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RESEARCH ARTICLE

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Attentional blink in adults with attention-deficit hyperactivity disorder

Influence of eye movements

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Abstract The attentional blink paradigm tests attention by overloading it: a list of stimuli is presented very rapidly one after another at the same location on a computer screen, each item overwriting the last, and participants monitor the list using two criteria [e.g. detect the target (red letter) and identify the probe (letter *p*)]. If the interval between the target and the probe is greater than about 500 ms, both are usually reported correctly, but, when the interval between the target and the probe is within 200–500 ms, report of the probe declines. This decline is the attentional blink, an interval of time when attention is supposedly switching from the first criterion to the second.

The attentional blink paradigm should be difficult to perform correctly without vigilantly attending to the rapidly presented list. Vigilance tasks are often used to assess attention-deficit hyperactivity disorder (ADHD). Symptoms of the disorder include hyperactivity and attentional dysfunction; however, some people with ADHD also have difficulty maintaining gaze at a fixed location. We tested 15 adults with ADHD and their age- and sex-matched controls, measuring accuracy and gaze stability during the attentional blink task. ADHD participants reported fewer targets and probes, took longer to recover from the attentional blink, made more eye movements, and made identification errors consistent with non-perception of the letter list. In contrast, errors made by control participants were consistent with guessing (i.e., report of a letter immediately preceding or succeeding the correct letter). Excessive eye movements result in poorer performance for all participants; however, error patterns confirm that the weak performance of ADHD participants may be related to gaze instability as well as to attentional dysfunction.

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Introduction

The attentional blink (AB) paradigm is a well-studied phenomenon of dual-task experiments (Jolicoeur 1999; Jolicoeur and Dell'Acqua 2000; Moroni et al. 2000; Raymond et al. 1992; Ross and Jolicoeur 1999; Shapiro et al. 1994) in which stimuli are presented in rapid serial order at the same location. In a typical AB study, stimuli may be presented at a rate of 11 items per second; the list of items includes a target and a probe—each with separate criteria for correct report. For example, the target may be a coloured letter in a list of white letters and the probe may be a letter from a predefined set. If the probe occurs more than 500 ms after the target, both items are usually identified correctly. However, when the probe follows within 200–500 ms of the target, there is a sharp decline in accuracy for the probe given correct identification of the target. The decline in accuracy is the AB and it has been attributed to an inability to switch attention to the second criterion under rapid presentation rates (Duncan et al. 1994; Peterson and Juola 2000).

We define attention as a resource that facilitates performance if it is directed towards some task and limits performance if it is withdrawn from a task (Raymond et al. 1992; Schachar and Logan 1990). The AB task is resource demanding: it challenges performance by limiting the duration that any particular stimulus is available to the senses. With only brief stimulus durations, successful AB performers require more resources to discriminate multiple stimuli and may choose instead to process the stimuli only insofar as such processing permits the disqualification of a stimulus based on some selection criterion. But in the AB task there are two selection criteria. Hence, attentional resources must be divided or switched between the selection criteria.

A dysfunction of attention should exacerbate the AB. Hollingsworth et al. (2001) found that adults with attention-deficit hyperactivity disorder (ADHD) made more errors than control participants on the AB task. ADHD symptoms include inattentiveness, impulsiveness and sometimes hyperactivity (Barkley 1997).

Two obvious reasons why people with ADHD might have more trouble with the AB task are: (1) they are not vigilant, a common diagnostic indicator of ADHD is poor performance on a vigilance task (Barkley 1990; Quay and Werry 1986), so, for those with ADHD, resources are not applied consistently; and (2), as suggested by Hollingsworth et al. (2001), even when vigilant, they may be less able to switch attention rapidly and, hence, cannot "recover" from identifying the first target in time to correctly detect the probe; that is, resources cannot be redirected as efficiently as for persons without ADHD. Both accounts imply attentional resource dysfunction. We hypothesize a third possibility: subjects with ADHD are compromised by inefficient gaze control; they cannot fixate a location for long time periods, they shift their gaze away from the list of letters during its presentation and therefore do not perceive and cannot identify targets or probes. In this account, resource consistency and allocation are not at issue, and resources may be applied appropriately; however, without gaze control, perception of the stimuli becomes more challenging.

