Electrophysiological studies on visual information processing in dyslexia and ADHD
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Chapter 3

Information processing differences and similarities in adults with dyslexia and adults with attention-deficit hyperactivity disorder during a Continuous Performance Test: A study of cortical potentials

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Abstract

Twenty male adults with ADHD, 16 dyslexic adults, 15 comorbid adults, and 16 normal controls were compared on performance and underlying brain responses, during a cued Continuous Performance Test (O-X CPT), with the aim of discovering features of information processing differentiating between the groups. The study evaluated both cue- and target-related processes by analysing performance measures (errors, reaction time, and variability of reaction time), and event-related potentials (ERPs). Cue-related ERP components included the N2, P3, contingent negative variation (CNV) consisting of the CNV1, related to cue orienting, and the CNV2, related to response preparation. For targets, a distinction was made between response-related (Go), and inhibitory (Nogo) processing. Target-related components included the N2 and P3.

Performance deficits were found only for the ADHD group, who demonstrated a faster decline in response speed with time-on-task and greater overall within-subject variability. ERP differences between groups included a smaller CNV1 in dyslexics compared to ADHD and also with comorbid participants, who in turn showed a reduced cue P3 in contrast with dyslexics. Compared to controls, inhibitory control was reduced in all clinical groups, as demonstrated by a smaller P3 in the Nogo condition compared to the Go condition.

The results suggest that the groups differed in various stages of information processing, with dyslexics showing reduced orienting to the cue, while in comorbid participants target expectation was diminished. In addition, inhibitory control may not exclusively be deficient in ADHD. The comorbid group showed an inconsistent profile compared to participants with dyslexia and ADHD.
Information Processing in Adults with Dyslexia and ADHD

Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is estimated to be one of the most prevalent child psychiatric disorders, with incidences as high as 5% (American Psychological Association [APA], 2000). Considerable advancement has been made towards our understanding of ADHD in children. However, although approximately half of the children continue to show symptoms of ADHD, i.e. inattention, impulsivity and hyperactivity, in adulthood (Kessler, Adler, Barkley, Biederman, Conners et al., 2006), only a modest number of studies have been conducted on adults with ADHD, and treatment is largely based on knowledge gained from research on children (Hervey, Epstein, & Curry, 2004). Besides the neurocognitive deficits, psychosocial consequences for adults with ADHD can be harrowing, as rates of incarceration and substance abuse are high in these adults (Collins & White, 2002).

Another common developmental disorder, dyslexia, manifests itself in school-age children who are unable to achieve age-appropriate reading skills, and continues to hinder many throughout adolescence and adulthood, hampering education and career development. Moreover, many children and adults with dyslexia suffer from co-occurring ADHD. The co-occurrence of ADHD and dyslexia, estimated at 25 - 40% (Samuelsson, Lundberg, & Herkner, 2004), compels further investigation into the cognitive effects of the co-occurrence.

Research on ADHD has largely discounted dyslexia as a confounding factor when investigating attention. However, there is evidence to suggest that the deficits in dyslexia extend beyond reading-related skills alone, and that attentional processing may be affected in dyslexics too (Facoetti, Zorzi, Cestnick, Lorusso, Molteni et al., 2006; Valdois, Bosse, & Tainturier, 2004). In particular, dyslexics have demonstrated difficulties with shifting spatial attention (Facoetti, Paganoni, Turatto, Marzola, Mascetti et al., 2000), rapid serial visual processing (Hari & Renvall, 2001), and visual search (Iles, Walsh, & Richardson, 2000), possibly due to deficits in the early, perceptual stages of visual information processing (Eden, Van Meter, Rumsey, & Zeffiro, 1996) while other investigators have reported deficiencies in inhibitory processes (Purvis & Tannock, 2000; Van der Schoot, Licht, Horsley, & Sergeant, 2000; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005), occurring at a later stage of information processing.

Continuous Performance Tests (CPTs) are widely used cognitive tasks that are sensitive to input-related perceptual processes, central cognitive attention-
controlled processes and output-related processes of response selection and execution (for an overview see Riccio, Reynolds, Lowe, & Moore, 2002). Therefore, the tasks can be useful to identify distinguishing features of clinical groups such as dyslexia and ADHD. To our knowledge, CPTs have been applied only a few times before with this objective (McGee Clark, & Symons, 2000; Purvis & Tannock, 2000; Willcutt et al., 2005). McGee and colleagues (2000) found that children with ADHD did not score worse on the Conners’ CPT than clinical controls, who were children referred for assessment to an outpatient child mental health clinic. Moreover, although the test discerned children with ADHD from typically developing controls, many dyslexic children also performed similarly to children with ADHD, thus using the CPT was likely to lead to false positives. Koelega (1995) had previously described the lack of specificity of the performance measures of CPTs to be a concern when attempting differential diagnosis. Also, Purvis and Tannock (2000) found inhibitory control to be a problem in children with dyslexia as well as children with ADHD. Yet, response variability was greater in children with ADHD only, suggesting that inhibitory control may not be the core deficit in ADHD, and moreover may not be specific to the disorder. However, in these studies only performance measures were used, which are rather insensitive to the activation of distinct processing stages. Investigating electrocortical event-related potentials (ERPs) to directly compare individuals with dyslexia and ADHD can be helpful in this respect, as the technique permits insight into covert information processing during the execution of a task.

The present study adopted a CPT variant, the O-X CPT, which requires participants to respond to the target “X” but only when it follows a cue letter, “O”, which acts as a warning stimulus. The use of this cued CPT allows a distinction between visual orienting to cues, visual attention processing related to the target and preparatory processes related to response execution. Also, as the cued CPT encompasses Go and Nogo trials, inhibitory control can be investigated on the Nogo trials on which a response has to be inhibited. Furthermore, as performance on attention tasks such as the CPT requires prolonged focussing of attention, subjects are expected to experience a decrease in vigilance. Gradual changes in performance and electrocortical activity, resulting from this vigilance decline, can be examined as a function of time-on-task (Lorist, Boksem, & Ridderinkhof, 2005).

