of the chessboard task, were administered, intermitted by a 5-min break. Thereafter, the WISC-III subtests were administered. In parallel, parents of children with ADHD were interviewed with the PDISC-IV. If the child met the inclusion criteria (s)he was included in the data set. To control for order effects, the order of administration of the reinforcement conditions and the task versions (STM and WM) were counterbalanced separately within groups (resulting in 8 orders of presentation).

Orders of presentation used in counterbalancing:

1	FO: STM > WM	10 euros: STM > WM
2	10 euros: STM > WM	FO: STM > WM
3	FO: WM > STM	10 euros: WM > STM
4	10 euros: WM > STM	FO: WM > STM
5	FO: STM > WM	10 euros: WM > STM
6	10 euros: STM > WM	FO: WM > STM
7	FO: WM > STM	10 euros: STM > WM
8	10 euros: WM > STM	FO: STM > WM

STM short-term memory, WM working memory, FO feedback-only

No information about the reinforcement conditions was provided before the test-session (e.g., to avoid expectations of receiving money). Children and their families were not compensated for participating in this study over and above the 10 euros from the high-reinforcement condition. Children with ADHD were tested at their mental-healthcare center, TD children at their school. Testing took place between 9 a.m. and 5 p.m. Test rooms were quiet and views from windows were blocked. Specific reinforcement instructions (e.g. 'If you perform well enough on this task you will get these 10 euros') were given to the child at the start of each reinforcement condition (for complete instructions see description of the reinforcement conditions

in ESM Appendix 1). During testing an experimenter was present, sitting behind the child pretending to read a book.

Data analysis

Given the difference in age range between the ADHD-I group (aged 9–12 years) and the ADHD-C and TD groups (aged 8–12 years), task scores were, after checking for normality and outliers,⁴ adjusted for age using a regression procedure. That is, in the entire sample we regressed task scores on age, and the discrepancy between observed and predicted data was taken as the age-adjusted task score. These age-adjusted task scores were used in all analyses.

Prevalence

On the STM- and WM task children with ADHD were characterized as impaired if their age-corrected task score fell below the lowest 10th percentile of scores in the TD group. Children with ADHD were characterized as impaired on the reinforcement sensitivity index if their score fell above the 90th percentile of the TD group (this 10 % cut-off was also used in [17, 19, 25]).⁵ Group differences were examined using 2-sided Chi square analyses.

Diagnostic validity

Discriminant analyses were conducted to evaluate the extent to which age-adjusted scores on STM and WM tasks in the feedback-only (FO) and 10 euros conditions, and on the reinforcement sensitivity index accurately discriminated between ADHD-C and controls, between ADHD-I and controls, and between both ADHD groups. Differences were examined using two-sided Chi square analyses.

Finally, analyses were conducted comparing clinical and demographic variables between children with ADHD who were classified as either impaired or non-impaired on WM, STM and/or reinforcement sensitivity (based on the 10 % cut-off), using MANOVAs or Chi square as appropriate. Partial Eta squared effect sizes (η_p^2) are reported for the MANOVAs: $\eta_p^2 = 0.01$ is regarded a small effect size, 0.06 a medium effect size, and 0.14 a large effect size [52]. For Chi square analyses phi (Φ) or Cramér's (V) effect sizes are reported (depending on the number of categories): $\Phi/V = 0.10$ indicates a small effect size, 0.30 a medium

⁴ Participants were excluded from analyses when both of the following criteria were met: (1) a standardized residual on any of the dependent measures with an absolute value >2 , and (2) a Cook's distance ≥ 1 [51]. Based on this criterion none of the participants had to be excluded.

⁵ For the sake of completeness prevalence using a 5 % cut-off is reported in ESM Appendix 3.

effect size, and 0.50 a large effect size [67]. Unless otherwise stated, analyses had adequate statistical power (power ≥ 0.80) to detect at least medium effects.

Results

Counterbalancing and mean scores

The three groups did not differ in the relative number of times that each counterbalancing-order was presented, $\chi^2(14) = 1.83$, $p = 0.999$, Cramér's $V = 0.07$, power to detect a medium effect was 0.72. Also, including counterbalancing-order as a covariate did not change the results.

Group demographics and age-adjusted mean scores for each of the five performance indices (STM performance in both reinforcement conditions, WM performance in both reinforcement conditions, and the reinforcement sensitivity index) are listed in Table 1. For a detailed discussion of comparable mean results see Dövis et al. [13, 35].

Prevalence of impairment

To account for the effect of motivational deficits on performance, only WM- and STM performance in the 10 euros condition were used to estimate prevalence of WM and STM impairment (unless otherwise stated). Figure 2 presents the proportion of children with ADHD-C and ADHD-I who met the 10 % threshold for an impairment on the WM-, the STM-, and/or the reinforcement sensitivity index. 75.6 % of the ADHD-C group, 55.6 % of the ADHD-I group, and 27.4 % of the TD group had an impairment on any one of these dependent measures, these group differences were significant (ADHD-C vs. TD, $\chi^2(1) = 33.82$, $p < 0.001$, $\Phi = 0.48$; ADHD-I vs. TD, $\chi^2(1) = 6.47$, $p < 0.05$, $\Phi = 0.27$; ADHD-C vs. ADHD-I, $\chi^2(1) = 3.99$, $p < 0.05$, $\Phi = 0.19$).