Inefficient gaze control in the ADHD population is suggested by various studies examining eye movements in volunteers with ADHD. Munoz et al. (1999, 2003) showed that children and adults with ADHD have less stable gaze control than individuals with no psychopathology and they suggest that a saccade-suppression deficit is the result of frontostriatal pathophysiology. In the eye movement task, subjects were required to look at a central fixation marker and continued to hold their gaze at that location after the marker disappeared, moving their eyes only when an eccentric target appeared. Control participants performed this task well, but ADHD subjects reliably made more eye movements during the pre-target phase of the task. Although more stable gaze control might be expected with more compelling stimuli such as in the AB task, Hollingsworth et al. (2001) found that subjects with ADHD produced a prolonged AB; however, gaze stability was not measured in their experiment. Gaze stability is a necessary requirement in the AB task (it would seem impossible to report the target and probe correctly from a rapidly presented stream if the subject looked away); weaker performance among ADHD participants may therefore reflect gaze instability.

We tested gaze stability during performance of the AB task by monitoring eye movements throughout the task. We expect eye movements and error rates in the AB task to be positively correlated in all participants, and we expect more errors from ADHD participants, a finding already demonstrated (Hollingsworth et al. 2001). The type of error should act as an indicator of the amount of processing a list has received. Assuming that subjects will guess when they are unsure, we can categorize guesses in terms of where the "guess" appeared in the list. For example, if participants look away from the list during presentation, none of the letters is perceived and, in this case, an erroneous guess could be any letter, including those not presented in the list. On the other hand, if participants stop paying attention or move their gaze during list presentation, they may guess from the section of the list that they paid attention to. Finally, if participants are attending to the task, but cannot switch attention at the critical moment, they may guess a letter near the correct item, say the preceding letter or the letter immediately following the correct letter. The idea that a nearby letter is substituted when guessing is supported by theories of visual attention (see Brehaut et al. 1999; Shapiro and Raymond 1994).

We specifically hypothesize that ADHD participants will produce a longer AB than age- and sex-matched participants without attentional dysfunction. We also hypothesize that ADHD participants will move their eyes during the displays more than control participants and, due to gaze instability, that more of the errors made by participants with ADHD will be guesses unrelated to the list.

Methods

Participants

Fifteen non-medicated ADHD adults (mean age ± SD: 29±12 years) and 15 age- and sex-matched controls [33±10 years; $t(28)=0.94$, $P>0.35$] gave informed consent and were paid \$10 per session to participate in the study. ADHD participants (eight men) were already diagnosed in the community, but psychopathology was confirmed by a psychologist who also administered Brown's Attention Deficit Disorder Scale (BADDS; Brown 1996). A score greater than 50 on the BADDS is indicative of ADHD. BADDS scores were reliably higher in the ADHD group (mean ± SD=80.7±11.2; range: 64–96; controls: 23.7±9.3, range: 9–34; $t(24)=14.1$, $P<0.001$). The four ADHD participants using medication performed the task off medication at least 20 h after their last dose.

Materials

Visual stimuli were presented on a 17-inch monitor with display resolution of 640×480 pixels and a frame rate of 60 Hz. Eye-movement data were collected using a video-based eye-tracker (Eyelink; SR Research) that was mounted on the subject's head with an adjustable headband. The eye-tracker uses infrared cameras to track the movements of the left pupil, measuring vertical and horizontal eye position and sampling at a rate of 250 Hz. It also provided spatial information about head position for head motion compensation. Acceleration and velocity thresholds were set to detect saccades greater than 0.15°.

Stimuli were 12-pt lower-case letters that subtended a visual angle of 0.13°, presented in white on a dark background. The red target letter, when used, maintained a luminance level similar to the remaining list letters. The room was lit indirectly by a small fluorescent light.

Procedure

On each trial, participants saw a list of letters presented one letter at a time in the same (central) location on the computer monitor (Fig. 1). No letter was presented more than once in a list. Every list

