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Attention-Deficit/Hyperactivity Disorder and Working Memory: A Task Switching Paradigm

K.K. WU,[1] V. ANDERSON,[2] AND U. CASTIELLO[3]

[1]Department of Clinical Psychology, Caritas Medical Centre, Hospital Authority of Hong Kong,
[2]Department of Psychology, The University of Melbourne,
[3]Department of Psychology, Royal Holloway – University of London, and Dipartimento di Psicologia Generale, Università di Padova, Italy.

This study investigated working memory (WM) in children with Attention-Deficit/Hyperactivity Disorder (ADHD) using a task switching paradigm with Stroop color-word stimuli which required participants to switch from color-naming to word-reading. High and low WM load conditions were compared by manipulation of task reminders as a tempo cue. The sample comprised 83 children with ADHD and 29 normal children comparable in age (aged 7 to 13). Within the ADHD group, participants were divided according to the presence or absence of Learning Disability (LD). Results indicated that children with ADHD had slower response times and less accurate responses in general, however, the ADHD groups were not consistently slower in the high WM load condition. Instead, an impairment in adjusting response speed to cope with higher task demands (i.e., high WM load condition) was found. These results do not support the previously documented association between ADHD and a primary deficit in WM for task switching. However, children with ADHD do demonstrate a specific difficulty in slowing down for a demanding task. Present findings suggest that earlier proposals of under-arousal and poor state regulation in ADHD deserve renewed attention.

Introduction

Specific Deficits Associated with ADHD

In recent years, a number of studies have reported that Attention-Deficit/Hyperactivity Disorder (ADHD) may be associated with specific deficits in executive skills, which are purported to be subsumed by frontal brain regions (Pliszka, Borcherding, Spratley, Leon, & Irick, 1997; Schachar & Logan, 1990; Tannock, Schachar, Carr, Chajczyk, & Logan, 1989). Many of these studies have focused on investigating inhibition as a measure of executive functioning (Pliszka et al., 1997; Schachar, Tannock, Marriott, & Logan, 1995; Tannock et al., 1989). Like inhibition, working memory (WM) is also considered an executive function requiring intact frontal functioning (Baddeley, 1997; Pennington & Ozonoff,

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Address correspondence to K.K. Wu, Department of Clinical Psychology, Caritas Medical Centre, 111 Wing Hong Street, Shamshuipo, Kowloon, Hong Kong. E-mail: wukyk@ha.org.hk.

1996). Although inhibition and WM can be viewed as independent processes, they do not necessarily need to be mediated by separate cognitive or neural mechanisms (Goldman-Rakic, 1987). Some researchers have suggested that inhibition is an intrinsic property of a WM system (Cohen & Servan-Schreiber, 1992; Kimberg & Farah, 1993), while others argued that it is only when high demands are placed on inhibition and WM that the prefrontal cortex is activated (Cohen & Servan-Schreiber, 1992; Diamond, 2002; Diamond, Kirkham, & Amso, 2002).

Studies examining these aspects of executive function in children with ADHD have reported conflicting findings. Those focussing on interference control and WM load have shown no differential WM load effect in ADHD children when compared to controls (Schachar, Logan, Wachsmuth, & Chajczyk 1988; Van der Meere & Sergeant, 1987, 1988a, b). Similarly, in a study comparing ADHD and control children, using measures of WM capacity designed specifically to load the 'central executive' component of WM, no group differences were identified (Kuntsi, Oosterlaan, & Stevenson, 2001). However, as high demand on both inhibition and WM are argued to be necessary for activating prefrontal regions, inadequate task demand in previous studies may have contributed to failures in tapping prefrontal function, and WM deficit associated with ADHD.

Task switching paradigms may provide the necessary task demands to accurately examine these issues, as WM and response inhibition are both highly demanded in task switching. Rogers and Monsell (1995) have developed the *alternating runs* paradigm for examining the cognitive processes involved in task switching. In this paradigm, the switch and non-switch trials are mixed together in a block of trials. The switching occurs on every second trial, thus, the sequence for the switch and non-switch trials for tasks 'A' and 'B' is AABBAABB and so on. The first trial of a task is the switch trial and the second trial of a task is the non-switch trial. The increase in RT and errors in the switch trials, as compared to the nonswitch trials, is considered the cost incurred for the switching process. Allport and Wylie (1999, 2001) have argued that the appropriate baseline for measuring task switching performance under optimal task preparation in the alternating runs paradigm is questionable. They found that task set inertia would pull one back to acting in terms of the alternative task when the stimulus attribute of the nonswitch trial that is relevant for the alternative task is seen. Thus, extra time (i.e., residual switch cost) is needed to inhibit the effect associated with task set inertia, and subjects will slow down even on non-switch trials. Moreover, performance in the switch trials of the alternating runs paradigm, against which the baseline (i.e., nonswitch trials) is compared for the switch cost, is found to be confounded by the *restart effect* (Allport & Wylie, 1999, 2001). For this restart effect, there is a significant increase of RT and decrease of error rate for the first trial in a block of trials, even though it is preceded by another block of trials of the same task.

Though the alternating runs paradigm may not be reliable for estimating the switching cost, the paradigm provides a well-controlled context for studying WM and inhibition in task switching. Confounding factors like difference in strategy and mental load are controlled because the switch and nonswitch trials are embedded within a single block of trials. By using ambiguous task stimuli, for example, Stroop color-word, the task switching paradigm enables systematic examination of the inhibitory effect associated with switching between tasks (Allport & Wylie, 1999, 2001). The high demand on inhibition for performing task switching with ambiguous stimuli is evidenced by the robust switch cost found in these studies with adult participants. Allport and colleagues (1994) found that switching from a more difficult task (e.g., Stroop Color-Word) to an easier task (e.g., Stroop Word) takes longer than switching in the opposite direction because the inhibition requirement is greater in this kind of switching. The demand on WM in switching has also been studied previously. Spector and Biederman (1976) reported that task switching has a large effect when the selection of the appropriate operation requires that one keep track of previously performed operations. When there is no task reminder, the load on WM will significantly increase as participants have to depend solely on their WM to perform the switching task.

