

Disentangling the Adult Attention-Deficit Hyperactivity Disorder Endophenotype: Parametric Measurement of Attention

Kathrin Finke and Wolfgang Schwarzkopf
Ludwig-Maximilians-University

Ulrich Müller
University of Cambridge and Adult ADHD Research Clinic,
Cambridgeshire & Peterborough NHS Foundation Trust

Thomas Frodl
Trinity College

Hermann J. Müller
Ludwig-Maximilians-University

Werner X. Schneider
University Bielefeld

Rolf R. Engel, Michael Riedel, Hans-Jürgen Möller,
and Kristina Hennig-Fast
Ludwig-Maximilians-University

Attention deficit hyperactivity disorder (ADHD) persists frequently into adulthood. The decomposition of endophenotypes by means of experimental neuro-cognitive assessment has the potential to improve diagnostic assessment, evaluation of treatment response, and disentanglement of genetic and environmental influences. We assessed four parameters of attentional capacity and selectivity derived from simple psychophysical tasks (verbal report of briefly presented letter displays) and based on a “theory of visual attention.” These parameters are mathematically independent, quantitative measures, and previous studies have shown that they are highly sensitive for subtle attention deficits. Potential reductions of attentional capacity, that is, of perceptual processing speed and working memory storage capacity, were assessed with a whole report paradigm. Furthermore, possible pathologies of attentional selectivity, that is, selection of task-relevant information and bias in the spatial distribution of attention, were measured with a partial report paradigm. A group of 30 unmedicated adult ADHD patients and a group of 30 demographically matched healthy controls were tested. ADHD patients showed significant reductions of working memory storage capacity of a moderate to large effect size. Perceptual processing speed, task-based, and spatial selection were unaffected. The results imply a working memory deficit as an important source of behavioral impairments. The theory of visual attention parameter working memory storage capacity might constitute a quantifiable and testable endophenotype of ADHD.

Keywords: vision, theory of visual attention, experimental, neuropsychology, psychophysics

Attention deficit hyperactivity disorder (ADHD), especially inattention and executive deficits, can persist into adulthood (Barkley, Fischer, Smallish, & Fletcher, 2002; Biederman, 2005). With a prevalence around 2.5%, adult ADHD is a rather frequent psychiatric disorder (Simon, Czobor, Balint, Meszaros, & Bitter, 2009). Partly owing to heterogeneity of theoretical conceptualizations and tasks to measure attention, the pattern of the persisting deficits in adult ADHD is debated (Gallagher & Blader, 2006; Hervey, Epstein, & Curry, 2004). Endophenotypes are continu-

ously quantifiable latent traits indexing an individual’s liability for developing or manifesting a particular psychiatric disease (Seidman, 2006; Westerberg, Hirvikoski, Forssberg, & Klingberg, 2004; Woods, Lovejoy, & Ball, 2002). It is assumed that causative brain abnormalities lead to candidate endophenotypes of ADHD (i.e., latent attentional parameters) that then give rise to observable behavioral manifestations (Almasy & Blangero, 2001; Castellanos & Tannock, 2002). Neuropsychological and brain-imaging evidence indicates dysfunction of (especially right-hemispheric)

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Kathrin Finke, Wolfgang Schwarzkopf, and Hermann J. Müller, Department of Psychology, Experimental Psychology/Neuro-Cognitive Psychology, Ludwig-Maximilians-University; Ulrich Müller, The Cambridge Institute of Behavioural and Clinical Neuroscience, Department of Experimental Psychology and Department of Psychiatry, University of Cambridge, and Adult ADHD Research Clinic, Cambridgeshire & Peterborough NHS Foundation Trust; Thomas Frodl, Department of Psychiatry, Trinity College, Dublin; Werner X. Schneider, Neuro-cognitive Psychology, University Bielefeld; Rolf R. Engel, Michael Riedel, Hans-Jürgen Möller, and Kristina Hennig-Fast, Department of Psychiatry and Psychotherapy, Ludwig-Maximilians-University.

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K. Finke and W. Schwarzkopf have contributed equally as first authors.

Correspondence concerning this article should be addressed to Kathrin Finke, Department of Psychology, Experimental Psychology/Neuro-Cognitive Psychology, Ludwig-Maximilians-University, Leopoldstr. 11, Munich, Germany. E-mail: finke@psy.lmu.de

fronto-subcortical and parietal circuits in adult ADHD (Faraone et al., 2000; Krause, Dresel, Krause, Kung, & Tatsch, 2000; Makris, Biederman, Monuteaux, & Seidman, 2009). Accordingly, isolating endophenotypes should target cognitive functions that rely on the integrity of these systems.

One example that has been successfully used for the parametric assessment of dysfunctions in the field of visual attention is based on the formalized “theory of visual attention” (TVA; Bundesen, 1990). Combined with simple psychophysical tasks (partial and whole report of brief letter arrays), TVA-based assessment permits different functional components of visual attention to be extracted independently, in unconfounded measurement. Its high sensitivity and clinical validity has already been documented in studies of neurological and neuropsychiatric diseases. Importantly, the various parameters functionally load on the frontal cortex, which is affected in ADHD, its connections to striatal and parietal areas, and on potential asymmetries in this neural attentional system (Bublak et al., 2005; 2006; Duncan et al., 1999; Finke, Bublak, Dose, Müller, & Schneider, 2006; Habekost & Bundesen, 2003).

Among the four TVA parameters, two determine general capacity aspects: visual perceptual processing speed (parameter C) and visual working memory (WM) storage capacity (parameter K).

The parameter perceptual processing speed C is the number of visual elements that can be processed by a person per second. The rate of perceptual processing is closely related to the concept of alertness, both as a short-term (ability to respond to novel stimuli) and as a long-term process (sustained alertness or vigilance) (Finke et al., 2010; Matthias et al., 2010; Posner, Sheese, Odludas, & Tang, 2006). It has been suggested that the regulation of the alertness state is affected in ADHD, resulting in a generalized slowness of information processing, as reflected, for instance, in decelerated and variable reaction times (Holdnack, Moberg, Arnold, Gur, & Gur, 1995; Seidman, 2006; Sergeant, 2000, 2005; Woods et al., 2002). Intrinsic regulation of the alertness state relies on right frontoparietal, thalamic, and brain stem regions (Sturm et al., 1999) that are affected in ADHD; and consistent with this, psychostimulant medication is effective in adults with ADHD (Wender, 1998). On the other hand, a vigilance dysfunction would be expected to give rise to pronounced time-on-task effects (Rueckert & Grafman, 1996), but a number of studies have failed to demonstrate these in adults with ADHD (e.g., Tucha et al., 2009). Furthermore, as has been acknowledged, reaction time alterations may reflect slowing of late, motor execution stages, rather than of attentional stages (Sergeant, 2005).