Next, prevalence of impairment was examined per performance index (see Fig. 2):

Working memory

58.1 % of the ADHD-C group, 33.3 % of the ADHD-I group, and 9.7 % of the TD group was impaired on WM. These group differences were significant (ADHD-C vs. TD, $\chi^2(1) = 35.97$, $p < 0.001$, $\Phi = 0.49$; ADHD-I vs. TD, $\chi^2(1) = 7.51$, $p = 0.012$, $\Phi = 0.29$; ADHD-C vs. ADHD-I, $\chi^2(1) = 5.07$, $p = 0.024$, $\Phi = 0.21$).

STM

40.7 % of the ADHD-C group, 18.5 % of the ADHD-I group, and 9.7 % of the TD group was impaired on STM.

Except for the difference between the ADHD-I and the TD group, these group differences were significant (ADHD-C vs. TD, $\chi^2(1) = 17.31$, $p < 0.001$, $\Phi = 0.34$; ADHD-I vs. TD, $\chi^2(1) = 1.36$, $p = 0.298$, $\Phi = 0.12$; ADHD-C vs. ADHD-I, $\chi^2(1) = 4.42$, $p = 0.036$, $\Phi = 0.20$).

Reinforcement sensitivity

22.1 % of the ADHD-C group, 22.2 % of the ADHD-I group, and 9.7 % of the TD group was classified as having an abnormal reinforcement sensitivity (motivational impairment). Only the difference between the ADHD-C and the TD group was significant, but the effect size was comparable to the effect size of the difference between the ADHD-I and TD group (ADHD-C vs. TD, $\chi^2(1) = 3.96$, $p < 0.05$, $\Phi = 0.16$; ADHD-I vs. TD, $\chi^2(1) = 2.54$, $p = 0.174$, $\Phi = 0.17$; ADHD-C vs. ADHD-I, $\chi^2(1) = 0.00$, $p = 0.989$, $\Phi = 0.001$).

In the ADHD-C group, WM impairments were more prevalent than STM impairments [$\chi^2(1) = 5.23$, $p = 0.022$, $\Phi = 0.17$], and both were more prevalent than motivational impairments (WM vs. motivation, $\chi^2(1) = 23.26$, $p < 0.001$, $\Phi = 0.37$; STM vs. motivation, $\chi^2(1) = 6.91$, $p = 0.009$, $\Phi = 0.20$). In the ADHD-I group these differences were non-significant (WM vs. STM, $p = 0.214$, $\Phi = 0.17$; WM vs. motivation, $p = 0.362$, $\Phi = 0.12$; STM vs. motivation, $p = 0.735$, $\Phi = 0.05$, power to detect medium effects was 0.60).

Overlap of impairments

In both ADHD groups there was significant overlap between WM and STM deficits [ADHD-C: $\chi^2(1) = 6.32$, $p = 0.01$, $\Phi = 0.27$; ADHD-I: $\chi^2(1) = 6.01$, $p = 0.03$, $\Phi = 0.47$; 30.3 % of children with ADHD-C and 14.8 % of children with ADHD-I were impaired on both indices; see Fig. 2]. However, overlap between the reinforcement sensitivity index and the memory indices was non-significant [WM and motivation: ADHD-C, $\chi^2(1) = 0.304$, $p = 0.581$, $\Phi = 0.06$; ADHD-I, $\chi^2(1) = 0.964$, $p = 0.628$, $\Phi = 0.19$; STM and motivation: ADHD-C, $\chi^2(1) = 0.450$, $p = 0.502$, $\Phi = 0.07$; ADHD-I, $\chi^2(1) = 1.75$, $p = 0.555$, $\Phi = 0.16$], suggesting that these impairments are not associated. However, the power for the analyses of the ADHD-I group was low (power to detect a medium effect was 0.34).

Prevalence differences between reinforcement conditions

In both ADHD groups prevalence rates of WM- and STM impairments were not significantly influenced by type of reinforcement condition [ADHD-C: WM 10 euros (58.1 % prevalence) vs. WM FO (50 %), $\chi^2(1) = 1.15$, $p = 0.284$, $\Phi = 0.08$; STM 10 euros (40.7 %) vs. STM FO (54.7 %), $\chi^2(1) = 3.36$, $p = 0.067$, $\Phi = 0.14$; ADHD-I: WM 10

