Original Article

Basic numerical processing, calculation, and working memory in children with dyscalculia and/or ADHD symptoms

Jörg-Tobias Kuhn[1], Elena Ise[2], Julia Raddatz[1], Christin Schwenk[1], Christian Dobel[3]

[1] Institute of Psychology, University of Münster
[2] Department of Child and Adolescent Psychiatry and Psychotherapy, Medical Faculty, University of Cologne
[3] Department of Otorhinolaryngology, Friedrich-Schiller University Jena

Abstract: *Objective:* Deficits in basic numerical skills, calculation, and working memory have been found in children with developmental dyscalculia (DD) as well as children with attention-deficit/hyperactivity disorder (ADHD). This paper investigates cognitive profiles of children with DD and/or ADHD symptoms (AS) in a double dissociation design to obtain a better understanding of the comorbidity of DD and ADHD. *Method:* Children with DD-only (N = 33), AS-only (N = 16), comorbid DD+AS (N = 20), and typically developing controls (TD, N = 40) were assessed on measures of basic numerical processing, calculation, working memory, processing speed, and neurocognitive measures of attention. *Results:* Children with DD (DD, DD+AS) showed deficits in all basic numerical skills, calculation, working memory, and sustained attention. Children with AS (AS, DD+AS) displayed more selective difficulties in dot enumeration, subtraction, verbal working memory, and processing speed. Also, they generally performed more poorly in neurocognitive measures of attention, especially alertness. Children with DD+AS mostly showed an additive combination of the deficits associated with DD-only and A_Sonly, except for subtraction tasks, in which they were less impaired than expected. *Conclusions:* DD and AS appear to be related to largely distinct patterns of cognitive deficits, which are present in combination in children with DD+AS.

Keywords: Mathematical learning disabilities, dyscalculia, basic numerical processing, ADHD, comorbidity

Basisnumerische Verarbeitung, Rechenfertigkeiten und Arbeitsgedächtnis bei Kindern mit Dyskalkulie und/oder ADHS-Symptomen

Zusammenfassung: *Fragestellung:* Defizite in basisnumerischer Verarbeitung, Rechenfertigkeiten und der Arbeitsgedächtniskapazität sind nicht nur für Kinder mit Dyskalkulie (DD), sondern auch für Kinder mit einer Aufmerksamkeitsdefizit-/Hyperaktivitätsstörung (ADHS) berichtet worden. Die vorliegende Studie untersucht die kognitiven Profile von Kindern mit DD und/oder ADHS-Symptomen (AS) in einem 4-Gruppen-Design. Ziel der Studie ist es, einen Beitrag zum Verständnis der Komorbidität von DD und ADHS zu leisten. *Methode:* Kinder mit DD (N = 33), AS (N = 16), komorbider DD+AS (N = 20) sowie eine unbeeinträchtigte Kontrollgruppe (N = 40) wurden mit psychometrischen Tests untersucht, die die basisnumerische Verarbeitung, Rechenfertigkeiten, Arbeitsgedächtnis sowie neurokognitive Maße der Aufmerksamkeit erfassten. *Ergebnisse:* Kinder mit DD (DD, DD+AS) zeigten Defizite in allen basisnumerischen Aufgaben sowie in Rechenfertigkeiten und dem Arbeitsgedächtnis. Zudem machten sie mehr Fehler in der Daueraufmerksamkeitsaufgabe. Kinder mit AS (AS, DD+AS) zeigten selektivere Schwierigkeiten (Abzählen, Subtraktion, verbales Arbeitsgedächtnis) und wiesen Beeinträchtigungen bei der Alertness sowie im Mittel geringere Aufmerksamkeitsleistungen auf. Kinder mit komorbider DD+AS zeigten ein kognitives Profil, das sich weitgehend additiv aus den einfachen Störungen ergab, obwohl bei Subtraktionsaufgaben geringere Beeinträchtigungen als erwartet vorlagen. *Schlussfolgerungen:* DD und AS scheinen mit überwiegend verschiedenen Mustern kognitiver Defizite assoziiert zu sein, die bei Komorbidität (DD+AS) weitgehend additiv auftreten.

Schlüsselwörter: Rechenschwäche, Dyskalkulie, basisnumerische Verarbeitung, ADHS, Komorbidität

Introduction

Low mathematical abilities are associated with a higher risk of psychopathological symptoms and lower quality of life in childhood (Kohn, Wyschkon & Esser, 2013). In addition, they are predictive of lower socioeconomic status in midlife (Ritchie & Bates, 2013). A key cause of severe difficulties in mathematics is developmental dyscalculia (DD), which according to DSM-5 is defined as a specific learning disorder affecting calculation and arithmetic fact retrieval as well as more basic skills such as understanding of numbers or magnitudes. DD is a congenital, substantially heritable disorder with a prevalence rate of 3.5–6.5 % in the general population (Alarcón, DeFries, Light & Pennington, 1997; Butterworth & Kovas, 2013), with mixed evidence on gender differences (Barbaresi, Katusic, Colligan, Weaver & Jacobsen, 2005; Moll, Kunze, Neuhoff, Bruder & Schulte-Körne, 2014).

It is generally assumed that DD is a neurocognitive disorder with a biological origin (Butterworth, Varma & Laurillard, 2011), implying that children with DD exhibit structural and functional alterations of specific, mostly frontoparietal brain areas. An fMRI study revealed that during a nonsymbolic magnitude comparison task, children with DD displayed fewer and less adaptive activity in the right intraparietal sulcus (IPS), a key area for magnitude and number processing (Price, Holloway, Räsänen, Vesterinen & Ansari, 2007). Further, using voxel-based morphometry, several studies showed that children with DD, in contrast to controls, had reduced gray matter in brain areas thought to be related to number and magnitude processing (i.e., IPS), but also in areas that probably underlie attention and working memory processes (e.g., middle frontal gyrus, left inferior frontal gyrus; Rotzer et al., 2008; Rykhlevskaia, Uddin, Kondos & Menon, 2009). Finally, studies using diffusion tensor imaging showed that DD is related to a disruption of white matter integrity in the superior longitudinal fasciculus, among others, which is one of the main projection fibers from inferior parietal to prefrontal brain regions. Hence, DD is also related to impaired neural connectivity between brain areas involved in magnitude processing (Kucian et al., 2014; Rykhlevskaia et al., 2009).

A large body of research has shown that children with DD exhibit substantial impairments in basic numerical skills that developmentally precede calculation and arithmetic (von Aster & Shalev, 2007). For example, it was found that children with DD display substantially longer response times in dot enumeration (Reigosa-Crespo et al., 2012). Further, their precision in number line estimation tasks is lower (Geary, Hoard, Nugent & Byrd-Craven, 2008), and they exhibit difficulties in writing heard numbers (transcoding; Moura et al., 2013). Finally, DD consistently results in impaired efficiency in symbolic magnitude comparison tasks (Geary, Hoard, Byrd-Craven, Nugent & Numtee, 2007; Landerl, Bevan & Butterworth, 2004). A careful assessment of such basic numerical skills is required in DD, as interventions usually need to address deficits in these basic skills prior to targeting calculation difficulties (Cohen Kadosh, Dowker, Heine, Kaufmann & Kucian, 2013).