The task manipulations are expected to elicit a number of ERP components that are electrophysiological manifestations of cue and target processing. In
response to cues, a negative deflection, the N2, is elicited. This frontally located component is considered to be a correlate of selective attention and stimulus identification (for a review see Patel & Az zam, 2005). The subsequent parietal positivity to cues, the P3, is thought to be related to processing of relevant or motivationally significant stimuli (Donchin & Coles, 1988; Carrillo-de-la-Peña & Cadaveira, 2000; Tekok-Kilic, Shucard, & Shucard, 2001). Also, this cue-related component has been related to expectation of the subsequent stimulus (Bekker, Kenemans, & Verbaten, 2004; Jonkman, 2006). The posterior attention system, which receives norepinephrine projections from the locus coeruleus (Arnsten, Steere, & Hunt, 1996; Aston-Jones, Chiang, & Alexinsky, 1991; Bouret & Sara, 2005; Posner, 1993), is assumed to play a role in the appearance of this component.

Moreover, in a dual stimulus paradigm such as the cued CPT, a negativity develops between the cue (S1) and the imperative stimulus (S2). This slow wave, the Contingent Negative Variation (CNV), consists of two consecutive parts related to distinct processes: an early, more fronto-centrally dominant wave reflecting orienting to the cue (CNV1), and a later, more centro-parietally dominant wave reflecting motor preparation and anticipation, called the CNV2 (Van Boxtel & Böcker, 2004).

In response to the imperative stimulus (S2), again an N2-P3 complex is generated, whereby a distinction is made between Go trials (O-X) and Nogo trials (O-not-X). The Go stimulus elicits a P3 for which the amplitude is maximal at parietal scalp sites, and has been associated with conscious controlled stimulus processing, and attention allocation (Hruby & Marsalek, 2003; Kok, 2001; Polich & Kok, 1995). On the other hand, on Nogo trials when a response has to be inhibited, the P3 was shown to have a more enhanced fronto-central maximum, and a longer latency than to Go stimuli at the same location (Bokura, Yamaguchi, Matsubara, & Kobayashi, 2002; Eimer, 1993; Fallgatter, Brandeis, & Strik, 1997; Tekok-Kilic et al., 2001). This so-called Nogo anteriorisation is assumed to be mediated by the anterior cingulate cortex (ACC) (Fallgatter, Bartsch, & Herrmann, 2002; Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005). The frontal Nogo N2 and P3 have both been related to inhibitory control (De Jong, Coles, Logan, & Gratton, 1990; Jonkman, Lansbergen, & Stauder, 2003; Smith, Johnstone, & Barry, 2006).

In previous CPT studies, smaller parietal P3s have been found in children with ADHD to cues (Banaschewski, Brandeis, Heinrich, Albrecht, Brunner et al., 2004; Brandeis, Van Leeuwen, Steger, Imhof, & Steinhausen, 2002; Van Leeuwen,
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Steinhausen, Overtoom, Pascual-Marqui, Van ‘t Klooster, 1998), as well as to targets (Overtoom, Verbaten, Kemner, Kenemans, Van Engeland et al., 1998; Strandburg, Marsh, Brown, Asarnow, Higa et al., 1996). The results concerning anticipation of the target stimulus and preparation of a response are not so clear-cut. Some have found these processes to be weaker in children with ADHD, as indicated by a reduced CNV2 (Banaschewski, Brandeis, Heinrich, Albrecht, Brunner et al., 2003; Banaschewski, Yordanova, Kolev, Heinrich, Albrecht et al., 2008; Perchet, Revol, Fourneret, Mauguière, Garcia-Larrea et al., 2001), while others reported no group differences for the CNV2 (Jonkman, 2006; Van Leeuwen et al., 1998), or even a larger CNV2 in children with ADHD (Henninghausen, Schulte-Körne, Warnke, & Remschmidt, 2000). In some studies evidence was found for a smaller CNV1 in children with ADHD, suggesting reduced orienting to the cue, in addition to the smaller CNV2 (Hennighausen et al., 2000; Sartory, Heine, Müller, & Elvermann-Hallner, 2002; Van Leeuwen et al., 1998). Also, research on frontal Nogo components in ADHD has been inconsistent, as some have found evidence for reduced central Nogo activity (N2 and P3) in ADHD-affected children (Brandeis et al., 2002) and reduced fronto-central Nogo P3 in adults (Fallgatter, Ehls, Rösler, Strik, Blocher et al., 2005; Fallgatter, Ehls, Seifert, Strik, Scheuerpflug et al., 2004), whereas others discovered no group differences in frontal Nogo N2 (Fallgatter et al., 2004; Wiersema, van der Meere, Roeyers, Van Coster, & Baeyens, 2006), and an increased frontal Nogo P3 in children with ADHD (Banaschewski et al., 2004).

The only ERP study to investigate attentional processing abilities in dyslexics using a cued CPT was conducted on adolescents (Taroyan, Nicolson, & Fawcett, 2007). Although no behavioural differences were reported, dyslexics showed a smaller Nogo P3 compared to controls.