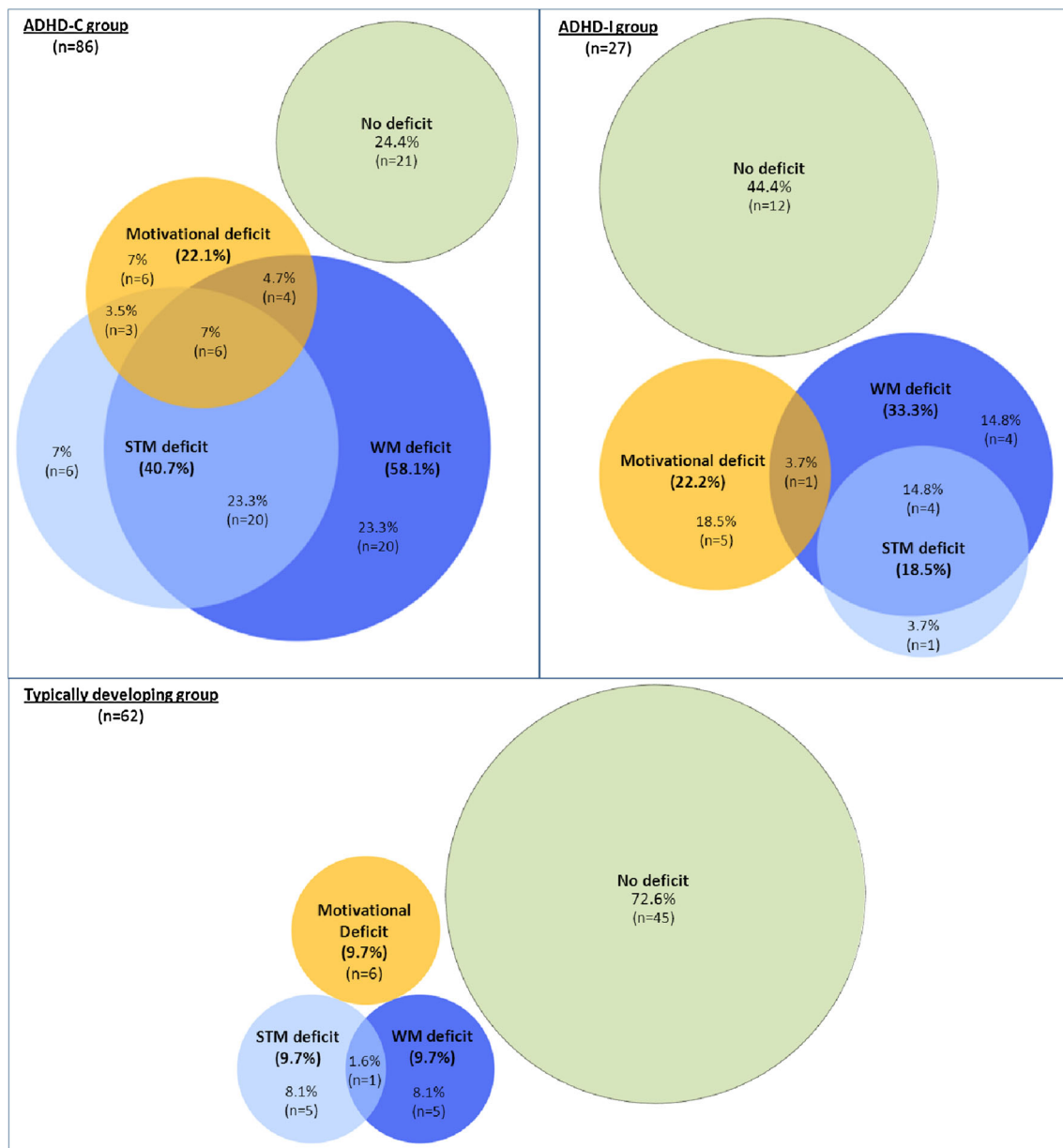


Fig. 2 Proportion of the ADHD-C, ADHD-I and TD children with visuospatial working memory- (WM), visuospatial short-term memory- (STM) (based on performance in the high-reinforcement

condition), and motivational deficits (i.e., abnormal reinforcement sensitivity), and their degree of co-occurrence (totals may not equal 100 % because of rounding)

euros (33.3 %) vs. WM FO (37 %), $\chi^2(1) = 0.081$, $p = 0.776$, $\Phi = 0.04$; STM 10 euros (18.5 %) vs. STM FO (25.9 %), $\chi^2(1) = 0.429$, $p = 0.513$, $\Phi = 0.09$, the power to detect a medium effect for the ADHD-I group was 0.60], but note the trend for the effect of reinforcement on the prevalence of STM impairments in the ADHD-C group.

Discriminant analyses

Multiple discriminant analyses were conducted to evaluate the extent to which the five age-corrected performance

indices could accurately discriminate between the groups (see Table 2).

ADHD-C vs. TD children

First, the five indices were entered in the analysis together (see Table 2). The overall Wilks's lambda was significant ($\Lambda = 0.61$, $\chi^2(5, N = 148) = 72.23$, $p < 0.001$). Canonical variate correlation coefficients for the five indices were: WM FO (0.88), WM 10 euros (0.81), STM FO (0.66), STM 10 euros (0.60), reinforcement sensitivity index (−0.30).