DD is characterized by a substantial comorbidity with other neurodevelopmental disorders. Children with DD show significantly more attentional problems than unimpaired children (Shalev, Auerbach & Gross-Tsur, 1995), and comorbidity rates between DD and attention deficit hyperactivity disorder (ADHD) vary between 5 % and 30 % (DuPaul, Gomley & Laracy, 2013). ADHD is a neurodevelopmental disorder defined by pervasive and severe symptoms of inattention, hyperactivity, and impulsivity according to current diagnostic systems (DSM-5, ICD-10). Its mean prevalence rate is 5.3 % (Polanczyk, de Lima, Horta, Biederman & Rohde, 2007), with a high degree of heritability (around 70–80 %; Faraone et al., 2005). ADHD is a heterogeneous disorder, and different subtypes have been suggested. For example, DSM-5 describes a predominantly inattentive presentation, a predominantly hyperactive/impulsive presentation, and a combined presentation of symptoms, although long-term stability of ADHD subtype classification tends to be low (Willcutt et al., 2012). Numerous studies showed that ADHD is related to abnormalities in frontostriatal brain regions involved in cognitive inhibition and control (e.g., Durston et al., 2003). Further, a recent fMRI-based meta-analysis revealed that children with ADHD displayed hypoactivation in large-scale brain networks related to executive functions (frontoparietal network) and attention (ventral attentional network), whereas they displayed hyperactivation in the default and somatomotor networks (Cortese et al., 2012). Because the default network is active when subjects are not focusing attention on tasks in the external environment, the former result suggests that lapses of attention in ADHD are related to insufficient inhibitory control of the default network while executing cognitive tasks.

Children with ADHD show lower scholastic achievement than unimpaired children ($d = .71$ in a meta-analysis by Frazier, Youngstrom, Glutting & Watkins, 2007), with more consistent results for the inattentive subtype (Massetti et al., 2008). A core problem of children with ADHD, especially those with inattentiveness symptoms, appears to be a deficit in working memory (Martinussen, Hayden, Hogg-Johnson & Tannock, 2005), which is a central cognitive resource in mathematical processes. Generally, with respect to mathematics, it has been found that children with ADHD show deficits in fact retrieval, calculation, and word problems (see Tosto, Momi, Asherson & Malki, 2015, for a systematic review). Several other studies have used inattention as a covariate when comparing children with DD, dyslexia, and control groups, showing that inattention was related to impairments in fact retrieval and multidigit tasks (e.g., Cirino, Fletcher, Ewing-Cobbs, Barnes & Fuchs, 2007; Raghubar et al., 2009).

Yet, only relatively few studies have investigated to which degree basic numerical skills are affected by ADHD. Kaufmann and Nuerk (2008) showed that children with ADHD produced significantly more errors in a number comparison task than the control group. Further, Colomer, Re, Miranda, and Lucangeli (2013) reported that substantial proportions of children with ADHD displayed severe impairments (-2 *SD* below age mean) in standardized tests of counting (36 % of children), transcoding (18 %), and mental calculation (18 %).

Results on the familial or genetic relationship between ADHD and DD are relatively sparse and inconsistent. In one early study, ADHD and DD showed independent familial transmission (Monuteaux, Faraone, Herzig, Navsaria & Biederman, 2005), suggesting that both disorders are etiologically distinct. However, a more recent study found that inattentiveness showed substantial genetic associations with low mathematical ability, whereas hyperactivity/impulsivity did not (Greven, Kovas, Willcutt, Petrill & Plomin, 2014). These authors also found that associations between ADHD and mathematics ability were largely attributable to genetics. In contrast to Greven et al. (2014), the study by Hart et al. (2010) reported that both groups of ADHD symptoms (inattention and hyperactivity/impulsivity) and academic outcomes shared similar influences of general genes. Other studies suggest that the phenotypic overlap among many neurodevelopmental symptoms is attributable to a single genetic factor (Petterson, Anckarsäter, Gillberg & Lichtenstein, 2013). From a genetic perspective, therefore, neurocognitive disorders may not be fully distinct diagnostic categories (cf. Haworth et al., 2009).

The present study contributes to a better understanding of the comorbidity between DD and ADHD by investigating the cognitive profiles of these disorders in a double dissociation design. Four groups were studied: children with DD, children with high levels of parent-reported ADHD symptoms (AS), children with comorbid DD+AS, and a typically developing control group (TD). A battery of tasks was used to measure basic numerical processing, calculation skills, and working memory. To our knowledge, dissociation designs that contrast groups with "pure" forms of DD and ADHD symptoms with a comorbid group and a control group (Pennington, Groisser & Welsh, 1993) are still lacking. Dissociation designs allow a closer investigation of several behavioral genetic causal hypotheses on comorbidity. The "phenocopy" hypothesis (Pennington et al., 1993) assumes that the profile of the comorbid group is similar to that of the pure groups. For example, in the comorbid group, ADHD symptoms may arise as a secondary consequence of DD. The "cognitive subtype" hypothesis suggests that the comorbid group displays more severe impairments than the groups with pure disorders (Rucklidge & Tannock, 2002). Finally, the "shared etiology" hypothesis implies that children with pure disorders show distinct patterns of cognitive impairments, and both forms of impairment co-occur in the comorbid group (Willcutt, Pennington, Olson, Chhabildas & Hulslander, 2005).

Methods

Subjects

Overall, 109 children from elementary schools in Germany participated in this study, all of whom were native German speakers. Participants with neurocognitive disorders (DD, AS, DD+AS; *n* = 69) were recruited via newspaper articles, searching for elementary school students with mathematical difficulties, and received a free computer-based training of basic math skills after psychometric testing was finished (Kuhn & Holling, 2014). They were selected from a sample of 151 children (see below). Children in the control group (*n* = 40) were selected from a different sample comprising 598 children and had to show normal mathematics skills, reading, and IQ (see Kuhn, Raddatz, Holling & Dobel, 2013, for additional information on recruiting). All children visited regular schools (second to fourth grade), came from families of middle socioeconomic status, and received regular mathematical instruction. Parental consent was obtained prior to testing. All subjects in this study were medication naïve.

Classification Measures

Mathematical ability was assessed using a neuropsychological battery examining basic skills in calculation and arithmetic (ZAREKI-R; von Aster, Weinhold-Zulauf & Horn, 2006). In accordance with DSM-5, the definition of dyscalculia used in this study did not require a substantial IQ-math achievement discrepancy. We also assessed IQ, based on four WISC-IV subtests (German version; Petermann & Petermann, 2011): Block design, Picture concepts, Matrix Reasoning, and Vocabulary. IQ estimates based on these subtests and full-scale IQ correlate at *r* = .90 or higher (Sattler, 2008). Further, reading fluency was assessed (SLS 1-4; Mayringer & Wimmer, 2003). The classification scheme of the study is summarized in Table 1.