Theories for ADHD

The findings that suggest inhibitory dysfunction are consistent with the behavioral inhibition theory (Quay, 1988), which argues that children with ADHD may respond rapidly relative to their own baseline rate, but in an inaccurate manner, and demonstrate difficulty slowing down appropriately when necessary. Such findings also support the executive dysfunction theory of ADHD developed by Barkley (Barkley, 1994, 1997, 1999). According to this model, impairments in behavioral inhibition is the primary deficit in ADHD, particularly for children exhibiting symptoms of hyperactivity (i.e., the Predominantly Hyperactive-Impulsive Type and Combined Type). The model hypothesizes that ineffective execution of behavioral inhibition leads to secondary impairments in four 'executive' neuropsychological abilities: (a) WM; (b) self-regulation of affect-motivation-arousal; (c) internalization of speech; and (d) reconstitution. Impairments of these functions in turn interfere with effective self-regulation and adaptive functioning. Based on this model, deficits in any aspects of executive functions can be seen as support for the theory. Although both theories may account for symptoms of impulsivity in ADHD children, it does not easily explain why these children's responses are often found to be slow and variable, even for simple nonexecutive RT tasks (Douglas, 1999; Sergeant, Oosterlaan, & Van der Meere, 1999; Van der Meere, 1996).

The resource allocation hypothesis for ADHD offers an alternative explanation for the deficits observed in children with ADHD (Sergeant & Van der Meere, 1990a; Sergeant et al., 1999). Based on Sternberg's (1969, 1975) additive-factors model and Sander's (1977, 1983) cognitive-energetic model of information processing, Sergeant and Van der Meere (1990a, 1990b, 1994) proposed that there are three 'energetic pools' in information processing (i.e., arousal, activation, and effort) and that children with ADHD are deficient in the motor response stage of information processing. Using an experimental manipulation of attentional variables to increase processing demands at the encoding and searching stages of Sternberg's model, these investigators failed to identify differences in performance between children with ADHD and controls. Based on these results they questioned the notion that attentional or executive problems are the primary deficit in ADHD. Further, they attributed the slow and variable reaction time (RT) identified for children with ADHD as reflecting deficits in the output stage of information processing (Sergeant & Van der Meere, 1990a, 1990b, 1994).

Taking this approach, ADHD is not associated with an attentional deficit, but rather with a deficit in the regulation of effort, activation, or both, often termed a 'state regulation deficit' (Sergeant et al., 1999; Van der Meere, 1996). Accordingly, the concept of state refers to the overall level of alertness of the person (Posner, 1978). State regulation refers to 'energy mobilization', which is necessary to change the state of the person in the direction that is optimal for a task or situation (Hockey, 1979). Therefore, performance deficiencies may reflect mismatches between the actual state of the person and the state required for performing a particular task. Employing this framework, factors affecting motivation can be important variables that may affect state regulation, and contribute to the problems observed in children with ADHD. Such a model is consistent with a variety of broadly 'motivational' accounts of ADHD in terms of an enhanced aversion to low levels of stimulation (e.g., Sonuga-Barke, 1994; Zentall and Zentall, 1983).

Co-morbidity of LD

Co-morbidity in ADHD is a complicating factor in research on ADHD. One of the most frequent co-morbidities found in ADHD is learning disability (LD) (Ackerman & Dykman, 1990; Stanford & Hynd, 1994) and is reported to be present in between 10% to 92% of cases (Biederman, Newcorn, & Sprich, 1991). Despite its frequencies, the confounding effect associated with the co-existence of LD in ADHD has been largely ignored (e.g., Pieneda, Ardila, & Rosselli, 1999; Cepeda, Cepeda, & Kramer, 2000). Thus, while many studies reported that children with ADHD can be reliably discriminated from normal controls, it remains unclear if the difference between the ADHD and control groups was due solely to ADHD or could be explained by LD alone or a synergetic effect of ADHD and LD.

It is plausible that both ADHD and LD are associated with deficits in the same component of executive functioning or in different cognitive components, resulting in a cumulative effect, causing the comorbid group to demonstrate poorest performance. Support for this hypothesis can be found from previous studies that have examined cognitive problems associated with LD. For example, Cermak and his colleagues (Cermak, Goldberg, Cermak, & Drake, 1980; Cermak, Goldberg-Warter, DeLuca, Cermak, & Drake, 1981) found deficiencies for the rate and level at which children with LD process information, and Swanson (1993) found that children with LD suffer WM deficits. There is also evidence indicating that LD is a reflection of central nervous system disturbance (Hynd, Marshall, & Gonzalaz, 1991).

A number of studies have investigated whether executive dysfunction in ADHD could be attributed to the comorbidity with LD. These studies have compared performances between the control, ADHD with no LD (ADHD-LD) and comorbid (ADHD + LD) groups. Seidman and colleagues (2001) found that children who had both ADHD and LD were significantly more impaired on both executive and non-executive tasks than those with ADHD alone. According to these authors, LD itself may be associated with cognitive deficits which include speed of processing, attention, WM and executive function. Pennington and colleagues (1993) reported similar findings documenting that 'ADHD' symptoms of the ADHD comorbid group were secondary to reading disability. Other reports found that ADHD is associated with inhibition deficits whereas reading disability is related to deficits in phoneme awareness and verbal WM (Willcut et al., 2001), and that the best predictors for ADHD are deficits in processing speed, object naming, behavioral disinhibition and greater variability in RT, with reading disability related to deficits in verbal WM and slower verbal retrieval speed (Rucklidge & Tannock, 2002). Based on these findings, the general deficit of various executive dysfunctions in ADHD (i.e., attention, WM, and executive function) suggested by the executive dysfunction model (Barkley, 1994, 1997, 1999) might be attributed to the comorbidity of LD. However, the specific deficits of ADHD might include impulsivity suggested by the behavioral inhibition model (Quay, 1988) and state regulation deficit manifested in variable processing speed suggested by the state regulation model (Sergeant et al., 1999; Van der Meere, 1996).