Table 2 Classification rates based on the age-corrected performance measures

Measure(s) included in discriminant analyses	Group comparison								
	ADHD-C vs. TD children			ADHD-I vs. TD children			ADHD-C vs. ADHD-I		
	(n = 148)			(n = 89)			(n = 113)		
	Correct ADHD-C classif. (%)	Correct TD child classif. (%)	Correct overall classif. (%)	Correct ADHD-I classif. (%)	Correct TD child classif. (%)	Correct overall classif. (%)	Correct ADHD-C classif. (%)	Correct ADHD-I classif. (%)	Correct overall classif. (%)
All measures/indices	76.7	83.9	79.7*	66.7	72.6	70.8*	65.1	59.3	63.7
Working memory									
Feedback-only	73.3	85.5	78.4*	63	74.2	70.8*	52.3	63	54.9*
10 euros	74.4	75.8	75.0*	55.6	66.1	62.9*	62.8	63	62.8*
Short-term memory									
Feedback-only	66.3	75.8	70.3*	70.4	62.9	65.2*	61.6	63	61.9*
10 euros	70.9	72.6	71.6*	59.3	64.5	62.9	62.8	59.3	61.9*
Reinf. sensitivity index	53.5	62.9	57.4*	55.6	61.3	59.6 [†]	40.7	55.6	44.2

TD typically developing children, *Correct ADHD classif.* correctly classified children with ADHD, *Correct TD child classif.* correctly classified TD children, *Correct overall classif.* overall correct classification of group membership; *all measures* using the five indices; both short-term memory and working memory tasks in both reinforcement conditions and the motivational index, *Reinf. sensitivity* reinforcement sensitivity

* Wilks's lambda was significant ($p < 0.05$); [†] $p = 0.06$

The higher the absolute value of the coefficient, the more the dependent measure contributes to group separation; positive and negative coefficients contribute to group separation in opposite ways.

Next, separate discriminant analyses were run to investigate how useful each single measure was at discriminating between the ADHD-C and TD group. Wilks's lambda was significant for each measure,⁶ suggesting that each of these measures significantly discriminates between the ADHD-C and TD group. Classification rates for these measures are shown in Table 2. The overall correct classification rates based on WM performance (WM FO = 78.4 %; WM 10 euros = 75 %) or STM performance (STM FO = 70.3 %; STM 10 euros = 71.6 %) were not significantly influenced by the amount of reinforcement [WM FO vs. WM 10 euros, $\chi^2(1) = 0.47$, $p = 0.492$, $\Phi = 0.04$; STM FO vs. STM 10 euros, $\chi^2(1) = 0.066$, $p = 0.798$, $\Phi = 0.02$], suggesting that the diagnostic validity of WM performance and STM performance does not change when motivation is taken into account.

The reinforcement sensitivity index provided a significantly worse overall classification rate (57.4 %) than all other indices [motivation vs. WM FO, $\chi^2(1) = 14.90$, $p < 0.001$, $\Phi = 0.22$; motivation vs. WM 10 euros,

$\chi^2(1) = 10.21$, $p = 0.001$, $\Phi = 0.19$; motivation vs. STM FO, $\chi^2(1) = 5.28$, $p = 0.022$, $\Phi = 0.13$; motivation vs. STM 10 euros, $\chi^2(1) = 6.51$, $p = 0.011$, $\Phi = 0.15$].

ADHD-I vs. TD children

When the five indices were entered in the analysis together, Wilks's Lambda was significant ($\Lambda = 0.82$, $\chi^2(5, N = 89) = 16.88$, $p = 0.005$, power for this analysis to detect a medium effect was 0.56). Canonical variate correlation coefficients were: WM FO (0.91), WM 10 euros (0.74), STM FO (0.58), STM 10 euros (0.36), reinforcement sensitivity index (−0.43).

Next, separate discriminant analyses were run for each single measure. Wilks's Lambda was not significant for STM performance in the 10 euros condition ($p = 0.121$), nor for the reinforcement sensitivity index (although there was a trend; $p = 0.06$), suggesting that these measures do not significantly discriminate between the ADHD-I group and the TD group. For all other measures Wilks's Lambda was significant.⁷ Classification rates are shown in Table 2. The overall correct classification rates based on WM performance (WM FO = 70.8 %; WM 10 euros = 62.9 %) or STM performance (STM FO = 65.2 %; STM 10 euros = 62.9 %) were not significantly influenced by the amount of reinforcement (WM FO vs. WM 10 euros, $\chi^2(1) = 1.24$, $p = 0.265$, $\Phi = 0.08$; STM FO vs. STM 10

⁶ WM FO, $\Lambda = 0.67$, $\chi^2(1, N = 148) = 59.12$, $p < 0.001$; WM 10 euros, $\Lambda = 0.70$, $\chi^2(1, N = 148) = 52.25$, $p < 0.001$; STM FO, $\Lambda = 0.78$, $\chi^2(1, N = 148) = 36.25$, $p < 0.001$; STM 10 euros, $\Lambda = 0.81$, $\chi^2(1, N = 148) = 30.73$, $p < 0.001$; reinforcement sensitivity index, $\Lambda = 0.94$, $\chi^2(1, N = 148) = 8.42$, $p = 0.004$.