Participants' symptoms of ADHD were rated by their parents using a 20-item questionnaire based on DSM-IV and ICD-10 diagnostic criteria (FBB-ADHS; Döpfner, Görtz-Dorten & Lehmkuhl, 2008). The FBB-ADHS consists of the three subscales Inattention (9 items), Hyperactivity (7 items), and Impulsivity (4 items). Each item describes specific symptom behavior. Respondents are asked to rate each item on a four-point Likert scale ranging from 0 (not at all) to 3 (very much). The FBB-ADHS scale scores are computed by averaging the responses to items on each scale, with higher scores indicating worse problem behavior. Stanine scores of 8 or higher indicate clinically meaningful symptoms (Döpfner et al., 2008). Groups defined by the classification scheme did not differ on age, $F(3, 105) = 1.02$, $p = .39$, sex ratio, $\chi2(3) = 5.86$, $p = .12$, or class level, $\chi2(6) = 3.03$, $p = .81$ (see Table 2).

Basic Numerical Skills

All tasks assessing basic numerical skills were self-constructed and administered on a computer. Instructions were presented to participants verbally using headphones to minimize reading effort. Each task was first practiced using example items with feedback before test items were presented.

- *Dot enumeration (DE)*. One to nine black dots were presented in the middle of the screen. Participants were supposed to enumerate them as quickly as possible and then to press the corresponding number key on the keyboard (Reigosa-Crespo et al., 2012). Time limit was 2 minutes. The test included 18 items. The median of correct answers was used as the test score.
- *Number comparison (NC)*. Two single-digit numbers were presented to the left and right on screen. Participants had to decide as quickly as possible which number was larger by pressing one of two response keys. Numerical distance between stimuli was systematically manipulated to be small (1–3) or large (4–6). The test included 24 items, with a time limit of 1.5 minutes. The median of correct answers was used as the test score.
- *Mixed comparison (MC)*. The setup was identical to number comparison, except that a single-digit number and a cloud of one to nine dots were presented on screen.
- *Transcoding (TC)*. Participants heard numbers and were supposed to type them using the keyboard. Each number could be heard a maximum of two times. The test

Table 1. Classification scheme of the study

Criterion	Measure	TD	DD	AS	DD+AS
Number processing & calculation	ZAREKI-R	SS > 80	SS ≤ 80	SS > 80	SS ≤ 80
Inattention	FBB-ADHS (Inattention scale)	SN < 8	SN < 8	SN ≥ 8	SN ≥ 8
IQ	WISC-IV[a]	IQ ≥ 80	IQ ≥ 80	IQ ≥ 80	IQ ≥ 80
Reading fluency	SLS 1-4	SS ≥ 80	SS ≥ 80	SS ≥ 80	SS ≥ 80

Note. TD = Typically-developing children, DD = Dyscalculic children, AS = children with ADHD symptoms, DD+AS = Dyscalculic children with ADHD symptoms, SS = Standard score (M = 100, SD = 15), SN = Stanine score (M = 5, SD = 2). [a]IQ estimate based on subtests Block Design, Picture Concepts, Matrix Reasoning, Vocabulary.

Table 2. Means (*SD*) of diagnostic and descriptive variables

Measure	TD (*N = 40*)	DD (*N = 33*)	AS (*N = 16*)	DD+AS (*N = 20*)	Posthoc comparisons
Descriptives					
Age (in months)	107.45 (7.52)	105.42 (11.54)	109.44 (10.36)	104.20 (12.28)	
Sex (girls/boys)	23/17	27/6	12/4	12/8	
Class level (2nd, 3rd, 4th)	19/15/6	12/16/5	7/5/4	7/8/5	
Mathematics					
ZAREKI-R (SS)	100.68 (13.67)	70.41 (5.15)	91.00 (8.97)	72.25 (6.37)	TD > AS > DD = DD+AS
IQ					
WISC-IV (IQ)	104.50 (10.91)	94.24 (8.30)	99.69 (9.91)	95.75 (9.50)	TD > DD = DD+AS
Reading					
SLS 1–4 (SS)	104.33 (12.60)	94.58 (9.55)	103.75 (16.21)	92.75 (8.77)	TD > DD = DD+AS
ADHD symptoms					
FBB-ADHS, inattention (SN)	5.85 (1.37)	6.24 (1.09)	8.06 (0.57)	8.05 (0.60)	TD = DD < AS = DD+AS
FBB-ADHS, hyperactivity (SN)	4.48 (2.40)	4.64 (2.49)	7.25 (1.95)	6.95 (1.93)	TD = DD < AS = DD+AS
FBB-ADHS, impulsivity (SN)	3.65 (2.33)	3.73 (2.35)	6.31 (1.70)	5.65 (2.08)	TD = DD < AS = DD+AS
FBB-ADHS, total (SN)	5.40 (1.24)	5.76 (1.28)	7.94 (0.68)	7.65 (0.75)	TD = DD < AS = DD+AS

Note. Posthoc comparisons between groups were based on the Games-Howell procedure ($p < .05$). SS = Standard scores, SN = Stanine scores.

consisted of eight class level-specific items, and the time limit was 2 minutes. The number of correct items was used as the test score.

- *Number sets (NC)*. Participants saw a target number on screen. Below the target, a number set consisting of two or three cells was shown. In each cell, a structured set of objects or a number could be shown (Geary et al., 2007). Participants had to decide as quickly as possible by pressing one of two response keys whether the total magnitude in the number set matched the target number. Two target numbers (5 and 9) were used for 1.5 minutes each. This test was a speed test, and the number of correct answers minus the number of false alarms was used as the test score.
- *Number line estimation (NL)*. Participants saw a number between 1 and 99 on screen. Below, a number line with endpoints 0 and 100 was shown. Participants were supposed to click onto the number line at the position that corresponded to the shown target number (Siegler & Booth, 2004). Mean deviation between target number and answer was taken as the test score. This test consisted of 23 items, time limit was 3.5 minutes.

Processing Speed

A choice reaction time task (CRT) was used to assess processing speed without numerical or verbal content. Participants were presented with a white square on an initially black screen, and they quickly had to decide whether the square was left or right of a white vertical line at the center of the screen by pressing one of two response keys. The test score was the median of correct response times. The test consisted of 20 items with a time limit of 1 minute.