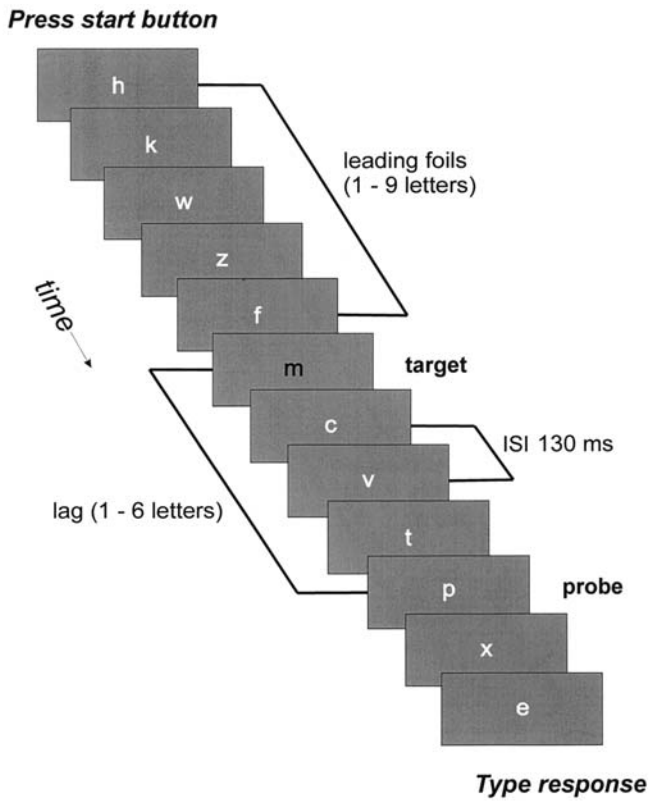

Fig. 1 The attentional blink paradigm: lower-case letters are presented one at a time in the same location at 130 ms inter-stimulus interval (*ISI*; 50-ms presentation with 80-ms delay). Unspeeded responses are typed directly on a computer keyboard

contained exactly one of the four possible probes (*b*, *d*, *p* or *q*). A list often also contained a target (red letter), which was always displayed before the probe and which never had a probe's identity. There was at least one intervening letter between the target and the probe, and the number of intervening letters varied between 1 and 6. The number of letters presented before the target was also varied. Participants made an unspeeded response by typing the identities of the target (if presented) and probe on the computer keyboard.

Participants sat approximately 60 cm from the display monitor. Each trial started with the presentation of a 1-cm white, octagonal fixation marker subtending a visual angle of 0.95° centred on the monitor. When ready, subjects initiated the trial with a button press, the fixation marker disappeared immediately, and a list of lower-case letters appeared one at a time at the same location as the fixation marker. Each letter was displayed for 50 ms followed by an inter-stimulus interval such that there was approximately 130 ms between letter onsets. Each list began with 1–9 foils (letters which were not to be reported), followed by the target, if used, then by 8 letters, and the probe configured so that the probe followed the target with a lag ranging from 1 to 6 foils. One in five trials was a catch trial and did not contain a target. The trial ended when the participant pressed the correct number of response keys [one only in the probe-only condition and catch trials, and two in the target-plus-probe (AB) condition]. Participants were not restricted with a bite bar or chin rest. All participants were provided breaks from the task as required. Protocol was approved by the Queen's Ethics Committee.

Design

The experiment included two randomly ordered blocks. In the probe-only block, subjects were instructed to identify the probe; in the probe-plus-target block, subjects were instructed to identify the target, if one appeared, and then to identify the probe. Participants were informed that a probe letter never appeared in red (the target's colour), and that every trial contained only one probe letter. Each block had a total of 270 trials, reflecting the factorial combination of lag (1–6), probe identity (*b*, *d*, *p*, or *q*), and the number of lead foils (1–9), plus 54 catch trials without a target. Trials were presented in random order that was determined separately for each subject and each block; blocks took place on separate days.

Each block started with a practice set of 20 trials. During practice, the rate of presentation was incremented twice to reach the experimental rate. Practice was not scored.

Analysis

Eye movements were counted if they had an amplitude greater than 2° and a peak velocity greater than 20°/s. Blinks were automatically recorded by the eye-tracker. Subjects' responses were credited in any order, although they were asked to report the target and probe in the presentation order. Most dependent measures were analysed using a repeated-measures analysis of variance, lag and pathology used as discriminating factors, with alpha set at 0.05; post hoc tests were performed using Fisher's least-significant difference procedure. Non-normal data were analysed with the Wilcoxon rank sum test.

Results

Attentional blink

The AB is the difference in performance between the probe-only block and the probe-plus-target block across lag. We found AB for both controls and ADHD groups and confirmed that the deficit was not because the rate of presentation made the stimuli imperceptible. Finally, we found that the ADHD group were more impaired at the AB task than the control group, resulting in the interaction of performance across blocks with pathology. The statistics confirming this summary follow.

