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Research Article

Examining the Relative Contribution of Memory Updating, Attention Focus Switching, and Sustained Attention to Children's Verbal Working Memory Span

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Whereas considerable developmental memory research has examined the contributions of short-term memory, processing efficiency, retention duration, and scope of attention to complex memory span, little is known about the influence of controlled attention. The present study investigated the relative influence of three understudied attention mechanisms on the verbal working memory span of school-age children: memory updating; attention focus switching; and sustained attention. Results of general linear modeling revealed that, after controlling for age, only updating accuracy emerged as a significant predictor of verbal working memory span. Memory updating speed (that subsumed attention focus switching speed) also contributed but was mediated by age. The results extend the developmental memory literature by implicating the mechanism of memory updating and developmental improvement in speed of attention focus switching and updating as critical contributors to children's verbal working memory. Theoretically, the results provide substantively new information about the role of domain-general executive attention in children's verbal working memory.

1. Introduction

Working memory (WM) refers to a limited-capacity system that functions to encode, store, and retrieve information being processed in any cognitive task [1–6]. Working memory is conventionally measured using complex memory span tasks that are characterized by maintenance of items during processing [7, 8]. Developmental memory research indicates that children's WM system comprises the components of short-term memory storage, processing speed [9–11], and a central executive [2, 12–20]. There are considerable developmental data focusing on the influence of storage and processing speed on children's WM [10, 13, 21–24]. However, few studies have directly explored the contribution of attention mechanisms on WM [25]. The present study, therefore, was designed to directly investigate the contribution of attention to school-age children's verbal WM.

Working memory, functionally defined as the ability to manage information storage and retrieval during an ongoing cognitive task, requires controlled attention toward both storage and processing [13, 14, 16, 19, 26–29]. Individuals with better controlled attention are better able than those with poorer attention to maintain more items while performing a cognitive activity [19]. Cowan and colleagues have proposed that WM is defined functionally as the number of information units/chunks that can be held in the scope of attention at any given point and attention control allows individuals to rapidly bring items from outside the scope of attention back into the scope of attention [16]. Barrouillet and colleagues [13, 30] have proposed the time-based resource-sharing model (TBRS) in which individuals in a rapid serial fashion switch their attention between processing and storage. If attention is captured by processing then it is unavailable for refreshing storage items.

Much of the research addressing the specific aspects of attention of children's WM system has been based on Baddeley's model of the central executive (i.e., attentional supervisor), which controls the flow of information in WM [2, 20, 25, 31]. Overall, research suggests that there are several central executive functions important to children's WM system. Researchers have also explored the role of attention by assessing the effects of cognitive load on children's complex memory span [13, 16, 17, 30, 32, 33] and dual task performance [34–36]. While attention functions are associated with children's WM, continued research is required to better understand the influential nature of attention on WM performance, especially given the fact that attention is a multicomponent construct. Because attention is a complex construct, it is important to better understand which components may contribute to WM performance and which do not. Such understanding has two important broad implications. Theoretically, such knowledge will advance developmental models of WM by incorporating empirically derived components of attention. There are also clinical implications. There is increasing evidence that executive functions (i.e., attentional functions) in children may be improved with training [37–41]. However, in evaluating the efficacy and transfer effects of any WM training, it is important to understand which mechanisms may underlie the transfer [42, 43].

1.1. Role of Attention in Working Memory. In current conceptions of WM, there is not only a capacity-limited attention constraint that determines the number of items that can be held in WM, but also attention control function(s), which appear to influence the way information is stored and retrieved. While attention capacity has been consistently indexed as the number of units or "chunks" of information that can be held in the scope of attention, in the absence of strategies such as rehearsal [16, 17, 44], attention control has been conceptualized in multiple ways, for example, allocation, inhibition, updating, and switching [3, 13, 17, 20, 21, 23, 26, 29, 30, 45–49].

