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Published in:
Archives of Clinical Neuropsychology

DOI:
10.1093/arclin/acw016

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Gmehlin, D., Fuermaier, A. B. M., Walther, S., Tucha, L., Koerts, J., Lange, K. W., Tucha, O., Weisbrod, M., & Aschenbrenner, S. (2016). Attentional Lapses of Adults with Attention Deficit Hyperactivity Disorder in Tasks of Sustained Attention. *Archives of Clinical Neuropsychology*, *31*(4), 343-357. https://doi.org/10.1093/arclin/acw016

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Archives of Clinical Neuropsychology 31 (2016) 343–357

Archives
of
CLINICAL
NEUROPSYCHOLOGY

Attentional Lapses of Adults with Attention Deficit Hyperactivity Disorder in Tasks of Sustained Attention

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Accepted 12 March 2016

Abstract

Adults with attention deficit hyperactivity disorder (ADHD) show attentional dysfunction such as distractibility and mind-wandering, especially in lengthy tasks. However, fundamentals of dysfunction are ambiguous and relationships of neuropsychological test parameters with self-report measures of ADHD symptoms are marginal. We hypothesize that basic deficits in sustaining attention explain more complex attentional dysfunction in persons with ADHD and relate to ADHD symptoms. Attentional function was analyzed by computing ex-Gaussian parameters for 3 time Blocks in a 20 min test of sustained alertness. Changes in performance across these blocks were analyzed by comparing adult persons with ADHD ($n = 24$) with healthy matched controls ($n = 24$) and correlated with neuropsychological measures of selective and divided attention as well as self-report measures of ADHD symptoms. We found a significantly steeper increase in the number of slow responses (ex-Gaussian parameter τ) in persons with ADHD with time on task in basic sustained alertness. They also performed significantly worse in tasks of sustained selective and divided attention. However, after controlling for an increase in τ during the alertness task, significant differences between groups disappeared for divided and partly selective attention. Increases in τ in the sustained alertness task correlated significantly with self-report measures of ADHD symptoms. Our results provide evidence that very basic deficits in sustaining attention in adults with ADHD are related to infrequent slow responses (=attentional lapses), with changes over time being relevant for more complex attentional function and experienced ADHD symptoms in everyday life.

Keywords: ADHD; Attention

Introduction

According to DSM-5 (APA, 2013), symptoms of inattention, such as distractibility and concentration difficulty, are core features of attention deficit hyperactivity disorder (ADHD). Whereas ADHD had been historically understood as an exclusive childhood disorder (cADHD), longitudinal and follow-up studies of children with ADHD suggested that core symptoms of ADHD persist into adulthood (aADHD) in ∼30%–60% of cases (Mannuzza et al., 2011). Although discussed lively, there is evidence suggesting a decline of impulsivity and hyperactivity with age in ADHD, while symptoms of inattention are rather stable across the life span (Biederman, Mick, & Faraone, 2000). However, similar to children and adolescents, symptoms in adult persons with ADHD profoundly impair functioning in social, academic, and occupational areas (Vadala, Giugni, Pichiecchio, Balottin, & Bastianello, 2011).

doi:10.1093/arclin/acw016 Advance Access publication on 24 April 2016

Attention, Sustained Attention, and Adult Attention Deficit Hyperactivity Disorder

Established models of the dimensionality of attention (Sturm, 2006; Van Zomeren & Brouwer, 1994) postulate a distinction between intensity and selectivity aspects of attention. With regard to the intensity aspect of attention, alertness is of special importance and requires a person to remain ready to react to one target stimulus. With regard to the selectivity aspect of attention, models distinguish between selective and divided attention. While selective attention requires the ability to focus attention on one or more particular target stimuli but to suppress reactions to other irrelevant stimuli, divided attention reflects the ability to divide attention between a number of information channels.

Sustained attention, however, can be distinguished from the above-mentioned aspects of attention, as sustained attention requires participants to remain ready to react or to maintain the focus to one or more sources over a relatively long and unbroken period of time (Van Zomeren & Brouwer, 1994). Consequently, measurements of sustained attention typically involve tasks lasting at least 15–20 min and focus on changes over time, as indicated by so-called time-on-task Effects (ToT-effects) (van der Meere & Sergeant, 1988). Analogously to shorter tasks, sustained alertness or response readiness is a prerequisite for more complex sustained selective or sustained divided attentional function. Sustained alertness is therefore crucial for successful daily functioning, affecting both the private (e.g., driving a vehicle, contributing to conversations, participating in sports) and the occupational setting (e.g., attending to a lengthy business conference).

In the last decade, a large body of research revealed attentional deficits in adults with ADHD by predominantly using rather short neuropsychological tests (i.e., 3–5 min) (Dinn, Robbins, & Harris, 2001; Fuermaier et al., 2013; Rohlf et al., 2012; Schoechlin & Engel, 2005; Tucha et al., 2006, 2008), which do not fulfill the above-mentioned criteria for assessing sustained attention. However, drawing upon the DSM-5 criteria, it may be mainly sustained attention, which accounts for deficits associated with (a)ADHD (e.g., "often has difficulty sustaining attention in tasks or play activities"; p. 59) (APA, 2013). Furthermore—as postulated by attentional models touched above—sustained alertness is a precondition for more complex attentional function over time and may influence a broad range of everyday problems in aADHD (e.g., "often fails to give close attention to details or makes careless mistakes in schoolwork, work, or during other activities," "is often easily distracted by extraneous stimuli;" both p. 59) (APA, 2013). Taken together, this suggests a high ecological validity of tasks measuring sustained attention and especially sustained alertness in aADHD.

It has to be noted that a bulk of studies examining attentional function in aADHD used vigilance tests (e.g., different forms of the CPT) (Huang-Pollock, Karalunas, Tam, & Moore, 2012; Tucha et al., 2009). Although vigilance also requires participants to remain attentive over longer periods of time, one key feature of vigilance tests are infrequently occurring stimuli under very monotonous conditions. Daily life situations requiring sustained attention, however, usually demand higher activation levels and more frequent interactions with the environment. This may reduce the ecological validity of vigilance tests when compared with tests of sustained attention (Tucha et al., 2015).

Although recent studies suggest that objective and subjective measurements provide distinct information (Fuermaier et al., 2014, 2015; Sandra Kooij et al., 2008), marginal correlations between standardized neuropsychological test-scores and self-reported ADHD symptoms may also be due to a reduced ecological validity of some neuropsychological tests. Moreover, besides characteristics such as the length of the test and the frequency of the stimuli in the paradigms used, there is recent evidence that certain neuropsychological test parameters assessing intraindividual variability (IIV) systematically produce larger and more consistent differences between persons diagnosed with ADHD and healthy control persons (Tamm et al., 2012).