Aims of the Present Study

The present study investigated deficits associated with ADHD in WM within a task switching context where both WM and inhibition are demanded. Stroop stimuli and the alternating-runs task switching paradigm were utilized. The presence of task reminders for task switching was manipulated. Performance of children in the high (absence of task reminders) and low (presence of task reminders) WM load conditions were compared. The study aimed to test the two currently popular models of ADHD: executive dysfunction model and the state regulation model. It was predicted, if the executive dysfunction model (Barkley, 1994, 1997, 1999) was correct, that children with ADHD would reveal problems in WM within a task switching context (i.e., ADHD would be associated with higher cue-absence costs in RT and error rate, particularly for the high WM load task). However, in order to accept the state regulation model (Sergeant et al., 1999; Van der Meere, 1996), that ADHD is related to problems in regulating an appropriate mental 'state' to perform task switching (i.e., slower and more variable RT in general; and a speed-accuracy trade-off would be identified in the demanding condition). In addition, the prediction of the behavioral inhibition theory of Quay (1988) would be consistent with the finding of speed-accuracy trade-off.

The present study also examined the impact of comorbidity with LD. In accordance with previous findings, it was predicted that differences in patterns of performance would emerge with respect to the presence of LD in ADHD. If there were significant differences between the normal Comparison and ADHD, with or without LD, groups, this would suggest specific impact related to ADHD. If the ADHD with LD group performed significantly poorer than the other two groups, while there was no significant difference between the normal Comparison and ADHD without LD groups, this would suggest specific deficit related to LD. If there was progressive significant difference between the normal Comparison, ADHD without LD, and ADHD with LD groups, this would suggest specific impact related to ADHD, along with additional impact related to LD.

Methods

Participants

The present study involved three groups of children: 58 with ADHD but not LD (ADHD-LD), 25 with ADHD and LD (ADHD + LD), and 29 normal children from the community as Comparison. They were aged 7 to 13. The gender distribution for the three groups was as follows: Comparison (22 boys & 7 girls); ADHD-LD (50 boys & 8 girls); ADHD + LD (20 boys & 5 girls). The children with ADHD were recruited from referrals from the Royal Children's Hospital, Melbourne, Australia. Judgement by experienced pediatric clinicians and reports by parents using standardized behavioral rating scales were both utilized to define ADHD and minimize the possibility of false positives in identification. Clinical judgements were derived based on DSM-IV criteria (American Psychiatric Association, 1994). The Behavioral Assessment System for Children – Parent Rating Scale (BASC-PRS: Reynolds & Kamphaus, 1992) was used to collect information regarding the child's behavior. The present study included only those children with ADHD whose scores in either one or both of the *Attention Problems* and *Hyperactivity* subscales of the BASC-PRS were greater than the 90th percentile.

Participants were seen individually in two sessions. In the first session, a battery of screening and neuropsychological tests were administered (Wu, Anderson, & Castiello, 2002). In the second session, the experiments described in the present study were conducted.

IQ was estimated by using a short form of the Wechsler Intelligence Scale for Children – 3rd edition (WISC-III: Wechsler, 1991) consisting of the Similarities, Vocabulary, Block Design and Object Assembly subtests. Only children with an overall estimated IQ greater than or equal to 85 with no history of neurological problems other than ADHD and LD were recruited. All children were assessed for LD to determine comorbidity of LD with ADHD.

Comorbidity of LD in the present study was indicated when either the Spelling or Reading subtests of the Wide Range Achievement Test – 3rd edition (WRAT-3: Wilkinson, 1993) were below or equal to the 16th percentile and the standard score of any of the WRAT-3 subtests was 20 points below the estimated IQ. Thus, children classified with LD satisfied the DSM criteria with academic achievement below age expectation and measured IQ. Based on previous findings, the 20-point difference between WRAT-3 and IQ was considered a necessary criteria for defining LD in ADHD (Semrud-Clikeman et al., 1992). The ADHD group was classified into two subgroups, according to the presence of LD: (a) ADHD-LD, for those who did not meet the criteria of LD; and (b) ADHD + LD, for those who met the criteria of LD.

Children for the Comparison group were recruited from local state schools, and met the following criteria: (a) no history of involvement with mental health services for behavioral or emotional problems based on parent report, (b) subscales scores of BASC-PRS were below the 90th percentile of the appropriate age norms; and (c) scores in WRAT-3 and WISC-III did not meet the criteria of LD.

If the 90th percentile in the *Hyperactivity* and *Attention Problems* subscales of the BASC-PRS were used as the cut off point for defining the subtypes of ADHD according to DSM-IV (American Psychiatric Association, 1994), most of the children with ADHD recruited in the study would be classified as belonging to the Combined subtype. The number of participants for different subtypes among the three groups was presented in Table 1.

The sample composed 92 boys and 20 girls. No significant difference in age, gender distribution, and socioeconomic status (as measured by the Daniel’s Scale of Occupational Prestige: Daniel, 1983) was found between the three different groups. Significant group differences were found for estimated IQ (F [2, 109] = 6.74, $p < .01$), and standard scores in WRAT-3 Reading (F [2, 109] = 36.02, $p < .001$) and Spelling (F [2, 109] = 33.05, $p < .001$). Post hoc tests revealed that the IQ for the ADHD-LD group (M = 103, SD = 12) was significantly lower than that for the Comparison group (M = 113, SD = 12) ($p < .01$). Progressive significant differences between the Comparison, ADHD-LD and ADHD + LD groups were found in WRAT-3 Reading and Spelling (ps < .001). The results of age, IQ and standard scores of WRAT-3 subtests were presented in Table 2.

Table 1

The number of participants for different DSM-IV ADHD types among the ADHD groups based on the 90th percentile cut-off point on the Attention Problems and Hyperactivity subscales of the BASC-PRS

	ADHD-LD	ADHD + LD
Subtype		
Inattentive	9	2
Hyperactive-Impulsive	7	4
Combined	42	19

Note: BASC-PRS = Behavioral Assessment System for Children – Parent Rating Scale.

Table 2
The means and standard deviations of Age, IQ, Reading and Spelling Scores for the three participant groups

	Comparison *M* (*S.D.*)	ADHD-LD *M* (*S.D.*)	ADHD + LD *M* (*S.D.*)
Age[a]	10.60 (1.97)	10.45 (2.00)	10.13 (2.19)
IQ[b]	113.65 (12.80)	103.32 (12.80)	105.64 (11.04)
Standard Score for Reading[c]	111.96 (11.01)	100.63 (13.29)	82.60 (13.32)
Standard Score for Spelling[c]	106.03 (14.55)	93.53 (11.43)	79.80 (8.79)

Note: [a]Age in years. [b]Etimated IQ based on performance in WISC-III. [c]Standard Score based on performance in WRAT-3.