⁷ WM FO, $\Lambda = 0.85$, $\chi^2(1, N = 89) = 14.57$, $p < 0.001$; WM 10 euros, $\Lambda = 0.89$, $\chi^2(1, N = 89) = 9.80$, $p = 0.002$; STM FO, $\Lambda = 0.93$, $\chi^2(1, N = 89) = 6.26$, $p = 0.012$.

euros, $\chi^2(1) = 0.098$, $p = 0.755$, $\Phi = 0.02$), suggesting that the diagnostic validity of WM performance and STM performance does not change when motivation is taken into account.

The overall correct classification rate of the reinforcement sensitivity index (59.6 %) was not significantly different from other indices (motivation vs. WM FO, $\chi^2(1) = 2.48$, $p = 0.116$, $\Phi = 0.12$; motivation vs. WM 10 euros, $\chi^2(1) = 0.21$, $p = 0.644$, $\Phi = 0.04$; motivation vs. STM FO, $\chi^2(1) = 0.60$, $p = 0.439$, $\Phi = 0.06$; Motivation vs. STM 10 euros, $\chi^2(1) = 0.21$, $p = 0.644$, $\Phi = 0.04$).

ADHD-C vs. ADHD-I

When the five indices were entered in the analysis together, Wilks's Lambda was not significant, $\Lambda = 0.92$, $\chi^2(5, N = 113) = 9.38$, $p = 0.095$; but note that the power to detect a medium effect was 0.69. Canonical variate correlation coefficients for the five indices were: WM FO (−0.70), WM 10 euros (−0.85), STM FO (−0.72), STM 10 euros (−0.84), reinforcement sensitivity index (0.09).

Next, separate discriminant analyses were run for each single measure. Wilks's Lambda was not significant for the reinforcement sensitivity index ($p = 0.771$), suggesting that this measure did not significantly discriminate between the ADHD groups. For all other measures Wilks's Lambda was significant.⁸ Classification rates are shown in Table 2. The overall correct classification rates based on WM performance (WM FO = 54.9 %; WM 10 euros = 62.8 %) or STM performance (STM FO = 61.9 %; STM 10 euros = 61.9 %) were not significantly influenced by the amount of reinforcement (WM FO vs. WM 10 euros; $\chi^2(1) = 1.48$, $p = 0.224$, $\Phi = 0.08$; STM FO vs. STM 10 euros; $\chi^2(1) = 0.00$, $p = 1.00$, $\Phi = 0.00$).

Comparing impaired vs. non-impaired children with ADHD

Of all independent variables (see Table 1), only teacher-rated inattention on the DBDRS, medication-use, and IQ differed significantly between impaired⁹ and non-impaired children with ADHD-C (power to detect medium effects was 0.59). Teacher-rated inattention and medication-use were higher in impaired children (DBDRS-score = 18.2 vs. 15.8, $p = 0.026$, $\eta_p^2 = 0.07$; medication-use = 75.4 vs. 38.1 %, $p = 0.002$), and IQ was lower in impaired children (99 vs. 107 points; $p = 0.002$, $\eta_p^2 = 0.11$). Subdividing the

impaired ADHD-C sample into a memory impaired (only impaired on WM and/or STM) and a motivationally impaired group did not reveal specific memory- or motivation-related effects (but power to detect medium effects was 0.60). No differences were found between impaired and non-impaired children with ADHD-I, but sample sizes were too small (power to detect medium effects was only 0.13). For correlations between ADHD symptoms and performance on the indices see ESM Appendix 4.

Discussion

This study investigated (1) the prevalence and diagnostic validity of visuospatial WM and STM impairments in children with ADHD when motivational deficits are taken into account; (2) the prevalence and diagnostic validity of reinforcement sensitivity deficits in children with ADHD, and (3) whether the prevalence and diagnostic validity of these impairments differ between ADHD subtypes. Exploratively, differences between the impaired (see Footnote 9) and unimpaired children with ADHD-C and ADHD-I were examined.

The present findings showed that when motivational deficits of children with ADHD were taken into account, both WM and STM impairments were more prevalent in the ADHD-C group than in the ADHD-I and TD group. In the ADHD-I group, only WM impairments, not STM impairments, were more prevalent than in the TD group. In the discriminant analyses the same pattern of results was found. In general, correct classification- and prevalence rates were not significantly affected by the type of reinforcement condition, except that STM performance only discriminated between ADHD-I and TD children in the feedback-only condition. In both ADHD groups there was a significant association between WM and STM impairments, but these memory impairments were not associated with deficits in reinforcement sensitivity (although power for the analysis in the ADHD-I group was low). Reinforcement sensitivity deficits were equally prevalent in both ADHD groups, but only in the ADHD-C group this deficit was significantly more prevalent than in the TD group. In children with ADHD-C, this motivational deficit was less prevalent than impairments of WM and STM. The reinforcement sensitivity index only discriminated significantly between ADHD-C and TD children (although there was a trend for ADHD-I and TD children), and its predictive power was significantly lower than that of either WM or STM performance. Children with ADHD-C who were classified as impaired (see Footnote 9) had more teacher-rated inattention symptoms, were more likely to use ADHD medication, and had lower IQ scores.