Intraindividual Variability, Omission Errors, and Attentional Lapses in Attention Deficit Hyperactivity Disorder

IIV refers to short-term changes of a person's performance on a single task measured on multiple occasions and can be defined as within-person inconsistency that cannot be accounted for by systematic and more enduring changes attributable to development, learning or fatigue (Hultsch, MacDonald, & Dixon, 2002). Recent research provides systematic evidence that IIV—as a reliable measure of the stability of information processing—is fundamentally disturbed in aADHD. Moreover, there is consistent behavioral and cognitive evidence, suggesting that increased IIV in aADHD is due to some overly slow responses in almost all speeded reaction time (RT) tasks (Kofler et al., 2013).

These slow RT can be assessed by estimating so-called ex-Gaussian parameters for intraindividual RT distributions. The ex-Gaussian distribution is described by the convolution of a normal and an additional exponential function. Fitting the ex-Gaussian function to empirical RT data provides estimates of three independent parameters (Matzke & Wagenmakers, 2009):

(i) Mu (μ) represents the mean of the normal component and mainly reflects average performance.
(ii) Sigma (σ) corresponds to the *SD* of the normal component and indicates variability of performance.
(iii) Tau (τ) corresponds to the variability of the exponential function and reflects extremes in performance.

In other words, higher τ values are consistent with RT distributions in ADHD, which are marked by infrequent but overly prolonged RTs forming the right tail of the RT distribution (Kofler et al., 2013). In contrast to classical measures like the mean RT and standard deviation of RT (*SD*) as the most common and easy to compute variability measure, ex-Gaussian parameters provide independent measures of speed and variability (Wagenmakers & Brown, 2007) and additionally distinguish between general variability (σ) and variability due to isolated slow responses (τ).

Beyond these parameters of RT and variability, error measures are essential indicators of attentional functioning. Although playing a rather subordinate role in alertness tests, they are of great importance in tests of selective and divided attention (Sturm, 2006). If participants respond to trials where no response is required, they commit commission errors, which can—dependent on task characteristics—be taken as an index of failed interference or rather inhibitory control (Ballard, 2001; Kaiser, Aschenbrenner, Pfueller, Roesch-Ely, & Weisbrod, 2012). In contrast, omission errors occur when participants do not respond to trials where they are required to respond and are—although other explanations are still being discussed (Tamm et al., 2012)—considered as indicating attentional lapses (Leth-Steensen, Elbaz, & Douglas, 2000).

Given correlations between the parameter τ and omission errors in different attentional (Gu, Gau, Tzang, & Hsu, 2013) and executive tasks in ADHD (Gmehlin et al., 2014), one may speculate that failures of sustained attention, which did not last long enough to produce errors of omission, may have resulted in an abnormally prolonged RT producing higher variability in the slow portion of the distribution of RTs in ADHD. This assumption is in line with a study of Epstein and colleagues (2010), which revealed that children with ADHD show a pronounced slowing of responses before and after omission errors. Cheyne, Carriere, and Smilek (2009) supposed that such "attentional lapses" may begin with transient disengagement of attention, then move to automatic responding without actively attending (=prolonged RT, indicated by τ) and finally result in "mind wandering," which produces omission errors.

Summing up, we propose that both IIV as indicated by the ex-Gaussian parameter τ and omission errors are adequate measures to examine attentional dysfunction due to attentional lapses in the course of sustained attention tasks in aADHD. We therefore speculate that the use of ex-Gaussian variability measures in an ecologically valid sustained alertness task may help to assess neuropsychological deficits in aADHD which are related to everyday symptoms of the disorder. Such systematic examination of attention may also have some impact on neuropsychological models of ADHD which are described below.

Implications of Attentional Dysfunction for Neuropsychological Models of Attention Deficit Hyperactivity Disorder

Recent theories on ADHD predict dysfunction in sustained attention (i.e., greater deterioration of performance over time compared with a normal functioning level of controls, e.g., ToT-effects as described above) due to very basic deficits in arousal, activation, and/or effort (Kofler et al., 2013). Although different causes are stated, all approaches predict common neuropsychological dysfunction on the behavioral level as defined by (periodic) lapses of attention in speeded tests (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Leth-Steensen et al., 2000). Against this theoretical background, attentional deficits in aADHD should already affect basic attentional functions like the readiness to react in a simple alertness tasks. Moreover, deficits should not so much appear as simple group differences relative to controls but be indicated by ToT-effects (i.e., deficits in sustained attention as described above) (van der Meere & Sergeant, 1988) in the sense of a more marked increase in slow responses indicated by the parameter τ in patients when compared with healthy controls.

To the best of our knowledge, no study examined basic sustained alertness in aADHD on the basis of ex-Gaussian parameters. With regard to classical measures of mRT, a bulk of studies used vigilance tasks (e.g., the CPT; Marchetta, Hurks, De Sonneville, Krabbendam, & Jolles, 2008) instead of sustained attention tasks. In our workgroup, Tucha and colleagues (2015) recently differentiated sustained attention with regard to alertness, selective, and divided attention. Compared with healthy individuals, adult persons diagnosed with ADHD differed significantly with regard to sustained attention in measures of alertness, selective attention, and divided attention. However, given a dysfunction in alertness as indicated by an increased IIV, attentional lapses as indicated by omissions in more complex selective or divided attention tasks, may be the consequence of increased IIV in the alertness task. For this reason, we decided to additionally apply ex-Gaussian measures to parts of our data. (Differences in sample size are mainly due to more strict selection and matching criteria in the present study in order to provide stable estimates for ex-Gaussian parameters.)

Summary and Research Questions

It is an open question, whether an increase in the *SD* of RT in sustained alertness in aADHD is due to an increase in the number of isolated slow responses or a more general increase in variability. For both children (Tarantino, Cutini, Mogentale, & Bisiacchi, 2013) and adolescents (Gu et al., 2013), recent studies using vigilance tasks showed a larger increase in τ in children with

ADHD compared with controls with non-significant changes in σ or μ. However, both differences in age and paradigms used complicate a transfer to sustained attention in aADHD.

(i) We propose that—similar to cADHD—adults with ADHD show deficits in sustained alertness relative to healthy controls. Deficits will be indicated by a significantly more pronounced increase in the number of slow responses (τ) in the course of the alertness task (ToT-effect).

(ii) Based on a particular relevance of sustained alertness for everyday function and the ex-Gaussian measure τ for indicating attentional deficits, we propose a significant correlation of the increase in the number of slow responses in the alertness task with self-report scales of ADHD symptoms.

(iii) From a more theoretical point of view, we hypothesize that an increase in the number of slow responses (τ) in the course of the alertness task correlates significantly positive with omission errors made in tasks measuring more complex attentional functions such as selective and divided attention.

Materials and Methods

Participants

Our sample consisted of a total of $n = 48$ adult participants aged 19–63 years ($M = 34.1$ years; $SD = 12.3$ years). $n = 24$ were diagnosed with ADHD and $n = 24$ were healthy control participants matched for age, gender, and education. All individuals participated voluntarily in the study and gave written informed consent prior to neuropsychological assessment. The study protocol was approved by the University of Heidelberg Ethics Review Committee and was conducted according to the Declaration of Helsinki.