One participant from each of the ADHD-LD and ADHD + LD groups failed to attend the second session for the present experiments. Medication for ADHD symptoms (e.g., methylphenidate) was withdrawn both on the screening day and on the day of the experiments to ensure that children with ADHD were off medication for at least 12 hours prior to assessment.

Tasks, Types of Stimuli and Number of Trials

The present study utilized the alternating runs predictable task switching paradigm (Rogers & Monsell, 1995). The Stroop color-word stimuli were used (Stroop, 1935). The words—*red, blue, green* and *pink*—were used as the stimuli for the word-reading task and the ink colors – red, blue, green and pink – were used as the stimuli for the color-naming task. All stimuli were incongruent Stroop stimuli. The ink in which each word was written was incongruent with the color named by that word. As the Stroop stimuli consisted of the word and color associated with the color-naming and word-reading tasks respectively, the stimulus did not indicate which the appropriate task the current trial was. The correct responses for successive trials were always different. Participants were required to switch between the color-naming and word-reading tasks on every second trial in the AABB sequence within a block of trials.

There were two types of switching blocks (i.e., Cue-Present and Cue-Absent). In the Cue-Present condition, task reminders were provided to inform the participants which of the two tasks was presented for a particular trial. In the Cue-Absent condition, task reminders were not given. There were two separate blocks of trials for each of the Cue-Present and Cue-Absent condition. In each block, there were 26 trials. Thus, there were 13 trials for each trial type (i.e., Switch Color, Non-switch Color, Switch Word, Non-switch Word) in each block. The two separate blocks of trials of the same condition were conducted consecutively. The order of the four separate blocks of trial was either (Cue-Absent; Cue-Absent; Cue-Present; Cue-Present) or (Cue-Present; Cue-Present; Cue-Absent; Cue-Absent). The order of conducting the two experimental conditions was counterbalanced over participants within each group. By using the alternating runs paradigm, each block of trials contained an equal number of trials with every combination of the following variables: task (Color or Word) and trial type (Switch no Non-switch). The alternating runs paradigm was used to maximize demands on WM and inhibition, which were the major focus of the present study. The switching cost was not examined due to the confounding effect identified in previous studies (Allport & Wylie, 1999, 2001).

Apparatus

The experiments were driven by an IBM A-T compatible computer with VGA color-monitor and a button-box with voice-activated switch, connected to the parallel port of the computer. Response times were measured as the interval between stimulus onset and the participant's vocal response input to a microphone. The resolution of the timer was 1 ms. The verbal response was keyed in by the experimenter on line. To avoid susceptibility to the Stroop and task switching effect, the experimenter only attended to the participant's verbal response without looking at the screen displaying the stimulus. The checking of accuracy for the participant's response was computerized. The display of the circle with task reminders for the Cue-Present blocks is schematically presented in Figure 1.

The stimuli for the experiments were presented on the computer monitor. An outline circle was displayed on the screen in black against a white background before the first stimulus of each block appeared and remained present throughout the block. The diameter of the circle was 15 cm. The sentence "Switch every 2nd trial" was also displayed on the margin of the screen.

For the Cue-Present blocks, the circle was divided into four equal segments. Stimuli were presented consecutively in a clockwise direction in the center of these segments. The horizontal diameter of the circle, in which stimuli would be displayed, was thickened. Participants were informed that in a specified half of the circle (e.g., upper or lower), they had to perform one of the two tasks (i.e., color-naming or word-reading); and the responses for the other task were required in the other half of the circle. The four segments provided the external cues for the position of the stimulus presentation in each trial. Successive task stimuli were presented in adjacent quadrants of the circle in clockwise order. Next to the upper and lower half of the circle the word *Color* or *Word* was displayed continuously to remind participants which task they had to perform for the particular condition. The assignment of the switching tasks (i.e., between the color-naming and word-reading tasks) and their positions in the upper or lower segments were counterbalanced over participants.

For the Cue-Absent condition, the segments and task reminders were removed. All the stimuli were displayed in the centre of the circle consecutively.

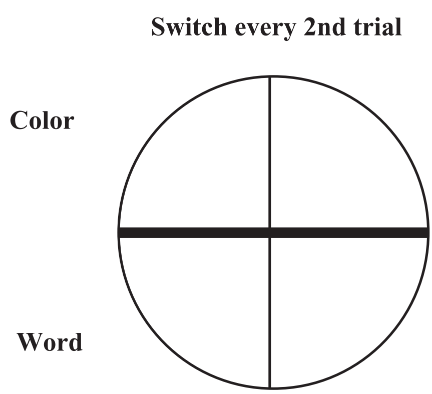

Figure 1. An example of display of circle, segments and reminders as external cues for task switching in the Cue-Present condition. In this example, the color-naming and word-reading tasks are assigned for the upper and lower two quadrants respectively.

Procedures

Prior to the administration of Cue-Present and Cue-Absent conditions, instructions were given on task switching according to position of the trials in the circle or according to the sequence of the trials in the AABB cycle respectively. Participants were instructed to be as fast and accurate as possible. The practice block ended as soon as the child had reached the success criterion of 8 consecutive correct responses.

To start each block of trials, the word ‘Ready?’ was displayed on the screen until the participant answered ‘Yes’. The experimenter then pressed a key to display the outline of the circle with or without task reminders. After a beep (a 2000 Hz tone of 200 ms in duration), the first stimulus appeared 2 s later in a position of which the participant was forewarned by a 5 mm blinking cross ‘+’.

For the Cue-Present condition, the first trial started at the upper left quadrant of the circle next to the horizontal diameter. For both the Cue-Present and Cue-Absent conditions, each color or word stimulus remained on the screen for a minimum of 150 ms until the voice key was activated, or until 5,000 ms had elapsed. This was followed by a 1,000 ms response-stimulus interval (RSI). If the participant made an incorrect response or failed to respond, the following RSI was extended to 1,500 ms. Such a recovery period has been found to be useful in previous research on task switching with normal adult participants (Rogers & Monsell, 1995). This is because, in the task switching conditions, participants are more liable to lose track of which task was appropriate following an error.

