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Covert orienting and focusing of attention in children with attention deficit hyperactivity disorder

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Abstract

Performance on the covert visuo–spatial attentional functions of orienting and focusing by a group of ADHD children ($n = 20$) was compared to that of age and sex-matched control children. In Experiment 1, responses were given to cued targets at valid and invalid locations. In Experiment 2, responses were given to targets presented in small, medium-sized or large visual field locations. For both experiments, the hypotheses that reaction times of ADHD children would be greater than those of control children and that performance would be asymmetrical, were supported. For Experiment 1, ADHD children showed bilaterally greater 'benefits' from having directed attention to the cued location and greater 'costs' in having to relocate the attentional focus than controls. In Experiment 2, the hypothesis that the function of focusing attention by ADHD children may show breakdown in the usual pattern of an increase in reaction time with focus area was partly supported by the finding of similar reaction times to targets presented in medium-sized and large regions of the left visual hemifield. These results have been interpreted as reflecting a stronger anchorage of attention by ADHD children upon a cued location and an inability to shift covert attention easily to an alternative location. The breakdown of the focusing function suggests adoption of similar time response sets across focus area size by the more compromised right hemisphere. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

It is estimated that attention deficit hyperactivity disorder (ADHD) affects between 3–7 children in every 100 [2]. It typically manifests prior to the age of seven years, with most diagnosed cases being male (3 : 1 male : female ratio [3]; however, see [16]). The main behavioural assessment techniques used to determine diagnosis of this disorder include parent and teacher rating scales and interviews, psychometric tests and continuous performance tasks (see [28] for review). It is only recently that experimental psychology paradigms have been employed to study the cognitive operations of these children and that inferences have been made from the results in determining the sites/pathways of neuropathology.

One such stream of cognitive research has been directed to the assessment of the covert attentional system. Essentially this system is said to allow attention to be directed to, and manipulated within, certain regions of visual space in the absence of eye movements. Allocation of attention in a covert manner ensures that the processing of stimuli in the attended area is more efficient than the processing of stimuli in non-attended areas. The well-known Posner paradigm [33] assesses this function by presenting the subject with cues that direct covert attention to regions of the visual space within which an imperative stimulus may subsequently appear. If the stimulus appears within the location indicated by the cue (e.g. cue points to the left and stimulus appears in the left visual hemispace) the trial is said to be 'valid'. If the stimulus appears in a location which was not indicated by the cue (e.g. cue points to the left but stimulus appears in the right visual hemispace) the trial is said to be 'invalid'. Relative to a neutral condition, in which the cue gives no directional information about the potential location of the stimulus, quicker reaction times ('benefits') to the stimulus are usually found for validly cued trials while slower reaction times ('costs') are usually found for invalidly cued trials. A comparison of benefits and costs gives an indication of the viability of the covert orienting system. This paradigm allows assessment of the dissociable functions of orienting attention to either the left or right, of engaging and disengaging attention, and of

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redirecting attention [35] and has been applied widely in the testing of non-brain-damaged subjects and various neurological populations [5, 26, 34, 35, 37, 43].

Relating the anatomy of pathology to the aforementioned elements tested by the Posner paradigm has promoted the formulation of hypotheses as to the neural substrates of covert attentional functions [6]. Conversely, in cases where the neuroanatomical bases of dysfunction are ill-defined, as is often the case for children with attention deficit hyperactivity disorder, theories of the cognitive anatomy of attention can assist in speculating about underlying neuropathology [40].

Few studies have assessed the viability and efficiency of the covert visuo–spatial attentional system in children with ADHD. As argued by Swanson et al. [40], such research is of obvious importance given that the designation of this syndrome suggests an attentional disorder but the 'presumed attentional deficits have not been linked either to specific cognitive operations or to specific neural systems' (p. S119). Further, the fourth edition of the *Diagnostic and Statistical Manual of Mental Disorders* [1] includes 'inattention' as one of the two major impairments, yet as supposed by Barkley [4] "research has not identified a deficit in attention in these children".

Swanson et al. [40] used one version of the Posner paradigm to test children who had been diagnosed with ADHD by use of parent interviews and teacher ratings of inattention/overactivity on the Iowa Conners scale [21]. They reported that the ADHD children showed reaction times to targets, presented 800 ms following an invalid cue, that were much greater for those targets presented on the right than for those presented on the left. There was no such laterality difference for validly cued targets or for any targets presented 100 ms following the cue. These results were explained as reflecting a dysfunction in the ability to sustain the engagement of attention upon a cued right visual field location, with the result that targets in alternative locations recaptured the attentional focus more readily.

Swanson et al. [40] supposed that the difference according to cue/stimulus interval could reflect the use of overt orienting responses in the 800 ms interval, and recommended further research to define such possible dysfunction. Further, the paradigm they used involved the use of peripheral cues (highlighting of a left or right box) which appeared at the probable location of the stimulus. Such cues are said to elicit exogenous, more automatic, mechanisms for the shift in covert attention to the cued location [15, 17, 29, 41, 45]. As noted by Carter et al. [6], the use of these peripheral cues plus the weighting towards valid trials could mean that both exogenous and endogenous mechanisms are recruited, making interpretation of the Swanson et al. [40] results difficult both in terms of the underlying cognitive deficit and the neural systems involved.