The aADHD group contained outpatients who were self-referred or referred from local psychiatrists or neurologists to the Department of Psychiatry and Psychotherapy—SRH Clinic Karlsbad-Langensteinbach (Germany). Diagnostic assessment was done by experienced clinicians applying both a clinical psychiatric interview according to DSM-4 criteria (Barkley & Murphy, 1998) and the retrospective diagnosis of an ADHD in childhood (DSM-4 criteria). Childhood ADHD symptoms were self-rated with the short version of the Wender Utah Rating Scale (WURS-K; Ward, Wender, & Reimherr, 1993). Severity of adulthood ADHD symptoms was self-rated with the ADHD self-report scale corresponding to the diagnostic criteria of DSM-4 (APA, 2000; Rösler, Retz-Junginger, Retz, & Stieglitz, 2008). In the diagnostic assessment of the $n = 24$ persons with ADHD, $n = 8$ persons met DSM-4 criteria for ADHD—predominantly inattentive type (ADHD-I), $n = 16$ persons met criteria for ADHD-combined type (ADHD-C), whereas none of the persons met criteria for ADHD-hyperactive-impulsive type (ADHD-H). Nine of the 24 individuals with ADHD were diagnosed with one or more comorbid disorders, including mood disorders ($n = 5$), anxiety disorders ($n = 3$), post-traumatic stress disorders ($n = 2$), eating disorders ($n = 2$), and obsessive-compulsive disorder ($n = 1$). None of the participants were currently treated with stimulant medication. However, three persons were treated with antidepressant medication for a prolonged period of time because of affective disorders. Moreover, none of the participants reported having a history of substance abuse disorder during the previous 6 months and none reported a history of neurological disorder including head injury. Characteristics of individuals with ADHD are presented in Table 1.

Furthermore, 24 healthy individuals were assessed. Healthy participants were recruited from the local community via public announcements, word-of-mouth, and through contacts of the researchers involved. None of the healthy individuals reported having a history of neurological or psychiatric diseases and none were taking any medication known to affect the central nervous system at the day of the assessment. All healthy persons completed the same self-rated questionnaires for current and retrospective ADHD symptoms prior to the assessment.

Table 1. Distribution of participants with regard to age, gender, and education

	aADHD	Control participants
Age (M ± *SD*, range in years)	34.13 ± 12.35, 20–58	34.00 ± 12.62, 19–63
Gender (♀, ♂)	10, 14	10, 14
Education^1 (median, range)	3, 1–3	3, 1–3
Verbal IQ (*M* ± *SD*, range)	105 ± 12, 88–136	111 ± 17, 91–145

Notes: aADHD = adult persons with attention deficit hyperactivity disorder; *M* = mean; *SD* = standard deviation of the mean; ♀ = female, ♂ = male; 1Education was ordinally measured with 1 = completed compulsory schooling (“Hauptschule” with 9 years of school); 2 = completed secondary school (“Realschule” with 10 years of school); 3 = highschool graduation with university entrance exam (“Gymnasium” with 12–13 years of school).

Intellectual functions of all participants were measured using the Multiple Choice Vocabulary Test (Lehrl, 1995). Persons with aADHD and healthy controls did not differ significantly with regard to age [$t(46) = -0.35; p = .972$], gender (exactly the same distribution), education [$U(288) < 0.001; p = 1.000$], or intellectual function [$t(46) = -1.36; p = .182$] (Table 1). As expected, healthy individuals scored significantly lower on both questionnaires for ADHD symptoms: WURS-K: $t(46) = -8.07; p < .001$ and ADHD self-report scale: $t(46) = -13.71; p < .001$.

Measures

Self-report scales for attention deficit hyperactivity disorder symptoms. Two standardized self-report rating scales designed to quantify ADHD symptoms currently and retrospectively were applied to all participants (Rösler et al., 2008). Childhood ADHD symptoms were self-rated with the short version of the Wender Utah Rating Scale (WURS-K) including 25 items on a 5-point scale (Ward et al., 1993). Severity of current ADHD symptoms was self-rated with the ADHD self-report scale (Rösler et al., 2008) consisting of 18 items on a 4-point scale corresponding to the diagnostic criteria of DSM-4 (APA, 2000). A sum score was calculated for each rating scale.

Intellectual functions. Intellectual functions (IQ) were measured using the Multiple Choice Vocabulary Test (Lehrl, 1995). This test consists of 37 lines, each comprising of one authentic word and four fictitious words. The participants were required to find the authentic word by underlining it. The Multiple Choice Vocabulary Test is a valid and short test procedure which provides a measure for verbal intellectual functioning.

Assessment of attention. Attentional function was assessed by applying different WAF subtests of the Vienna Test System (VTS) (Schuhfried, 2000). The VTS is a computerized test battery for the measurement of various neuropsychological functions which had originally been developed under theoretical-based considerations to assess different dimensions of attention, i.e., alertness, selective attention, and divided attention (Häusler & Sturm, 2009). All tests were adapted with regard to test duration and prolonged, so that the respective test took ~20 min. This is a typical time-span used in the most common neuropsychological tests of sustained attention used in both clinical and research contexts [e.g., TAP 2.3 (15 min): Zimmermann & Fimm, 2002; Conners CPT (14 min): Conners & Sitarenios, 2011; IVA-CPT (14 min): Tinius, 2003; T.O.V.A. (21 min): Leark, Greenberg, Kindschi, Dupuy, & Hughes, 2007].

Sustained Alertness was assessed by applying the adapted subtest WAF-A of the VTS. The reliability of the test was reported to be 0.93. In this test, participants were instructed to fixate on a cross in the center of a computer screen and to press a button on a response panel as soon as a black dot (target stimulus) appeared in the center of the screen. Each target stimulus was presented for 1500 ms but disappeared as soon as a response was given. A total number of 340 target stimuli were presented, whereas the time between the presentations of two subsequent target stimuli [inter-stimulus interval (ISI)] varied between 3000 and 5000 ms. An instruction phase and a short practice phase preceded the actual test phase. The practice phase was repeated if necessary until participants understood the task instructions adequately (more than 80% correct responses in practice phase). The duration of the test phase was ~20 min which was split into three time blocks consisting each of the same number of target stimuli (each time block took ~400 s or 6–7 min).

Sustained selective attention was measured with an adaption of the test for perception and attention functions called "selective attention" (WAFS—subtest unimodal visual). The reliability of the test was reported to be 0.95. In this test, a series of stimuli (circles, squares, or triangles) was presented in consecutive order in the center of a computer screen. Each stimulus was presented for 1500. After 500 ms of each stimulus presentation, a change may take place, i.e., the stimulus may get lighter or darker or stay the same. The participants were requested to react as quickly as possible to changes in circles and squares but to ignore changes in triangles. A response was given by pressing a button on a response panel. A total number of 475 stimuli were presented in pseudo-randomized order of which 100 stimuli required a response. The time between the presentations of two subsequent stimuli (ISI) was 1000 ms. An instruction phase and a short practice phase preceded the actual test phase. The practice phase was repeated until participants understood the task instructions adequately.