The present study aimed at identifying differences and similarities in information processing characteristics between ADHD and dyslexia. To this end four groups: male adults with dyslexia, those with ADHD, adults with both disorders and normal controls were compared. By using a cued CPT, processes related to cue-induced orienting and response preparation, as well as attention-controlled efficiency of target processing, were investigated. Perceptual, attentional and inhibitory/response processes were investigated through the use of ERP components that are associated with input-related, central cognitive, and output-related processes.
Information Processing in Adults with Dyslexia and ADHD

In line with previous research, participants with dyslexia were expected to show deviances in early cue-related information processing (Dhar, Been, Minderaa, & Althaus, 2008), and, in addition, possibly inhibitory processes (Purvis & Tannock, 2000; Van der Schoot et al., 2000; Willcutt et al., 2005), whereas participants with ADHD were expected to show problems with aspects of information processing that require central cognitive control, or allocation of energetic resources (van der Meere, 2005), as well as inhibitory processes (Fischer, Barkley, Smallish, & Fletcher, 2005). Only males were asked to participate in the study, as there is evidence for distinct mechanisms linked to electrophysiological arousal in female and male adults with ADHD (Hermens, Williams, Lazzaro, Whitmont, Melkonian, et al., 2004).

Materials and methods

Participants
Twenty male participants with dyslexia (mean age = 34.8 years; SD = 8.7), 16 males with ADHD (mean age = 33.1 years; SD = 8.5), 15 male participants with both dyslexia and ADHD (mean age = 36.1 years; SD = 8.3) and 16 male controls (mean age = 33.7 years; SD = 8.9) took part in the study. The age range of participants was 19 to 48 years. Participants were matched for age and handedness. Handedness was determined by means of a checklist (Van Strien, 1982). Exclusion criteria for all participants were: history of brain-related illness, diagnosed neurological disorder other than dyslexia or ADHD, and estimated IQ below 80. Intelligence was assessed with an abbreviated version of the Groninger Intelligentie Test (GIT) (Luteijn & Van der Ploeg, 1983). Mean IQ for dyslexia was 109.7 (SD 11.4), for the ADHD group 110.3 (SD 9.6), for the comorbid group 111.0 (SD 10.4), and for controls 116.4 (SD 9.4). No statistically-significant difference in IQ was found (p = .23). All participants had normal or corrected-to-normal vision. Recruitment took place through a newspaper advertisement and patient support groups. Furthermore, a number of dyslexic and control participants were recruited from the Dutch Longitudinal Study of Dyslexia.

All the participants with ADHD had sought help from mental health services and consequently had first of all been formally diagnosed according to DSM-IV-TR criteria for ADHD by clinical experts. To include participants in the ADHD or comorbid group, such a diagnosis was necessary. The participants were
then further tested for symptoms of ADHD in childhood and adulthood using a self-report scale based on the DSM-IV-TR criteria (Kooij, Buitelaar, Van den Oord, Furer, Rijnders et al., 2004), which was to be completed by the participant himself. This form encompassed of 9 features of inattentive and impulsive/hyperactive behaviour concerning adulthood and 9 features concerning childhood behaviour. The participants were requested to rate the frequency of each behaviour as it had occurred in the past 6 months on a 4-point scale (never, sometimes, often or very often). For the childhood items participants had to rate their behaviour from 0 to 12 years. To be included in the study, participants with ADHD had to rate 5 out of 9 adulthood features on either the inattention or the hyperactivity/impulsivity scale as occurring often or very often. So a score of 4 positive inattentive and 4 positive hyperactive features would not qualify the participant for inclusion in the ADHD group but a score of 5 inattentive and 4 hyperactive/impulsive would. In addition participants had to rate at least 6 out of 9 childhood features describing either inattentive or hyperactive/impulsive behaviour as occurring often or very often. Again at least on one of the 2 scales (inattention or hyperactivity/impulsivity), they had to have at least 6 positive items.

A retrospective rating could not be obtained from three participants. However, they were included in the study as they had received a clinical diagnosis, and in addition scored above the critical 97th percentile on the ADHD DSM-scale of the Adult Self Report (ASR) (Achenbach & Rescorla, 2003). The ADHD scale of the ASR was not used as an inclusion criterion, but was used to gain additional information on potential behavioural problems in the clinical groups and to exclude participants with behavioural problems from the control group.

All participants were screened for the presence of dyslexia. To this end, two standardised Dutch reading tests were used: the EMT (Eén Minuut Test: One Minute Test), which is a single word-reading test (Brus & Voeten, 1972), and the KLEPEL, a pseudoword reading test (Van den Bos, Spelberg, Scheepstra, & De Vries, 1994). For inclusion in the dyslexic group one of three criteria had to be met: 1) EMT or KLEPEL reading score had to be below the 11th percentile. 2) Both had to fall within the lowest quartile. 3) Percentile score of the verbal comprehension minus percentile score for pseudoword reading had to be greater or equal to 60. This criterion is based on a discrepancy between reading achievement and IQ which is important for discerning readers who are average on the reading tests but poorer than would be expected based on intelligence (Scarborough, 1989; APA, 2000). Verbal comprehension was measured using a subtest of the Wechsler
Information Processing in Adults with Dyslexia and ADHD

Adults Intelligence Scale-III (WAIS-III). The dyslexic adults who were recruited through the Dutch Longitudinal Study of Dyslexia had been previously screened for dyslexia and were consequently not screened again. For inclusion in the comorbid group, participants had to meet criteria for both ADHD and dyslexia.

Adults were included in the control group, provided there were no reading problems on the dyslexia screening tests or behavioural problems. All scores of controls fell within the normal range of the ASR and ADHD rating scale.

The study protocol was approved by a medical ethics committee. All participants were required to give informed consent before the experiment began.