If participants made an incorrect response or omitted the trial in the Cue-Absent condition, an error message would be presented for 300 ms within the RSI of 1500 ms. The error message consisted of two pieces of information. One was about the task for the upcoming trial, another was about the sequence of that trial on the AABB task cycle. For example, the message *Word* × *1* reminded participants that the coming trial was the first trial of the Word task, *Color* × *2* reminded participants that the coming trial was the second trial of the Color task. The error message is needed for the Cue-Absent block because in the Cue-Present block, where task-switching cues were present, the prolonged RSI could easily alert participant that an error has been made. Moreover, the task for the upcoming trial was cued. However, in the Cue-Absent block, which aimed at increasing the demand on WM, these cues were absent. Thus, the error message was found to be essential for helping participants orient back to the task after making an error in the Cue-Absent condition.

Trials that were inappropriately administered (i.e., inappropriate triggering or failure to trigger the voice-key, or delayed button key accuracy input) were replaced at the end of the block in a cyclical way. Each cycle consisted of one nonswitch and one switch trial for word-reading and color naming respectively. This replacement procedure applied to all trials in a block except for the first two trials. The maximum number of replacement trials was 14 (i.e., 3.5 cycles).

Data Analysis

The first two trials of each block were excluded from data analysis in order to avoid the confounding restart effect (Allport & Wylie, 1999, 2001). Other exclusion criteria included RTs less than 150 ms, and trials where both the voice input for recording RT and the key press input for the verbal response for checking accuracy were not recorded. These criteria led to exclusion of 6.0% of the data. Like previous studies using the task switching paradigm (e.g., Allport & Wylie, 1999, 2001; Cepeda, Cepeda and Kramer, 2000; Rogers & Monsell, 1995), RT data for incorrect trials and trials immediately following an error were excluded from analyses. According to the report by Rogers and Monsell (1995), 12.7% of the data were lost due to these exclusion criteria in their first experiment. In the present study, there was an exclusion of 28.0% of the RT data. For the analyses of error data, trials immediately following an error were excluded for the analyses because the error messages that were given in the Cue-Absent condition might serve as reminders for switching and confound the result. This has led to exclusion of 14.0% of error data. The replaced trials for the inappropriately administered trials were included in the calculation of the percentage of data exclusion. Based on these criteria, participants who had less than 2 out of 13 trials available for analyses in any trial type were excluded from the analyses. As a result, 8 children from the ADHD-LD group and 2 children from the ADHD + LD group were excluded from the analyses on mean RTs for the effect of cue-absence for switching. However, the pattern of results for RT and error rate was not changed in any significant way even when the trials following an incorrect trial were included in the analyses.

Adequacy of task demand was first examined by comparing the results of the Comparison group with previous findings in normal adults. For group comparisons, the RT, standard deviations of RT (SD) and error data extracted were examined by means of $2 \times 2 \times 2 \times 3$ mixed, repeated-measures ANOVA. All the group comparisons utilising ANOVA were also re-examined with the analysis of covariance (ANCOVA) with IQ as the covariate. IQ was treated as the covariate because the significant group difference in IQ between the ADHD-LD and Comparison groups might affect the result, and confound with the impact of ADHD on the ability examined. When both ANOVA and ANCOVA gave identical significant results, results from the more powerful ANOVA were reported. Otherwise, results from ANCOVA were reported.

Cue (Presence vs. Absence), Trial Type (Switch vs. Nonswitch), and Task (Color vs. Word) were the within-subjects factors, and Group (Comparison vs. ADHD-LD vs. ADHD + LD) was the between-subjects factor. For planned comparisons between groups, the cue-absence costs on each level of Trial Type and Task for each participant were also calculated. Cue-absence costs were estimated by subtracting the mean RT and error rate for the Cue-Present blocks from the corresponding value for the Cue-Absent blocks for individual participants.

Results of analyses based on RT and SD yielded the same pattern of findings. The present report thus was primarily based on the analyses of mean RT, with the exception of the group comparison for overall speed and accuracy. Results of factorial ANOVA and ANCOVA gave identical results for group comparisons, except for the interaction between Cue x Group for error rates: where the interaction was significant in ANOVA, but not when IQ was treated as the covariate in ANCOVA.

Results

Adequacy of Task Demand

The adequacy of the task demand in the study was first examined by investigating the effects of switching for the comparison group in the Cue-Present blocks. The present study replicates previous findings of the asymmetrical switching effect for word-reading and color-naming in the Stroop condition (Allport, Styles, & Hsieh, 1994; Allport

& Wylie, 1999, 2001). When participants have to switch between the color-naming and word-reading tasks with Stroop stimuli, there is a 'reverse Stroop' interference in the RT for word-reading. The asymmetrical effect of switching for Word and Color on RTs was examined by means of 2 × 2 ANOVAs, with Trial Type (Switch & Non-switch) and Task (Color & Word) as the within subjects factors. For RTs, the main effect for Trial Type ($F[1, 28] = 11.87$, $p < .01$, ES = .29) and Task ($F[1, 28] = 36.28$, $p < .001$, ES = .56), and the interaction of Trial Type × Task ($F[1, 28] = 9.41$, $p < .01$, ES = .25) were significant. The interaction was examined by investigating the simple effect of Trial Type for each Task. For Word, the simple effect of Trial Type was significant ($F[1, 28] = 17.30$, $p < .001$, ES = .38). For Color, the simple effect of Trial Type was not significant.

The comparisons of performance in RT between the Cue-Present and Cue-Absent blocks confirmed the importance of reminders for performing task switching as the RT for Cue-Absent block was higher than the Cue-Present block. The effect of cue-absence for different tasks and trial types was examined by means of 2 × 2 × 2 ANOVAs, with Cue (Cue-Present & Cue-Absent), Trial Type (Switch & Nonswitch) and Task (Color & Word) as the within-subjects factors. The main effect of Cue ($F[1, 28] = 4.66$, $p < .05$, ES = .14), Trial Type ($F[1, 28] = 17.55$, $p < .001$, ES = .38) and Task ($F[1, 28] = 41.37$, $p < .001$, ES = .59) were significant. No significant interaction effect involving Cue was found. This indicated that the memory load manipulation was adequate to challenge the WM capacity for performing task switching in the experiment. The results for the Comparison group were illustrated in the left panel of Figure 2.