We compared accuracy between the probe-only block and the probe-plus-target block. Figure 2 shows that, for both ADHD and control groups, the probability of correctly identifying the probe given the target depended on lag: the lowest recall occurred at lags 1 and 2 ($F_{5,\,70}$=27.29, MS_e=0.009, P<0.001). Post hoc pair-wise comparisons showed that recall in the probe-plus-target block at lags 1 and 2 was reliably worse than at every other lag, and recall at lag 1 was worse than at lag 2. This is the attentional blink. Performance at the remaining lags gradually improved such that there was no difference in recall at lags 4 through 6.

These results cannot be explained by the perceptual difficulty of the task. All ADHD and control participants successfully identified the probe on probe-only trials (Fig. 2; $F_{1,\,14}$<1, MS_e=0.075, n.s.). Performance did not vary across lag for either group; consequently, there was no interaction of lag and pathology in the probe-only block ($F_{5,\,70}$=1.93, MS_e=0.002, P>0.10). Hence, any

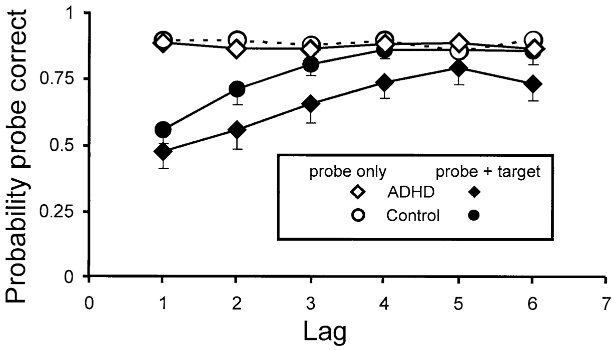

Fig. 2 Probe accuracy across lag for attention-deficit hyperactivity disorder (*ADHD*) and matched controls under probe-plus-target (given correct target) and probe-only blocks

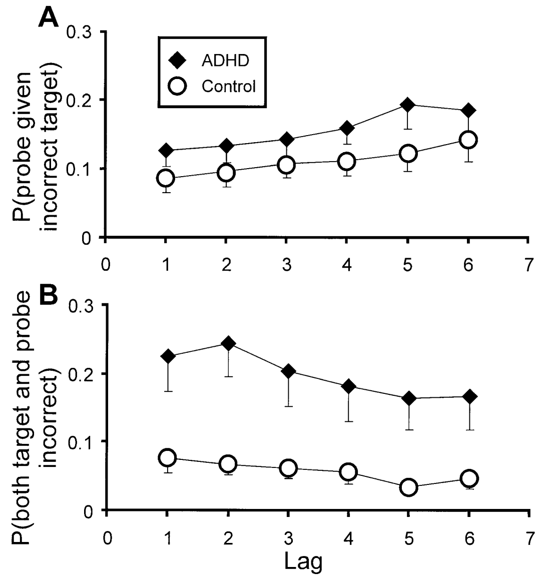

Fig. 3 **A** Probe accuracy across lag given incorrect target identification for the ADHD and control groups. **B** Both target and probe reported incorrectly as a function of lag for the ADHD and control groups

deficit found in the probe-plus-target block where the AB is expected cannot be attributed to sensory masking; that is, it is not the case that the speed of presentation left participants unable to perceive a letter that was rapidly replaced by another letter.

Finally, the AB deficit (probe-only minus probe-plus-target accuracy) was larger for ADHD subjects, resulting in an interaction between the factors of pathology and block ($F_{1,\,14}$=4.24, MS_e=0.06, P=0.059). Observed power measured 48%.

Finding a marginal deficit in performance for ADHD participants compared with controls may be due to lack of power. But the conditional AB score, probe-given-target, does not fully take into account the deficiency of ADHD participants' performance. The ADHD AB deficiency occurs on more than just the probe-plus-target measure. For example, ADHD subjects were less likely to report the *target* correctly on probe-plus-target trials: mean accuracy was only 64% compared with controls' 83% ($F_{1,\,14}$= 8.05, MS_e=251.06, P=0.01; as expected, target accuracy was independent of lag, $F_{5,\,70}$<1, n.s.). Because ADHD participants reported the target less frequently than controls, their AB measure excludes more trials (because AB requires correct report of the target and the probe). Counting fewer trials in the analysis infers greater variance statistically, limiting the power of the ANOVA test.