In an attempt to dissociate these two cueing mechanisms, Carter et al. [6] utilised both exogenous and endogenous cues to test 20 controls and 20 ADHD children, as diagnosed by DSM-III-R criteria [1] using parent and children interviews and psychiatric evaluation. Endogenous cues were presented centrally, and gave a symbolic indication of the true (valid) or false (invalid) position of subsequent targets in laterally positioned boxes. The results for this type of cueing mirrored those of Swanson et al. [40] with a reduction of costs for targets appearing in the left visual field after having being cued in the right visual hemispace 800 ms earlier. Because only the target was lateral, Carter et al. [6] argued that this reflected a dysfunction in the ability to orient to the left visual field (and thus of right hemispheric attentional control) rather than in the ability to maintain attention to a right cued location (and thus of left hemispheric control). The exogenous task was similar to that of Swanson et al. [40], with cues being presented peripherally at the site of the potential stimulus, but the ability of subjects to adopt probabilistic strategies was reduced by giving equal trial number allocation to valid and invalid conditions. In contrast to the Swanson et al. [40] results, the ADHD subjects showed asymmetry only at the 150 ms cue/stimulus interval with greater costs for left than for right visual field targets. At the 800 ms interval the results for both groups were indicative of a classic inhibition of return, with validly cued trials showing greater reaction times than invalidly cued trials. The ADHD subjects did not show an asymmetrical performance at this latter interval.

The finding of slower overall reaction times and asymmetry in the attentional dysfunction was confirmed by Nigg et al. [30] in a study of a group of ADHD boys who were slower to respond to targets in the left than in the right visual field. In contrast to previous studies however, this lateralised slowness was for trials that had not been cued, rather than showing any clear relation to invalid trials or to cue/stimulus interval. Such a result was counter to the proposed hypotheses that the boys would show dysfunction with maintaining attention in the left visual field [14], or that the left hemisphere would show problems maintaining attention [24]. The researchers concluded that the results suggested hypoarousal dysfunction to the noradrenergic system of the right hemisphere with the consequence of a rightward biasing of covert orienting [35].

It is clear from the foregoing summaries that the description of deficits to the covert attentional system in children with attention deficit hyperactivity disorder is not yet clearly defined. A primary aim of the current study was thus to assist in this definition. The function of orienting covert attention was assessed using an endogenous cueing paradigm whereby the cue is presented centrally and gives information about the probable location of targets to be presented in either the left or right visual field. The use of this paradigm was to provide an index of spatial attentional functioning for comparison with previous research. Given the results from other studies [6, 30, 40], it was predicted that ADHD children would show slower reaction times and evidence of performance asymmetry. Based on the results from Carter et al. [6] it was hypothesized that reaction times to stimuli presented in the left visual hemispace more than 200 ms after an invalid cue to the right hemispace would be lower than reaction times to invalidly cued targets in the right visual hemispace.

The present study also sought to characterise a covert attentional function that, to the authors' knowledge, has not yet been explored with the ADHD population. This function is that of modulating the size of the attentional focus so that the time efficiency of the processing of stimuli varies according to the area under covert focus [8–12, 20, 27]. Most studies have shown that there is an inverse relationship between the size of the attentional focus and the efficiency of processing, with reaction times to stimuli increasing as the area upon which attention is focused increases [7–10, 20]. A second primary aim of the present study was thus to investigate the modulation of the attentional focus in ADHD subjects. This was not only because this topic has not previously been addressed for this subject group, but because the results from assessment of the focusing of attention can give an index of cognitive processing abilities. It is of interest to determine whether the inverse function between focus size and processing efficiency holds for the ADHD subjects (and indeed for the control group of the present study). This assessment of the function of focussing is largely exploratory but tentative hypotheses can be made on the basis of previous studies. Firstly, given the generally slower processing of ADHD children, it was hypothesised that reaction times to stimuli in focus areas of small, medium-sized and large areas would be greater than those for control subjects at each of these focus sizes. Secondly, it was predicted that performance would show asymmetries. Finally, no firm prediction about the viability of the focussing function was postulated, but it was proposed that there would be some disturbance to the ability of children with attention deficit hyperactivity disorder in modulating suitably the efficiency of processing with the size of the covert attentional focus.

2. Experiment 1

In this first experiment the endogenously cued cost/benefit paradigm of Posner [33] was employed. The aim was to compare the ability of non-ADHD and ADHD children in the performance of the basic function of covertly orienting visual attention. The requirement in this task is for subjects to fixate on a central cross, and to respond as quickly as possible to the appearance of a lateral target. For most trials this stimulus is validly cued by a central arrow. For a few trials, the stimulus is invalidly cued, appearing in the hemispace opposite to that indicated by the central arrow. The central location of the stimulus together with the need for some interpretation of its meaning, and the greater probability of valid trials, should trigger the requirement for endogenous mechanisms of attentional control. Cue/stimulus interval was kept constant at 800 ms which should trigger the requirement for attention to be maintained upon the target location.

As mentioned previously in greater detail, and on the basis of the results obtained by previous researchers [6, 30, 40] it was predicted that: (a) ADHD children will show slower reaction times than non-ADHD children, and (b) ADHD children will show lateral asymmetries in the reaction time pattern of results that are not evident in the comparison group.

2.1. Method

2.1.1. Participants

Details of the ADHD ($n = 20$) and control children (age and sex-matched; $n = 20$) who took part in the experiments are shown in Table 1. The mean age of the children in the ADHD group was 8 years (range = 5.75–11 years). The mean age of the control subjects was 8 years (range = 6–11 years). The number of years that the ADHD had attended school ranged from 1–6, while the range for the control children was 2–6. There were fifteen males and five females in each group. Two ADHD subjects were unmedicated; eighteen were taking prescribed stimulant medication. For fourteen subjects this medication was Ritalin (methylphenidate hydrochloride), with doses ranging from 10–30 mg/day. For four subjects, medication was Dexamphetamine, with three children taking 10 mg/day, and one child, 17.5 mg/day. The time which had elapsed between the last dose of medication and the commencement of the test ranged from 18–48 h for medicated subjects. All children from both the ADHD group and the control group had had experience with the use of computers (included in school curriculum), and all were right handed [31].