⁸ WM FO, $\Lambda = 0.96$, $\chi^2(1, N = 113) = 4.71$, $p = 0.030$; WM 10 euros, $\Lambda = 0.94$, $\chi^2(1, N = 113) = 6.96$, $p = 0.008$; STM FO, $\Lambda = 0.96$, $\chi^2(1, N = 113) = 5.09$, $p = 0.024$; STM 10 euros, $\Lambda = 0.94$, $\chi^2(1, N = 113) = 6.88$, $p = 0.009$.

⁹ Impaired on WM (10 euros), and/or STM (10 euros), and/or reinforcement sensitivity; using the 10 % cut-off.

Memory

With motivation taken into account, 58.1 % of the children with ADHD-C were found to be impaired on visuospatial WM. This prevalence rate is somewhat higher than that of the only other study that examined the prevalence of visuospatial WM in ADHD ([25] where 29–47 % of the ADHD sample was found impaired). Our findings suggest that this difference might be related to the fact that Lambek et al. did not differentiate between ADHD subtypes, since the prevalence of WM impairments was significantly higher in ADHD-C than in ADHD-I (58.1 vs. 33.3 %). Further, our finding suggests that visuospatial WM impairments are at least as prevalent in children with ADHD-C as other ‘key’ neuropsychological dysfunctions (prevalence of inhibition, 45–51 %; reaction time variability, 44–48 %; delay aversion, 14–56 % [e.g., 17, 19, 22, 53]), and are more prevalent than phonological WM impairments (27–35 % impaired [25]). These findings further suggest that impaired visuospatial WM may indeed be a core causal executive process for a majority of children with ADHD-C [3]. However, at the same time, these results support models and previous findings which suggest that ADHD is a neuropsychologically heterogeneous disorder that cannot be characterized by a single core dysfunction [16–22, 25]. Furthermore, although WM impairments in ADHD-I were less prevalent than in ADHD-C, they were more prevalent than in the TD group, and WM performance significantly discriminated between ADHD-I and TD children, suggesting that visuospatial WM deficits may also cause problems in a substantial part (33.3 %) of the ADHD-I population.

This is the first study to investigate the prevalence of visuospatial STM impairments in children with ADHD. In children with ADHD-C, STM impairments were less common than WM impairments (40.7 vs. 58.1 % impaired). Furthermore, we found that about half of the WM-impaired children with ADHD-C could not be classified as STM-impaired. Since WM capacity is regarded as the sum of both STM- and central executive capacity [54], this finding suggests that about half of the cases with visuospatial WM impairments in the ADHD-C population are not the result of visuospatial STM impairments, but are solely caused by impairments in their central executive. In the other half of the cases WM impairments may be the result of STM impairments only, or of a combination of STM and central executive impairments. To examine this, future prevalence studies should include an additional task: one that only measures central executive performance.¹⁰

¹⁰ Future studies should be aware that impaired inhibitory performance can also have a small impact on the central executive performance of children with ADHD [see 12].

Although less prevalent than WM impairments, more than 40 % of the ADHD-C group was impaired on STM, and STM performance correctly discriminated between ADHD-C and TD children in 71.6 % of the cases. This suggests that STM impairments may give rise to ADHD-related problems in a substantial part of the ADHD-C population. In contrast, STM impairments were not more prevalent in the ADHD-I group than in the TD group, nor did STM performance significantly discriminate between these samples (at least not when the confounding effect of motivation was taken into account). These results are in line with the theoretical appraisal by Diamond [30] and with recent studies which suggest that children with ADHD-I, in contrast to children with ADHD-C, are especially impaired on the central executive component, but not on the STM component of WM [30, 35, 36]. Furthermore, STM performance only discriminated between ADHD-I and TD children in the feedback-only condition, not in the high-reinforcement condition. This suggests that impaired STM performance in children with ADHD-I results from insufficient motivation to perform (also see [35]), and promotes the use of additional incentives in studies that investigate STM in children with ADHD-I.

Motivation

Although both theory [e.g. 28, 29] and research [39, 40; also see 13, 33, 34] suggest that an abnormal sensitivity to reinforcement is characteristic of children with ADHD on a group level, our findings show that this motivational impairment, apart from being a valid and distinct impairment, is actually not so common among these children (only 22 % were classified as impaired). De Zeeuw et al. [23] found an even lower prevalence rate (<8 % impaired), but this difference in results probably is related to a difference in reward frequency schedules: It has been suggested that high reward frequency schedules attenuate reinforcement sensitivity problems in children with ADHD [23, 31] and reward frequency was much higher in the study of de Zeeuw et al. (80 % of the trials were rewarded, compared to 55 % of the trials in our study). Although further expansion of our research design was not possible in our current study (e.g., increasing testing time would potentially have impacted the sustained attention, motivation and performance of our participants), it would be interesting for future studies to explore the effects of different reward frequencies on the prevalence of reinforcement sensitivity problems in children with ADHD (e.g., by adding a condition where only a minority of the trials is rewarded, or a condition without reinforcement).