Sustained divided attention was measured with an adaption of the test for perception and attention functions called "divided attention" (WAFG—subtest crossmodal visual auditory). The reliability of the test was reported to be 0.97. In this test, participants were required to monitor simultaneously one visual and one auditory stimulus channel. In the visual stimulus channel, a series of 400 stimuli were presented in consecutive order in the center of a computer screen. Each stimulus consisted of a pair of shapes (two circles, two rectangles, or one of both), one displayed upon the other. Each stimulus was presented for 1500. After 500 ms of each stimulus presentation, a change may take place in one or both shapes of the stimulus presented, i.e., the shape may get lighter or stay the same. The participants were requested to react as quickly as possible if the same kind of shape (circle or rectangle) became lighter twice in succession (in two subsequent stimuli). The time between the presentations of two subsequent stimuli (ISI) was 1000 ms. In the auditory stimulus channel, a series of 400 sounds, each of the same pitch, was presented in consecutive order to participants. Each sound was presented for 1500. After 500 ms of each sound presentation, a change may take place, i.e., the tone may get softer or stay the same. The participants were requested to react as quickly as possible if the sound became softer twice in succession (in two subsequent sounds). The time between the presentations of two subsequent sounds (ISI) was 1000 ms. The task (visual and auditory information channel) required 100 responses in total, each by pressing the same specified button on a response panel. The presentation order of stimuli in both information channels was pseudorandomized. An instruction phase and a short practice phase preceded the actual test phase. The practice phase was repeated until participants understood the task instructions adequately.

Procedure

At the beginning of the experiment, descriptive and anamnestic information (e.g., age, school education, medical history) was obtained. Subsequently, four tests of sustained attention were performed, each taking ~20 min. However, data from the last test (Flexibility) were not taken into account for the given study. A break followed the execution of each test. Short breaks (1–2 min) were allowed between the first test and the second test, a longer break (10–15 min) was taken between the second and the third test. The order of the three relevant tests (alertness, selective attention, divided attention) was counterbalanced across participants.

Data Analysis

Preparation of data. Classical measures (mRT and *SD*) were calculated for sustained alertness separately for all three time blocks. For selective and divided attention, mRT and *SD* as well as error measures (omission and commission errors) were calculated for the complete test only.

In addition to classical measures, ex-Gaussian analyses were performed separately for all three time blocks of the alertness task by using the MATLAB toolbox "DISTRIB" according to Lacouture and Cousineau (2008). Data preprocessing and export to MATLAB was done with an individually tailored Excel macro. Estimates of the three ex-Gaussian parameters μ, σ, and τ were obtained by fitting an ex-Gaussian distribution to the frequency distribution of correct trials requiring a response in every time block for each subject. The fitting was done by an iterative search based on maximum likelihood criteria using the function "egfit.m." The number of RT observations used for each ex-Gaussian fit depended on the accuracy of responding; a summary of the number of observations is given in Table 2.

Statistical analyses. Statistical analyses were performed using SPSS 21 for Windows. Given violations of the normal distribution in some classical, ex-Gaussian, and error measures, we decided to log transform corresponding variables. Given equal *n* for the aADHD and healthy control group, violations of the homogeneity of variances should not have a heavy impact on the data. Using *a priori* hypotheses, an α-level was set to 0.05 for all tests.

Given our rather small sample size, we additionally calculated a formal *post hoc* power analysis in order to estimate the power of relevant statistical comparisons. Based on Schoechlin and Engel (2005), we believe medium effect sizes ($d = 0.50$) to indicate clinically meaningful differences between persons with aADHD and healthy controls with regard to attentional measures. As statistical power in the present study turned out not to be sufficient for all comparisons to detect medium effect sizes ($p <$ .80), p-values of $< .10$ are referred to as trend level of statistical significance and interpreted with caution. Moreover, we calculated effect sizes for multivariate (index η^2) comparisons. Effect size η^2 provides information about the proportion of variance that is accounted for by a factor group or combinations of factors in multivariate comparisons independent from all other factors. According to Cohen (1988), a small effect size ($d = 0.20$) corresponds to $\eta^2 = 0.0099$, a medium effect size ($d = 0.50$) corresponds to $\eta^2 = 0.0588$, and a large effect size ($f = 0.80$) corresponds to $\eta^2 = 0.1379$.

In a first step, we applied multivariate analyses of covariance (covariates AGE and IQ) with repeated measures (multivariate analyses of covariance, MANCOVA) as a two-factor (2 × 3) design with measures of alertness being the dependent variables.

Table 2. Number of reaction time observations used for ex-Gaussian analysis with regard to group and time block in the alertness task

	aADHD	Control participants
Block 1 ($M \pm SD$, range)	113.1 ± 1.3, 109–114	113.8 ± 0.7, 111–114
Block 2 ($M \pm SD$, range)	113.3 ± 1.2, 109–114	113.5 ± 1, 110–114
Block 3 ($M \pm SD$, range)	112.8 ± 2.2, 106–114	113.1 ± 2.5, 102–114

Note: aADHD = adult persons with attention deficit hyperactivity disorder; *M* = Mean; *SD* = standard deviation of the mean.

However, separate MANCOVAs with univariate comparisons were calculated for classical measures (mRT and *SD*) and ex-Gaussian measures (μ, σ, and τ). GROUP membership (aADHD or healthy controls) was defined as the between-subject factor and TIME BLOCK (3 time blocks of ~6–7 min) was specified as the within-subject factor. Significances and effect sizes (index η^2) were calculated for main effects (GROUP membership and TIME BLOCK) and their interaction [comparison of time-on-task (ToT) effects between adults with ADHD and healthy controls]. The Greenhouse–Geisser corrections were applied for repeated-measure MANOVAs if violation of sphericity was indicated by Mauchly's test of sphericity.

Moreover, complex sustained attention performance was compared between adults with ADHD and healthy control participants (factor GROUP membership) by applying MANCOVA with univariate comparisons separately for selective and divided attention with mRT, *SD*, omission, and commission errors being the dependent variables as well as AGE and IQ being the covariates. Furthermore, effect sizes were calculated (index η^2) for all comparisons. In order to asses differences in sustained selective and divided attention independent from differences in sustained alertness, we computed the same MANCOVA as described above with an additional covariate: If differences between adults with ADHD and healthy controls in selective and divided attention were due to differences in sustained alertness (i.e., increases in attentional lapses as indicated by changes of the parameter τ from time block 1 to time block 3 in the alertness task), corresponding differences between both groups should disappear after controlling for ToT-effects in sustained alertness.

Finally, we used non-parametric rank correlation coefficients in order to examine whether ToT-effects of the parameter τ in the alertness task are significantly correlated with the severity of self-rated ADHD symptoms. Given linear changes, ToT-effects were quantified by subtracting the mean of Block 1 from the mean of Block 3.

Given some unexpected findings, additional exploratory analysis was conducted in order to elucidate possible effects of comorbid disorders on performance of persons with ADHD in sustained attention tasks.