The parameter WM storage capacity K quantifies the number of items that can be categorized in parallel and transferred into a WM store (Cowan, 2001; Luck & Vogel, 1997). WM storage refers to the capacity to keep information online for a short period of time (Goldman-Rakic, Muly, & Williams, 2000) and is a prerequisite for various cognitive abilities and academic tasks (Barkley, 1997; Cowan, 2001). WM storage relies on fronto-striatal-parietal circuits and on the prefrontal dopamine system, which are affected in ADHD (Arnsten & Li, 2005; Finke, Bublak, & Zihl, 2006; Goldman-Rakic et al., 2000; Vaidya & Stollstorff, 2008); accordingly, multiple reports suggest WM storage deficits in adults with ADHD (Clark et al., 2007; Engelhardt, Nigg, Carr, & Ferreira, 2008; Gropper & Tannock, 2009). However, the WM tasks employed in prior studies were typically complex (for a comprehensive discussion, see Rapport et al., 2008, 2009) and did not

isolate storage capacity from other aspects of WM, such as dual process control (Westerberg et al., 2004). However, it is important to address the separate aspects specifically, as Martinussen and colleagues (2005) have shown that basic WM storage tasks and tasks including storage plus manipulation requirements yielded different results in ADHD children.

In TVA, visual attentional processing is assumed to rely on two further, specific weighting aspects. These determine how a person distributes the amount of attentional resources available when presented with multiple, alternative inputs, that is: when selective attention needs to be allocated. One aspect is the efficiency of top-down control (TVA parameter α) and the other is the laterality of the spatial distribution of attention (parameter w_λ).

The parameter efficiency of top-down control α quantifies a person’s ability to select task-defined relevant (target) information and ignore irrelevant (distracter) information. It has been suggested that a deficit in cognitive top-down, or inhibitory interference, control mediates secondary deficits (Barkley, 1997; Clark et al., 2007; Nigg, 2001; Quay, 1997), such as ineffective shielding of WM contents or items in the focus of attention (Cowan, 2001). Top-down control is assumed to rely on a frontal catecholaminergic gating system (Miller & Cohen, 2001). While it is well established that ADHD patients have deficits in inhibiting *behavioral outputs* (Bekker et al., 2005; Lijffijt, Kenemans, Verbaten, & van Engeland, 2005), it is less clear whether they also suffer from a deficit in *cognitive*, that is, *attentional*, top-down control (see Nigg, 2001, for a detailed analysis of this distinction in relation to ADHD). The proposal of cognitive disinhibition in ADHD has been questioned by, for example, Homack and Riccio (2004), as ADHD patients tend to perform equally poorly across attentional interference and (no-interference) control conditions in various tasks.

The parameter laterality of the spatial distribution of attentional weights w_λ determines how attentional resources are distributed across the left and right visual hemifields (Duncan et al., 1999). Some studies suggest that ADHD children show a leftward “minineglect,” that is, a slight abnormal spatial bias toward the right (Dobler et al., 2005; George et al., 2005; Johnson et al., 2009; Sheppard et al., 1999), similar to that more severe bias known from visual hemi-neglect (Duncan et al., 1999). Balanced spatial attention depends on balanced activity of bilateral temporo-parietal and fronto-striatal regions (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Peers et al., 2005). Thus, a pathological lateralization in ADHD children is in line with findings of right-sided volume reduction and hypoactivation in these structures (Castellanos et al., 1996; Giedd et al., 2001). However, to date, there have been no examinations of adults with ADHD on the spatial distribution of attention.

All TVA parameters outlined above are derived from two experimental tests: namely, whole- and partial-report tasks, which use similar stimuli and have similar response requirements and, thus, make comparable demands on perceptual and motor skills. As performance is assessed in terms of accuracy of nonspeeded verbal reports (rather than in terms of response times), the results are relatively independent of motor deficits known to exist in ADHD patients (Barkley, 1997).

The aim of the present study was to use the TVA-based approach to collect independent estimates of these four parameters—based on the assumption that (some of) these might constitute

endophenotypes of the behavioral difficulties displayed by adults with ADHD. That is, we wanted to systematically isolate those parameter(s) that are indicative of an enhanced risk for manifesting overt ADHD symptoms. In the whole-report task, participants had to name as many letters as possible that were presented on the screen. Performance on this task yields quantitative estimates of visual perceptual processing speed and WM storage capacity. In the partial-report task, participants had to name task-defined target letters only and ignore distracter letters which could appear in the same hemifield as the target or in the opposite hemifield. Performance on this task yields estimates of top-down control and of the spatial distribution of attention.

Method

Participants

Thirty unmedicated, right-handed, adult ADHD patients were recruited from the Department of Psychiatry, Ludwig-Maximilians-University Munich. They were tested a few days after the initial diagnostic assessment which was carried out at a specialized adult ADHD outpatient clinic.