The present study focused on three attention control mechanisms: *memory updating; attention switching; and sustained attention* and their relation to children's verbal WM (see below). The selection of these mechanisms was strongly motivated by the embedded process model of Cowan and colleagues [16, 27] and the TBRS model of Barrouillet and colleagues [13, 30]. Both models propose that WM performance involves selectively *updating* relevant information brought into the focus of attention while ignoring irrelevant information that is outside the focus of attention. On this view, the focus of attention is analogous to "WM storage." According to Cowan, the capacity of WM storage reflects what can be held in the focus of attention at any given moment. The TBRS model argues that memory updating (i.e., updating WM storage) requires the rapid *switching of attention* from processing to refresh storage items. The notion of attention switching is analogous to Cowan's conception of bringing items into/out of the focus of attention. Finally, *sustained attention* was included because its role in WM has not been explored but would seem to be a theoretically relevant contributor (see below). Results of the present study will provide a better understanding of the relative contribution of three understudied attention mechanisms on children's verbal WM performance.

1.2. Memory Updating. Several memory updating tasks such as running memory span and n-back have been used to index WM [25, 50–56]. This is because WM performance involves selectively updating relevant information in the focus of attention while ignoring irrelevant information. Studying the association of updating functions in children's WM, however, has seen little empirical evaluation. To our knowledge, the study by St Clair-Thompson and Gathercole [25] is the only study that has evaluated the role of updating, along with shifting and inhibition, in children's WM performance. Letter memory and keep-track tasks were used as updating measures. Results revealed that updating was closely associated with children's WM performance.

1.3. Attention Focus Switching. Attention switching during complex memory span tasks in children was first suggested by Towse and colleagues [22–24]. However, the relation of attention switching to complex memory span has seen little direct empirical investigation. Most studies examining switching in children have done so with reference to task switching and not attention focus switching [57]. (In task switching, participants are assessed for the ability to switch attention between two tasks while focus switching requires accurately and rapidly switching the focus of attention across dimensions of a given task.) There is some evidence that focus switching and task switching are distinct abilities [58]. This is an important distinction for the present study because it is attention focus switching which is more relevant to WM performance.

Attention switching in children's complex memory span development has been highlighted in the TBRS model. The model is rooted in four main assumptions [13, 33]. First, both processing and storage draw on the same limited pool of attention resources. Second, only one attention-demanding step in a complex memory span task can occur at a given moment due to an inherent "bottleneck" in the use of central/attention processes (i.e., if attention is captured by the processing, it is unavailable for storage). Third, immediately upon switching attention away from storage to processing, the stored items suffer activation decay and begin to fade until refreshed. Fourth, attention is shared via rapid, continuous switching between processing and storage. As the proportion of time for which attention is allocated to processing increases, so does the time required to store the memory items increase. An increase in storage time, in turn, leads to an increased probability of the memory traces decaying. In short, the TBRS model proposes that time-based attention control is a critical determinant of complex memory span, with attention switching being a crucial mechanism [48]. The literature also suggests that attention focus switching improves with age in children [59]. However, the switching mechanism has neither been measured nor examined in relation to children's complex memory span along with other attention mechanisms.

1.4. Sustained Attention. Sustained attention for purposes of the present study represents the capacity to maintain attention over the course of a given task in the presence of distracting stimuli. It is conventionally measured using continuous performance tasks that are a group of paradigms that reflect different but related aspects such as sustained attention, impulsivity, and vigilance [60]. Developmental improvement in sustained attention has been found to be related to early learning skills, IQ, language, and academic skills [61–65].

There are no developmental studies examining the relation of sustained attention and WM. However, it seems reasonable to assess this relation given that sustained attention is important to other cognitive skills. More important, brain mechanisms responsible for attention, including sustained attention, are also shared by WM [66]. We might assume that time-based storage across multiple processing trials requires vigilance.

Studies suggest the involvement of attention control in WM span performance [16, 19, 20, 48, 49]. However, the specific nature of this control and which specific mechanisms might subserve WM performance are not yet clear. The present study was designed to begin to address this issue.

2. Purpose of Present Study and Hypotheses

The purpose of the study was to evaluate the relative contributions of memory updating, attention focus switching, and sustained attention in predicting the verbal WM performance of 7- to 11-year-old children. We hypothesized that each of the three predictors would account for significant variance in children's verbal WM performance, after adjusting for age. Sustained attention should predict WM because we hypothesized that children need sustained attention to process incoming stimuli which act as distractors while needing to maintain items to be recalled. Updating and attention focus switching should emerge as even more robust predictors because it might be argued that the ability to rapidly switch attention from processing to refresh/update storage items that are outside the focus of attention is at the heart of WM performance [13, 25].