Results

The differences between aADHD-C and aADHD-I subgroups in classical and distributional measures of sustained alertness were non-significant for both main and interaction effects with TIME BLOCK (all $p > .532$, $\eta^2 < 0.029$). The same applies to classical measures of selective (all $p > .613$, $\eta^2 < 0.013$) and divided attention (all $p > .746$, $\eta^2 < 0.005$); therefore, data of both groups were pooled for further statistical analyses.

Sustained Alertness (Group Differences and ToT-Effects)

Non-significant group differences in classical measures (mRT and SD) with some evidence for a larger increase in the variability with time on task in adult attention deficit hyperactivity disorder. Two-factor analysis of covariance showed non-significant main effects for GROUP membership for both mRT [$F(1,44) < 0.01, p = .978, \eta^2 < 0.001$] and *SD* [$F(1,44) = 1.80, p = .186, \eta^2 = 0.039$]. Effects for the factor TIME BLOCK were also non-significant for mRT [$F(1.7,75.7) = 0.47, p = .601, \eta^2 = 0.010$] and *SD* [$F(2,88) = 0.99, p = .377, \eta^2 = 0.022$]. However, we found a significant linear influence of AGE on the *SD* of RT [$F(1,44) = 4.52, p = .039, \eta^2 = 0.093$]. IQ [$F(1,43) = 0.08, p = .781, \eta^2 = 0.002$] did not exert any significant influence ($p > .395$). These effects indicate non-significant differences in mRT and *SD* for adults with ADHD compared with healthy controls and also non-significant changes of mRT and *SD* with test duration (TOT effect) for the total group.

However, there was a significant interaction between TIME BLOCK and AGE [$F(1.7,75.7) = 3.42$, $p = .037$, $\eta^2 = 0.072$], indicating steeper increases in mRT in older participants independent of GROUP. The interaction between GROUP membership and TIME BLOCK did not reach significance [$F(1.7,75.7) = 0.71$, $p = .475$, $\eta^2 = 0.016$] for mRT. However, the interaction reached trend level with a small to medium effect size [$F(2,88) = 2.69$, $p = .074$, $\eta^2 = 0.058$; power = 0.733] for the *SD* of mRT, suggesting a somehow larger increase in variability for patients compared with healthy individuals.

Non-significant group differences in ex-Gaussian measures (μ, σ, and τ) with a larger increase in the number of slow responses (τ, significant) and evidence for an increase in general variability (σ, trend-level) with time on task only in adult attention deficit hyperactivity disorder. Two-factor analysis of covariance showed non-significant main effects for GROUP membership for μ [$F(1,44) < 0.01$, $p = .978$, $\eta^2 < 0.001$], σ [$F(1,44) = 0.98$, $p = .329$, $\eta^2 = 0.022$], and τ [$F(1,44) = 1.00$, $p = .323$, $\eta^2 = 0.022$]. The same applies to the main effects for TIME BLOCK for μ [$F(1.7,75.7) = 0.47$, $p = .601$, $\eta^2 = 0.010$], σ [$F(2,88) = 2.08$, $p = .131$, $\eta^2 = 0.045$], and τ [$F(2,88) = 0.36$, $p = .699$, $\eta^2 = 0.008$]. Furthermore, there was no significant linear influence of AGE (all $p > .103$) or IQ (all $p > 0.362$) on these dependent variables.

However, again there was a significant interaction between TIME BLOCK and AGE [$F(1.7,75.7) = 3.42$, $p = .037$, $\eta^2 = 0.072$], indicating steeper increases in μ in older participants independent of GROUP. A corresponding tendency was also found for the parameter σ [$F(2,88) = 2.79$, $p = .067$, $\eta^2 = 0.060$] reaching a medium effect size. The interaction between

GROUP membership and TIME BLOCK reached significance for τ [$F(2,88) = 4.08$, $p = .020$, $\eta^2 = 0.085$], indicating significantly larger increases in the number of slow responses in patients compared with healthy individuals. Corresponding effects did not reach significance for μ [$F(1.7,75.7) = 0.71$, $p = .475$, $\eta^2 = 0.016$]; however for the variable σ, the effect just failed significance [$F(2,88) = 3.02$, $p = .054$, $\eta^2 = 0.064$, power = 0.780] with a medium effect size.

Sustained Selective and Divided Attention (Group Differences)

Significant group differences without controlling for sustained alertness indicate slower mRT and more commission errors in selective attention as well as more omission errors in divided attention in adult persons with Attention Deficit Hyperactivity Disorder compared with healthy controls. Regarding selective attention, MANCOVA showed significant univariate main effects for GROUP membership for mRT [$F(1,43) = 5.16$, $p = .028$, $\eta^2 = 0.105$] and the number of commission errors [$F(1,43) = 6.04$, $p = .018$, $\eta^2 = 0.121$]. We did not find a significant linear influence of the covariates AGE or IQ ($p > .138$). Effects for the dependent variables *SD* [$F(1,43) = 0.96$, $p = .333$, $\eta^2 = 0.021$] or omission errors [$F(1,43) = 1.97$, $p = .168$, $\eta^2 = 0.043$] did not reach significance.

With regard to divided attention, we found significant effects of the factor GROUP only for the variable omission errors [$F(1,43) = 5.06$, $p = .030$, $\eta^2 = 0.105$]. Again, we did not find a significant linear influence of the covariates AGE or IQ ($p > .117$). There were no significant effects for mRT [$F(1,43) = 1.26$, $p = .268$, $\eta^2 = 0.028$], *SD* [$F(1,43) = 0.17$, $p = .680$, $\eta^2 = 0.004$], or commission errors [$F(1,43) = 1.95$, $p = .170$, $\eta^2 = 0.043$].

However, after controlling for sustained alertness significant differences between groups disappeared for divided and partly selective attention. With regard to selective attention, significant effects of the factor GROUP disappeared for the variable mRT [$F(1,43) = 2.34$, $p = .134$, $\eta^2 = 0.052$] after controlling for increases in variability in the alertness task. Although failing significance, GROUP effects still reached trend level with a medium effect size for the variable commission errors [$F(1,43) = 2.93$, $p = .094$, $\eta^2 = 0.064$, power = 0.780], indicating that while slower mRT in persons with ADHD compared with controls can be explained by basic deficits in sustaining alertness, differences in the number of commission errors may involve more than this. Generally, basic sustained alertness function (i.e., the covariate) exerted a significant linear influence on the dependent variables mRT [$F(1,43) = 4.29$, $p = .044$, $\eta^2 = 0.091$], omission [$F(1,43) = 8.11$, $p = .007$, $\eta^2 = 0.159$], and commission errors [$F(1,43) = 4.261$, $p = .045$, $\eta^2 = 0.090$].