The diagnostic procedure necessary for including a patient in this study comprised three steps. At first, two psychiatric interviews (according to *DSM-IV*) were conducted by psychiatrists of the ADHD outpatient clinic. Using a conservative criterion, patients were only included when both psychiatrists rated them as ADHD patients. Second, collateral information from different sources was obtained by a psychologist trained in ADHD assessment. This information had to confirm childhood onset according to the obligatory *DSM-IV* symptoms for childhood ADHD. Patients were only included if descriptions of the respective symptoms were listed in the first elementary school reports (obtained at an age <7 years) and then for a longer-term period in the following reports. In Germany, elementary school reports contain comprehensive descriptions of learning performance (e.g., participation in lessons, diligence with homework, accuracy in written reports), social behavior (e.g., impulsivity and aggression), and daily structure (e.g., forgetfulness and daydreaming), differentiated according to cognition, emotion, and motor behavior. Furthermore, prior psychiatric diagnoses, or third-party "informants" (siblings), had to confirm that these symptoms were also displayed at home and that there had been no alternative, suspected diagnosis. Four patients had been diagnosed with ADHD in childhood, three had received ADHD-medication during childhood (but not in adulthood). Third, in an assessment of current (Conners Adult ADHD Rating Scales Self Report, CAARS; Conners, Erhardt, & Sparrow, 2002) and retrospective childhood symptoms (Wender Utah Rating Scale, WURS; Ward, Wender, & Reimherr, 1993), self-reports had to indicate ADHD. Average ADHD symptom ratings in the ADHD patients (see Table 1) indicated severe subjective current impairments (all *t*-values >60) and retrospective childhood ADHD symptoms. In accordance with previous reports on symptoms in adulthood (Biederman, 2005), inattentiveness ratings were especially pronounced (*t*-values >70).

Neuropsychological tests of attention and WM (Test Battery for Attentional Performance, TAP; Zimmermann & Fimm, 2002), executive functions and memory (Verbal Learning and Memory test; Helmstaedter et al., 2001) were administered to the ADHD

patients. Test results were compared to norm values. The patients were, on average, "normal" in all tests (all *t* > 45; see Table 1). However, below- and above-average individual scores in each of the tests indicate that, across patients, the neuropsychological test results were subject to high variability, as observed before (e.g., Seidman, 2006).

German versions of the Minnesota Multiphasic Personality Inventory (MMPI-2; Hathaway, McKinley, & Engel, 2000) and Personality Assessment Inventory (Groves & Engel, 2007) were used to exclude patients with other mental and personality disorders. Furthermore, patients with either prior or comorbid neurological disorders, bipolar disorder, schizophrenia, or other psychotic disorders, substance abuse or addiction other than nicotine within the last 3 months, or with an IQ below 85 were excluded. Seven patients had a history of previous cannabis use and six were heavy smokers. Patients whose clinical picture was dominated by depressive symptoms were excluded. However, because depression and anxiety are frequent comorbid disorders in adult ADHD samples (Sprafkin, Gadow, Weiss, Schneider, & Nolan, 2007), secondary diagnoses (in addition to ADHD) had been given to three included patients with recurrent moderate depression (F33.1; World Health Organization, 1992) and to one patient with obsessive-compulsive disorder (F42.2). Five of the patients took antidepressant medication. None of them suffered from an acute major depression. Patients and control participants were asked to abstain from nicotine and caffeine at least 1 hr before and during the TVA testing procedure. This was meant to ensure that ADHD patients' performance could not profit from recent nicotine consumption, and that the results of heavy smokers were unlikely to be compromised by withdrawal effects (Heishman, Kleykamp, & Singleton, 2010).

To compare the TVA parameter estimates of the ADHD patients with those of healthy participants, the TVA tasks were also administered to a control group of 30 healthy, right-handed, and demographically matched participants without any neurological or psychiatric history. Gender and handedness distribution, age, education, IQ (German Multiple-Choice Vocabulary Test; Lehrl, Triebig, & Fischer, 1995), occupation (International Standard Classification of Occupation [ISCO]; International Labour Office, 1990), net monthly household income, and International Socio-Economic Index (ISEI; Ganzeboom, 1996) did not differ significantly between the two groups (all *p* > .25; except for ISEI, *p* < .09, with a tendency for a higher ISEI in controls). As expected, subjective ADHD symptoms (CAARS *t*-values and WURS scores) were generally significantly higher in the ADHD patient than in the control group (see Table 1). Informed consent according to the Declaration of Helsinki II was obtained from all participants. All had normal or corrected-to-normal vision and none suffered from red-green color blindness.

Measuring Attention and WM: The TVA Framework

TVA is a mathematical model (Bundesen, 1990; Bundesen, Habekost, & Kyllingsbaek, 2005) that instantiates the currently dominant 'biased-competition' framework of visual attention (Desimone & Duncan, 1995; Kastner & Ungerleider, 2000). Visual processing is conceived of as a parallel-competitive race of objects and features for selection, that is, conscious representation, into the capacity-limited visual WM store. Bias signals determine "atten-

Table 1
Group Demographics, ADHD Ratings and ADHD Patient Group's Neuropsychological Results

	ADHD (<i>n</i> = 30)	Con (<i>n</i> = 30)	<i>t</i>
Sex (F/M)	12/18	12/18	
Age (years)	35.50 (9.49) 19–52	35.96 (10.39) 18–54	0.18
School (years)	11.60 (1.65) 9–13	12.03 (1.48) 8–13	1.06
IQ (MWT)	113.92 (15.72) 93–143	113.13 (13.78) 89–143	−0.45
ISCO	4.17 (2.44) 1–9	3.85 (2.35) 2–9	−0.44
Income	3.11 (1.13) 1–5	2.82 (1.06) 1–5	−0.98
ISEI	45.17 (13.65) 25–73	53.80 (18.39) 23–85	1.79 [†]
CAARS-S subscales			
A	71.53 (10.36) 54–90	48.43 (7.62) 33–60	9.35**
B	61.13 (8.35) 41–84	45.43 (5.91) 38–60	7.65**
C	66.97 (10.35) 41–88	46.00 (7.83) 33–59	8.01**
D	62.37 (9.55) 42–76	44.87 (8.26) 36–61	7.00**
E	81.07 (9.36) 60–90	48.78 (8.71) 28–62	12.82**
F	61.77 (14.20) 12–86	43.74 (7.42) 32–59	5.97**
G	77.40 (10.37) 48–90	44.39 (10.10) 14–61	12.00**
H	71.70 (7.83) 60–88	49.35 (7.03) 36–61	10.76**
WURS	56.31 (15.61) 32–85	20.00 (12.74) 3–52	9.02**
TAP			
Alert <i>ton</i>	45.48 (13.85) 20–76	—	
Alert <i>phas</i>	45.37 (12.21) 20–65	—	
WM	45.72 (10.54) 31–74	—	
Go/ NoGo	46.33 (10.06) 27–65	—	
Flex	47.92 (8.19) 33–66	—	
D2	58.59 (13.87) 31–80	—	
HCT	53.07 (11.84) 22–69	—	
TMT			
A	47.00 (12.73) 15–63	—	
B	51.80 (8.97) 33–66	—	
VLMT			
Learn	58.56 (7.34) 43–66	—	
Mem	55.22 (8.20) 40–66	—	