Reinforcement sensitivity deficits were equally prevalent in both ADHD subtypes, but only in the ADHD-C group this impairment was significantly more prevalent

than in the TD group, and the reinforcement sensitivity index did not discriminate significantly between ADHD-I and TD children. These findings are consistent with theories stating that motivational abnormalities characterize the combined subtype only [31], and contradict theories stating they apply to the inattentive subtype in particular [30]. However, we found a trend towards significance ($p = 0.06$) for the reinforcement sensitivity index to discriminate between ADHD-I and TD children, which suggests that this difference would have been significant in a study with higher statistical power. Future studies should test this hypothesis using a more substantial ADHD-I sample. Based on our current results, we can conclude that reinforcement/reward sensitivity deficits are not so common in children with ADHD (e.g., less common than memory impairments in ADHD-C), and seem equally prevalent in both ADHD subtypes.

Memory and motivation

To our knowledge our data provide the first evidence that impairments in visuospatial WM and STM in ADHD are dissociable from impairments in reinforcement sensitivity. This absence of associations across motivational and memory domains highlights the neuropsychological heterogeneity in ADHD and supports recent evidence suggesting separable neuropsychological subtypes in ADHD [e.g., 16, 19, 23]. In this context our findings are especially strong since they are based on neuropsychological measures that were probably not confounded by motivational deficits. Furthermore, the absence of overlap between memory and reinforcement sensitivity suggests that the combined assessment of these domains may contribute to improved neuropsychological differentiation of ADHD. Nonetheless, it must be noted that this absence of associations between deficits in motivation and memory was also found in controls. This suggests that the neuropsychological heterogeneity in ADHD may be a derivative of normal variation (see also [16]).

Correlates of impairments on WM, STM and/or reinforcement sensitivity

Children with ADHD-C who were classified as impaired on WM, STM, and/or reinforcement sensitivity had more teacher-rated inattention symptoms, were more likely to use ADHD medication (methylphenidate), and had lower IQ scores than their unimpaired ADHD-C peers (for the ADHD-I group power was inadequate to interpret this analysis).

This seems consistent with models that suggest that inattentiveness results from WM dysfunctions [1, 3] and with previous studies demonstrating that inattention, not

hyperactivity/impulsivity, is associated with neuropsychological impairment in children with ADHD [7, 20, 27, 55, 56]. However, because this was a cross-sectional study it is difficult to make causal inferences. Further, it is unclear why impairment was only associated with teacher-rated inattention, not with parent-rated inattention.

Impaired children with ADHD-C (on WM, STM and/or reinforcement sensitivity) were more likely to be treated with methylphenidate (75.4 vs. 38.1 % medication-use). This is in line with evidence (in normal adults) suggesting that the effectiveness of dopaminergic medication can be predicted by WM performance in an un-drugged state [57], and might be explained by the finding that WM capacity predicts baseline levels of dopamine synthesis in the striatum [58]. Future studies should investigate this in ADHD, using larger samples (particularly for ADHD-I) to better differentiate between memory and motivational impairments (especially since there is also a strong relationship between dopamine synthesis and motivation [58]).

Our finding that WM, STM and/or reinforcement sensitivity impairments in ADHD-C are associated with lower IQ scores is in line with previous ADHD prevalence studies [21, 23], and with findings in TD children [e.g., 59]. Further, it supports the assumption that WM is crucial for the mental activities basic to children's intelligence [59], and is consistent with the idea that neuropsychological impairments (e.g., in WM) are responsible for the lower level of intellectual performance typically found in children with ADHD [1].¹¹

Limitations

The sample size of the ADHD-I group was relatively small ($n = 27$) and as a result some of the analyses (especially the within-group analyses) were underpowered (i.e., power was inadequate to detect medium effects). Therefore, the underpowered null findings in the ADHD-I group should be interpreted with caution (due to the possibility of type II error). Although it must be noted that effect sizes of the underpowered null findings were small, future studies should use a larger sample size to replicate the findings in the ADHD-I group.

Another potential limitation may have been the difference in IQ and weekly spendable income between the ADHD-C and the TD group, and the difference between the TD group and the ADHD groups on gender. However, in ADHD-TD group comparisons, covarying for these independent variables did not change the pattern of the mean results (see Table 1). Further, the ADHD groups differed on parent-rated inattention on the DBDRS.

¹¹ In ADHD-C only the mean IQ score of the impaired subsample was significantly lower than that of the TD group.

However, in ADHD group-comparisons, covarying for this inattention score did not change the mean results (see Table 1). This suggests that our outcomes were not confounded by this difference in inattention. In addition, the ADHD groups did not differ on teacher-rated inattention.

Although all children discontinued their ADHD medication at least 24 h before testing (allowing a complete wash-out), there was a difference between the ADHD groups in prior medication use: medication use was more common in ADHD-C. However, since evidence suggests that performance on WM measures is not influenced by the chronic use of ADHD medication [60], and because including medication use as a covariate did not change the pattern of our mean results, we assume that the outcome of this study was not confounded by this difference in prior medication use.