Calculation

Five tasks were used to measure calculation and quantitative reasoning, two of them computer-based. The self-constructed computer-based addition (ADD-P) and subtraction tasks (SUB-P) each were adapted to class level and presented items successively on screen. Participants had to solve addition or subtraction tasks on screen by mental calculation and type the correct solution. Item difficulties quickly increased, from simple items at the beginning (e.g., 2 + 6) to complex items later (e.g., 1075 – 28). Test score was the number of correct items. Seven items had to be solved within 2 minutes for each test, such that these tests can be considered power tests. Second, two speeded paper-pencil tests of addition (ADD-S) and subtraction (SUB-S) from a standardized test of arithmetic skills, the Heidelberger Rechentest (HRT 1-4; Haffner, Baro, Parzer & Resch, 2005), were administered. In each of the HRT tests, children had to solve as many items as possible from a list of 40 calculations (increasing gradually in difficulty). Time limit was 2 minutes for each speeded test. Third, the Arithmetic subtest from the WISC-IV (WISC-AR) was administered (Petermann & Petermann, 2011). In this test, mathematical word problems of increasing difficulty and complexity are presented orally, and subjects have to state the correct answer. After four consecutive wrong answers, testing stopped. The Arithmetic subtest can be regarded as a measure of quantitative reasoning (Keith, Fine, Taub, Reynolds & Kranzler, 2006).

Working Memory

Two complex span tasks were used to measure working memory capacity. First, a visual matrix span (MS) task was administered to assess processes that tax the central executive and the visuospatial sketchpad, which are typically impaired in children with DD and children with ADHD (Kuhn, 2015; Martinussen et al., 2005). Participants were shown an array of dots in a matrix on screen and were requested to remember the position of each dot. After 5 seconds, the dots disappeared. A row or column in the empty matrix was then colored yellow, and subjects had to indicate whether a dot had been present in one of the yellow cells before. Finally, an empty matrix was shown, and the pattern of dots shown initially had to be reproduced by clicking onto the respective cells (Andersson & Lyxell, 2007). The size of the matrix became larger in each successive item. After three incorrectly reproduced patterns, the task stopped. Test score was the number of items solved correctly. Time limit was 5 minutes.

Second, a verbal span task (VS) was administered (Vock & Holling, 2008). This task consisted of two different parts pertaining to storage and processing. Participants first had to memorize a list of words presented simultaneously on the screen (presentation time 6 seconds). List length in this storage task varied between three to six words. Then, between two and three verbal decision tasks followed in which participants had to respond as quickly as possible. In these processing tasks, participants had to decide which of four words displayed in each corner of the screen stood in a subconcept relationship to the word shown in the center of the screen (e.g., “animal” – “lion”). Finally, participants had to reproduce the learned words in correct order by selecting the first letter of the first word from a list, after which a list of words was shown all starting with the selected first letter. The child then was supposed to click the correct first word from the list. Next, the first letter of the second word had to be selected, and so on. The task consisted of two practice items and 10 test items. Because of a technical error, data for 5 children were missing for this task.

Neurocognitive Measures of Attention

Three computer-based, neurocognitive measures of attention were administered: alertness, sustained attention, and flexibility (KITAP; Zimmermann, Gondan & Fimm, 2002). Alertness required subjects to press a key as quickly as possible whenever a critical stimulus (a witch) appeared on screen. There were 30 trials, and testing time was about 2 minutes. Median response time and *SD* of response time are defined as key parameters for alertness. In the sustained attention task, ghosts of different color successively appeared at different locations on screen. Children were supposed to press a response button whenever two successive ghosts had the same color. There were 300 trials, 50 of which were target trials. Testing time was 10 minutes. Key parameters in sustained attention were errors (response to nontarget) and omissions (lack of response to target). Finally, the flexibility task showed a blue and a green dragon on screen. Two response keys were used: First, the key corresponding to the position of the green dragon had to be pressed; in the next trial, the key corresponding to the blue dragon had to be pressed, and so on. Positions of dragons varied randomly (50 trials, testing time varied individually). Key parameters were errors and median of response times.

Statistical Analysis

Group means in classification measures and descriptive statistics were compared using ANOVA, and posthoc comparisons to identify significant differences between specific groups were conducted using the Games-Howell procedure and corrected for multiple comparisons. To determine whether DD or AS was significantly associated with poorer performance on any of the cognitive measures, independent of the other disorder, a series of 2 × 2 ANOVAs (DD+/DD− × AS+/AS−) was conducted. A significant main effect of DD indicates that children with DD (DD, DD+AS) perform worse on the measure of interest compared to children without DD (AS, TD), whereas a significant main effect of AS indicates that children with AS (AS, DD+AS) perform worse on the measure than children without AS (DD, TD). Further, the absence of an interaction suggests that the effects of DD and AS are additive (i.e., the profile of the DD+AS group results additively from those of the DD and AS groups) and therefore statistically independent. In order to test the "cognitive-subtype" hypothesis that children with DD+AS show greater deficits than children with DD-only or AS-only, planned comparisons using independent sample *t*-tests were used. Age and class level were used as covariates in ANOVAs when unstandardized, but not when standardized data were analyzed such that age and school experience were taken into account. Further, because of group differences in IQ and reading (cf. Table 2), all ANOVAs of cognitive measures were rerun using these variables as covariates.

Results

As can be seen in Table 2, the control group (TD) displayed significantly higher scores than the AS group and the two DD groups (DD, DD+AS) in math ability (ZAREKI-R). The pure AS group showed higher math scores than the two DD groups (DD, DD+AS). With respect to IQ and reading, both DD groups had lower scores than the control group. As expected, both AS groups showed substantially higher (i.e., more clinically relevant) scores in the FBB-ADHS than the pure DD group and the control group. Importantly, the comorbid group neither differed from the DD group in math nor from the AS group in ADHD symptoms. The co-occurrence of DD and AS was therefore not confounded with severity of symptoms.

Results on the neurocognitive measures of attention (see Table 3) suggest that there was a main effect of AS on the variability of response times in the alertness task. This result is not surprising, as increased response time variability is one of the most robust findings pertaining to ADHD (Kofler et al., 2013). Further, there was a main effect of AS on the total score, implying poorer overall performance on these neurocognitive tasks in children with ADHD symptoms. A significant main effect of DD in the sustained attention task indicated that children with DD made more errors than those without DD, although no main effect was found for AS. We did not find any significant interaction of DD and AS for any of the neurocognitive tasks. Finally, planned comparisons between the DD and DD+AS groups as well as AS and DD+AS groups revealed that there was only one significant difference, which concerned the comparison of the DD and DD+AS groups on the variability of response times in the alertness task, $t(105) = 2.71$, $p < .01$. Results did not substantially change when rerunning analyses using IQ and reading as covariates. Overall, these results show a high overlap between groups in the neurocognitive measures of attention, in contrast to the behavioral ratings of ADHD symptoms by parents. However, the small number of significant main effects for AS may not come fully unexpected, as neurocognitive measures of attention often show low sensitivity and specificity in detecting ADHD (e.g., Renner, Stottmeister-Lessing, Irblich & Krampen, 2015). Further, mean correlations between neurocognitive measures of attention and basic numerical skills did not differ significantly between dyscalculic and nondyscalculic groups ($r = .16$ vs. $r = .18$, respectively).