One possibility is that ADHD participants expend more resources identifying the probe on trials where they failed to report the target correctly. However, as shown in Fig. 3A, ADHD participants were not more likely to report the probe letter when target report was incorrect ($F_{1,\,14}$=2.85, MS_e=0.033, P>0.10). Furthermore, they were more likely to fail to report either letter (Fig. 3B; $F_{1,\,14}$=8.27, MS_e=0.106, P=0.01), a finding that suggests strongly that ADHD participants were more challenged by the dual task than were control participants. Interestingly, the tendency of subjects with ADHD to miss both letters was more likely to occur at list locations where the AB was most expected (i.e., at lags 1 and 2) than at longer lags ($F_{5,\,70}$=5.71, MS_e=0.003, P<.001); hence, the proximity of the target and probe created difficulties for participants with ADHD that was not shown by the AB measure alone.

Gaze stability

ADHD subjects' difficulty detecting the presentation string may be directly related to gaze instability (Munoz et al. 1999, 2003). To test gaze stability, we counted eye movements greater than 2° in amplitude and blinks, across the entire trial duration (Fig. 4A) and in the interval from the start of the list until the presentation of the probe (Fig. 4B) for both groups in the probe-plus-target block and in the probe-only block. Both groups made roughly the same number of eye movements per trial when all eye movements were considered ($F_{1,\,14}$=1.60, MS_e=474,455.56, P>0.20); and both groups made more eye movements per trial during the probe-plus-target block than during the probe-only block ($F_{1,\,14}$=38.36, MS_e=302,231.79, P<0.001; Fig. 4A). Two points must be made regarding eye movements from list start to probe presentation (Fig. 4B). First, mean eye movements per trial was a very small number; however, recall that any eye movement during this display period will make it unlikely that the target and probe will be perceived, therefore, no eye movements were the expected behaviour. Second, for probe-only displays, participants with ADHD were 2.4 times more likely to make an eye movement than control subjects and, for probe-plus-target displays, they were 6 times more likely to move their eyes or blink (Fig. 4B). The greater propensity for eye movements during the critical start-to-probe period was confirmed statistically: ADHD participants made more eye movements per trial than controls from list start to

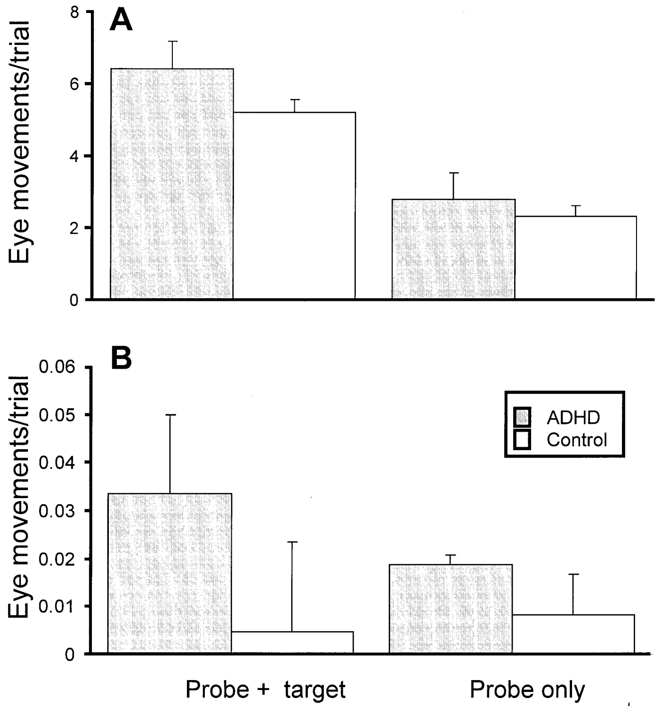

Fig. 4A, B Eye movements across all trials (**A**) and during list presentation only (**B**) for the ADHD and control groups under probe-plus-target and probe-only blocks

probe presentation in the probe-plus-target block only (Z=2.21, P<0.05; Wilcoxon Rank Sum Test; Fig. 4B).