Tasks and stimuli
Participants were seated approximately 120 cm from a computer monitor, on which the following letters were serially presented in a pseudo-random order: B, C, D, E, F, G, H, I, J, L, O, X. The participants were instructed to respond as quickly as possible with their preferred hand by pressing the space bar after the letter X, but only when it was preceded by an O. This O-X target sequence appeared 80 times. All other letters were to be ignored. On 80 trials a random letter other than an X followed the O (O-not-X). On 80 trials the letter X was preceded by a random letter other than an O (NogoX). In total 640 letters were presented with an inter-stimulus interval (ISI) of 1500 ms. All stimuli were presented centrally for a duration of 150 ms between two vertical bars that remained visible throughout the task, which lasted for 19 minutes. Fig. 1 depicts the timing of stimulus presentation. The experiment took place in a sound-attenuated chamber under low illumination. The experimenter was seated in the adjacent room and was able to monitor the participant throughout the experiment. The task was preceded by a practice session and started once the participants confirmed they understood the task. The described task was part of a larger study investigating a variety of information processing capacities in participants with dyslexia and ADHD. Only the task relevant to the present study will be reported in this paper. Presentation of the tasks was balanced in the same way for each group to control for effects of practice and fatigue.
Overt performance
Performance measures were response accuracy, mean reaction time (RT) to targets, and within-subjects variability of RT (SD-RT). Mean RT was calculated from correct trials only. Responses to the target sequence before 100 ms or 1500 ms after target offset were considered invalid. Three types of errors were discerned: errors of omission, where participants failed to respond to the target X when cued by the letter O, commission errors where participants reacted to a letter following an O other than an X, and commission errors where participants responded to the letter X preceded by a letter other than an O.

Electrophysiological recording and analysis
Continuous electroencephalogram (EEG) was sampled at 500 Hz with a SynAmps model 5083 amplifier (Neuroscan) with an input impedance of 10 MΩ, from 72 Ag/AgCl-sintered leads, embedded in an elastic electrode cap (EASYCAP GmbH). Linked reference electrodes were attached to the mastoids. A ground electrode was placed on the right cheekbone. Electrodes were arranged according to the international 10/20 system (Jasper, 1958). Horizontal electro-oculogram (EOG) was recorded from the outer canthus of each eye. Vertical EOG was recorded from infraorbital and supraorbital electrodes placed in line with the pupil of the left eye. Electrodes were filled with conductive gel using a syringe without a needle. Cotton buds were used to ensure that the impedance was maintained below 15 kΩ, which

Figure 1. The diagram depicts the timeline in ms for the presentation of cue and target stimuli. An example is given of an O-X trial.
was sufficiently low for accurate measurement, due to the high input impedance (Ferree, Luu, Russell, & Tucker, 2001)

Offline analyses were conducted separately for the cue-locked and target-locked averages. A suitable filter setting for the cue-locked averages was chosen to ensure detection of the low frequency CNV. To this end a 30 Hz high cut-off filter with a time constant of 5 s and a notch filter (50 Hz) were applied to the raw data. The Gratton and Coles algorithm (Gratton, Coles, & Donchin, 1983) was used to correct ocular artefacts. Subsequently, the EEG was divided into four equally-sized segments corresponding with four blocks of the whole task. Then, for each block, two further segmentations were performed, one for cue-related, and one for target-related ERPs. For the cue ERP, an interval from 200 ms before to 1650 ms after cue onset was segmented. Prior to averaging, segments containing activity above 100 μV or below -100 μV were rejected. Averages, based on correct responses only, were then computed with a baseline of 200 ms preceding cue onset. Grand averages were used to determine the windows for peak/area detection.

In the cue to target interval, an N2 with a fronto-central maximum was discerned, followed by a parietal P3, and a yet later occurring CNV. Peak amplitudes and latencies were calculated from 250 ms to 350 ms for the N2 at Fcz and from 300 ms to 500 ms for the P3 at Pz. For longer-lasting potentials mean area (μV x ms) was calculated for the early and late CNV (CNV 1 and CNV 2). The fronto-central CNV 1 was determined from 700 ms to 900 ms after cue onset. For the central-parietal CNV 2, an interval was taken from -100 ms to 0 ms before target onset. As reference for each of the cue-related components, a no cue component was calculated (in the corresponding interval) locked to stimuli that did not function as a cue. The comparison of the cue versus no cue condition provides a measure of the sensitivity to the cue (Bekker et al., 2004). Cue and no cue components were based on at least 100 trials.

For analysis of the target-locked components, again a high cut-off filter of 30 Hz and a notch filter of 50 Hz were used, but now with a time constant of 0.3 s. Separate averages were calculated for Go trials (O-X) and for Nogo trials (O-not-X) from 1850 ms before target onset to 1150 ms after target onset, encompassing an interval of 200 ms before S1 onset for baseline correction. After artefact rejection and averaging, a smaller target interval of 0 ms to 1150 ms from target onset was segmented. Again, only correct responses were used to calculate averages. For each condition, maximum peak amplitudes and their latencies were detected for the N2 from 220 ms to 340 ms at Fcz, and for the P3 from 300 ms to
450 ms at Pz (Go) and Fcz (Nogo). Go and Nogo components were based on at least 70 trials.

Statistical analyses
A repeated measures design was used with the between-subjects factor group consisting of four levels (control, dyslexic, ADHD, and comorbid). For the performance measures, dependent variables were accuracy, mean RT, and SD-RT. The three types of errors: O-not-X and Not-O-X commission errors, and omission errors, were analysed separately. For ERP measures, these were peak amplitudes and latencies of cue-locked components (N2 and P3), and target-locked components (N2 and P3), and mean area of CNV1 and CNV2. For the performance measures, the within-subjects factor ‘block’ was applied, consisting of four levels (blocks 1 to 4. This factor was used to investigate the time-on-task effect. For the cue-locked components, two within-subject factors were used: ‘block’, again with four levels, and ‘electrode’. As a reference for the cue manipulation, analyses of the cue-related components were adjusted for the no cue condition by including the no cue component as a covariate in the design. For the target-locked components, the within-subject factors were ‘block’ (four levels), ‘electrode’, and ‘condition’ consisting of two levels (Go and Nogo), which was used to investigate inhibitory control.

Bivariate correlations were calculated between symptoms, performance and ERP components in order to gauge the significance of the ERP components for task performance.