A clearer picture emerged with respect to the cognitive variables investigated (see Table 4). Main effects for DD were significant and substantial for all basic numerical skills, calculation tasks, and working memory tasks used in this study. Fewer main effects were found for AS, including processing speed, dot enumeration, subtraction (both power and speed), and verbal span. Interestingly, the two significant DD × AS interactions found both pertained to subtraction (power and speed condition) – and both provided evidence for underadditivity: Children in the comorbid group were less impaired in subtraction than expected, compared to the added main effects of DD and AS. Results did not substantially change when working memory was taken into account as a covariate in addition to age, class level, IQ, and reading. Finally, planned contrasts (DD vs. DD+AS, AS vs. DD+AS) showed that the comorbid group displayed poorer performance than the AS group in the number line task, $t(32.85) = -2.66$, $p < .05$, as well as in both addition tasks (power test addition: $t(105) = 2.25$, $p < .05$, speed test addition: $t(105) = 2.48$, $p < .05$). However, the DD and comorbid groups did not differ substantially on any measure of basic numerical skills, calculation, working memory, or processing speed.

Discussion

In this study, we compared children with DD-only, AS-only, comorbid DD+AS, and an unimpaired control group on measures of attention, basic numerical skills, calculation skills, working memory, and processing speed. Children with DD and AS showed distinct cognitive profiles: Whereas DD was associated with substantial impairments in all tasks pertaining to basic numerical skills, calculation, and working memory, results for AS were less clearcut. AS was associated with generally poorer performance in measures of attention as well as more variability in response times of the alertness task, which is a common finding in the literature (Kofler et al., 2013). In this vein, we also found that AS was associated with lower processing speed, which is a common result in ADHD research (e.g., Shanahan et al., 2006).

A possible explanation for the effect of AS on dot enumeration could be that the exact quantification of numerosities, especially in the subitizing range (1–4 objects), requires attention (Burr, Turi & Anobile, 2010). In the Burr et al. study, dot enumeration was affected by attention mechanisms even when controlling for mathematical skills, such that deficits in this marker of core number competence (Reeve, Reynolds, Humberstone & Butterworth, 2012) may also be attributed to attention problems. This finding has implications for utilizing dot enumeration as a measure in DD assessment, in that attentional skills need to be controlled. Interestingly, the present study showed that when taking group differences in IQ and read-

Table 3. Means and standard deviations (in standard scores) for the neuropsychological measures of attention (KITAP) for each of the four groups, including main effects and interactions from the 2 x 2 ANOVAs

	TD		DD		AS		DD+AS		Main effects				Interaction	
									DD		AS		DD × AS	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*F*	η_p^2	*F*	η_p^2	*F*	η_p^2
Alertness														
Median	98.16	12.36	101.64	15.50	97.19	14.55	95.96	14.51	.05	.00	1.74	.02	.97	.01
SD	98.43	14.47	101.68	16.66	94.19	14.26	90.03	14.82	.02	.00	6.51*	.06	1.42	.01
Sustained attention														
Errors	96.81	16.77	83.45	16.86	91.84	18.01	85.30	20.21	7.58**	.07	.19	.00	.89	.01
Omissions	99.51	14.00	92.95	17.57	93.91	16.59	88.53	12.59	3.62	.03	2.56	.02	.04	.00
Flexibility														
Errors	93.93	17.41	92.55	19.25	88.09	17.04	87.25	13.48	.10	.00	2.46	.02	.00	.00
Median	105.63	13.80	95.73	16.20	100.84	15.62	98.70	17.41	1.22	.01	.23	.00	3.84	.04
Total score	98.74	8.53	94.67	8.83	94.34	7.31	91.61	8.08	3.93	.04	4.71*	.04	.15	.00

Note. *p < .05, **p < .01.

Table 4. Means and standard deviations for processing speed, basic numerical processing, calculation, and working memory tasks for each of the four groups, including main effects and interactions from the 2 x 2 ANCOVAs

	TD		DD		AS		DD+AS		Main effects				Interaction	
									DD		AS		DD × AS	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*F*	η_p^2	*F*	η_p^2	*F*	η_p^2
Processing speed														
CRT (ms)	582.75	117.92	661.23	178.60	651.66	248.69	728.10	238.55	3.68	.03	4.12*	.04	.02	.00
Basic numerical skills														
DE (ms)	2892.26	574.77	3410.50	777.52	3257.19	446.09	3626.13	769.33	10.80**(-)	.10	5.74*	.05	.38	.00
NC (ms)	968.64	206.71	1227.05	296.27	1113.63	216.99	1223.40	256.58	15.41**	.13	3.18	.03	2.49	.02
MC (ms)	1811.98	640.83	2294.05	976.28	1925.06	632.85	2085.05	548.10	4.36*	.05	.03	.00	.99	.01
TC	7.30	1.11	6.03	1.65	6.94	1.61	5.80	2.40	18.33**	.15	1.83	.02	.02	.00
NS	16.10	7.12	12.36	6.82	13.81	5.61	10.70	4.99	6.71*(-)	.06	3.80	.04	.20	.00
NL	7.25	3.56	12.85	6.85	8.53	3.96	13.00	6.05	33.85**	.25	1.80	.02	.43	.00
Calculation														
ADD-P	5.18	1.71	3.45	1.68	4.50	2.07	3.15	1.90	19.45**	.16	2.94	.03	.36	.00
ADD-S (SS)	102.03	13.75	85.36	12.33	92.22	9.72	85.15	14.65	19.88**	.16	3.54	.03	3.25	.03
SUB-P	4.23	1.83	1.76	1.28	2.81	1.28	2.20	1.40	29.58**	.22	4.59*(-)	.05	11.93**	.10
SUB-S (SS)	104.05	14.15	85.18	14.32	89.22	14.72	82.90	10.78	20.03**	.16	9.25*	.08	4.97*	.05
WISC-AR (SS)	100.25	13.54	86.97	10.60	95.94	9.70	89.75	9.52	17.09**(-)	.14	.11	.00	2.27	.02
Working memory														
MS	3.75	1.33	2.55	1.44	3.25	1.24	2.85	1.42	12.47**	.11	.64	.00	2.29	.02
VS	3.49	2.44	1.91	1.67	2.86	2.18	2.13	1.86	27.44**	.22	4.88*	.05	.47	.00

Note. Age and class level were used as covariates in all analyses except for tests with standard scores (SS). CRT = choice reaction time, DE = dot enumeration, NC = number comparison, MC = mixed comparison, TC = transcoding, NS = number sets, NL = number line, ADD-C = addition (power), ADD-S = addition (speed), SUB-P = subtraction (power), SUB-S = subtraction (speed), WISC-AR = Arithmetic subtest from WISC-IV, MS = visual matrix span, VS = verbal span. (-) = effect no longer statistically significant after controlling for reading and IQ. * $p < .05$, ** $p < .01$.

ing into account, dot enumeration was no longer affected by DD, although the effect of AS remained.