The number of eye movements varied across the list presentation. Figure 5 shows the occurrence of saccades as a function of list location, that is, in terms of the number of letters preceding the probe (Fig. 5A) and the absolute number of letters from the red target (Fig. 5B). Across list locations, ADHD participants consistently made more saccades and blinks than controls relative to the probe (Wilcoxon Z=3.06, P<0.01) and to the red target (Wilcoxon Z=2.67, P<0.01). Saccades occurred least frequently closest to the probe, increasing in frequency as the distance before probe increased. In contrast, ADHD participants made relatively more saccades nearer the target compared with controls, whose saccade rate did not change across absolute distance from the red target.

The amplitude of most saccades was typically under 6° of visual angle. Figure 6 shows median saccade amplitude as a function of the number of letters preceding probe for correct trials (trials with both probe and target reported correctly; Fig. 6A) and for error trials (trials where either probe or target or both were not correct; Fig. 6B). Figure 6 also includes a summary of the proportion of correct and error trials containing a saccade or a blink (Fig. 6C and D, respectively). For both correct and error trials, ADHD participants made more eye movements, and the amplitude of those movements tended to be larger than the saccade amplitude shown for control subjects.

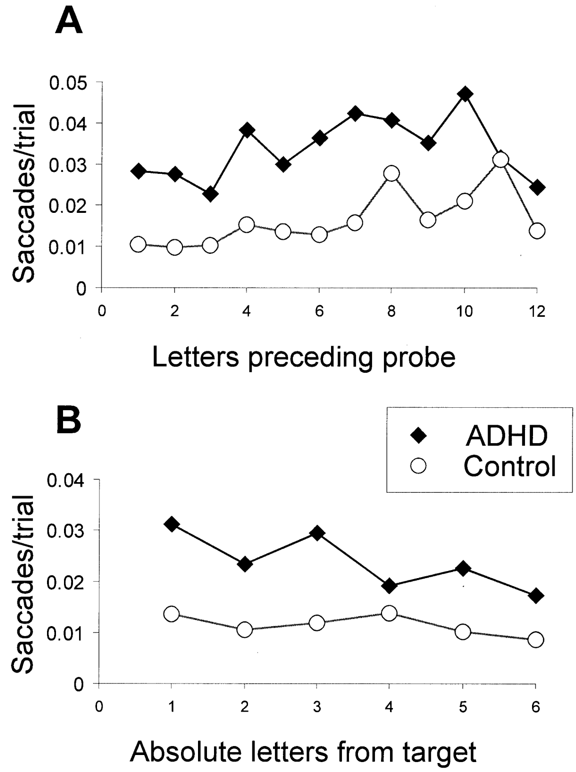

Fig. 5A, B Eye movements per trial as a function of the number of letters preceding the probe that they occurred (**A**) and as a function of their absolute letter distance from the red target (**B**) for ADHD and control participants

Correlating gaze stability and probe errors

One hypothesis is that poor performance at the attentional blink task is the result of excessive eye movements. In order to evaluate errors fairly, we counted all probe errors; that is, failure to report the probe given correct report of the target (AB) and failure to report both the target and the probe. Figure 7 shows the relationship between all eye movements and probe errors (Pearson product moment, r=0.47, P=0.01, for all participants). The control group shows a clear association between errors and eye movements (r=0.57, P<0.05). ADHD subjects alone did not show this relationship (r=0.34, P>0.20), probably because two participants (circled in Fig. 7) had excessive probe errors without making many excessive eye movements and not because some ADHD subjects performed well in spite of excessive eye movements.

Target (red letter) errors

Making eye movements during rapid presentation of successive letters will result in poorer perception of the stimuli. We categorized each error in terms of a guessing strategy; for example, by the error's proximity to the target (T-plus-1, T-minus-1), its presence in the list