Effect of ADHD and the Co-morbidity of LD on Speed and Accuracy for Processing

Based on the results of the overall ANOVA, the main effect of Group was significant for the overall RTs ($F[2, 94] = 12.38$, $p < .001$, ES = .20) and error rates ($F[2, 104] = 9.61$, $p < .001$, ES = .15). Post hoc comparisons revealed that the Comparison group was significantly faster and had a lower error rate than the ADHD-LD ($p < .01$) and the ADHD + LD groups ($p < .001$), and that the ADHD-LD group was significantly faster than the ADHD + LD group ($p < .05$) (see Figure 2).

A deficit in state regulation is directly tested by examining the variability in RT (SD) for individual participants. Significant group differences were found ($F[2, 94] = 6.82$, $p < .01$, ES = .12) with the mean SD for the Comparison group (45 ms) significantly lower than those for the ADHD-LD (588 ms) ($p < .05$) and the ADHD + LD groups (700 ms) ($p < .01$). The difference between the ADHD-LD and ADHD + LD groups did not reach statistical significance. The present finding suggests that ADHD is associated with slower and more variable RT, and lower accuracy compared to normal children. An additional deficit associated with LD in speed of processing was also found.

Effect of ADHD and the Co-morbidity of LD on WM for Task Switching

According to the executive dysfunction model (Barkley, 1994, 1997, 1999), ADHD is associated with a deficit in WM for task switching which should be reflected in a more pronounced deterioration of performance in RT and error rate for the Cue-Absent as compared to the Cue-Present blocks. The possible additional deficits associated with the comorbidity of LD in these areas were also examined.

The interaction of Cue × Task × Group was significant for RTs ($F[2, 94] = 7.56$, $p < .01$, ES = .13). To examine the effect of Cue for different groups and tasks, the Cue-Absent RT

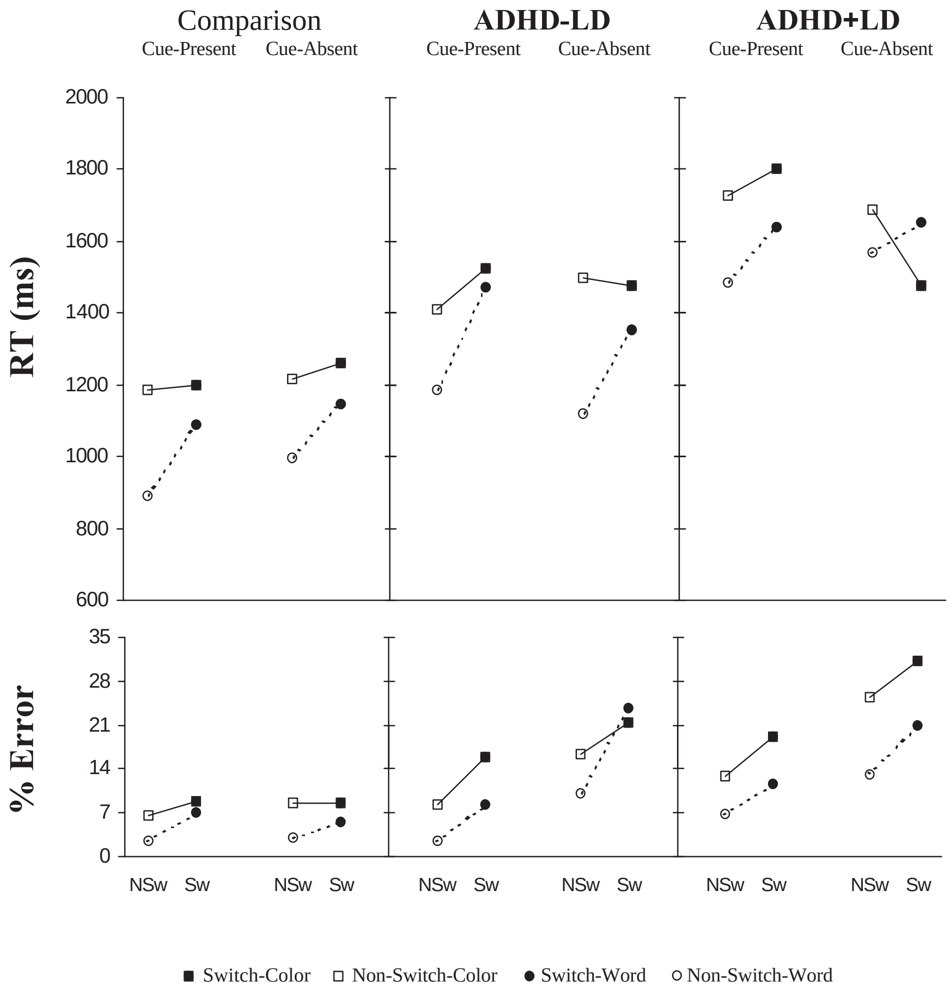

Figure 2. RT and error rate for different cue conditions, trial types, tasks, and groups.

cost was investigated (see Figure 3). For the Cue-Absent RT cost for different tasks, significant group differences were identified for the Color task ($F[2, 94] = 5.12$, $p < .01$, ES = .09). Post hoc tests revealed that the Cue-Absent RT cost for the ADHD + LD group was significantly *lower* than those for the Comparison and ADHD-LD groups (ps < .05). For the Word task, the group difference in Cue-Absent RT cost was not significant.

For error rate, the results of the ANOVA showed that the interaction of Cue × Task × Group was significant ($F[2, 104] = 3.24$, $p < .05$, ES = .05). To examine the effect of Cue for different groups and tasks, the Cue-Absent error cost was studied. This examination found that the group difference in Cue-Absent error cost for the Color task was not significant ($F[2, 104] = 2.28$, $p > .05$). For the Word task, significant group difference was identified ($F[2, 104] = 5.63$, $p < .01$, ES = .09). Post hoc tests revealed that the Cue-Absent error cost for the ADHD-LD group was significantly higher than that for the Comparison group (p < .01).