We also observed that mental subtraction scores, both in the speed and power condition, were substantially affected by AS. This finding confirms evidence that multi-digit calculation is affected by inattention (Raghubar et al., 2009). Benedetto-Nasho and Tannock (1999) found that children with ADHD, when solving addition problems, were unimpaired in accuracy, but attempted to solve less problems than controls. In contrast, they showed deficits in both accuracy and productivity when solving subtraction problems. A possible explanation for this finding is that subtraction problems require more working memory capacity (Benedetto-Nasho & Tannock, 1999).

DD was related to poorer performance on both verbal and spatial working memory tasks used in this study, whereas AS affected only verbal span. This finding was unexpected, because research has shown that children with ADHD generally show substantially poorer performance in visuospatial working memory tasks, compared to those with verbal content (Martinussen et al., 2005). A possible explanation for this finding could be that the task format of verbal span in this study heavily taxed secondary memory, which corresponds to the ability to retrieve items from long-term memory (Unsworth & Engle, 2007). Recent studies showed that secondary memory is substantially impaired in children with ADHD (Gibson, Gondoli, Flies, Dobrzenski & Unsworth, 2010). Verbal span as used in this study may have taxed secondary memory more strongly than the matrix span task.

Perhaps unexpectedly, we also found that, in contrast to AS, DD was associated with more errors in the sustained attention task, even when controlling for reading and IQ. Yet, impairments in sustained attention in DD have been reported before (Lindsay, Tomazic, Levine & Accardo, 2001), and sustained attention appears to be a key predictor of numeracy skills in early childhood (Steele, Karmiloff-Smith, Kornish & Scerif, 2012). However, in this study, no group effects were found for flexibility. This result conforms to the findings by Raghubar et al. (2009) that attention problems are unrelated to operation switching in calculation, suggesting that flexibility may not be a reliable indicator of inattention.

We evaluated three different hypotheses concerning the comorbidity of DD and ADHD. Since children with DD+AS performed poorly on neuropsychological measures of attention (compared to the DD group) as well as on basic numerical skills (compared to the AS group), our results refute the phenocopy hypothesis (Pennington et al., 1993). Our study also failed to provide convincing support for the cognitive subtype hypothesis (Rucklidge & Tannock, 2002) because children with DD+AS exhibited neither different nor more severe deficits than children with either pure DD or AS. Rather, our results suggest that the comorbid form corresponds to the effects of independent underlying cognitive causes (Willcutt et al., 2005). Importantly, underadditivity was found for both subtraction tasks (speed and power). This result suggests potentially shared causal factors between DD and AS. Hence, it may not necessarily be DD-related factors like deficient number processing or difficulties with multidigit number processing that lead to problems with subtraction; rather, inattention symptoms, which are often subclinically present in children with DD, or working memory deficits could produce subtraction problems (Shalev et al., 1995). An important consequence for diagnosing DD, therefore, is that, in order to consider attention-based explanations for mathematical difficulties, ADHD symptoms and attention behavior need to be assessed as well. Importantly, most basic numerical tasks in our study were not affected by AS and can therefore be used as reliable indicators in assessing DD.

This study has several caveats. Firstly, although the DD+AS group displayed substantial and clinically relevant symptoms of ADHD, no formal clinical diagnosis of ADHD was present. Results may differ when children with a clinical diagnosis of ADHD are investigated. Secondly, the behavioral ratings of AS were based on a single informant only, which may impact classification reliability (Sayal & Goodman, 2009). However, attention deficits related to AS reported by parents were at least partially corroborated by the neurocognitive measures. Thirdly, the assessment of mathematical ability in this study was based on a neuropsychological test battery (ZAREKI-R) that consisted of tasks of which some were similar to the basic numerical skills assessed in this study. However, mean correlation of the basic numerical tasks used here and ZAREKI-R tasks that were conceptually similar was $r = .29$, and most of these tasks differed structurally. For example, ZAREKI-R contains both a dot enumeration task and a number comparison task focusing on accuracy, whereas the dot enumeration task and number comparison task in this study focused on response times.

To conclude, we found substantial impairments in children with DD in a broad range of tasks assessing basic numerical processing, calculation, and working memory as well as more selective deficits (dot enumeration, subtraction, verbal span, processing speed) in children with AS. Clear evidence of underadditivity was found in both subtraction tasks, suggesting a common cognitive deficit in this mathematical skill. Our findings are consistent with the claim that DD and AS are the product of different, but partially overlapping cognitive deficits.

Acknowledgement

This study was supported by grant 01 GJ 1006 from the German Ministry of Education and Research.

References

Alarcón, M., DeFries, J.C., Light, J.G. & Pennington, B.F. (1997). A twin study of mathematics disability. *Journal of Learning Disabilities*, *30*, 617–623.

Andersson, U., & Lyxell, B. (2007). Working memory deficit in children with mathematical difficulties: A general or specific deficit? *Journal Of Experimental Child Psychology*, *96*, 197–228.

Barbaresi, W.J., Katusic, S.K., Colligan, R.C., Weaver, A.L. & Jacobsen, S.J. (2005). Math learning disorder: incidence in a population-based birth cohort, 1976–82, Rochester, MN. *Ambulatory Pediatrics*, *5*, 281–289.

Benedetto-Nasho, E. & Tannock, R. (1999). Math computation, error patterns, and stimulant effects in children with attention deficit hyperactivity disorder. *Journal of Attention Disorders*, *3*, 121–134.

Burr, D.C., Turi, M. & Anobile, G. (2010). Subitizing but not estimation of numerosity requires attentional resources. *Journal of Vision*, *10*, 1–10.

Butterworth, B., Varma, S. & Laurillard, D. (2011). Dyscalculia: From brain to education. *Science*, *332*, 1049–1053.

Cirino, P.T., Fletcher, J.M., Ewing-Cobbs, L., Barnes, M.A. & Fuchs, L.S. (2007). Cognitive arithmetic differences in learning difficulty groups and the role of behavioral inattention. *Learning Disabilities Research & Practice*, *22*, 25–35.

Cohen Kadosh, R., Dowker, A., Heine, A., Kaufmann, L. & Kucian, K. (2013). Interventions for improving numerical abilities: Present and future. *Trends in Neuroscience and Education*, *2*, 85–93.

Colomer, C., Re, A.M., Miranda, A. & Lucangeli, D. (2013). Numerical and calculation abilities in children with ADHD. *Learning Disabilities*, *11*, 1–15.