ADHD subjects were recruited through local Parent Support groups. Exclusion criteria for the ADHD group were as follows: (a) uncorrected visual problems (b) IQ

Table 1
Mean reaction times (ms) for ADHD and control subjects for the orienting task in the right and left visual field

Group	Valid		Invalid		Neutral	
	Left	Right	Left	Right	Left	Right
ADHD	612.5	577.5	702	672	669	641
Control	446	455.5	511	498.5	476	477.5

below 80 (c) diagnosis of ADHD by someone other than a qualified pediatrician (d) a diagnosis of a neurological or psychiatric disorder other than ADHD (e) criteria for comorbid mood or anxiety disorders, or conduct disorder. Exclusion criteria for the volunteer group were similar (a, b, d, e) with the inclusion of (f) a score on the behaviour rating scale which met the DSM-IV criteria for Attention Deficit Disorder with or without hyperactivity [1].

Parents of all children were asked to complete a brief behaviour rating scale based on DSM-IV criteria for ADHD. This consisted of 18 statements about behaviour patterns in the last six months. Four response options were given for each item with the minimum value (0) indicating no abnormality and the maximum value (3) indicating frequent manifestation of the described behaviour. The scores for the three core behaviours of inattention, hyperactivity and impulsivity were determined by averaging the scores given for items 1–9, 10–15 and 16–18, respectively. Subjects in the ADHD group fulfil the diagnostic criteria for ADHD on all three core behaviours, while no child in the control group had scores which approached requirements for diagnosis (Inattention: 3.33 vs 0.43; Hyperactivity: 3.63 vs 0.22; Inhibition/Impulsivity: 3 vs 0.4, for ADHD and control respectively, t-tests, $P_s < 0.0001$). The participants attended two sessions (Experiment 1 and Experiment 2), each on separate days. The order of the sessions was counterbalanced across subjects. The experiments were conducted at a convenient time for each participant and coinciding with a normal medication-free period for each child of the ADHD group.

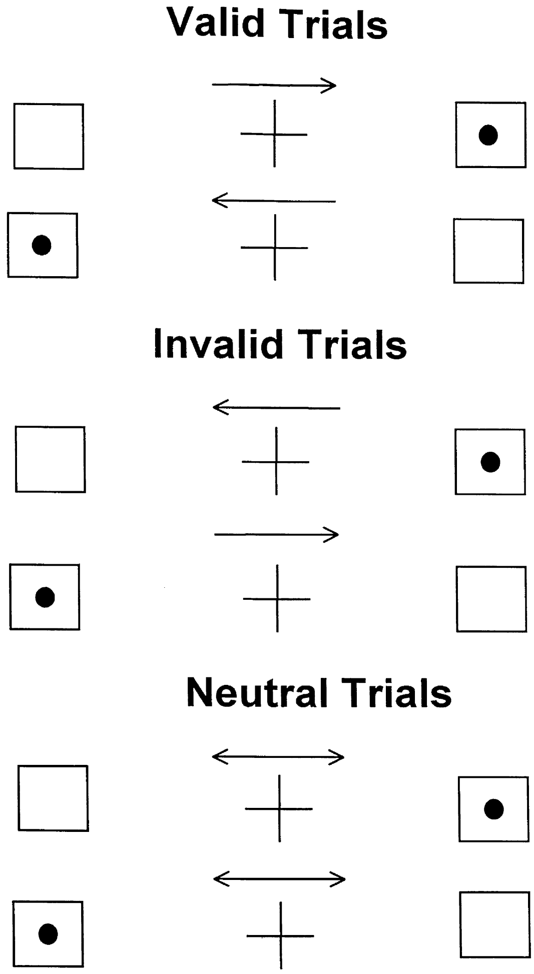

Fig. 1. Examples of trial types in Experiment 1. For all trials, the central fixation cross and the two squares were presented first. The arrow cue followed by the imperative stimulus were then displayed. For valid trials, the arrow indicated the box in which the target subsequently appeared. For invalid trials, the arrow indicated the box which was contralateral to that in which the target subsequently appeared. For neutral trials the arrow pointed to boxes in both hemifields.

2.1.2. Procedure

Each participant was seated comfortably in front of a computer screen, the display of which was driven by an IBM compatible personal computer. The child positioned his/her chin on a chin rest. The distance between the eyes and the screen was approximately 50 cm and the reflection of the child's face was centred on the screen. The child positioned the forearm so that the index finger of the right hand could easily touch the space bar of the computer keyboard.

At the beginning of each trial, a fixation cross ($0.5^\circ \times 0.5^\circ$) and two empty square boxes were displayed. These remained until the end of the trial. The cross was in the centre of the screen. The boxes ($1.5^\circ \times 1.5^\circ$) appeared horizontally to the right and to the left of this cross (Fig. 1) with the distance from the centre of the cross to the centre of each box being 10°. After an interval of 500 ms a cue was presented 5° directly above the cross. The cue was either a double-arrow (2° in length) or a single arrow (2° in length) which pointed to the left or to the right. After a further interval of 800 ms the cue was extinguished and the imperative stimulus, a red dot with a diameter of 0.4°, appeared in the centre of one of the boxes for a period of 100 ms.

Participants were instructed to fixate the gaze upon the cross in the centre of the screen. Upon detection of the red dot in one of the two boxes they were required to press the space bar as quickly as possible with the index finger of the right hand. The experimenter was seated next to the participant to monitor eye movements via a mirror placed above the screen. Individual trials were automatically discarded if the experimenter detected eye movement away from the fixation point during the execution of the response. Before the experiment commenced, the participant was given a practice run to familiarise themselves with the equipment and the basic procedures.

The experiment consisted of four types of trials: (i) catch trials (20%) where no imperative stimulus was presented following cueing; (ii) neutral trials (40%) where the cue was presented as the double-arrow and the probability of the imperative stimulus appearing was the same for each box (50%); (iii) valid trials (32%) where the cue was a single arrow and the imperative stimulus appeared in the box indicated by the arrow; (iv) invalid trials (8%) where the cue was a single arrow but the imperative stimulus appeared in the non-indicated box. Half the targets were presented in the left visual field and half in the right visual field. The different types of trial were presented in random order. For valid and invalid trials the direction of the arrow to the right or left was random and equally probable. Following each trial the subject was given visual feedback of response speed and accuracy on the screen. Each participant undertook 100 trials in each of four blocks of trials ($n = 400$), taking a total of approximately 60 min to complete the whole experiment. Short breaks were allowed between each block but the child remained at the workstation.