With regard to divided attention, significant effects disappeared for the variable omission errors [$F(1,43) = 2.30$, $p = .137$, $\eta^2 = 0.052$], suggesting that significant differences between adults with ADHD and healthy controls can be explained by basic deficits in sustained alertness. In general, we found significant linear influences of the covariate on the variables mRT [$F(1,43) = 5.02$, $p = .030$, $\eta^2 = 0.107$] and omission errors [$F(1,43) = 4.12$, $p = .042$, $\eta^2 = 0.095$].

Correlational Analysis

Sustained alertness deficits and errors in complex attention tasks are significantly related to self-reported symptoms of attention deficit hyperactivity disorder. We found significant linear relationships between increases in the parameter τ (from Block 1 to Block 3) in the alertness task and self-rated childhood ADHD symptoms ($r = .39$; $p = .006$; $n = 48$) on the one hand and self-rated adulthood ADHD symptoms ($r = 0.37$; $p = .011$; $n = 48$) on the other hand (see Table 3). Only omission errors in the task of divided attention (WURS-K: $r = 0.39$; $p = .006$; ADHS-SB: $r = 0.37$; $p = .011$; $n = 80$) and commission errors in the task of selective attention (WURS-K: $r = 0.44$; $p = .002$; ADHS-SB: $r = 0.35$; $p = .015$; $n = 80$) showed comparable correlations.

Self-rated symptoms in childhood and adulthood were strongly related ($r = 0.74$; $p < .001$; $n = 48$). However, as both childhood and adulthood symptoms are necessary for a diagnosis of aADHD, we decided to indicate both.

Discussion

Contribution of Ex-Gaussian Variability Measures to the Understanding of Sustained Alertness Deficits in Adult Attention Deficit Hyperactivity Disorder

The present findings suggest that deficits in aADHD already affect basic aspects of intensity of attention and mainly involve an increase in the number of slow responses which develops across blocks, although a more general increase in variability across blocks cannot be excluded.

Using classical neuropsychological measures, our data suggest that persons with aADHD differ from healthy controls in a sustained alertness task with regard to an increasing *SD* in the course of the task. Using a similar sample, this is naturally in line with a

Table 3. Non-parametrical correlations of basic sustained alertness functions (ToT-effects of ex-Gaussian measures) and sustained complex attentional functions with attention deficit hyperactivity disorder symptoms

	ADHS-SB r, p (n)	WURS-K r, p (n)
ToT Alertness (ex-Gaussian)		
μ	0.04, $p = .777$ (48)	0.09, $p = .543$ (48)
σ	0.21, $p = .149$ (48)	0.20, $p = .175$ (48)
τ	0.37, $p = .011$ (48)*	0.39, $p = .006$ (48)**
Selective Attention		
mRT	0.30, $p = .036$ (48)*	0.28, $p = .057$ (48)
SD of mRT	0.24, $p = .100$ (48)	0.24, $p = .100$ (48)
Omissions	0.13, $p = .372$ (48)	0.04, $p = .807$ (48)
Commissions	0.35, $p = .015$ (48)*	0.44, $p = .002$ (48)**
Divided Attention		
mRT	0.18, $p = .218$ (47)	0.20, $p = .171$ (47)
SD of mRT	0.10, $p = .502$ (47)	0.09, $p = .562$ (47)
Omissions	0.34, $p = .019$ (47)*	0.37, $p = .011$ (47)
Commissions	0.22, $p = .132$ (47)	0.21, $p = .160$ (47)

Note: ADHS-SB = severity of ADHD symptoms in adulthood (self-report scale); WURS-K = severity of ADHD symptoms in childhood (self-report scale); ToT = time on task effects quantified as linear changes from Block 1 to Block 3; r = correlation coefficient; p = significance level; n = number of observations.
*Significant $\alpha < 0.05$.
**Significant $\alpha < 0.01$.

recent paper of our workgroup (Tucha et al., 2015). However, it should be considered that—presumably due to slightly reduced power of our study—this effect only reached trend level significance. An additional *post hoc* power analysis revealed that statistical power in our data ($p = .788$) was not sufficient to detect medium-sized effects ($\eta^2 = 0.058$).

More importantly, ex-Gaussian analyses allowed us to confirm and specify this finding in view of the fact that sustained alertness deficits in adults with ADHD involve a significantly steeper increase in infrequent slow responses, as indicated by the parameter τ with ToT. Given a somehow larger effect size for the ex-Gaussian measure τ ($\eta^2 = 0.085$), power was sufficient ($p = .896$). Although generally elevated values of the parameter τ in aADHD are a pattern which is consistently described in different speeded RT tasks targeting attention or executive function (Kofler et al., 2013), the present study is the first to describe ToT-effects of the parameter τ in a very basic sustained alertness task in aADHD. It is worth mentioning that increases in the ex-Gaussian parameter σ across blocks—which indicates general variability in contrast to isolated slow responses—did not differ significantly between groups in the present study. However, given the slightly reduced power in the present study, we cannot rule out that increases in both isolated slow responses (τ: $\eta^2 = 0.085$, power = 0.896) and general variability (σ: $\eta^2 = 0.064$, power = 0.780) with ToT may have contributed to the observed differences between persons with aADHD and healthy controls in the present study.

Our findings are compatible with recent research in children and adolescents with ADHD using vigilance tasks: studying a childhood sample, Tarantino and colleagues (2013) described a steeper increase in the component τ in ADHD across blocks, thereby indicating that overly long RTs progressively increased soon after the beginning of the task. Investigating a large adolescent sample, Gu and colleagues (2013) also found a steeper increase in the parameter τ in adolescents diagnosed with ADHD with ToT. However—apart from differences in age—these findings are difficult to compare with our data, as these studies also differ with regard to higher attentional demands (selectivity instead of intensity aspects) on the one hand and reduced activation levels required by the vigilance tasks in contrast to our sustained alertness task on the other hand.

Beyond a stronger deterioration of sustained alertness over time in adults with ADHD when compared with healthy controls, we did not find group differences in the parameter μ, σ, or τ in the present data. The lack of significant differences in combination with minimal to small effect sizes speaks against a general slowing, a general increase in variability, or generally elevated numbers of isolated slow responses in basic intensity aspects of attention as indicated by ex-Gaussian parameters (Marchetta et al., 2008; Tucha et al., 2015). This is in line with causal attentional lapse models predicting time-dependent deficits in basic attentional function mainly due to deficits in arousal, activation, effort, or intrusions of task-negative resting brain activity (Halperin & Schulz, 2006; Halperin, Trampush, Miller, Marks, & Newcorn, 2008; Russell et al., 2006; Sonuga-Barke & Castellanos, 2007). However, on the basis of the current data, we cannot distinguish between these different causal hypotheses. Future studies using adapted paradigms of basic attention may differentiate whether mental fatigue due to attentional resource depletion or rather mindlessness due to routinization might underlie the stronger decrement in aADHD (Langner, Willmes, Chatterjee, Eickhoff, & Sturm, 2010).

Relations of Sustained Alertness to More Complex Measures of Attention: Theoretical Implications

The present data lend support to recent theories suggesting an important role of basic cognitive deficits that contribute to poor performance on more complex (attentional) functions. Moreover, we found preliminary evidence for more specific deficits in higher-order cognitive functions independent of basic deficits (Karalunas & Huang-Pollock, 2013). However, given the rather small sample size in combination with effect sizes mostly in the medium range, these results should be interpreted with caution and call for replication by independent data.