Cortese, S., Kelly, C., Chabernaud, C., Proal, E., Di Martino, A., Milham, M.P. & Castellanos, F.X. (2012). Toward systems neuroscience of ADHD: A meta-analysis of 55 fMRI studies. *The American Journal of Psychiatry*, *169*, 1038–1055.

Döpfner, M., Görtz-Dorten, A. & Lehmkuhl, G. (2008). *Diagnostik-System für psychische Störungen im Kindes- und Jugendalter nach ICD-10 und DSM-IV (DISYPS-II)* [Diagnostic system for mental disorders in children and adolescents based on ICD-10 and DSM-IV]. Bern: Huber.

DuPaul, G.J., Gormley, M.J. & Laracy, S.D. (2013). Comorbidity of LD and ADHD: Implications of DSM-5 for assessment and treatment. *Journal of Learning Disabilities*, *46*, 43–51.

Durston, S., Tottenham, N.T., Thomas, K.M., Davidson, M.C., Eigsti, I. & Yang, Y. & Casey, B.J. (2003). Differential patterns of striatal activation in young children with and without ADHD. *Biological Psychiatry*, *53*, 871–878.

Faraone, S.V., Perlis, R.H., Doyle, A.E., Smoller, J.W., Goralnick, J.J., Holmgren, M.A. & Sklar, P. (2005). Molecular genetics of attention deficit/hyperactivity disorder. *Biological Psychiatry*, *57*, 1313–1323.

Frazier, T.W., Youngstrom, E.A., Glutting, J.J. & Watkins, M.W. (2007). ADHD and achievement: Meta-analysis of the child, adolescent, and adult literatures and a concomitant study with college students. *Journal of Learning Disabilities*, *40*, 49–65.

Geary, D.C., Hoard, M.K., Byrd-Craven, J., Nugent, L. & Numtee, C. (2007). Cognitive mechanisms underlying achievement deficits in children with mathematical learning disability. *Child Development*, *78*, 1343–1359.

Geary, D.C., Hoard, M.K., Nugent, L. & Byrd-Craven, J. (2008). Development of number line representations in children with mathematical learning disability. *Developmental Neuropsychology*, *33*, 277–299.

Gibson, B.S., Gondoli, D.M., Flies, A.C., Dobrzenski, B.A. & Unsworth, N. (2010). Application of the dual-component model of working memory to ADHD. *Child Neuropsychology*, *16*, 60–79.

Greven, C.U., Kovas, Y., Willcutt, E.G., Petrill, S.A. & Plomin, R. (2014). Evidence for shared genetic risk between ADHD symptoms and reduced mathematics ability: A twin study. *Journal of Child Psychology and Psychiatry*, *55*, 39–48.

Haffner, J., Baro, K., Parzer, P. & Resch, F. (2005). Heidelberger Rechentest (HRT 1–4). Göttingen: Hogrefe.

Hart, S.A., Petrill, S.A., Willcutt, E., Thompson, L.A., Schatschneider, C., Deater-Deckard, K. & Cutting, L.E. (2010). Exploring how symptoms of attention-deficit/hyperactivity disorder are related to reading and mathematics performance: General genes, general environments. *Psychological Science*, *21*, 1708–1715.

Haworth, C.A., Kovas, Y., Harlaar, N., Hayiou-Thomas, M.E., Petrill, S.A., Dale, P.S. & Plomin, R. (2009). Generalist genes and learning disabilities: A multivariate genetic analysis of low performance in reading, mathematics, language and general cognitive ability in a sample of 8000 12-year-old twins. *Journal of Child Psychology & Psychiatry*, *50*, 1318–1325.

Kaufmann, L. & Nuerk, H. (2008). Basic number processing deficits in ADHD: A broad examination of elementary and complex number processing skills in 9- to 12-year-old children with ADHD-C. *Developmental Science*, *11*, 692–699.

Keith, T.Z., Fine, J.G., Taub, G.E., Reynolds, M.R. & Kranzler, J.H. (2006). Higher order, multisample, confirmatory factor analysis of the Wechsler Intelligence Scale for Children-Fourth Edition: What does it measure? *School Psychology Review*, *35*, 108–127.

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*, 795–811.

Kohn, J., Wyschkon, A. & Esser, G. (2013). Psychische Auffälligkeiten bei umschriebenen Entwicklungsstörungen: Gibt es Unterschiede zwischen Lese-Rechtschreib- und Rechenstörungen? [Mental peculiarities in specific developmental disorders: Are there differences between dyslexia and dyscalculia?], *Lernen und Lernstörungen*, *2*, 7–20.

Kucian, K., Ashkenazi, S., Hänggi, J., Rotzer, S., Jäncke, L., Martin, E. & von Aster, M. (2014). Developmental dyscalculia: A disconnection syndrome? *Brain Structure & Function*, *219*, 1721–1733.

Kuhn, J.-T. (2015). Developmental dyscalculia: Neurobiological, cognitive, and developmental perspectives. *Zeitschrift für Psychologie*, *223*, 69–82.

Kuhn, J.-T. & Holling, H. (2014). Number sense or working memory? The effect of two computer-based trainings on mathematical skills in elementary school. *Advances in Cognitive Psychology*, *10*, 59–67.

Kuhn, J.-T., Raddatz, J., Holling, H. & Dobel, C. (2013). Dyskalkulie vs. Rechenschwäche: Basisnumerische Verarbeitung in der Grundschule [Dyscalculia vs. severe math difficulties: Basic numerical capacities in elementary school]. *Lernen und Lernstörungen*, *2*, 229–247.

Landerl, K., Bevan, A. & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8-9-year-old students. *Cognition*, *93*, 99–125.

Lindsay, R.L., Tomazic, T., Levine, M.D. & Accardo, P.J. (2001). Attentional function as measured by a continuous performance task in children with dyscalculia. *Journal of Developmental and Behavioral Pediatrics*, *22*, 287–292.

Martinussen, R., Hayden, J., Hogg-Johnson, S. & Tannock, R. (2005). A meta-analysis of working memory impairments in children with attention deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry*, *44*, 377–384.

Massetti, G.M., Lahey, B.B., Pelham,W.E., Loney, J., Ehrhardt, A., Lee, S.S. & Kipp, H. (2008). Academic achievement over 8 years among children who met modified criteria for attention-deficit/hyperactivity disorder at 4–6 years of age. *Journal of Abnormal Child Psychology*, *36*, 399–410.

Mayringer, H. & Wimmer, H. (2003). *Salzburger Lese-Screening für die Klassenstufen 1–4 (SLS 1–4)* [Salzburg Screening of Reading Skills for Grades 1–4]. Göttingen: Hogrefe.

Moll, K., Kunze, S., Neuhoff, N., Bruder, J. & Schulte-Körne, G. (2014). Specific learning disorder: Prevalence and gender differences. *Plos ONE*, *9*, ee103537.