All hypotheses were tested against a .05 significance level. In cases of non-sphericity, degrees of freedom were corrected with the Greenhouse-Geisser epsilon coefficient. Non-corrected degrees of freedom are presented in the results section.

Results

Symptom scores
Means, SDs, and ranges of the EMT, KLEPEL, ADHD self report scale and ASR test scores are presented in Table 1. As expected, dyslexics and comorbids were poorer on the EMT and KLEPEL. ADHD and comorbid participants scored higher than controls and dyslexics on measures of internalising and externalising.
Symptom scores

<table>
<thead>
<tr>
<th></th>
<th>Con Mean (SD)</th>
<th>Dysl Mean (SD)</th>
<th>ADHD Mean (SD)</th>
<th>Com Mean (SD)</th>
<th>Contrasts</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMT percentile</td>
<td>72.8 (29.0)</td>
<td>20.3 (24.0)</td>
<td>59.4 (23.2)</td>
<td>21.2 (22.5)</td>
<td>* con = ADH &lt; dysl = com</td>
</tr>
<tr>
<td>score</td>
<td>(5 – 100)</td>
<td>(5 – 100)</td>
<td>(15 - 100)</td>
<td>(5 - 70)</td>
<td></td>
</tr>
<tr>
<td>KLEPEL percentile</td>
<td>68.8 (30.7)</td>
<td>18.8 (13.6)</td>
<td>65.6 (20.6)</td>
<td>14.1 (11.7)</td>
<td>* con = ADH &lt; dysl = com</td>
</tr>
<tr>
<td>score</td>
<td>(15 - 100)</td>
<td>(5 - 50)</td>
<td>(40-100)</td>
<td>(5 - 40)</td>
<td></td>
</tr>
<tr>
<td>ADHD self-report</td>
<td>2.2 (2.9)</td>
<td>7.3 (4.3)</td>
<td>26.5 (4.8)</td>
<td>24.8 (7.7)</td>
<td>* con &lt; dysl &lt; ADH = com</td>
</tr>
<tr>
<td>mean total score</td>
<td>(0 - 10)</td>
<td>(2 - 17)</td>
<td>(18 - 36)</td>
<td>(9 - 37)</td>
<td></td>
</tr>
<tr>
<td>(t-score)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASR ADHD problems</td>
<td>53.5 (3.8)</td>
<td>58.4 (6.1)</td>
<td>71.7 (6.7)</td>
<td>73.9 (11.1)</td>
<td>* con = dysl &lt; ADH = com</td>
</tr>
<tr>
<td>scale</td>
<td>(50 - 63)</td>
<td>(51 - 69)</td>
<td>(64 - 87)</td>
<td>(53 - 93)</td>
<td></td>
</tr>
<tr>
<td>ASR internalising</td>
<td>48.6 (10.5)</td>
<td>55.7 (10.5)</td>
<td>67.6 (7.7)</td>
<td>64.3 (13.3)</td>
<td>* con = dysl &lt; ADH = com</td>
</tr>
<tr>
<td></td>
<td>(30 - 67)</td>
<td>(32 - 72)</td>
<td>(57 - 82)</td>
<td>(32 - 83)</td>
<td></td>
</tr>
<tr>
<td>ASR externalising</td>
<td>48.8 (7.1)</td>
<td>54.5 (10.7)</td>
<td>60.7 (7.4)</td>
<td>68.4 (9.4)</td>
<td>* con = dysl &lt; ADH = com</td>
</tr>
<tr>
<td></td>
<td>(30 - 59)</td>
<td>(32 - 71)</td>
<td>(44 - 71)</td>
<td>(55 - 87)</td>
<td></td>
</tr>
</tbody>
</table>

Notes. Control: con; dyslexia: dysl; comorbid: com; attention-deficit hyperactivity disorder: ADHD. * = p < .05.

Table 1. Means and SDs are presented of the EMT, KLEPEL, and the ASR scales: ADHD problems, internalising, and externalising, with score ranges between brackets.

Performance data

Accuracy

As plotted in Fig. 2a, overall, accuracy decreased with time-on-task, as indicated by a main block effect [F(3,61) = 5.79, p < .002]. Although the figure suggests that the ADHD group showed a steeper decline in accuracy with time-on-task, there was no significant interaction between group and block. Errors of commission were infrequent in all participants. Therefore too few were made to observe group differences. Table 2 shows the means, SDs and ranges for the three types of errors: O-not-X and Not-O-X commission errors, and omission errors.
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Table 2. Means, SDs and ranges for the three types of errors are presented.
Figure 2. For each group, percentage of correct target responses (a), mean RT (b), and SD-RT(c) are shown per block.
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RT and SD-RT

Figs. 2b and 2c depict RT and SD-RT per block for all four groups. RT deteriorated with time-on-task, resulting in a main effect for block, \[ F(3,61) = 3.70, \ p < .017 \]. This increase appeared to differ between groups, as reflected by a significant block x group interaction, \[ F(3,63) = 3.63, \ p < .048 \]. Fig. 2b suggests a steeper increase in RT with time-on-task for mainly ADHD participants. When considering all four blocks no significant differences were found. Yet, when taking the difference between block 4 and 1, we could demonstrate a significantly greater time-on-task effect for ADHD in comparison to controls (\( p = .014 \)).

As depicted in Fig. 2c, there was an overall block effect for SD-RT \[ F(3,61) = 6.72, \ p < .025 \]. No interaction of block was found with group, yet there was a significant main effect for group \[ F(1,63) = 2.93, \ p = .040 \], demonstrating a larger overall variability in participants with ADHD. Post-hoc comparisons revealed a significantly greater variability in the ADHD group compared to controls (\( p = .005 \)).