Regarding complex selectivity aspects of attention, we found group differences in divided attention as indicated by a higher number of omission errors in adults with ADHD relative to controls. In line with our hypotheses, changes in the number of slow responses during basic sustained attention function across blocks were significantly related to mRT and the number of omission errors in divided attention. Moreover, after controlling for sustained attention (i.e., increases in the number of slow responses), the significant group differences in divided attention disappeared. We therefore suggest that omission errors in the divided attention task are related to more basic sustained attention dysfunction and—possibly—rather particularly slow responses (Cheyne et al., 2009; Epstein et al., 2010) than specific deficits in dividing attention. Regarding differences in selective attention, as indicated by slower mRT and higher numbers of commission errors in aADHD, similar conclusions were supported by the present data: again basic sustained attention function was significantly related to mRT, the number of omission and commission errors. While significant differences between adults with ADHD and healthy controls vanished for mRT after controlling for changes of sustained attention across time blocks, differences in the number of commission errors remained significant on a trend level. Consequently, one may speculate that increases in mRT in sustained selective attention in aADHD are related to an increase in infrequent slow responses in the course of the task, which over-proportionally influence mRT. We therefore suggest that differences in complex measures of divided attention and partly selective attention can be explained by differences in more basic sustained alertness function. This is in line with classical neuropsychological models of attention, conceptualizing alertness as a very basic function, influencing more complex attentional functioning (Sturm, 2006; Van Zomeren & Brouwer, 1994). Moreover, these findings are in line with recent formulations of attentional lapse models of ADHD, predicting very basic attentional deficits in (a)ADHD which may in turn influence more complex attentional functioning (Russell et al., 2006).

However, a significant trend suggests that differences in sustained alertness do not completely explain differences in commission errors between adults with ADHD and healthy controls. Given that commission errors indicate an erroneous responding to trials where participants were not required to respond, they are typically related to deficits in behavioral inhibition or interference control as described in the behavioral inhibition model postulated by Barkley (1997). However, as the present selective attention task does not create a prepotency toward responding like typical inhibitory tasks (e.g., GoNogo-Task by increasing the frequency of Go trials at the expense of Nogo trails) (Kaiser et al., 2012), we suggest that a failure of interference control is a more plausible candidate to explain differences in commission errors between adult persons with ADHD and healthy controls in the current task. This is also in line with recent findings of our workgroup, questioning a primary inhibitory deficit in aADHD (Gmehlin et al., 2014).

In a nutshell, our data provide preliminary evidence for basic sustained alertness deficits influencing more complex attentional function and more specific deficits in interference control in aADHD which may go beyond deficits in basic alertness. Consequently, we tentatively suggest that neither attentional lapse models nor behavioral inhibition models alone can explain our results. This is in line with evidence from children diagnosed with ADHD: Johnson and colleagues (Johnson, Kelly, et al., 2007; Johnson, Robertson, et al., 2007) suggested that both slow-frequency RT variability—which is closely related to the parameter τ (Feige et al., 2013)—and omission errors separate from commission errors. Moreover, the present data are congruent with a recent multicenter-multivariate familial analysis on a large sample of children with ADHD and control siblings: Kuntsi and colleagues suggested two key cognitive impairments phenotypically associated with ADHD symptoms, which can be captured by IIV of RT and commission errors (Kuntsi et al., 2010, 2014). From a developmental perspective, the subcortical deficit model (Halperin & Schulz, 2006; Halperin et al., 2008) gains additional relevance for aADHD examined in the present study: the model discriminates between subcortical dysfunction as indicated by increased IIV on the one hand and prefrontally mediated control dysfunctions as reflected by failure in interference control on the other hand. An additional developmental perspective predicts that subcortical dysfunction is linked to the etiology of ADHD and is therefore stable with age, whereas prefrontally mediated control functions are linked to the persistence or remission of ADHD symptoms during adolescence and adulthood. As we examined, an adult sample of participants diagnosed with ADHD, attentional lapses in sustained attention and deficits in interference control correspond to the predictions of the model. However, it is worth mentioning that there is also recent longitudinal and meta-analytic evidence contradicting this view (Coghill, Hayward, Rhodes, Grimmer, & Matthews, 2014; van Lieshout, Luman, Buitelaar, Rommelse, & Oosterlaan, 2013). Beyond the heterogeneity of neuropsychological profiles in ADHD, the use of different measures for attentional and executive functions may account for these deviant results.

Relations of Sustained Alertness to Self-Report Measures of Attention Deficit Hyperactivity Disorder

Significant correlations between objectively assessed sustained attention and self-reported ADHD symptoms suggest that changes in the number of slow responses as indicated by the parameter τ in a basic alertness task as well as omission and commission errors in more complex attentional tasks are related to a person's experience of ADHD symptoms in everyday life. Although our results need replication, this is of special importance because correlations between neuropsychological tests and self-report measures were found to be marginal (Fuermaier et al., 2014, 2015). There may be different explanations for the relationships found in the present data: With regard to correlations of the parameter τ and self-report measures, we suggest that both the use of ex-Gaussian measures and ToT-effects may have helped to uncover some variance shared by neuropsychological testing and self-reports of persons with ADHD and control participants. Regarding correlations of both ex-Gaussian and classical error measures with self-report measures, we point out that everyday situations demand attention over long and unbroken periods of time. For this reason, the use of sustained attention tasks may have assessed everyday demands more adequately when compared with shorter tasks. In particular, the use of sustained attention tasks with randomized ISI intervals (Lee et al., 2012) in the present study instead of frequently used vigilance tasks (e.g., CPT) may have contributed to higher activation levels and more frequent interactions which are typical for everyday situations. Summing up, we suggest that typical attentional lapses in aADHD are not restricted to short paradigms using monotone, low frequent stimuli but also appear in more ecologically valid tests and are related to self-report measures.

Clinical Implications

In line with the recent studies described above, the present findings underscore the importance of measures of IIV and—with regard to selectivity aspects of attention—omission and commission errors in order to differentiate between adults with ADHD and healthy controls. It is important to mention that effect sizes for ex-Gaussian measures of IIV in the alertness task were larger when compared with classical measures of IIV. Consequently—beyond extending the knowledge about the more basic principles of neuropsychological dysfunction in aADHD—ex-Gaussian parameters may provide additional potential to discriminate between both groups. However, this is worth investigating in future studies of larger samples employing logistic regressions and/or receiver operating characteristic curves. Although ADHD is a clinical diagnosis and neuropsychological data can only provide supplementary information, an overlap of self-reported ADHD symptoms in adults and objective sustained attention performance in neuropsychological tests may ease diagnosis due to additional objective information which can be integrated in the diagnostic process. Given high uncertainty in ADHD diagnosis, especially in adults based on clinical evaluation, this may be of importance (Thome et al., 2012).