Reaction times were discarded if they were less than 100 ms and greater than 3000 ms (or absent). Respectively, these discarded trials were registered as anticipation and delay errors. The experiment continued until sufficient numbers of error-free trials (no observable eye movements, no anticipation or delay) were achieved.

2.1.3. Data analysis

The mean reaction times of accepted trials were entered into a mixed factor design ANOVA. This consisted of a between-subjects factor, Group (ADHD, Control) and two within-subjects factors, Condition (Valid, Invalid, Neutral) and Visual Field (Left, Right). Post hoc comparisons between means of interest were performed using the Newman–Keuls procedure (α-level = 0.05).

The mean numbers of each type of error trial were also subject to analysis. Such trials included those in which an eye movement was detected, those in which the participant gave a response to a catch trial, those in which the response had been anticipated, and those in which the response was delayed/missing. Numbers of each of these trial types were determined for each Group, Condition and Visual Field. These numbers were also entered into a three-way repeated analysis of variance. The effect of fatigue was examined by performing a three-way analysis of variance on reaction time values with Group, Block (1, 2, 3 and 4) and Condition as factors.

Further analyses were conducted on the calculated dependent variables of 'costl1', 'cost2' and 'benefit'. Given the consistent finding of performance asymmetry in ADHD children [6, 30, 40] these analyses were conducted to determine whether 'costs' (for orienting attention towards the falsely indicated location) or 'benefits' (for orienting attention towards the correctly indicated location) differed according to hemifield. For each subject, the mean 'cost1' measure was determined by subtracting the mean reaction time of neutral trials from that of invalid trials. The mean 'cost2' measure was determined by subtracting the mean reaction time of valid trials from that of invalid trials. (This second 'cost' calculation was conducted in order to avoid the ambiguous effect that often characterises neutral trials [18]). The 'benefit' measure was determined by subtracting the mean reaction time of valid trials from that of neutral trials. These mean values were entered into mixed factor design ANOVAs, with the between subjects factor as Group (ADHD, control) and the within subjects factor as Visual Field (left, right).

2.2. Results

With the analysis of the various types of error trials, the results showed no obvious difference between the two groups. This was also the case for Experiment 2 and, for the sake of brevity, the results and statistics for these discarded trials will only be presented for Experiment 1.

Summing the number of all types of error trials ('catch', eye movements, anticipations, delays/misses), both ADHD and control subjects showed a low percentage of such trials and there was no significant difference when comparing the two groups (ADHD = 10% Control = 8%; $P > 0.05$). Anticipations and omissions did not differ significantly between the two groups ($P > 0.05$) or across the three conditions ($P > 0.05$). Both type of errors did not correlate with any of the factors considered in the analysis. For example, the Group × Visual Field interaction was not significant ($P > 0.05$). Both groups showed the same percentage of trials with eye movements (2%). The number of misses was no different across the two groups ($P > 0.05$) nor was there a significant difference for the number of responses to catch trials (ADHD: 1%, Control: 1%; $P > 0.05$).

For the assessment of fatigue, the main factor, Block, was not significant ($P > 0.05$); nor was the interaction between Group and Block ($P > 0.05$). The main factor Condition also did not interact significantly with the factors Group and Block ($P > 0.05$). Such results suggest that both groups showed similar effects from fatigue and that these effects were equally distributed across the three conditions. Again, as no fatigue effects were found for Experiment 2 the results will not be presented.

With the analysis of the mean reaction time of accepted trials, ADHD subjects showed the expected result of longer reaction times than control subjects ($F(1,19) = 38.22$, $P < 0.0001$; 646 vs 477 ms, respectively). As shown in Fig. 2, both groups also showed the expected result of a difference in reaction times according to cueing condition (main effect of Condition: $F(2,38) = 27.09$, $P < 0.0001$). Mean reaction time to validly cued targets (523 ms) was faster than that for neutrally cued targets (566 ms) which in turn was faster than that for invalidly cued targets (596 ms).

ADHD subjects showed slower reaction times to tar-

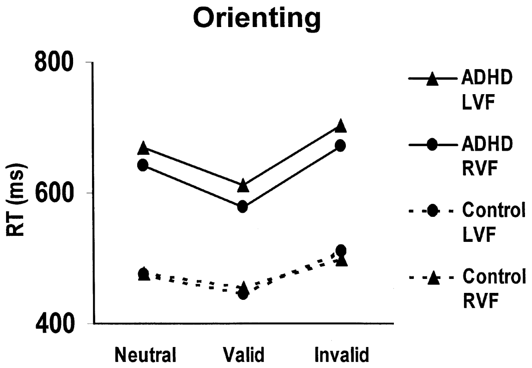

Fig. 2. Mean reaction times for each trial type for ADHD and control children. Note for ADHD children, that reaction times to targets presented in the left visual field (LVF) are generally longer than those to targets in the right visual field (RVF).

gets presented in the left (661 ms) than to targets presented in the right (630 ms) visual hemispace (Group by Visual Field interaction: $F(1,19) = 8.06$, $P < 0.001$; see Table 1). As illustrated in Fig. 2, this slowness is evident for all left targets irrespective of cueing condition. Control children did not show differences in reaction time between the left and right hemifields (478 vs 477 ms).

Interestingly, the analysis of 'costs' and 'benefits' showed no further evidence for a lateralisation of performance by ADHD children. The costs incurred in having to disengage attention from the right to re-engage it upon a left target were no different from those incurred for the opposite requirement from left to right. Benefits also showed no difference according to side of target presentation. However, there were Group differences for costs (cost2 only) and benefits. ADHD children showed greater 'benefits' than control children (60 vs 26 ms; $F(1,19) = 18.83$, $P < 0.0001$). For 'costs', the Group effect was only when this parameter was calculated as the difference between valid and invalid trials (92 vs 54 ms for ADHD and control children respectively, $F(1,19) = 21.32$, $P < 0.001$) rather than when it was calculated the difference between invalid and neutral trials (32 vs 28 ms, respectively).