Electrophysiological measures

Cue-locked components

N2. When, the no cue condition was controlled for by entering the no cue N2 at Fcz as a covariate in the analyses of N2, no block or group differences in latency were found. Yet, for the N2 amplitude at Fcz, there was an effect of time-on-task (block) \[ F(3,58) = 4.49, \ p < .008 \]. No significant main effect was found for group, nor was there an interaction of group by block.

P3. For cue P3 latency, again adjusting for the no cue condition by entering the no cue P3 latency at Pz as a covariate, there was no effect of time-on-task. Yet, a significant main effect for group was found \[ F(3,61) = 2.86, \ p < .045 \]. Significant planned contrasts between the control and comorbid group (\( p = .018 \)) and dyslexic and comorbid group (\( p = .018 \)), revealed a later onset of the P3 in controls and dyslexics compared to comorbid participants.

For the P3 amplitude, with adjustment for the no cue condition, no block effect was found. Yet, a main group effect was found at Pz \[ F(3,60) = 2.75, \ p = .05 \]. Planned comparisons revealed a significantly smaller P3 in comorbids compared to dyslexics (\( p = .009 \)), suggesting a reduced P3 in comorbid participants. Furthermore, trend to significant differences were found between
comorbid and controls (p = .087), and dyslexics and ADHD participants (p = .064). No block by group interaction was found.

**CNV1 area.** The following electrodes were entered in the design: Fcz, Fc1, Fc2, Fc3, and Fc4. After covarying for the no cue CNV1 (700-900 ms) measured at Fcz, significant main effects were found for block [F(3,58) = 4.58, p = .006], and for electrode [F(4,58) = 18.76, p < .001], indicating that the negativity decreased with time on task and differed for the electrodes. Yet, no group by block effect were present. Analysis of the electrodes separately resulted in a main effect for group at only Fc3 [F(3,61) = 3.05, p = .035]. Planned comparisons resulted in differences between participants with dyslexia and comorbid participants (p = .006) as well as ADHD participants (p = .037), suggesting a less negative CNV1 in dyslexic adults.

**CNV2 area.** A main effect was found for block [F(3,58) = 8.44, p < .001], demonstrating a reduction in CNV2 negativity, measured at Cz. No significant group differences were present.

Fig. 3 represents the cue-locked grand averages plotted against the no cue grand averages, for each group separately. Means and SDs of maximum peak amplitudes (N2, P3) and area (CNV1, CNV2) in each condition (cue/no cue, Go/Nogo) are presented for the groups in Table 3.
Table 3. Means and SDs are represented of ERP component amplitudes (μV) in the cue, no cue, Go and Nogo conditions for each group.

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Dyslexia</th>
<th>ADHD</th>
<th>Comorbid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cue Mean (SD)</td>
<td>No cue Mean (SD)</td>
<td>Cue Mean (SD)</td>
<td>No cue Mean (SD)</td>
</tr>
<tr>
<td>N2 (250 – 350 ms)</td>
<td>-3.2 (4.5)</td>
<td>-2.3 (4)</td>
<td>-3.7 (4.6)</td>
<td>-2.9 (3.6)</td>
</tr>
<tr>
<td>P3 (300 – 500 ms)</td>
<td>7.5 (2.5)</td>
<td>3.7 (2.2)</td>
<td>8.6 (2.6)</td>
<td>4.5 (1.8)</td>
</tr>
<tr>
<td>CNV1 (700 – 900 ms)</td>
<td>-367 (487)</td>
<td>318 (274)</td>
<td>-122 (371)</td>
<td>386 (352)</td>
</tr>
<tr>
<td>CNV2 (1550 – 1650 ms)</td>
<td>-786 (504)</td>
<td>-20 (75)</td>
<td>-483 (399)</td>
<td>27 (109)</td>
</tr>
<tr>
<td></td>
<td>Go Mean (SD)</td>
<td>Nogo Mean (SD)</td>
<td>Go Mean (SD)</td>
<td>Nogo Mean (SD)</td>
</tr>
<tr>
<td>N2 (220 – 340 ms)</td>
<td>0.4 (3.2)</td>
<td>-1.7 (3.6)</td>
<td>-1.3 (4.2)</td>
<td>-3.2 (3.2)</td>
</tr>
<tr>
<td>P3 (300 – 450 ms)</td>
<td>13 (3.7)</td>
<td>14.5 (5.0)</td>
<td>11.7 (4.2)</td>
<td>9.4 (3.6)</td>
</tr>
</tbody>
</table>
Figure 3. Cue-locked grand averages for Fcz, Fc3, Cz, and Pz.
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Target-locked components

N2. For N2 latency at Fcz, no effects of the task manipulations block and condition were found. Neither were there any interactions of the task manipulations with group.

For amplitude, a significant effect of block \( [F(3,60) = 3.43, p = .019] \), and condition \( [F(1,62) = 36.73, p < .001] \) was found, reflecting reduced amplitudes with time-on-task, and greater amplitudes in the Nogo compared to the Go condition. However, no interactions of block or condition with group were found. Fig. 4 represents the Go and Nogo grand averages at Fcz and Pz.

Parietal P3. No effects of block or group were found for latency of the P3 at Pz. Yet, for P3 amplitude there was no main effect for group, but a main effect for block was found \( [F(3,60) = 12.26, p < .001] \), although this effect did not differ between groups.

Fronto-central P3. Inhibitory control was investigated by contrasting the fronto-central P3 in the Go and Nogo condition at Fcz.

For the P3 latency, no effect of block was found. Yet, there was an effect of condition \( [F(1,62) = 129.31, p < .001] \), and interaction of block with condition \( [F(3,60) = 3.94, p = .012] \). No interactions between group and block or group and condition were found for P3 latency.