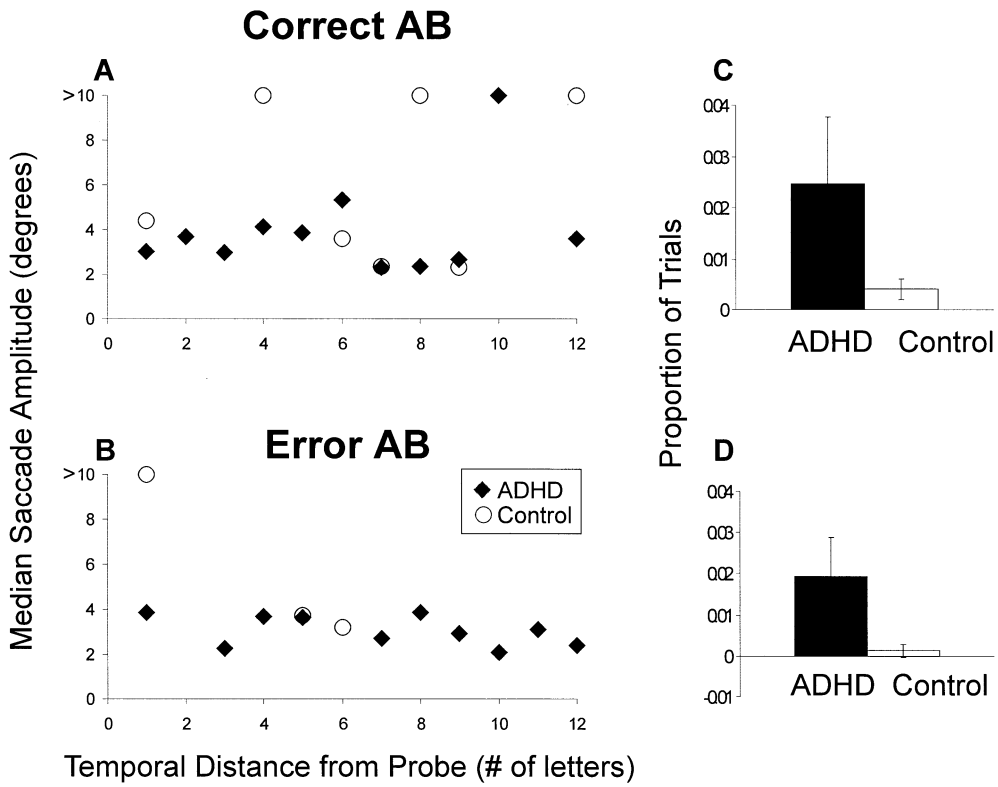

Fig. 6A–D Median saccade amplitude as a function of their distance (number of letters) from the probe in correct (**A**) and error (**B**) trials. The proportion of correct trials (**C**) and the proportion of error trials (**D**) with eye movements for the ADHD and the control groups

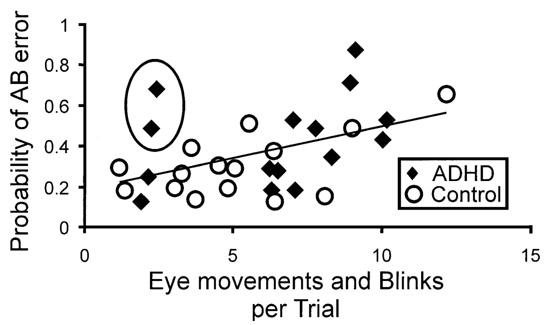

Fig. 7 The correlation of AB error as a function of the frequency of eye movements. Two ADHD outliers are *circled*

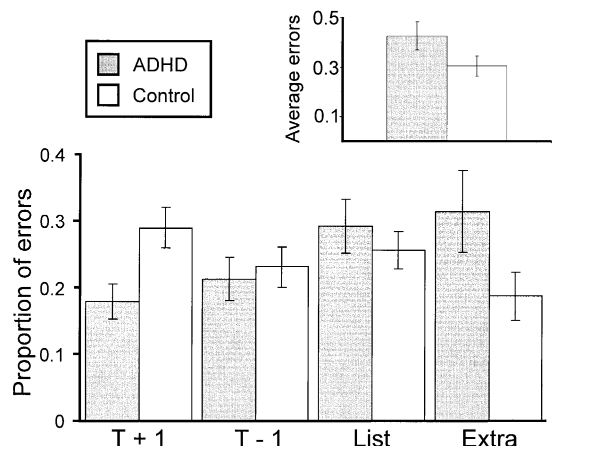

Fig. 8 Target errors by type: *T+1*—the letter following the target; *T-1*—the letter preceding the target; *List*—any other letter from the current list; *Extra*—a letter not presented in the current list, for the ADHD and control groups

otherwise, or as an extra-list item, that is, as an item not shown during the trial. (The same analysis cannot be done for the probe because only one probe letter was presented in a list; hence, an error would necessarily be from outside the list). Figure 8 shows error type as a proportion of total error for ADHD and control participants. Control participants were more likely to report the T-plus-1 and T-minus-1 items when they were wrong and less likely to report extra list items, that is, items not from the presentation list. In contrast, ADHD participants were more likely to report an extra list item or an item from the list that was not near the target in the list. The difference in the proportion of error types resulted in a linear interaction between errors and pathology ($F_{1,\,14}$=5.83, MS_e=0.228, P<0.05). Control participants' errors were guesses close to the target that indicate some confusion over provisionally identified list items. Participants with ADHD made errors that were not from the list, suggesting that ADHD subjects were simply guessing.