Note. Group demographics: Sex distribution, mean, *SD*, and range of age, attended school years, IQ, indices of occupation, income, and socio-economic status for each group. Mean *t*-values, *SD*, and range of subjective current symptoms and neuropsychological test results for the ADHD group. F: female; M: male; School: Duration of education (in years); MWT: German Multiple-Choice Vocabulary Test (Lehrl, et al., 1995); ISCO: International Standard Classification of occupation (International Labor Office, 1990); Income: Income in categories (0€-400€/ 401€-1000€/ 1001€-2500€/ 2501€-5000€/ 5001€-7500€) (Lampert & Kroll, 2006); ISEI: International Socio-Economic Index of Occupational Status (Ganzeboom, 1996); CAARS-S: Connors Adult ADHD Rating Scale Self-Rating (Conners, et al., 2002); CAARS-subcales: A: inattention/memory problems; B: hyperactivity/restlessness; C: impulsivity/emotional instability; D: problems with self-concept; E: inattentive symptoms according to DSM-IV; F: hyperactive-impulsive symptoms according to DSM-IV; G: total ADHD symptoms according to DSM-IV; H: ADHD Index. WURS: Wender Utah Rating Scale (Ward et al., 1993); TAP: Test Battery for Attentional Performance (Zimmermann & Fimm, 2002); Subtests—Alert *ton*: tonic alertness; Alert *phas*: phasic alertness; WM: working memory; Go/NoGo: Go/NoGo; Flex: flexibility; VLMT: Verbal Learning and Memory Test (Helmstaedter, Lendt, & Lux, 2001); D2: German D2 Test of Attention (Brickenkamp, 1994); TMT: German Trail-Making Test (Reitan, 1986); HCT: Haelstaed-Category-test (Reitan, 1986), PC version (Fast & Engel, 2007); ADHD: ADHD patients; Con: control participants.

[†]*p* < .09. ***p* < .01.

tional weights” for the objects. Depending on their relative weights, some objects are favored for selection, either automatically in ‘bottom-up’ manner or by intentional, ‘top-down’ intentional set. Bottom-up influences result from stimulus saliency, and top-down influences from specific task instructions, such as the way in which targets and distracters are defined. The probability of selection is determined by an object’s processing rate *v*, which depends on the attentional weight (*w*) assigned to it, and by the capacity of the WM store (if the store is filled, the selection process terminates). TVA provides parameters for the general efficiency of the system (processing rate and storage capacity), and for specific aspects of attentional weighting (prioritization of tar-

gets over distracters and spatial distribution of attention). For formal descriptions of the TVA, details on the maximum likelihood model fitting procedure (e.g., Ross, 2000), and the software, see Kyllingsbæk (2006).

The processing rate depends on the dynamics of the processing system. This is expressed in an exponentially increasing probability for an object to be selected with increasing exposure duration (in TVA-based whole-report paradigms, the number of different, “effective” exposure durations is typically doubled by using masked as well as unmasked exposures of the same, “absolute” durations). The general information processing efficiency is assessed by a whole-report task, in which participants are briefly

presented with multiple stimuli and have to identify as many of them as possible. The probability of identification is modeled by an exponential growth function in which the growth parameter reflects the rate at which the stimuli (objects) can be processed (processing speed C : number of element/s) and the asymptotic level of the function indicates the maximum number of objects that can be represented within WM (storage capacity K).

The attentional-selectivity parameters (top-down control and laterality of spatial attention distribution) can be estimated from performance on a partial-report task, in which participants have to report prespecified (e.g., with respect to color) targets only, while ignoring distracters. From the probabilities of target identification, separate attentional weights are derived for the left hemifield (w_L) and the right hemifield (w_R). The parameter spatial distribution of attention w_λ is defined as the ratio $w_L/(w_L + w_R)$. Hence, a value of $w_\lambda = 0.5$ indicates balanced weighting; values of $w_\lambda > 0.5$ indicate a leftward and values of $w_\lambda < 0.5$ a rightward spatial bias. Parameter top-down control α indicates the relative attentional weights of distracters compared to targets (w_D/w_T). Targets receive more weight than distracters if $\alpha < 1$. Accordingly, the lower the α -value, the more efficient the top-down control.

General Procedure

Stimuli were presented on a 17-inch monitor (1024×1280 -pixel resolution, 60-Hz refresh rate). Viewing distance was approximately 50 cm. The experimental laboratory was dimly lit. Each participant completed the whole- and partial-report assessment, each lasting ~ 0.5 hr, within one testing session. The order of tasks was balanced across participants. In both experiments, first, the participants were instructed to fixate a central white cross (0.3° visual angle) presented for 300 ms. Then, following a gap of 100 ms, red and/or green letters (0.5° high \times 0.4° wide) were briefly presented on a black background. Individual exposure durations were determined in a practice session to meet a certain criterion value (see below). The letters were randomly chosen from a prespecified set (ABEFHJKLMNPRSTWXYZ), with the same letter appearing only once on a given trial. Each participant received the same displays in the same randomized sequence.

Stimuli were either masked or unmasked. In unmasked conditions, the effective exposure durations are prolonged by several hundred milliseconds because of "iconic" memory buffering (Sperling, 1960). Pattern masks are assumed to interrupt the iconic buffering at each letter location. The verbal report of individual letters could be performed in arbitrary order and without stress on response speed. The experimenter entered the responses on the keyboard. The total number of trials was 288 in the partial-report and 192 in the whole-report experiment, separated into blocks of 48 trials. In a previous study (Finke et al., 2005), reliable estimates of the TVA parameters were obtained on the basis of these numbers of trials. Because participants report fewer items in the partial-report task (that consisted of more trials), the durations of both tasks were similar (i.e., around 30 min). Within each block, the different trial types were presented equally often in randomized order.