For P3 amplitude, at Fcz, a main block effect \( [F(3,60) = 23.07, p < .001] \) demonstrated smaller amplitudes with time-on-task. An effect of condition was also found \( [F(1,62) = 14.88, p < .001] \), reflecting the overall greater amplitude in the Nogo condition. Moreover, a two-way condition x group interaction was found \( [F(3,63) = 5.52, p = .002] \). The interaction, as plotted in Fig 5, suggests that controls show a greater P3 amplitude at Fcz in the Nogo condition compared to the go condition. This larger P3 amplitude at Fcz was not seen for the other three groups. Entering the difference between the Go and Nogo condition into an ANOVA resulted in a significant main effect for group \( [F(3,63) = 5.52, p = .002] \). Planned contrasts revealed significant differences between the control and dyslexic group \( (p = .015) \), and the control and ADHD group \( (p = .001) \). A trend to significant difference was found between the control and the comorbid group \( (p = .08) \).
Figure 4. Grand averages for the Go and Nogo conditions are plotted for electrodes Fcz and Pz.
Correlations

Correlations were calculated across all groups due to the relatively small number of participants in each group. For the cue-related components, partial correlations were calculated between symptom scores and the dependent measures, the no cue condition being controlled for. A significant correlation was found only between the cue P3 at Pz and the total problems t-score of the ASR \((r = -.30, p = .018)\), indicating that more behavioural problems coincided with a smaller P3. No systematic correlations were found between the dependent variables and other symptom scores.

Correlations between the performance measures and ERP measures revealed several significant correlations. For the CNV2 at Cz, after adjustment for the no cue condition, there were significant relationships with the performance measures accuracy \((r = -.29, p = .02)\), O-not-X errors \((r = -.28, p < .03)\), RT \((r = \)
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.38, p = .002), and SDRT (r = .53, p < .001), all indicating that enhanced performance, expressed by fewer errors, shorter RT, and reduced variability, coincided with greater CNV2s. There were no correlations of performance measures with CNV1.

A significant correlation was also found between the parietal GoP3 amplitude and RT. Across participants, the GoP3 in blocks 3 and 4 correlated negatively with RT, with the strongest correlation in block 4 (block 3: r = -.27, p = .027, block 4: r = -.30, p = .015), revealing that smaller P3s co-occurred with longer RTs.

Discussion

Adults with ADHD, with dyslexia, adults with both disorders, and normal controls were compared on performance and underlying brain responses during a CPT with the aim of discovering features of information processing differentiating between the groups. In this section, the main results will be discussed in relation to the existing literature. First, the performance results will be discussed, followed by the cue-related and target-related components. Finally, limitations of the present study will be considered.

Performance

As expected, an effect of time-on-task was observed for the measures accuracy, RT, and variability of RT. Moreover, the ADHD group showed a steeper RT decline with time-on-task as well as an overall greater variability. This time-on-task induced performance deterioration corroborates previous findings of impaired sustained attention in adults with ADHD (for a review see Boonstra, Oosterlaan, Sergeant, & Buitelaar, 2005). Our results for dyslexic adults are consistent with reports of intact sustained attention abilities in dyslexic children and adolescents (Moores & Andrade, 2000; Schulte-Körne, Remschmidt, & Warnke, 1991; Taroyan et al., 2007). In one study (Kupietz, 1990) sustained attention problems were uncovered in dyslexics. Yet, these were attributed to the presence of comorbid ADHD.

The ADHD group exhibited greater within-subject variability in response time, which was not seen for the other groups. Greater within-subject variability is one of the most consistent findings in ADHD as it is seen on a variety of tasks
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(reviewed by Klein, Wendling, Huettner, Ruder, & Peper, 2006). This behavioural characteristic has been related to temporary lapses in attention, possibly caused by an impaired connectivity between two functionally conjunctive networks: a cognitive control network, and a default-mode network, which is activated during resting state (Castellanos, Margulies, Kelly, Uddin, Ghaffari, et al., 2007). Moreover, increased response variability in ADHD is considered to be a manifestation of inefficient effort allocation/inefficient information processing, and has been hypothesised to stem from a deficiency in energy supply at a cellular level (Russell, Oades, Tannock, Killeen, Auerbach et al., 2006), strengthening the idea of a deficit in the mobilisation of energetic resources in ADHD (van der Meere, 2005).

Cue-related ERP

The decline in vigilance as demonstrated by the time-on-task effect resulted in the decrease of several cue-evoked components with time-on-task, thus demonstrating that the task manipulation was effective on an electrocortical level as well as a behavioural one. Yet, the groups did not differ with respect to this time-on-task effect. Overall group differences were not found for the N2, implying that groups did not differ in discrimination of the cue. In our previous study on covert orienting (Dhar et al., 2008), a smaller cue N2 was found in dyslexic adults. Yet, in contrast to the present task, the previously published study concerned a relatively fast-paced task, relying heavily on automatic processing, which is thought to be deficient in dyslexics (e.g., Eden et al., 1996). For the P3, comorbids demonstrated a smaller amplitude compared to dyslexics. Moreover, cue P3 onset was earlier in the comorbid group compared to controls and dyslexics. Fig 3 shows the cue P3 in all four groups, controls having the largest P3, followed by dyslexics, ADHD participants, and comorbids who clearly demonstrate a considerably smaller P3. The cue P3, therefore, appears to be related to the degree to which the participants were affected; the most severely affected participants showing the smaller P3. Moreover, the significant correlation between the cue P3, after controlling for the no cue condition, and the total problems score of the ASR supports this notion, as a smaller cue P3 coincides with the presence of more behavioural problems overall.