Although all children were screened for externalizing disorders, ASD, learning disorders (i.e., reading disorder and mathematics disorder) and intellectual disabilities (i.e., an IQ score ≥ 80), and control children were only included in the study if their parents stated they had no prior or current DSM-IV-TR diagnosis (other than a reading disorder or a mathematics disorder), participants were not specifically screened for internalizing disorders such as anxiety or depressive disorders. However, evidence suggests that anxiety and depressive disorders can affect WM performance in typically developing groups [e.g., 66, 68–71], and there is some (although conflicting) evidence regarding the effect of comorbid anxiety or depression on the working memory performance of children with ADHD [e.g., see 66, 71–74]. There is also recent evidence suggesting that high levels of anxiety and depression can differentially modify WM performance according to ADHD subtype [66]. Interestingly, it is suggested that emotional states (e.g., anxiety) interact with cognitive functioning through motivation [75]. However, little is known about this interaction in children with ADHD [but see 66]. Therefore, future prevalence studies investigating ADHD subtype differences in WM, STM and/or motivational deficits should also assess and examine effects of symptoms of anxiety and depression.

A strong point of the current study is that we investigated the prevalence and diagnostic validity of WM and STM impairments in children with ADHD by using measures that were probably not confounded by motivational deficits (i.e., as strong incentives were used to optimize performance¹²). Nonetheless, the prevalence and diagnostic validity of many other important ADHD-associated neuropsychological dysfunctions are still not examined in this way. For example, we are unaware of studies that

investigate the prevalence and diagnostic validity of impairments in inhibition or sustained attention in children with ADHD by using measures that are not likely to be confounded by motivational deficits. Future prevalence and diagnostic validity studies should therefore adapt their neuropsychological assessment tools to account for these motivational deficits in children with ADHD.

We did not specifically investigate the extent to which problems with sustained attention impacted the WM and STM performance of children with ADHD. However, we did control for situational factors (e.g., test rooms were quiet and views from windows were blocked) and cognitive factors (e.g., the task versions were self-paced for optimal attention/vigilance) that could provoke lapses of attention. Moreover, in a previous study [33], where we used the same WM task, we found that a 10 euros reinforcement condition (the same as in the current study) normalized the sustained attention of children with ADHD (i.e., if children with ADHD were motivated with 10 euros, their mean WM performance was as stable over time as the WM performance of controls). Because the WM and STM-related results in the current study were mainly based on performance in the 10 euros condition, we assume that these results were not confounded by problems with sustained attention in children with ADHD. This assumption is also substantiated by the slopes of the figures in ESM Appendix 2.

In the current study, we only investigated the effects of immediate reinforcement. However, as the prevalence of delay aversion in children with ADHD might be at least as high as the prevalence of immediate reinforcement deficits [e.g., see 19, 22], it would be interesting to also investigate the impact of delayed reinforcement on the prevalence and diagnostic validity of WM and STM impairments in children with ADHD-I and ADHD-C (especially as there might be some conceptual overlap between delay aversion and memory; e.g., see [22]; but also see [76]).

Clinical implications

First of all, it should be noted that 24.4 % of the children with ADHD-C and no less than 44.4 % of the children with ADHD-I showed no impairment on any of the investigated indices (WM, STM, or reinforcement sensitivity). Furthermore, clinicians should be aware that although all these indices discriminated significantly between children with ADHD-C and TD children, only the WM and STM measures showed clinically acceptable diagnostic validity, with both sensitivity and specificity being ≥ 70 % (as was recommended by Glascoe and Squires [61]). In addition, based on these guidelines, none of the indices showed acceptable diagnostic validity to distinguish children with ADHD-I from TD children, or to distinguish between the ADHD subtypes. Moreover, when it comes to distinguishing children with

¹² The 10 euros condition was previously found to optimize task performance in children with ADHD-C [33].

ADHD-C from TD children, the diagnostic validity of ADHD rating scales is, at this point, still much better (with correct overall classification rates of 90–95 % [62]) than that of any neuropsychological task (including visuospatial WM or STM measures). As such, measures of visuospatial WM, visuospatial STM or reinforcement sensitivity are not the best choice for making DSM-oriented ADHD diagnoses in children (especially not for diagnosing ADHD-I). That said, a majority of children with ADHD-C are characterized by a visuospatial memory and/or motivational impairment, and assessment of these impairments may (independently) provide information about possible causal mechanisms of the ADHD behavior of an individual child (e.g., the association between his/her low WM and his/her classroom inattention problems), and can help clinicians choose the best approach for treatment. For example, it may help clinicians choose the best treatment approach within behavioral parent- and teacher training¹³ (e.g., using reward systems versus techniques to unburden WM; only a minority of children with ADHD-C may require an intensive reward system, whereas a majority of these children require strategies to unburden WM and have less need for an additional intensive reward system), or may help determine the relevance of a neuropsychological training program (like STM or WM training) for an individual child with ADHD. In line with this, our results imply that interventions such as Cogmed working memory training, of which there is debate as to whether mainly STM is trained [e.g., 79], should focus more on training the central executive, especially in children with ADHD-I.

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Conflict of interest SvdO has been a paid consultant for Janssen pharmaceuticals in the development and evaluation of a serious game “Healseeker” aimed at training cognitive functions. Other authors report no conflicts of interest.

¹³ These evidence-based interventions [77, 78] aim at improving behavioral control in children with ADHD by teaching parents and teachers to use token (reward) systems and techniques to unburden the WM of these children (e.g., providing reminders and a structured environment).

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