3. Method

3.1. Participants. Sixty-one 7- to 11-year-old typically developing children participated (M_{Age} = 9.5 years; Range = 7–11.6 years). (This age range was selected because (a) there is evidence of developmental improvements in school-age children's verbal WM [17, 67] and (b) previous studies suggest that school-age children demonstrate attention focus switching skills [13, 21, 31, 33, 59, 68].) All of the children demonstrated normal-range nonverbal IQ (>85), normal-range hearing sensitivity, and normal/corrected vision and presented no history of any developmental disorders or academic difficulties. All children also passed standardized language screening. (The screening battery consisted of: Developmental questionnaire; Test of Nonverbal Intelligence [69]; Audiometric hearing screening [70]; Concepts and Directions and Recalling Sentences subtests of the Clinical Evaluation of Language Fundamentals-4 [71]; Test for Reception of Grammar-2 [72]; Peabody Picture Vocabulary Test [73]). Children were seen individually across three to four testing sessions, each lasting for about an hour with rest breaks.

3.2. Experimental Tasks. The three predictor constructs were memory updating, attention focus switching, and sustained attention. The outcome variable was verbal WM. Two measures of each construct were used to derive a robust index of each construct [51]. Three different counterbalanced orders of the experimental tasks were created. About equal numbers of children completed each order. All computerized tasks were created and delivered using E-Prime version 1 [74]. Standard demonstration and practice trials were carried out for all experimental tasks prior to the test trials. A composite score for each construct was created by converting raw scores from individual tasks to z scores and then combining them (Table 1).

3.2.1. Memory Updating and Attention Focus Switching. Two tasks were developed based on the Garavan paradigm which involved count updating and attention switching [49, 75, 76] an auditory task, and a visual task. (Because the memory updating and attention focus switching tasks were developed based on the adult literature, various versions of both tasks were piloted on 7- to 8-year-olds and 10- to 11-year-olds to determine their suitability for children, consistency and to determine stimulus features, trial length, and ceiling and floor effects.) The Garavan paradigm is based on the proposal that only one item can be maintained in the focus of attention at a time. The Garavan proposal with its assumptions of memory updating and attention switching is in line with both Cowan's model of WM and the TBRS model of Barrouillet and colleagues.

Memory Updating/Attention Focus Switching Tasks

Stimuli. The stimuli for the auditory task consisted of a 250 Hz tone (500 ms) and a 4000 Hz tone (500 ms). The stimuli for the visual task consisted of a small red square and a big red square. Each task consisted of a total of 30 test trials. Each trial sequence consisted of 7 to 11 tones or squares with six trials at each sequence length. The order of appearance of stimuli followed a predetermined order within a trial. A random sequence length was used across trials. The entire task consisted of six blocks of five trials each.

Presentations were switch or nonswitch in nature. In a non-switch presentation, the stimulus presented was the same as the previous one (i.e., low-pitch tone followed by a low-pitch tone; small square followed by a small square). In a switch presentation, the stimulus presented was different from the previous one (i.e., low-pitch tone followed by a high-pitch tone and vice versa). Approximately one-third (108) of the total 270 presentations were switch presentations while

Table 1: Summary of all experimental tasks, examined variables, and variables used in the model.