In summary, children with ADHD were not more affected by the cue-absence effect than normal children, as predicted by the executive dysfunctioning theory. The ADHD +

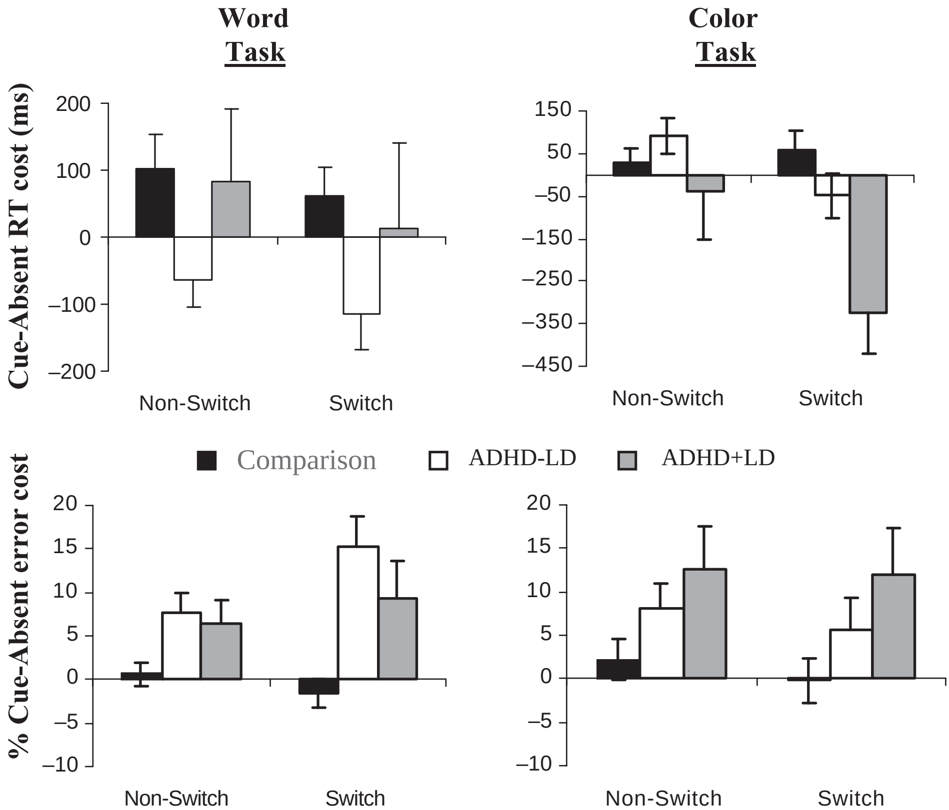

Figure 3. Cue-Absent RT and error costs for different trial types, tasks, and groups.

LD group was found to have a lower Cue-Absent RT cost than the Comparison and the ADHD-LD groups for the Color task. As Stroop stimuli were used for the cue-absence and cue-presence conditions, the difference in Cue-Absent cost for the Color task was not likely related to the lack of Stroop effect that has been observed in beginning readers or children with reading problems (Golden, 1987). For accuracy, the ADHD-LD group was found to have higher cue-absence error cost than the Comparison group only in the Word task, but the difference between the ADHD + LD group and Comparison group was not significant.

For the planned group comparison for the Cue-Absent RT and error costs for different tasks and trial types (i.e. the Switch Color, Switch Word, Nonswitch Color and Nonswitch trials), significant group differences were identified for Cue-Absent RT cost only on the Switch Color trials ($F[2, 94] = 7.48$, $p < .01$, ES = .13). Post hoc tests revealed that the Cue-Absent RT cost for the ADHD + LD group was significantly lower than those for the Comparison group ($p < .01$) and ADHD-LD ($p < .05$) groups. For Cue-Absent error cost, a significant group difference was only identified for the Switch Word trials ($F[2, 104] = 5.83$, $p < .01$, ES = .10) (see Figure 3). Post hoc comparisons revealed that the Cue-Absent error cost for the Comparison group was significantly lower than that for the ADHD-LD group ($p < .01$) on these particular trials.

To summarize, the Cue-Absent RT cost for the ADHD-LD and ADHD + LD groups were not significantly higher than that for the Comparison group. In addition, it was unexpected to find that, for the Switch Color trials, the Cue-Absent RT cost for the ADHD + LD group was significantly lower than those for the Comparison and ADHD-LD groups. The hypotheses regarding the deficit associated with ADHD and the comorbidity of LD in WM for task switching were not supported by the results of planned comparisons for the RT data. For accuracy, the Cue-Absent error cost for the ADHD-LD group was significantly higher than that for the Comparison group *only* for the Switch Word trials. No significant difference in Cue-Absent error cost between the Comparison and ADHD participants was found for the other three trial types (i.e., Switch-Color, Nonswitch Word and Nonswitch Color). As the Cue-Absent error costs for the ADHD + LD group were not significantly different from those for the Comparison group in any of the trial types, this is inconsistent with the suggestion that ADHD is associated with a deficit in WM for task switching.

Discussion

The aim of the present experiment was to investigate the specific deficit associated with ADHD in WM using the alternating runs paradigm. Results of the normal comparison group suggest that the experimental manipulation was adequate for tapping the WM capacity for performing the present task switching.

In the present study, the error rates of the ADHD-LD and ADHD + LD groups, particularly in the Cue-Absent blocks, have exceeded the constant response strategy criterion of 10% errors as recommended by Sternberg (1975). The RT data might be confounded by response strategy differences between conditions. This indicates that caution has to be taken when treating the RT data as process indexes. The difficulty in performing the more demanding self-regulatory task is mainly reflected in error rate.

The present findings are inconsistent with the hypothesis based on Barkley's executive dysfunction model which predicts that ADHD children would reveal WM deficits within a task switching context, in terms of higher cue-absence costs in RT and error rate, particularly for the high WM load task. In the present study, a deficit associated with ADHD in the high memory load condition for task switching was not found on RT measures. Further, difficulties associated with the ADHD-LD group in the high WM load condition are suggested in the comparison of cue-absence error cost for only one of the three trial types. However, the cue-absence error cost of the ADHD + LD group was not significantly higher than that for the Comparison group. The result implies that, even if a specific deficit was identified for the ADHD groups, it would be associated with adjusting speed to cope with a more demanding task, rather than in WM for task switching. More specifically, if ADHD were related to a selective difficulty in the control operations underlying WM for task switching, deterioration in performance for performing the more demanding task (i.e., Cue-Absent blocks) would be greater than that reported for normal children. However, this was not identified in the present study.