2.3. *Summary and discussion of Experiment 1*

The results from Experiment 1 demonstrate that this group of ADHD subjects could perform suitably the dissociable elements tested in the classic Posner paradigm when the delay between cue and stimulus was 800 ms. As found also for the control children, benefits to processing time were incurred by directing covert visuo–spatial attention to a visual field location within which an imperative stimulus subsequently appeared. Evidence that attention was suitably engaged to this attended site was provided by the finding of greater reaction times for invalidly cued targets, suggesting that attention needed to be disengaged, moved and re-engaged upon the new location.

As expected, reaction times of ADHD children were longer, by on average more than 150 ms, than those of the control children, suggesting a generalised reduction in the time efficiency of the central processing of cognitive functions. As further expected, the ADHD children showed performance asymmetry, with reaction times to stimuli presented in the left visual hemifield being around 30 ms longer than those presented in the right hemifield. This suggests that the right hemisphere is slightly more compromised in its ability to perform in a time efficient manner. Given the finding of no asymmetry in the cost/benefit pattern, these results appear to indicate a more general right hemispheric dysfunction in the management of attentional resources [6, 30, 40].

A particularly interesting finding was the generally longer benefits and costs of ADHD children. The former result suggests that ADHD children are 'super'-attended to the cued location to the extent that responses to stimuli presented at the cued location are very well primed. However, caution in adopting this view must be stressed. The calculation of the 'benefit' value is in part derived from the 'neutral' value, the mean reaction time of trials which had been cued by a double arrow pointing to both visual hemifields. As can be seen with the analysis of the two cost values, which involved derivation from the 'neutral' value did not show Group differences. This is probably a reflection of the 'ambiguous' nature of this type of cueing where subjects could be jumping attention from one to the other visual hemifield, splitting attention between the hemifields or adopting some other attentional management strategy. Basically, the equivocal character of these cues makes it ill-justified to use the 'neutral' value as a reference point for the calculation of cost/benefit measures.

When costs are calculated as the difference between reaction time for invalid and valid trials, a Group difference emerges, with ADHD children showing longer costs than control children. This suggests that the processes of disengaging, moving and re-engaging attention upon the unexpected location takes longer, and adds support to the idea that the ADHD children of the current study anchor covert attention strongly to the cued location. Contrary to previous findings [6, 40] the ADHD group do not appear to re-orient attention more quickly than control subjects, but have difficulty in disengaging attention once anchored to a particular position.

There are a number of factors that may explain the differences in results between the current and previous studies. Subtle aspects of the methodology differed. For example, in the current study there is a fixed cue/stimulus delay that may have favoured the adoption of a strategy which differs from that used when more than one cue/stimulus interval is employed [6, 30, 40]. A further difference from some previous studies is that eye movements were controlled to ensure that covert as opposed to overt mechanisms of attention were adopted.

Another reason why the results may differ from that of previous research could lie in the heterogeneity of the population under investigation. Investigations of certain subject groups with neurological damage have demonstrated differences of results according to participant characteristics. For example, in Parkinson's disease subjects, factors such as age, duration of illness, level of disability, and response to the absence of medication all contribute to diversity of results [5, 25, 44, 46].

3. Experiment 2

In the previous experiment the emphasis was on the assessment of the covert orienting of attention rather than on other attentional functions. In Experiment 2 the function of focusing covert visuo–spatial attention is assessed by changing the size of the area to which attention is oriented. In non-brain-damaged subjects the usual result is that reaction times to stimuli presented in small regions of the peripheral visual field are lower than those to stimuli presented in larger regions [8–12]. This has been interpreted as reflecting an inverse relationship between processing efficiency and size of the attentional focus.

The level of interdependence between the two functions of orienting and focusing is not yet known. The limited evidence to date suggests that there could be some distinction between the two processes. For example, Stoffer [39] proposed that focusing is subsequent to orienting or that the two processes act in parallel but focusing takes longer. In Experiment 1, there was no need to change the size of the covert attentional focus, that is, the focusing component could be held constant from trial to trial. Experiment 2 manipulates the focusing component across trials by changing the size of the area to which attention is to be directed. The restriction of the orienting task to one hemisphere for the duration of a trial means that the subject is not required to shift attention between hemispheres, and this may add to the emphasis placed on the focusing component. This experiment has been designed to confirm the presence of a lateralised deficit in ADHD children and to further characterise the nature of the covert attentional deficit in this population.

3.1. Methods

3.1.1. Apparatus and procedure

The apparatus and the procedures are similar to those utilised for Experiment 1. Each trial began with the display of the central fixation cross ($0.5^\circ \times 0.5^\circ$), which remained on until completion of the trial. After a 500 ms interval, one square box appeared either to the right or to the left of the cross. The box could be one of three sizes: small ($1.5^\circ \times 1.5^\circ$), medium ($2.5^\circ \times 2.5^\circ$), or large

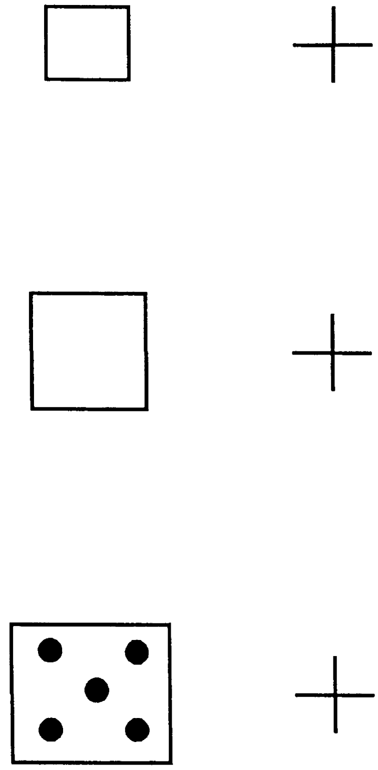

Fig. 3. Example of screen displays used in Experiment 2. In this case the block in which left targets were presented is illustrated. Each trial commenced with the central fixation cross. This was followed by presentation of one box (in this case on the left) which was either of small, medium or large size. The imperative stimulus would then appear in one of five positions in the box.