Whole Report

The whole-report task yielded estimates of visual perceptual processing speed C and of WM storage capacity K . On each trial,

a column of five equidistant red or green letters was presented 2.5° of visual angle to the left or the right of fixation (see Figure 1). All letters were either red or green. Different colors were used to check whether patients reached an equal level of performance for green and red stimuli, which served as distracters and target, respectively, in the partial-report task. Participants' task was to identify and report as many letters as possible.

In a pretest (24 trials), the individual exposure duration was determined at which the participant could report, on average, one letter correctly. In the whole-report task, this value was then used as an "intermediate" exposure duration, along with a shorter (half as long) and a longer (twice as long) exposure duration. The ADHD group's average exposure durations were 64 ($SD = 24$), 127 ($SD = 48$), and 254 ($SD = 97$) ms, and those of the control group were 56 ($SD = 24$), 113 ($SD = 36$), and 222 ($SD = 67$) ms. Letter displays were presented either masked or unmasked. The resulting six effective exposure durations aimed at a broad performance spectrum describing the early as well as the late section of the participant's whole-report function. There were 12 different conditions (2 hemifields, 3 exposure durations, 2 masking conditions), each with 16 trials. Performance, that is, the number of letters reported correctly, was measured as a function of (effective) exposure duration.

Partial Report

The partial-report task served for quantifying the attentional selectivity parameters efficiency of top-down control α and spatial distribution of attentional weights w_λ . On each trial, either a single target (letter), or a target plus a distracter (letter), or two targets appeared at the corners of an imaginary square with an edge length of 5° , centered on the midpoint of the screen (see Figure 2). Two stimuli were presented either horizontally or vertically, but never diagonally. Sixteen conditions (4 single target, 8 target + distracter, 4 dual target conditions) resulted. All stimuli were masked. Participants were asked to identify and report all red target letters and ignore the green distracter letters.

In a pretest (32 trials), the individual exposure duration was determined at which the participant could report presented single targets with 80% accuracy. In the partial-report task, 6 blocks, each with 48 trials, were administered. The average exposure duration determined for the ADHD group was 132 ms ($SD = 57$), and that of the control group was 103 ms ($SD = 38$).

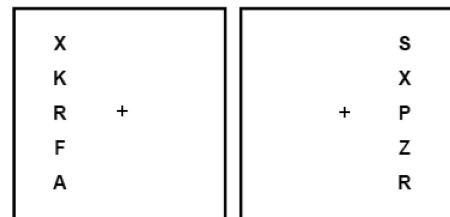


Figure 1. Sample trial types of the whole report experiment with presentation of five equidistant letters in columns on the left or right side of the fixation cross.

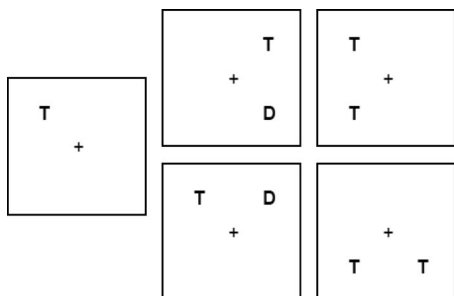


Figure 2. Sample trial types of the partial report experiment with target letters (T) and distracter letters (D). Presentation of a single target (left), of a target accompanied by a distracter (middle) and of two targets (right).

Results

Whole-Report Results

Figure 3 presents the mean numbers of correctly reported letters as a function of the (effective) exposure duration in one representative participant from the ADHD group and one from the control group. The scores predicted by the TVA-model fits (approximately represented by the solid curves) and the observed scores were in close correspondence.

For each single participant, TVA model fitting yielded individual estimates for perceptual processing speed C and WM storage capacity K (see Table 2 for group values). Estimations for the left and right hemi-fields were combined. The average Pearson product-moment correlation coefficients, r , between the observed values at the different exposure durations and TVA's best fits to the data were high (ADHD group: 0.93, $SD = 0.05$; control group: 0.90, $SD = 0.07$).

Separate ANOVAs for visual perceptual processing speed C and visual WM storage capacity K were carried out, both with the between-subjects factor Group (2). The results are reported below. To control for potential influences other than ADHD, the ANOVAs were repeated including age, IQ, education, income, ISCO, and ISEI as covariates. None of these covariates were found to be significant (all $F < 1.85$, all $p > .15$), and their inclusion did not change the significance levels of the results. Furthermore, the ANOVAs were repeated excluding the four patients with additional diagnoses. Again, no significant changes of the results were observed.

Perceptual processing speed. The average processing speed estimates based on TVAs best fit to each participant's data are comparable between the two groups (see Table 2), which is also indicated by a nonsignificant effect of Group ($F(1, 58) = 0.57$; $p > .45$) and a small effect size (Cohen's d ; Cohen, 1988). Accordingly, in Figure 3, both representative participants have similar initial slopes that approximately reflect the rate of information uptake in objects per second (high processing speed is indicated by a steep increase).

WM storage capacity. The ANOVA of WM storage capacity estimates revealed the effect of group to be significant ($F(1, 58) = 53.69$; $p < .01$): the maximum number of items that could be maintained in parallel was higher for normal participants than for ADHD patients (see Table 2). Figure 3 shows that with prolonged

exposure duration, an asymptotic level of reported letters is reached (indicated by the dashed horizontal line), which is taken to be an approximation of the WM storage capacity. The control participant reached a maximum number of about four objects, which is representative for healthy persons (Cowan, 2001; Luck & Vogel, 1997); by contrast, the patient's asymptote is lower, indicative of a reduced number of letters that can be represented in WM. Figure 4 presents the distribution of K -values for both groups.

To obtain an estimate of the magnitude of the observed WM storage capacity deficit, we computed Cohen's d (Cohen, 1988) for the differential parameter estimates between the two groups (d is defined as the difference between two means divided by their pooled standard deviations). The obtained value of $d = 0.69$ indicated a moderate-to-large effect size, with a nonoverlap of 43% of the two groups' distributions of K scores.

Partial-Report Results

The parameter estimates derived from the partial-report task focuses on specific aspects of attentional selectivity: the spatial distribution of attentional weighting w_λ , and the ability to prioritize targets over distracters, top-down control α . To illustrate spatial-attentional weighting and top-down control, Figure 5 shows the mean proportions of target letters correctly identified by the two groups, separately for each hemi-field and for the five experimental conditions: single-target letter; target accompanied by a distracter or, respectively, by a target in the ipsilateral field; and target accompanied by a distracter or, respectively, a target in the contralateral field. The average Pearson product-moment correlation coefficient, r , between the observed values at the different exposure durations and TVAs best fits to the data were high (ADHD group: 0.82, $SD = 0.11$; control group: 0.73, $SD = 0.18$).