Task	Examined variables
Memory updating-attention focus switching	
Auditory stimuli	Overall accuracy (across all 30 trials)
	Accuracy—high-frequency trials; low-frequency trials
	Accuracy—high tones; low tones
	Mean switch cost accuracy (difference in accuracy between high and low frequency trials)
	Mean switch RT; mean non-switch RT
	Mean switch cost RT (difference in RT between switch and non-switch presentations)
Visual stimuli	Overall accuracy (across all 30 trials)
	Accuracy—high-frequency trials; low-frequency trials
	Accuracy—big squares; small squares
	Mean switch cost accuracy (difference in accuracy between high and low frequency trials)
	Mean switch RT; Mean non-switch RT
	Mean switch cost RT (difference in RT between switch and non-switch presentations)
Variables used in the model	*Composite of z scores of overall accuracy from the two tasks*
	Composite of z scores of mean switch RT from two tasks
	Composite of z scores of switch cost accuracy from two tasks
	Composite of z scores of switch cost RT from two tasks
Sustained attention	
	Hit rate (child hits/45-total possible hits)
Gordon—auditory stimuli	False alarm rate (child false alarms/495-total possible false alarms)
	d' prime (difference between z scores of hit and false alarm rates)
	Hit rate (child hits/45-total possible hits)
Gordon—visual stimuli	False alarm rate (child false alarms/495-total possible false alarms)
	d' prime (difference between z scores of hit and false alarm rates)
Variable used in the model	*Composite d' prime from auditory and visual d' prime indices*
Verbal working memory	
Listening span	Total trials with accurate digit recall; Sentence comprehension accuracy and processing time
Counting span	Total trials with accurate count recall
Variable used in the model	*Composite z scores from recall scores on listening and counting span*

the remaining two-thirds (162) were non-switch. Across the 30 trials, 15 included high-frequency switches (where 50% of the presentations within a trial were switch presentations) while the other half included low-frequency switches (where 25% of the presentations within a trial were switch presentations).

Procedure. Each child was asked to keep count of each type of stimulus that was heard/seen (high tone, low tone or big square, small square). The child pressed the space bar to deliver each stimulus. Each task began with a fixation point on the screen for 150, 300, or 600 ms (random across trials) followed by a stimulus item. After the child overtly updated the count (e.g., "one high, two low" or "three big, four small"), he/she pressed the space bar for the next stimulus. The child was instructed to be as fast and accurate as possible in updating the counts and as fast as possible pressing the space bar. At the end of each trial, the computer screen turned green cueing the child to verbally report each count.

Four dependent variables were derived [49, 77, 78]. Variable 1 was count accuracy indexing memory updating. A score of 1 was given for every trial where both counts were recalled correctly, a score of .5 was given if one of the two was correct, and 0 if neither were correct. Count accuracy on high- and low-frequency switch trials was also computed. The second and third variables were RT based. RT was defined as the time taken to update each count (i.e., the time between the onset of one space bar press to the next space bar press). Variable 2 was updating speed, that is, speed of count updating on switch presentations. Variable 3 was switch cost RT, the difference between the mean RT between switch and non-switch presentations. (Switch cost RT used in the study was based on all trials irrespective of the frequency of switches. Switch cost RT was also computed separately for high-frequency and low-frequency switch trials but not used in the modeling because (a) there was no significant difference in the switch cost RT between high- versus low-frequency trials on the visual focus switching task that involved updating counts of squares, (b) overall cost of switching attention was of primary interest, and (c) switch cost RTs by frequency did not contribute new or unique findings to the existing model and its conclusions.) Variable 4 was switch cost accuracy, the difference in accuracy between high-frequency and low-frequency switch trials.

3.2.2. Sustained Attention. Children's ability to sustain attention was assessed using two continuous performance subtests of the *Gordon Diagnostic System*, a commercially available test [79]. Continuous performance tests measure sustained attention using stimulus repetition and task duration as key task design features [80].

Sustained Attention Tasks

Stimuli. Stimuli consisted of a random series of numbers between 1 and 9 presented from the Gordon box. Each digit was presented for 400 ms, with a silence of 600 ms separating each digit.

Procedure. In the auditory task, the child listened to a male speaker saying a series of numbers and pressed a button each time he/she heard the number sequence "1, 9." In the visual task, the child saw a series of digits on the screen and pressed the button each time he/she saw the sequence "1, 9." The child was not provided any feedback during the task. The primary dependent variable was d' prime (i.e., the difference between z scores of hit rate and false alarm rate) [81, 82]. D' prime indexes the ability to distinguish target stimuli from nontarget stimuli.

3.2.3. Verbal Working Memory Span. Complex memory *span* tasks are the most commonly used measures to index WM capacity. Verbal WM span was assessed using conventional listening span and counting span tasks.

Listening Span Task. The listening span task was a revised version of the span task used by Magimairaj et al. [83]. Children were presented sets of sentences (auditorily) and asked to comprehend the meaning of each sentence and remember a digit presented immediately after the last word of each sentence [21].