($3.5^\circ \times 3.5^\circ$; Fig. 3), and the sequence of presentation according to box size was random. The imperative stimulus (a red dot with a diameter of 0.4°) was presented 800 ms later, randomly at one of five possible locations inside the boxes (Fig. 3). Four locations were around the inside perimeter of the box, while the fifth location was at the centre of the box. This procedure was adopted in order to enhance the attentional scanning of the entire portion of space delimited by the box. Please note, however, that in the case of the small box the stimulus appeared almost in the same position.

Two blocks of trials were administered. In one block of 100 trials the box appeared only in the left hemifield. In the other block of 100 trials the box appeared only in the right hemifield. The order of these blocks according to hemifield was counterbalanced across subjects to reduce sequencing effects. Of the total number of trials, 90% were valid with the imperative stimulus appearing in the expected hemifield. The remaining 10% of the trials were 'catch' trials with no stimulus appearing. In all other respects the procedures for task performance feedback, trial rejection, and practice were the same as described for Experiment 1.

3.1.2. Data analysis

The mean reaction time of accepted trials were entered into a mixed factor design ANOVA. This consisted of a between-subjects factor, Group (ADHD, Control), and two within-subjects factors, Size (Small, Medium, Large) and Visual Field (Left, Right). Post hoc comparisons were with the Newman–Keuls procedure. The number of misses, responses to catch trials, trials rejected due to eye movements and 'error' trials were determined for each Group, Size and Visual Field. As mentioned previously, the results of these analyses will not be reported as there was no difference between ADHD and control subjects.

3.2. Results

With the analysis of accepted trials, reaction times for ADHD subjects were more than 200 ms longer than reaction times for control subjects ($F(1,19) = 44.12$, $P < 0.0001$; 661 ms vs 456 ms respectively). With data collapsed according to hemifield, both subject groups showed the expected result of an increase in reaction time with an increase in box size (main effect for Size: $F(2,38) = 50.12$, $P < 0.0001$). For ADHD children the mean reaction times were 618, 674 and 693 ms for the small, medium-sized and large boxes respectively. For the control children these values were 405, 448 and 514 ms, respectively. Performance differences between the groups became evident when comparing reaction time focusing patterns of the right and left visual hemifields. As illustrated in Fig. 4, control children show an increase of reaction time with focus area size in both visual hemifields. In contrast, for the ADHD children this progressive increase is found only for stimuli presented in the right visual field. In the lower part of Fig. 4 it can be seen that the mean reaction times to stimuli presented in the left visual field do not show a progressive increase. This result is reflected in the significant interaction between Group by Size by Visual Field ($F(2,38) = 7.29$, $P < 0.001$). Post-hoc comparisons showed that there was no significant difference between mean reaction times for the medium-sized (678 ms) and large (674 ms) boxes in the left visual field for ADHD children (Table 2).

3.3. Summary and discussion of Experiment 2

A global assessment of the results for this experiment gives the impression that ADHD subjects modulate suitably the efficiency of processing according to the size of the attentional focus. Generally reaction times increase with focus size, a result which is in accordance with previous research on this focusing function [7–11]. However, subtle indications of abnormality are evident for responses given to stimuli presented in the left visual hemispace. Specifically, reaction times do not show a progressive increase from the medium-sized to the largest cued areas used in this study. In other words, the efficiency of processing the covertly attended space is similar across different sized regions of the left visual field.

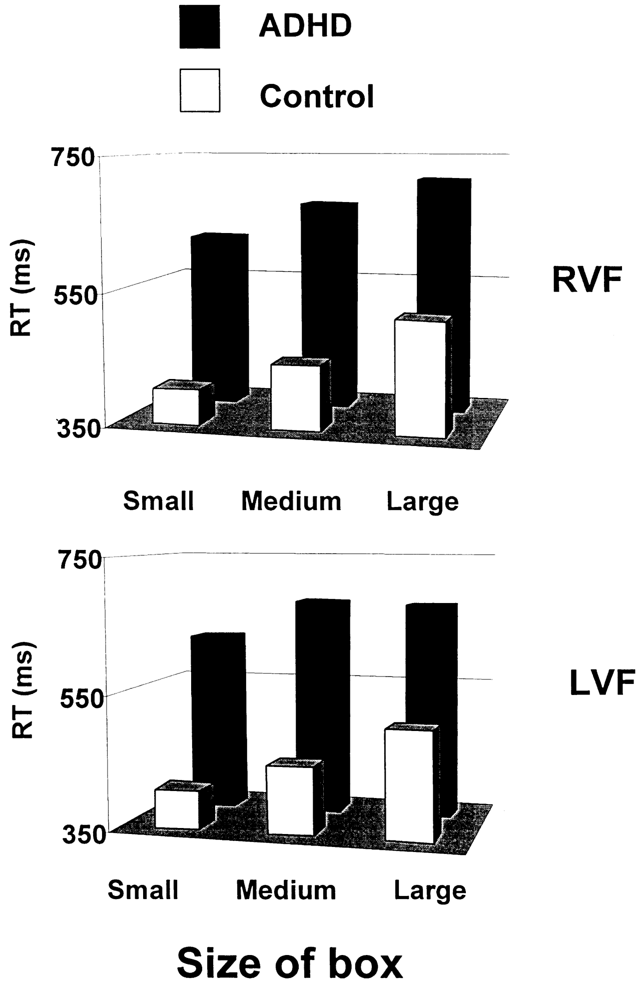

Fig. 4. Mean reaction times for the small, medium-sized and large boxes for ADHD (black columns) and control (white columns) children to targets presented in the right (above; RVF) and left (below; LVF) visual fields. Note that reaction time generally increases with box size. The exception is for ADHD children in response to targets presented in large regions of the left visual field.