The present findings are, however, consistent with the prediction based on the state regulation model (Sergeant et al., 1999; Van der Meere, 1996) and the under-arousal model (Zentall & Zentall, 1983). As hypothesized by both models, the slower and more variable RT performance of children with ADHD related to the deficit in the regulation of effort, or an under-aroused state was found. The present findings revealed that children with ADHD demonstrated a different speed-accuracy bias than normal children. Normal comparison children held accuracy nearly constant, but showed a generalized slowing in the no-cue condition to compensate. In comparison, children with ADHD-LD and ADHD + LD maintained relatively stable RT, but with a 10% increase in errors. Thus, instead of revealing a general deficit in WM, these results point to impairment in adjusting speed to cope with increasing task demands, and a higher tolerance to errors than normal children. This is consistent with the state regulation model, which argues that the primary deficit in ADHD is not due to the control process of WM for task switching, but relates to mismatches between the actual state of the person and the state required for performing a particular task. Also, the speed-accuracy trade-off found in the present study is consistent with models that emphasis under-arousal in ADHD (Zentall & Zentall, 1983). The presence of a cue might serve as a reminder or a stimulus that helps the ADHD children to maintain an appropriate arousal state to perform task switching. When the cue was absent, the external reminder or stimulation is decreased, leading to poorer accuracy due to under-arousal.

The hypothesis based on Quay's behavioral inhibition theory (1988), which predicts that ADHD children may respond rapidly relative to their own baseline rate, but in an inaccurate manner, and demonstrate difficulty slowing down appropriately when necessary is supported by the pattern of speed-accuracy trade-off identified for ADHD children. However, the behavioral inhibition model alone cannot provide a sufficient explanation for the finding that children with ADHD had the overall RT slower and more variable than normal children. The behavioral inhibition theory can thus be incorporated into the state regulation and under-arousal framework for explaining the deficits manifested by children with ADHD. Specifically, the inappropriate state, or under-aroused condition, can be manifested in terms of behavioral inhibition and an inability to benefit from error feedback, as found in previous studies (Oosterlaan & Sergeant, 1995; Vance & Luk, 2000).

The present results do not support the notion that ADHD is associated with a deficit in WM for task switching, and thus, do not support an executive dysfunction theory that adopts an 'all-inclusive' definition of executive function (i.e., ADHD is associated with deficits in all areas of executive function which encompass concepts of WM, self-regulation, and inhibition) (Barkley, 1994, 1997, 1999). Rather, the present results suggest that the primary deficit of ADHD lies in state-regulation or under-arousal which may manifest as slow, variable and inaccurate responses, characterized by behavioral disinhibition. Thus, earlier proposals in terms of under-arousal in ADHD and intolerance of low levels of stimulation deserve renewed experimental attention.

The specific impact associated with the co-morbidity of LD is identified in the present study when the ADHD + LD children performed significantly poorer than ADHD-LD children. The progressive significant differences between the Comparison, ADHD-LD and ADHD + LD groups in speed of processing show that LD itself is associated with deficits in speed of processing. Significant difference between the ADHD-LD and ADHD + LD groups in cue-absence error rate was not found, thus, WM deficit associated with LD was not supported. Even though the ADHD + LD group was found to have significantly lower cue-absence RT cost than the other two groups, such positive effect of Cue on RTs for the ADHD + LD group was probably due to the confounding effect of response strategy differences between the Cue-Present and Cue-Absent blocks as the present data suggests that the ADHD + LD group did not slow down for the more demanding self-regulatory task in this experiment (i.e., Cue-Absent blocks).

The present findings suggest that the specific deficits related to ADHD include slow processing speed, greater variability in RT, and speed-accuracy trade-off. The additional impact of the co-morbidity of LD is found in processing speed. Although prefrontal dysfunction in ADHD is not ruled out in the present study as state regulation deficit related to prefrontal functions was found, specific prefrontal dysfunction manifested in terms of WM deficit is not identified for ADHD, with or without LD. The involvement of the other cerebral locations in ADHD, with or without LD, such as midline-thalamic and brain stem, which have been hypothesized as governing variability of RT and error response (Mirsky, 1996) is suggested.

There are methodological limitations that need to be considered in the present study. Firstly, in the present study, trials that immediately followed an error were excluded for the analyses to ensure that all trials from the Cue-Absent condition included for analyses were genuinely ‘uncued’. Hence, long error strings and any nonswitch trial following a switch trial on which the subject erred would be omitted. Given that children with ADHD may have difficulty benefiting from feedback and exhibit a higher tolerance for error, error rates might be under-estimated under the present data exclusion criteria. Based on the exclusion criteria adopted in the study, ten children from the ADHD groups were excluded from the analysis for RT data due to too few data points. As children with ADHD were found to have a higher error rate in the demanding condition, the mean number of trials available for comparison was less than that for normal children. However, the pattern of result did not change significantly, even when the trials following an error were included in analyses. Thus, the possible bias caused by the exclusionary criteria would not affect the speed-accuracy trade-off interpretation implicated in the present results.

For direct testing of the state regulation and under-arousal theories, it is worthwhile to examine RT and error data as a function of trial number for a monotonous task when task switching is not required. However, the alternating runs paradigm is not appropriate for this examination because task switching itself could be a stimulating element confounding the ‘arousal’ factor.

Barkley (1994, 1997, 1999) suggested that the specific deficit of ADHD children with hyperactivity lies in executive dysfunction, and the deficit of ADHD children without hyperactivity relates to perceptual-motor processing and speed. The present study with its emphasis on functional comorbidities such as LD, does not address the issue of ADHD subtypes based on the presence of hyperactivity. Thus, there is a need for larger sample size to examine the effects related to subtypes of ADHD in future study. Another important implication of the present study for future study lies in the emphasis on isolating specific effect associated with ADHD and comorbidities. In addition, specific cognitive abilities should be isolated and examined by specific tasks so that different levels of cognitive processing could be studied distinctively. Otherwise, the effect identified for ADHD might be related to the impact of comorbidity rather than ADHD, and the cognitive deficit found is non-specific and confounded by different levels of cognitive processing.

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