The functional significance of the P3 to cues requires some discussion. For instance, it seems odd why a component reflecting expectation of an imperative stimulus should appear before the CNV1 that is thought to reflect orienting to the cue. In general, the parietal P3 has been related to attention and memory processes
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(Reichle, 2007). A smaller P3 microstate to cues previously reported in children with ADHD (Banaschewskii et al., 2004; Van Leeuwen et al., 1998), was interpreted as a deficit in orienting to the cue or arousal regulation. A major difference with the present study is that we evaluated the P3, and other cue-related components, relative to the no cue condition. Bekker and colleagues (2004), who also measured the cue P3 relative to the non-cues, manipulated the probability of the Go stimulus. They found that an increase in Go probability was accompanied by an increase in the amplitude of the cue P3, suggesting that this component reflects the expectation of the imperative stimulus. In the present study it seems that the comorbid group had the most difficulty in extracting relevance information from the cue, and therefore target expectancy was poorer.

As can be observed in Fig 3, in the no cue condition no negativity resembling a CNV, as seen in the cue condition, can be discerned. Group comparisons of the CNV1 resulted in a smaller CNV1 for the dyslexic group. This component is thought to reflect orienting to the cue (Loveless & Sanford, 1974). Previous studies have also suggested that dyslexics suffer from problems in visual orienting (Buchholz & Davies, 2007; Facoetti et al., 2000). This finding corroborates with our earlier study, in which participants with dyslexia could be discerned from those with ADHD by visual orienting deficits (Dhar et al., 2008).

In contrast, no group differences were found for the CNV2, which has been associated with the preparation of a response (Rohrbaugh & Gaillard, 1983). Our results from the correlation analyses support this association as performance, as indexed by speed and accuracy, improved with a larger CNV2. The CNV1, however, did not correlate with any of the performance measures, supporting the notion that the two components are related to distinct processes (Van Boxtel & Böcker, 2004).

**Target-related ERP**

For the Nogo N2, no group differences were found. There has been ongoing debate as to whether this component reflects inhibitory control (Jonkman et al., 2003). Most other studies also reported no difference in Nogo N2 amplitude between participants with ADHD and normal controls (e.g., Banaschewski et al., 2003 and 2004; Wiersema et al., 2006). With respect to the significance of the Nogo N2, its amplitude was found not to be modulated by inhibitory processes (Davis, Bruce, Snyder, & Nelson, 2003; Smith et al., 2006). In another study, the Nogo N2 was noted to specifically be related to the conflict that arises when a response has to be
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withheld, rather than the inhibitory process itself (Nieuwenhuis, Yeung, & Cohen, 2004).

For the Go P3 amplitude, no significant group differences were found. Curiously, this was in contrast with the results of the cue P3, for which smaller amplitudes were found in comorbidics compared to dyslexics, and a trend to smaller amplitudes was found in the ADHD group compared to dyslexics. However, the cue P3 was interpreted as an index of expectation of the imperative stimulus unlike the Go P3, which may be tapping more attention-demanding working memory processes as the target stimulus had to be compared to the cue in order to reach a decision on whether or not a response was appropriate. Although the performance data suggested an inefficient effort allocation in the ADHD group, as demonstrated by greater response variability, ERP support for inefficient processing in the ADHD group was not found as indexed by the Go P3. In this study, the Go P3 did not appear to reflect processes related to the increased performance variability, as confirmed by the absence of a correlation between the Go P3 and SD-RT. As expected, there was a significant relationship between the Go P3 and RT, smaller Go P3s coinciding with longer RTs.

Inhibitory control was reflected in the difference between Go and Nogo P3. As expected, controls showed a larger fronto-central P3 in the Nogo condition compared to the Go condition in contrast to the ADHD group, which did not show any difference between conditions. This is suggestive of reduced inhibitory control or impulsiveness (Ruchsow, Groen, Kiefer, Hermle, Spitzer et al., 2008), as has previously been found in adults with ADHD (Fallgatter et al, 2005). Moreover, an almost absent difference between the Go and Nogo condition was seen in the dyslexic and comorbid groups as well. It would seem that reduced inhibitory control, originally thought to be typical of ADHD, may not be exclusive to this disorder and may occur in individuals with other disorders as well. These results are in line with previous behavioural studies on dyslexic children (Purvis & Tannock, 2000; Van der Schoot et al., 2000), which have been corroborated by ERP findings (Van der Schoot, Licht, Horsley, & Sergeant, 2002; Van der Schoot; Licht, Horsley, Aarts, Koert et al., 2004). In these studies, reduced inhibitory control, as reflected by a smaller fronto-central Nogo P3, was associated with an impulsive, guessing style of reading in dyslexics.

Concerning the comorbid group, several profiles of comorbidity are possible. Comorbidics could have the profile of just one of the disorders, show an additive effect of both disorders, or they could show an alternative profile, i.e. a
profile that is not characteristic of either of the two disorders. However, regarding our comorbid group, results were inconsistent. Concerning the performance measures, comorbids did not perform worse than ADHD participants, thus showing no evidence for an additive profile. The CNV1 was unaffected in contrast to the dyslexic group, and similar to that of ADHD participants, their cue P3 was smaller compared to dyslexics. With respect to the Nogo P3, all clinical groups showed problems with response inhibition. Hence, the fact that comorbids differed from dyslexics and controls on some measures, but not from the ADHD group on any, suggests that this group resembles the ADHD group most of all, although not completely.

To summarise, the present study revealed distinguishing features of information processing for ADHD and dyslexia, whereby ADHD participants showed a deficiency in response control, as indexed by greater response variability, while dyslexics demonstrated problems with orienting to cues. The comorbid group showed a diminished expectation to the target. Yet, all clinical groups showed problems with inhibitory control.

The present study had the disadvantage that the task was too easy for the adult participants. The fact that very few errors were committed suggests a ceiling effect. Consequently, we recommend using more difficult tasks in future when studying adults, so that groups can be compared on behavioural as well as the electrophysiological measures of inhibition. Also, the measures can then be correlated to verify the functional significance of the ERP components related to inhibition. Another limitation of the present study concerns the use of only male participants. Further research is necessary to evaluate how the present results relate to women with dyslexia and ADHD.
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