Table 2
Mean reaction times (ms) for ADHD and control subjects for Experiment 2 for small, medium and large boxes in both left and right visual fields

Group	RVF			LVF		
	Small	Medium	Large	Small	Medium	Large
ADHD	615.5	670.5	711	619.5	677.5	674
Control	402.5	446.5	518	407	450.5	509.5

Note: RVF = Right Visual Field; LVF = Left Visual Field.

Of note, is that performance asymmetry is again confined. Further, and as found in Experiment 1, the abnormality is confined to the left visual space suggestive of right hemispheric dysfunction. An interesting interpretation of the lower than expected processing time for stimuli presented in reasonably large areas of the visual space is that ADHD children show greater efficiency of processing of large regions in the left visual field.

4. General discussion

In this study, children with attention deficit hyperactivity disorder were compared with control children on performance in tasks requiring quick responses to targets presented on a computer screen. Two main covert visuo–spatial attentional functions were assessed: (a) the orienting and re-orienting of attention to the left and right visual fields, and (b) the focusing of attention to different sized regions of the left and right visual fields. Clear results emerged. Firstly, the ADHD children showed generally longer reaction times than the control children (Experiments 1 and 2), and reaction times of ADHD children to stimuli presented in the left visual field were generally longer than those to stimuli presented in the right visual field (Experiment 1 and Experiment 2, small and medium-sized boxes only). Secondly, ADHD children showed greater 'benefits' and 'costs' to stimuli presented in both fields (Experiment 1). Thirdly, ADHD showed similar reaction times to stimuli presented in medium-sized and large boxes in the left visual field, rather than a progressive increase as found for the right visual hemispace (Experiment 2).

The finding of a general augmentation to processing time in ADHD children is generally consistent with the results of previous research [6, 30, 40]. For both experiments of the current study, mean reaction times of ADHD subjects were more than 150 ms greater than those of control subjects. Two studies have presented neuropsychological theories to explain this bilateral increase of processing time in ADHD children. Heilman et al. [14] postulate that the primary dysfunction is in the right hemisphere, with resultant disruption to the bilateral role in attentional functioning played by this hemisphere. This dysfunction is responsible for reduced ability to maintain arousal in the right hemisphere. Malone et al. [24] postulate that slower responses to stimuli in the right field reflect left hemisphere primary dysfunction (to the dopaminergic system) and that slower responses to left field stimuli reflect the secondary effect of inadequate regulation of an overactive right hemisphere (noradrenergic system).

The results of the current study indicate that ADHD children show performance asymmetry, with responses to targets presented in the left visual field being generally slower (by around 30 ms) than responses to targets presented in the right visual field. Such results are in line with the prediction of Heilman et al. [14] of slower responses to the left than the right visual field because of decreased arousal levels in the right cerebral hemisphere. The model of Malone et al. [24] of left hemisphere dysfunctions is less well supported.

The asymmetry component of this dysfunction is consistent with all previous research on visuo–spatial attentional functions with the ADHD population. However, differences in the exact characterisation of this asymmetry are apparent. In contrast to the results of the current study, Swanson et al. [40] report that ADHD children showed greater reaction times to exogenously cued stimuli presented in the right visual hemifield than to those stimuli presented in the left field. However, Nigg et al. [30], using the same paradigm, found longer reaction times to uncued stimuli presented in the left visual hemifield. The current study suggests that dysfunction is in both hemifields with greater dysfunction in the left field.

Unlike some previous studies, the performance asymmetry found in the current study was not related to the type of trial. For example, the greater reaction times were not confined to invalid trials in which the right hemispace had been cued but the stimulus appeared in the left hemispace. Further, the benefit to reaction time from having oriented covert attention to the correct location of the subsequent stimulus was greater for ADHD children than for control children, irrespective of the side on which the stimulus was presented. Acknowledging that the calculation of 'benefits' may be subject to error (see Discussion following Experiment 1), this result suggests that covert visuo–spatial attention is well-anchored to the field location and that efficiency of processing is greatly enhanced by this strong anchorage. Both hemispheres of ADHD children appear to show this strong anchorage and accrued temporal benefits in performance.

Support for the concept that attention is more strongly anchored to the attended region is given by the finding that 'costs' are also greater bilaterally for ADHD than for control children. This suggests that ADHD children show time inefficiency in the process of disengaging attention from the cued location for re-deployment and re-engagement upon an unexpected location in the contralateral hemispace. Given the greater 'benefits', this inefficiency may result from difficulties in releasing the attentional focus from the location to which covert attention is anchored. Covert attention of ADHD children could be said to become more easily locked onto a cued region of visual space with the result that it is less easily released to alternative locations.

The finding of greater costs, is not consistent with previous studies. On finding a reduction in costs for exogenously cued targets in the left visual field, Swanson et al. [40] postulated a dysfunction in the ability to sustain the engagement of attention upon a cued right visual field location, with the result that alternative locations recapture the attentional focus more readily. Because 'costs' for invalidly cued targets in the right visual field were similar to those of control children the authors favoured less the idea that the greater reaction time to right than to left visual field targets which had been invalidly cued, could reflect a "persisting cost associated with an invalid cue presented in the LVF" (p. S126). Using an endogenously cued task, Carter et al. [6] also found asymmetry, with reaction time 'costs' to invalidly cued left visual field targets being lower than 'costs' to invalidly cued right visual field targets. They suggested that this reflected difficulty in sustaining attention or a dysfunction in the ability to inhibit processing in the non-cued field. The idea of attention being abnormally locked to a cued left field location was not raised.