Again, separate ANOVAs were carried out for top-down control and spatial attentional weighting, with the between-subjects factor Group (2). Additional control analyses revealed none of the covariates listed above to have a significant effect (all $F < 2.20$; all $p > .15$). Neither including these covariates nor excluding comorbid ADHD patients changed the ANOVA results in a significant manner.

Top-down control. The average estimates and standard deviations of top-down control parameter α (also listed in Table 2) are comparable between the two groups: an ANOVA with the

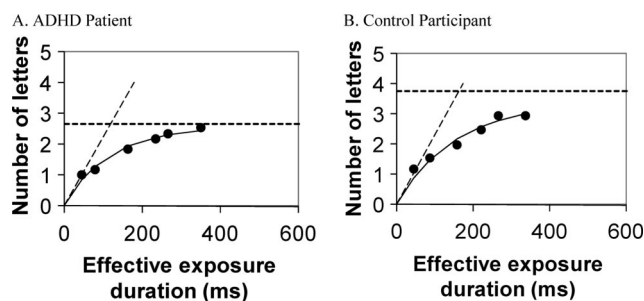


Figure 3. Whole-report performance for a representative ADHD patient and a representative, age-matched control participant. Mean number of correctly reported letters as a function of effective exposure duration. Solid curves represent the best fits from the TVA to the observations. The estimate of WM storage capacity K is marked by a dashed horizontal line.

Table 2
TVA Whole- and Partial-Report Parameters in ADHD Patient and Control Group

	ADHD (<i>n</i> = 30)		Con (<i>n</i> = 30)		<i>F</i>	<i>d</i>
<i>C</i>	20.87 (6.89)	10.60–36.47	22.19 (6.68)	10.41–35.37	.57	0.10
<i>K</i>	2.72 (0.21)	2.00–3.00	3.39 (0.45)	2.65–3.95	53.71**	0.69
$w_L/(w_L + w_R)$.50 (.08)	.31-.65	.50 (.05)	.43-.60	.16	0.00
α	.48 (.19)	.13-.93	.47 (.24)	.00-.89	.25	0.02

Note. Mean, *SD* (in brackets), and range for the group of ADHD patients and the control group, *F* values of ANOVAs comparing ADHD and control group and Cohen’s *d* effect sizes for the differences between parameter values in the groups. *C*: Visual perceptual processing speed (elements/sec); *K*: Visual working memory storage capacity (number of elements); $w_L/(w_L + w_R)$: spatial distribution of attentional weighting (parameter w_λ); α : efficiency of top-down control; ADHD: ADHD patients; Con: control participants.
** $p < .01$.

between-subjects factor Group (2) revealed no significant effect ($F(1, 58) = 0.09$; $p > .75$). The effect size (Cohen’s *d*) is small. Figure 4 accordingly shows that, for both the ADHD and the control group, accuracy was highest for single targets; adding a distracter led only to a slight accuracy loss, whereas adding a second target resulted in a pronounced decrement. Thus, both groups were able to prioritize targets over distracters and they did so with comparable efficiency, that is, they were equally able to allocate greater attentional weights to task-relevant than to -irrelevant items.

Laterality of attentional weighting. The average estimates of the spatial distribution of attentional weighting w_λ ($w_L/(w_L + w_R)$) are also listed in Table 2. The attentional weights for the left and the right side, w_L and w_R , were calculated as the mean of the attentional weights for the upper and lower positions on a given side. Both groups show a relatively balanced estimate of spatial-attentional weighting, indicated by values close to the optimum of 0.5. An ANOVA revealed no significant group difference ($F(1, 58) = 0.16$; $p > .65$). The effect size (Cohen’s *d*) is small. Left- and right-side target reports (see Figure 5) are generally similar in both groups, indicating that they allocate a comparable amount of attentional resources toward each side.

Specificity of the WM Storage Capacity Deficit

The only significant difference between healthy participants and patients was that the latter showed a reduced WM storage capacity. For healthy participants, a modest correlation between the two attentional capacity parameters, WM storage capacity *K* and processing speed *C*, has been reported (Finke et al., 2005). Given this,

for the ADHD group (which is of major interest in the present study), we correlated WM storage capacity *K* with the other TVA parameters to ascertain whether *K* is indeed independent and specific, that is, indicative of a single, latent trait that might serve as an ADHD endophenotype. No significant correlation between *K* and any of the other TVA parameters was found (processing speed *C*: $r = -.23$; laterality of attentional weighting w_λ : $r = -.34$; top-down control α : $r = .15$; all $p > .10$). In line with the assumptions of TVA, the correlations among the other, nonaf-

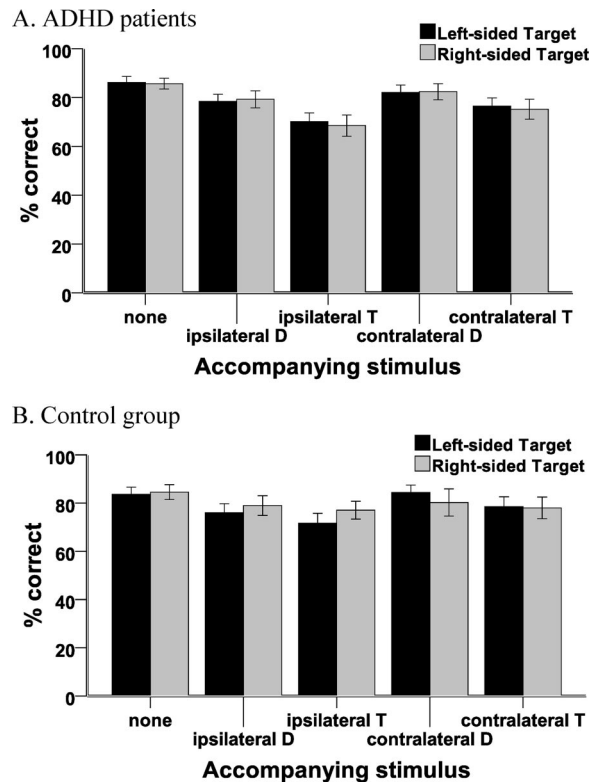


Figure 5. Mean proportion of correctly reported letters for left- (black bars) and right-sided targets (gray bars) for the group of ADHD patients (upper graph) and the control group (lower graph): single targets, targets accompanied by an ipsilateral target or distracter, and by a contralateral target or distracter. The error bars show standard deviations. T = target; D = distracter.