Monuteaux, M.C., Faraone, S.V., Herzig, K., Navsaria, N. & Biederman, J. (2005). ADHD and dyscalculia: Evidence for independent familial transmission. *Journal of Learning Disabilities*, *38*, 86–93.

Moura, R., Wood, G., Pinheiro-Chagas, P., Lonnemann, J., Krinzinger, H., Willmes, K. & Haase, V.G. (2013). Transcoding abilities in typical and atypical mathematics achievers: The role of working memory and procedural and lexical competencies. *Journal of Experimental Child Psychology*, *116*, 707–727.

Pennington, B.F., Groisser, D. & Welsh, M.C. (1993). Contrasting cognitive deficits in attention deficit hyperactivity disorder versus reading disability. *Developmental Psychology*, *29*, 511–523.

Petermann, F. & Petermann, U. (2011). *Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV)*. Frankfurt am Main: Pearson.

Pettersson, E., Anckarsäter, H., Gillberg, C. & Lichtenstein, P. (2013). Different neurodevelopmental symptoms have a common genetic etiology. *Journal of Child Psychology & Psychiatry*, *54*, 1356–1365.

Polanczyk, G., de Lima, M.S., Horta, B.L., Biederman, J. & Rohde, L.A. (2007). The worldwide prevalence of ADHD: A systematic review and metaregression analysis. *The American Journal of Psychiatry*, *164*, 942–948.

Price, G.R., Holloway, I., Räsänen, P., Vesterinen, M. & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology*, *17*, R1042–R1043.

Raghubar, K., Cirino, P., Barnes, M., Ewing-Cobbs, L., Fletcher, J. & Fuchs, L. (2009). Errors in multidigit arithmetic and behavioral inattention in children with math difficulties. *Journal of Learning Disabilities*, *42*, 356–371.

Reeve, R., Reynolds, F., Humberstone, J. & Butterworth, B. (2012). Stability and change in markers of core numerical competencies. *Journal of Experimental Psychology: General*, *141*, 649–666.

Reigosa-Crespo, V., Valdés-Sosa, M., Butterworth, B., Estévez, N., Rodríguez, M., Santos, E. & Lage, A. (2012). Basic numerical capacities and prevalence of developmental dyscalculia: The Havana Survey. *Developmental Psychology*, *48*, 123–135.

Renner, G., Stottmeister-Lessing, T., Irblich, D. & Krampen, G. (2015). Psychometrische Eigenschaften der „Testbatterie zur Aufmerksamkeitsprüfung für Kinder" (KITAP) in einer klinischen Stichprobe [Psychometric properties of the Test of Attentional Performance for Children (KITAP) in a clinical sample]. *Diagnostica*, *61*, 63–75.

Ritchie, S.J. & Bates, T.C. (2013). Enduring links from childhood mathematics and reading achievement to adult socioeconomic status. *Psychological Science*, *24*, 1301–1308.

Rotzer, S., Kucian, K., Martin, E., Aster, M. v., Klaver, P. & Loenneker, T. (2008). Optimized voxel-based morphometry in children with developmental dyscalculia. *NeuroImage*, *39*, 417–422.

Rucklidge, J. & Tannock, R. (2002). Neuropsychological profiles of adolescents with ADHD: Effects of reading difficulties and gender. *Journal of Child Psychology & Psychiatry*, *43*, 988–1003.

Rykhlevskaia, E., Uddin, L.Q., Kondos, L. & Menon, V. (2009). Neuroanatomical correlates of developmental dyscalculia: Combined evidence from morphometry and tractography. *Frontiers In Human Neuroscience*, *3*, 51.

Sattler, J.M. (2008). *Assessment of children: Cognitive foundations* (5th ed.). San Diego, CA: Author.

Sayal, K. & Goodman, R. (2009). Do parental reports of child hyperkinetic disorder symptoms at school predict teacher ratings? *European Child & Adolescent Psychiatry*, *18*, 336–344.

Shalev, R.S., Auerbach, J. & Gross-Tsur, V. (1995). Developmental dyscalculia behavioral and attentional aspects: A research note. *Journal of Child Psychology & Psychiatry*, *36*, 1261–1268.

Shanahan, M.A., Pennington, B.F., Yerys, B.E., Scott, A., Boada, R., Willcutt, E.G. & DeFries, J.C. (2006). Processing speed deficits in attention deficit/hyperactivity disorder and reading disability. *Journal of Abnormal Child Psychology*, *34*, 585–602.

Siegler, R.S., & Booth, J.L. (2004). Development of numerical estimation in young children. *Child Development*, *75*, 428–444.

Steele, A., Karmiloff-Smith, A., Cornish, K., Scerif, G. (2012). The multiple subfunctions of attention: Differential developmental gateways to literacy and numeracy. *Child Development*, *83*, 2028–2041.

Tosto, M.G., Momi, S.K., Asherson, P. & Malki, K. (2015). A systematic review of attention deficit hyperactivity disorder (ADHD) and mathematical ability: Current findings and future implications. *BMC Medicine*, *13*, 204.

Unsworth, N. & Engle, R.W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, *114*, 104–132.

Vock, M. & Holling, H. (2008). The measurement of visuo-spatial and verbal-numerical working memory: Development of IRT-based scales. *Intelligence*, *36*, 161–182.

Von Aster, M.G. & Shalev, R.S. (2007). Number development and developmental dyscalculia. *Developmental Medicine & Child Neurology*, *49*, 868–873.

Von Aster, M., Weinhold Zulauf, M. & Horn, R. (2006). *Neuropsychologische Testbatterie für Zahlenverarbeitung und Rechnen bei Kindern (ZAREKI-R)* [Neuropsychological test battery of number processing and calculation in children]. Frankfurt am Main, Germany: Harcourt Test Services.

Willcutt, E.G., Nigg, J.T., Pennington, B.F., Solanto, M.V., Rohde, L.A., Tannock, R. & Lahey, B.B. (2012). Validity of DSM-IV attention deficit/hyperactivity disorder symptom dimensions and subtypes. *Journal of Abnormal Psychology*, *121*, 991–1010.

Willcutt, E.G., Pennington, B.F., Olson, R.K., Chhabildas, N. & Hulslander, J. (2005). Neuropsychological analyses of comorbidity between reading disability and attention-deficit/hyperactivity disorder: In search of the common deficit. *Developmental Neuropsychology*, *27*, 35–78.

Zimmermann, P., Gondan, M. & Fimm, B. (2002). *Testbatterie zur Aufmerksamkeitsprüfung für Kinder (KITAP)* [Test battery for assessing attention in children]. Herzogenrath: Psytest.

Manuscript submitted: 10.09.2015
Accepted after revision: 26.02.2016
Conflicts of Interest: None
Article online: 29.06.2016

Dr. Jörg-Tobias Kuhn
Institut für Psychologie
Westfälische Wilhelms-Universität Münster
Fliednerstr. 21
48149 Münster
Deutschland
t.kuhn@wwu.de