A possible argument to explain the differences between the results of the current study and those of previous studies relates to the experimental design. Swanson et al. [40] and Carter et al. [6] had variable intervals (100 and 800 ms) between the cue and stimulus. In the present study, the cue/stimulus interval was fixed at 800 ms. Even though 'catch' trials (where no target was presented subsequent to cue presentation) were interspersed amongst valid, neutral and invalid trials, the use of a fixed interval may have introduced a greater degree of automatic behaviour in relation to awareness and detection of the stimulus target, with the set time interval acting as an additional cue to the arrival of the target and promoting a heightening of attention to the instant the target was expected. This temporal cueing may have reduced the spatial attentional demands required to prepare for arrival of the target. If we are to accept this argument and given that differences in reaction time between the two groups were much larger than expected, it could be proposed either that the control group used this to their advantage, or that the ADHD group were not able to take advantage of the temporal cueing. This would suggest an impairment in the anterior attentional network proposed by Posner and Petersen [36], involved in the awareness and detection of targets. A completely contrasting explanation could be used to explain the observed ADHD performance feature of prolonged maintenance of attention upon the cued location. Perhaps ADHD children are more sensitive to the additive effects of spatial and temporal cueing, and this results in a stronger anchorage of attention.

Of note however, is that the small number of responses to 'catch' trials, suggests that neither the ADHD nor control children time-locked responses to cue appearance. Further, both groups showed a validity effect with reaction times to validly cued trials being lower than reaction times to invalidly cued trials. If responses were automatically time-locked to the cue appearance the expectation would be for no differences in reaction time according to trial type. This was not the case, and suggests that the effects of spatial cueing were paramount in determining response performance patterns.

The results for the focusing attentional function also suggested that time-locking was not occurring and in many respects the ability of ADHD subjects to modulate the focus of attention with respect to attended visual field size appears to be very similar to that of control children. As shown in Experiment 2, ADHD subjects could vary the extent of attentional focus, and generally showed the same pattern of decreasing processing efficiency with increases in the extent of the attentional focus [8–12]. They were able to orient attention appropriately to an exogenously cued location and to modulate the attentional focusing according to the area within which the imperative stimulus appeared.

A group difference in the focusing function was evident at the larger focus area sizes. Control subjects showed appropriate modulation of the focus from medium to large areas in both visual hemifields. In contrast, ADHD subjects did not show the usual increase in processing time from medium to large areas of the left field. This processing time plateau may be a product of the higher reaction times for the ADHD group, such that the maximum processing time is reached at the medium sized area and there is no possibility of increase for the larger focus area. However, the value of the mean reaction time to stimuli presented in the large left field area is more than 40 ms less than that to stimuli presented in the large right field area. This suggests preclusion of a ceiling effect explanation.

Together with the generally longer reaction times to left stimuli, the subtle disturbance to the focusing function adds confirmatory evidence of greater right hemispheric abnormality in ADHD [16, 17, 26–28, 43, 44]. The remarkably similar reaction times to targets presented in medium and large focus areas of the left hemisphere could reflect the adoption of one response timing set for both focus areas. In one respect, this timing equivalence could also be interpreted as a compensatory strategy for an inability of ADHD children to scan thoroughly or distribute attention evenly over large regions in the left visual field.

In conclusion, the results of the current study suggest that ADHD children have subtle deficits with the specific covert visuo–spatial attentional functions of orienting and focusing attention. Though signs are bilateral, it appears that greater dysfunction is of the right rather than of the left hemisphere. It is tentatively proposed that the behavioural equivalent to this attentional dysfunction maybe the reported dysfunction of 'behavioural inhibition' which includes the inability to cease ongoing responses [4]. Children with ADHD tend to continue to respond in the same inappropriate way, repeatedly, seemingly unable to learn from their mistakes and repeated directions by parents and teachers. This tendency could be interpreted as a form of 'anchorage' to a particular response set, which in this case would be the situational factors which trigger certain behaviours.

The proposed pathophysiology of ADHD supports the idea of involvement of the frontostriatal system [19, 21]. Assessing regional cerebral blood flow distributions, Lou et al. [22] reported bilateral hypoperfusion of the striatum and hyperperfusion of cortical sensory regions in ADHD children. Administration of methylphenidate increased striatal perfusion but more so on the left than on the right. The theory used by the authors to explain these findings fits in well with the results of the current study. They proposed that the striatum plays a role in modulating (via inhibition) the polysensory activity of the primary and sensorimotor regions via thalamic connections, and that the right striatum is more compromised than that of the left in ADHD. The underlying frontostriatal basis to ADHD has been confirmed by two recent neuroimaging studies [7, 13]. Relating this to the current study, the abnormally strong anchorage of attention to the cued location could reflect inappropriate inhibition, and thus persistence, of the sensory information given by the cue and the attentional mechanisms subsequently activated by this information. Similarly, persistence with a response timing set across different focus areas could reflect inappropriate setting at the cortical level, particularly of the more damaged right hemisphere, for differentiation between different sized focus areas.

4.1. Limitations

Despite the interest of the present findings we agree with Nigg et al. [30] that caution is warranted regarding specific covert orienting abnormalities in ADHD. The current experiment provides additional evidence for lateral asymmetry in the performance of speeded responses by children with ADHD. Previous research on this topic has provided conflicting results. Consistent with the difficulty in pinpointing the exact attentional deficit in this group, our results add to this conflict by replicating only in part those of other studies. Undoubtedly such differences reflect the different experimental paradigms and the selection criteria for ADHD. As mentioned previously this study monitored eye movements, only endogenous cueing mechanisms were performed and a constant cue/stimulus interval of 800 ms was employed. ADHD children who participated in this study were referred by clinicians who were not members of our investigative team. Diagnostic practices across a diverse set of community practitioners can vary considerably with no assurance that these subject had the disorder. However, the use of a rating scale to describe the types and severity of ADHD symptoms shown by the subjects suggest that these children had ADHD symptoms.

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