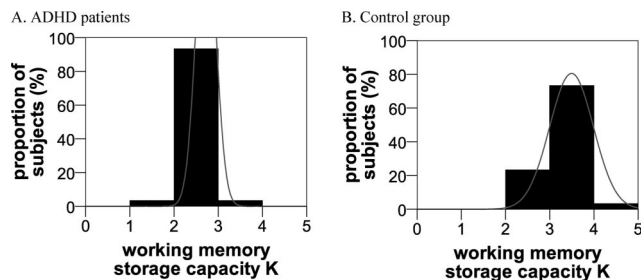


Figure 4. Distribution of visual working memory storage capacity (*K*) in ADHD patient and control group.

fected, parameters were also all nonsignificant (all $p > .10$; the highest $r = .36$ was found between processing speed C and top-down control α). We further correlated age, IQ, income, ISCO, and ISEI to the WM storage capacity estimates of the patients. None of these correlations was significant (all $r < .25$; all $p > .15$).

Discussion

In our study, we were able to isolate a putative neuro-cognitive endophenotype of ADHD, which is characterized by a reduced general attentional capacity, rather than by impaired selectivity. Our results, derived from the TVA-model, indicate that reduced WM storage capacity imposes the critical constraint on attentional processing in ADHD patients: The normal limitation of the number of items that can be maintained in parallel in WM, that is characteristic for human information processing (Cowan, 2001), is further accentuated, by more than 20%, in adult ADHD patients. This holds true even after controlling for IQ, age, education, indices of socioeconomic status, occupation and income, and comorbidity.

This finding clearly supports a WM deficit model of adult ADHD (Castellanos & Tannock, 2002; Engelhardt et al., 2008; Rapport et al., 2000, 2008; Westerberg et al., 2004). None of the ADHD patients in our group was able to maintain more than three visual items in the WM store, indicating a prevailing, general deficit in this basic component of attentional capacity. Accordingly, the medium to high effect size of the difference in WM capacity in patients relative to controls (Cohen's d) exceeds the effect sizes reported by Schoechlin and Engel (2005) in a review of neuropsychological deficits in adults with ADHD ($d \leq 0.6$). Rapport et al. (2008) reported that children with ADHD could maintain and repeat around four sequentially presented items. Although showing reduced WM storage scores compared to healthy children, the number of items reported by these ADHD children exceeds that achieved by our adult ADHD participants. Note that this does not contradict our present findings, as the study of Rapport, et al. used a span task with relatively long stimulus presentations. Such tasks allow for the use of rehearsal and in this way impede the precise estimation of the basic (i.e., strategy-free) storage capacity of WM, which is typically overestimated (see Cowan, 2001, for a detailed review of the assessment of WM storage capacity). Our results are, therefore, complementary (rather than contradictory) to those of Rapport et al. (2008); who, in their model of functional WM emphasized the contribution of executive and rehearsal deficits in ADHD. What we show here is that the WM buffer for item storage is itself affected (besides presumable additional deficits in the control of rehearsal processes).

A number of possibly confounding deficits in visual attentional selection could give rise to the reduced amount of information encoded and maintained in WM by ADHD patients. Before target information can be stored in WM, it has to be encoded, often in the face of distracting (i.e., to-be-ignored) information. Therefore, a primary impairment in top-down controlled distracter inhibition could facilitate the entry of distracting information into WM (Nigg, 2001; Quay, 1997). However, average values, standard deviations, and ranges of the estimates of the top-down control parameter indicate that adult ADHD patients are as efficient as control participants in shielding WM target information against

distracting inputs. Accordingly, a deficit in the cognitive inhibition of interfering stimuli is unlikely to be the (primary) cause of the low WM capacity estimates.

Alternatively, one potential and more upstream deficit in adult ADHD that might cause WM storage deficits as a secondary consequence, might be a low level of alertness—that would slow the rate of information uptake into the system (Sergeant, 2005) and, thus, the speed of encoding into WM. However, contrary to the energetic-state model (e.g., Sergeant, 2005), we found no indication of slowed processing speed in adult ADHD; ruling out an account of the low WM storage capacity estimates in terms of lowered alertness. The normal scores for processing speed also effectively rule out that the low WM storage capacity estimates are owing to generally low task motivation. Recall that the speed estimates are derived from whole-report performance on trials with the shortest exposure durations, more precisely, from the increase in the number of items reported with only slightly increasing exposure durations (as is illustrated in Figure 3). If patients had performed below maximum capacity, they would not have displayed such a systematic increase in report performance from the shortest to only slightly longer exposure durations.

Finally, the absence of a visuospatial bias in ADHD patients in our study rules out any account based on hemi-inattention as a relevant factor for impaired information encoding into WM, as might be suggested by reports of left-sided minineglect in ADHD children (George et al., 2005; Johnson et al., 2009; Sheppard et al., 1999).

In summary, based on the cognitive specificity of the TVA-based parametric assessment, we suggest a reduction of WM storage as a primary deficit in adult ADHD. We found WM storage capacity as an isolated component to be affected in the attentional selection process, quite distinct from other potentially critical components. Generally nonsignificant correlations can be taken to be indicative of the independence of this from the other TVA parameters (a basic assumption underlying TVA; Bundesen, 1990).

Limitations

To date, we have not assessed children with ADHD using the TVA-based approach. Thus, it is possible that WM storage capacity reductions are equally present in earlier preadult stages of life. Halperin, Trampush, Miller, Marks, and Newcorn (2008) argued that remitters might differ from persisters, in that the latter are not able to compensate, via effort, for deficits in subcortical, more automatic and less consciously controlled functions such as regulatory control of fidgetiness. Thus, what we have identified might be a specific impairment of ADHD persisters, who are unable to compensate because of compromised WM functioning.