Furthermore, our data suggest that neuropsychological assessment of attentional function in aADHD should involve sustained attention (i.e., ToT-effects) (Marchetta et al., 2008; Tucha et al., 2015). Regarding basic alertness functions, simple group differences did not sufficiently differentiate between adults diagnosed with ADHD and healthy controls in the present data independent of the neuropsychological variables used. With regard to the corresponding effect sizes, this does not seem to be due to our rather small sample size.

Although our data allow only rough temporal characteristics, a closer look at the course of the parameter τ across time blocks in the sustained alertness task suggests that differences between adults with ADHD and controls widen after the second block (i.e., after ~12 min). Consequently, sustained attention tasks should at least last for 15 min, although other factors like fixed ISI with infrequent stimuli as used in vigilance tasks may have an influence on the time course of deficits. Given that common neuropsychological test batteries (e.g., VTS, TAP, and CANTAB) (Schuhfried, 2000; Zimmermann & Fimm, 2002) do not provide ToT parameters or ex-Gaussian measures, a closer look on RT distributions with special focus on linear trends (corresponding to ToT-Effects) or infrequent slow responses (corresponding to τ) of intraindividual RT may be helpful.

With regard to more complex attentional function, we found evidence that deficits in divided attention can be explained by basic deficits in sustained attention. However, at least selective attention may provide additional information—possibly with regard to deficits in interference control—in aADHD. Looking at relationships with ADHD symptoms, both variability measures in basic sustained attention tasks and error measures in more complex selective attention tasks provide similar correlation coefficients. However, as neuropsychological assessment in ADHD can provide information about personal strength and weaknesses which is also relevant for therapy and prognosis of ADHD, we recommend a comprehensive attentional diagnostic process including measures of alertness, selective and divided attention, and at least one lengthy task with a focus on ToT effects.

There is recent evidence that infrequent slow responses as indicated by the parameter τ can be influenced by stimulant medication (Epstein et al., 2011). According to the present findings, stimulant medication may therefore reduce the impact of attentional lapses in lengthy tasks. This includes both rather basic and more complex attentional tasks requiring alertness or readiness to react as a precondition. However, deficits in interferences control may not be attenuated by stimulant medication. It is unclear whether ToT-effects of the parameter τ may be a good indicator for the response to medication, too. Given the face validity of sustained attention deficits, an examination with a special emphasis on ToT-effects may be a promising approach. With regard to a treatment of attentional dysfunction in ADHD, the present data tentatively suggest that behavioral therapy and cognitive remediation should target both attentional lapses and deficits in interference control. However, having high face validity, especially deficits in sustained attention may help to communicate attentional deficits more comprehensibly and therefore boost compliance and facilitate the transition to concrete behavioral or pharmacological interventions in aADHD.

Limitations, Conclusions, and Future Directions

One limitation of our study is that we did not estimate ex-Gaussian parameters for complex attentional function for the whole tasks or across different time blocks. As stable ex-Gaussian estimates require a considerable number of RTs, parameter estimates for selective and especially divided attention were not sufficiently stable, as indicated by significantly reduced model fitting parameters. This was mainly a problem for persons with ADHD, as an increased number of omission errors reduced the number of RT.

Regarding power and sample size a formal *post hoc* power analysis revealed that power to detect effects in the lower medium range may have not been totally sufficient in the present study ($p \approx .78$). Calculating additional analysis with our empirical effect sizes showed that a sample size with $n = 30$ would have provided a more adequate power of $p = .80$. It must be noted that in the present study a larger n increases power for some hypotheses (e.g., detecting group differences in sustained attention) but decreases likelihood of confirming other hypotheses (e.g., showing non-significant group differences in selective attention when taking into account effects of basic alertness). Consequently, a much larger sample size may have resulted in under-powered calculations on the effects of basic alertness on selective attention. In conclusion, we suggest that our results should be interpreted with caution and strongly recommend replication by independent data with an optimal sample size.

We have not corrected for an increase in the frequency of type one error due to multiple comparisons in the present study. However, we believe that this is acceptable for our approach which uses *a priori* hypotheses and effect sizes providing information independent from sample size. With regard to the large age range in the current study, it should be noted that the use of age as covariate controls for linear age-effects in the current data. Although older participants were marked by a more pronounced slowing of RTs in the alertness task across blocks as indicated by the variables mRT and μ (Carriere, Cheyne, Solman, & Smilek, 2010), these effects were independent from group-effects.

Another point worth discussing is diagnosis: We put a lot of diligence in our diagnostic process which involved a clinical psychiatric interview according to DSM-IV criteria for ADHD as devised by Barkley and Murphy (1998) and two standardized self-report rating scales designed to quantify current and retrospective ADHD symptoms. However, we did not consider information from family members or more objective measures like school certificates in order to corroborate reported symptoms, which clearly is a limitation. It is therefore possible that patients with adult ADHD may have over-reported symptoms, especially in self-report measures (Fuermaier et al., 2016). However, we did not compare groups with regard to symptom severity. Moreover, correlation analyses with self-report measures were not run for the group diagnosed with ADHS alone but calculated for the whole group.

Another confounding factor possibly limiting the interpretation of our data is comorbidity. We are aware that slightly more than 1/3 of our aADHD group had a concomitant diagnosis. However, although we cannot completely rule out possible influences of comorbid disorder in the present data, we did not find significant differences between adults with and without depressive symptoms and a corresponding medication in neuropsychological variables. As such comorbid disorders are common in ADHD, future studies may use a control group also matched for psychiatric diagnosis. It is worth mentioning that increased IIV can be found in different psychiatric and neurologic disorders (Tamm et al., 2012). Consequently, increased IIV may not be specific to ADHD but a more general marker for problems with attention or some kind of psychopathological process. Beyond other clinical conditions, future studies should also extend the present approach to more comprehensive subsets of memory and executive tasks highly dependent on intact attentional functioning in order to provide additional insight into cognitive mechanisms characterizing adult but also childhood ADHD symptoms.

Applying a well established and theoretically based attention paradigm, we found systematic differences in different aspects of attention in a sample of adults with ADHD without medication when compared with healthy controls matched for age, sex, and education. Basic deficits in sustained alertness (intensity aspect of attention) as indicated by an increase in infrequent slow responses (ex-Gaussian measure τ) across time blocks were related to more complex aspects of selective and divided attention. This is in line with the subcortical deficit model, predicting basic deficits in arousal—which in turn influence higher attentional functions—and deficits in interference control in ADHD. Moreover, significant correlations of sustained alertness deficits as indicated by the parameter τ and self-report measures underscore the importance of sustained attention deficits in everyday functioning in aADHD.

Conflict of Interest

The authors MW, SA, OT, LT, ABMF, and DG have contracts for development of neuropsychological diagnostic and training tools with Schuhfried GmbH. This does not alter our adherence to Archives of clinical Neuropsychology policies on sharing data and materials.

Acknowledgements

The authors would like to thank Annett Bergt for helping with data acquisition.

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