Discussion

ADHD participants produced a prolonged AB, although they identified the probe alone without difficulty. Only when *two* tasks were imposed did ADHD performance decline more than control performance. The AB alone is an insufficient measure to describe ADHD behaviour, partly because the dual task interfered with the report of both the target and the probe. Instead, for the probe-plus-target trials, we counted all probe errors and found that they increased when the probe was near the target even when the target was not reported correctly. Eye movements also increased during the probe-plus-target blocks. Probe errors correlated with eye movement activity for all participants. The prolonged AB for participants with ADHD related to their inability to perceive the stimuli as well as controls, probably in part due to gaze instability.

The AB task is too difficult for participants with ADHD. There are several possible reasons for this: (1) persons with ADHD have an attentional dysfunction which may result in an inability to switch between attention-demanding tasks; (2) gaze instability related to ADHD leads them to look away from the list before completing the tasks; or (3), knowing that the test was directed at their disability, the participants with ADHD may simply give up trying. This last option lacks credibility because all participants were self-paced; although each list was presented in rapid serial order, participants were not compelled to start the list until they felt ready. Often, participants with ADHD would stop the experiment to stretch and move around before continuing. Anecdotally, at least one participant with ADHD predicted that the experiment would demonstrate superior performance within the ADHD group because the dysfunction allowed him to attend to many things successfully at the same time.

Our gaze instability hypothesis is supported by the analysis of recall errors. Most ADHD participants' errors were guesses that were extra list items, not from the presentation list. ADHD subjects did perceive some lists (not all errors were extra-list items), but over half of their errors suggest an inability to process the stimuli. This was not the case for control participants, whose errors were most often from the stimulus list, and most likely to be a letter near the target. People with ADHD have greater difficulty with inhibitory control (Barkley 1997) and the burden of the additional task in the attentional blink paradigm left ADHD participants unable to focus attention; as a result, their errors were not from the presentation stimuli.

Gaze instability had an effect on AB performance for all participants. Control subjects whose eyes moved during rapid list presentation also made more errors in reports. However, because some participants with ADHD showed little eye movement activity yet produced relatively poor report of the probe (see Fig. 6), we cannot argue that eye movements alone limited performance. Eye movements and blinks may reflect inattentiveness *or* inattentiveness may be the result of gaze instability. For some people with ADHD, attentional dysfunction may be caused by oculomotor dysfunction. If this is so then treatment protocols should change: instead of medication to help to focus attention, these patients require training in saccadic suppression to stabilize gaze control (see training in dyslexia: Fischer and Hartnegg 2000)

Marois et al. (2000) suggest that the neural correlates of the AB include the intraparietal and frontal cortices, based on the hypothesis that AB measures failures of attention. They measured neural activation using functional magnetic resonance imaging techniques while subjects performed the AB task and tasks that differed in spatial or temporal characteristics. Their findings suggest that the right intraparietal sulcus especially, and also frontal areas, represent the neural correlates of the limited capacity network of attention that is demonstrated with the AB task. They note that these areas are also active for attentional orienting, which would seem to confirm that these brain areas are part of an attentional network.

Other researchers have shown differences in neural activity for persons with ADHD in areas related to oculomotor behaviour. Rubia et al. (1999) found reduced activity in the prefrontal cortex in boys with ADHD during a stopping task that required impulse suppression. Mehta et al. (2000) showed that methylphenidate, a drug known to enhance cognitive performance and commonly prescribed for people diagnosed with ADHD, reduced blood flow to the dorsolateral prefrontal cortex and to the posterior parietal cortex. These areas are also instrumental in the control of saccadic eye movements (Conolly et al. 2002).

We conclude that performance of persons with ADHD is worse at AB because they appear unable to perceive the stimulus list. The failure to see items has two causes: inattentiveness (or lack of vigilance) and gaze instability. We conclude that gaze instability is a contributing factor in ADHD participants' inability to perform the AB task.

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