In addition, we did not assess the contribution of higher-order executive functions, which seem to play an important role in WM impairments in ADHD (e.g., Rapport et al., 2008) and have been shown to contribute to inhibition processes in the stop task (Alderson et al., 2010). When assessing top-down control, furthermore, we used displays with only four possible stimulus locations, which might have allowed participants to monitor all possible locations of upcoming stimuli and target. Thus, we cannot rule out that increasing the task difficulty by introducing more stimulus

locations would reveal (slight) impairments in the efficiency of distracter inhibition, which we were unable to find.

Although the TVA-based assessment is assumed to deliver cognitively specific components of the visual selection process, it has to be acknowledged that differences between the whole- and partial-report tasks are potential sources of “artificial” findings. Although the whole- and partial-report paradigms are comparable in terms of the stimulus material, response requirements, administration format, and duration, the number of trials is lower in the whole- than in partial-report tasks. Furthermore, tasks relying on performance accuracy are generally prone to effects of differential task difficulty between conditions (Miller, Chapman, Chapman, & Collins, 1995); we cannot rule out such differences between our whole- and partial-report. Note though that baseline accuracy was effectively matched in our study by individual adjustments of exposure durations. Therefore, these tasks were at least comparable in difficulty between the control and the patient group. Furthermore, at least the central parameters processing speed and WM storage capacity have been extracted from performance on exactly the same trials.

We do not provide interrater reliability with respect to the ADHD diagnosis (i.e., no data on the number of patients excluded from our study because of disagreement on the diagnosis). However, we assume that the conservative criterion (both psychiatrists confirm ADHD) combined with collateral information and rating scales ensures diagnostic validity.

Conclusions

WM Storage Capacity in Adult ADHD: Identification of a Putative Endophenotype Based on TVA

In light of our results, deficits displayed by ADHD patients in various experimental attentional tasks might be related to a compromised ability to maintain multiple items of information in WM. We propose that the probability of attentional lapses increases with low WM storage capacity. If fewer items of information already fill up WM to its limit, no slots are available for new perceptual stimuli seeking access whereby the probability for task-relevant information to get lost from the current focus of attention is increased. In the same vein, increased reaction time variability in ADHD patients (Seidman, 2006) might result from impaired maintenance of task-context information, rather than from a slowing of stimulus perception because of a lowered energetic state (Sergeant, 2005). WM storage deficits might also contribute to deficits in *behavioral* inhibition, that is, deficits in stopping inappropriate responses in the stop task (Bekker et al., 2005; Lijffijt et al., 2005). Here participants have to sustain attention to frequent go-stimuli and additionally attend to less frequent stop signals. When WM storage capacity is low, the store may already be loaded up to its limit by the more frequent input source. As a result, additional encoding of the stop signal and the evaluation of these competing signals within WM might be delayed. Alderson, Rapport, Hudec, Sarver, and Kofler (2010), who used a similar rationale for explaining children’s performance, found that, in addition the central executive component of WM, WM storage, also plays a decisive role in stop-signal performance in ADHD.

An interpretation along these lines could thus account for a broad range of clinically observable, behavioral symptoms shown

by ADHD patients. WM storage deficits might explain why ADHD patients make careless mistakes, do not seem to listen when spoken to, and fail to finish duties in their workplace. WM storage capacity has been shown to be closely linked to various everyday-life problem-solving situations and to be a prerequisite for the acquisition of arithmetic and reading skills (Alloway, Gathercole, Kirkwood, & Elliott, 2009; Cowan, 2001). Thus, academic and occupational failure is exactly what would be predicted when WM storage capacity is low.

While our findings on processing speed appear to be inconsistent with some studies that have used reaction time paradigms, they fit well with recent meta-analytic results (Schöchlin & Engel, 2005). Reaction times do not necessarily reflect early attentional stages of processing (Prinzmetal, McCool, & Park, 2005), and especially in ADHD reaction time deficits might rather be related to later stages of motor response selection and execution (Barkley, 1997). The TVA-based approach permits these processing stages to be disentangled, in that it targets purely perceptual processing and, thus, attentional, deficits.

In conclusion, we wish to emphasize that the identification of a single affected component in adult ADHD that can be measured unconfounded by other potentially affected functions is a major strength. First, it permits us to pinpoint the stage of deficient attentional functioning and to exclude alternative sources of primary impairment (e.g., deficient encoding of stimuli into WM) that would only secondarily manifest in a WM deficit. Second, it provides a clear-cut hypothesis as to which component should be further investigated in future studies with regard to its usability in ADHD endophenotypes research.

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Call for Nominations

The Publications and Communications (P&C) Board of the American Psychological Association has opened nominations for the editorships of **Journal of Experimental Psychology: Animal Behavior Processes**, **Journal of Experimental Psychology: Applied**, **Neuropsychology**, and **Psychological Methods** for the years 2014–2019. Anthony Dickinson, PhD, Wendy A. Rogers, PhD, Stephen M. Rao, PhD, and Scott E. Maxwell, PhD, respectively, are the incumbent editors.

Candidates should be members of APA and should be available to start receiving manuscripts in early 2013 to prepare for issues published in 2014. Please note that the P&C Board encourages participation by members of underrepresented groups in the publication process and would particularly welcome such nominees. Self-nominations are also encouraged.

Search chairs have been appointed as follows:

- **Journal of Experimental Psychology: Animal Behavior Processes**, John Disterhoft, PhD, and Linda Spear, PhD
- **Journal of Experimental Psychology: Applied**, Jennifer Crocker, PhD, and Lillian Comas-Diaz, PhD
- **Neuropsychology**, Norman Abeles, PhD
- **Psychological Methods**, Neal Schmitt, PhD

Candidates should be nominated by accessing APA's EditorQuest site on the Web. Using your Web browser, go to <http://editorquest.apa.org>. On the Home menu on the left, find "Guests." Next, click on the link "Submit a Nomination," enter your nominee's information, and click "Submit."

Prepared statements of one page or less in support of a nominee can also be submitted by e-mail to Sarah Wiederkehr, P&C Board Search Liaison, at swiederkehr@apa.org.

Deadline for accepting nominations is January 10, 2012, when reviews will begin.