Stimuli. The task consisted of syntactically simple 8-word subject-verb-object (SVO) structures for which 6- to 12-year-old children show very good comprehension (93% or higher; e.g., [84–86]). All of the words in the sentences were high-familiarity words [87, 88]. The task consisted of a total of 40 sentences ranging from two-sentence sets to six-sentence sets (order of presentation by set size: 4, 3, 6, 2, 5). (List length was not incremental from two- to six-sentence sets to avoid children's expectancies that the task would get incrementally harder, which could likely influence their motivation [51].) The sentences were read at a normal rate ~ 4.4 syllables/second [89], and with normal prosodic variation by a male speaker.

There were two trials at each set size. Half of the sentences required a "Yes" response and half required a "No" response. For the "No" sentences, the sentence was false because of a semantic violation (e.g., *The cat saw the house that was hopping*). Immediately following each Yes/No response, a monosyllabic number between one and nine was heard which was to be remembered for later recall. No sentence-final number was repeated within a set.

Procedure. The child sat in front of the computer monitor, resting his/her elbow on a soft pad and was instructed to place his/her middle finger tips of his/her dominant hand on the "+" that appeared in the middle of the screen. The child was told that he/she would hear a man saying some groups of sentences and he/she would need to do two things: (1) respond to the truth value of each sentence (i.e., whether the sentence reflected an event that could occur in real life) by touching the word "yes" or "no" on the touch screen as quickly as possible after the sentence ended and (2) at the end of the set (cued by the screen turning green) recall as many of the sentence-final numbers in the set as possible in serial order. As soon as the child responded to the sentence, a number was presented. Immediately following the number, the experimenter presented the next sentence. (Presenting each sentence immediately after the digit was intended to prevent the child from rehearsing the numbers between sentence trials. While stimulus presentations in this study were based on Conway et al., [51], recent studies in the memory literature suggest that better time control of the processing episode is obtained by fixing the total processing time allowed (see [13, 14]).) The primary dependent variable was total trials for which the child correctly recalled the sentence-final numbers. Sentence comprehension accuracy and processing time were also examined. Processing time was calculated as the difference between sentence offset and when the child made his/her response. Any response occurring before sentence offset was scored a false alarm.

Counting Span Task. A computerized adaptation of the counting recall subtest from the *Working Memory Test Battery for Children* [90] was the second WM task. Children were asked to count arrays of dots presented on a computer screen, one array at a time. After a set of arrays was counted, the child recalled the total count from each array in serial order, which determined the counting span of the child. Because there was a verbal component to this task, we considered it a verbal WM task.

Stimuli. Stimuli consisted of arrays of dots with each array ranging between four and seven. The dots (85 px in diameter) were red and appeared on a white background. Before each array was presented, a fixation point "+" appeared on the screen for 100 ms. Arrays ranged from one to six arrays. At each array length there were six trials. The selection of array length had a predetermined order (4, 3, 6, 2, 5).

Procedure. The child sat in front of the computer screen and was instructed to point to and count each dot aloud on each array while at the same time keeping the total count of each previous array in memory for later recall. The child was instructed to count aloud to ensure he/she was counting each dot thereby allocating attention to the "processing" component of the task. After the child counted the dots on all successive arrays, the screen turned green and the child recalled the total from each array. The task was discontinued if the child incorrectly recalled the totals on four trials at any given array length.

For each trial recalled accurately and in the correct order, the child was allotted a score of 1. The maximum possible score was 36 (credit was given for array length 1 though it was not administered unless there was a failure at length 2). Occasionally, if a child made an error in counting, the respective count reported was regarded as the number to be recalled.

4. Data Preparation

On the updating and attention focus switching tasks, there were missing data for one child due to inability to complete the task. For accuracy of less than 50% on count updating on either high- or low-frequency switch trials, three children's data were excluded from analyses. The remaining children's RT data for switch and nonswitch presentations (on auditory and visual tasks) for high- versus low-frequency trials were separated. This procedure yielded four separate RT data sets each for high- versus low-frequency trials. Each RT data set was trimmed in two phases based on the approach by Friedman and Miyake [91]. First, arbitrary lower and upper cut-off criteria were established by visual inspection. The criteria turned out to be the same across RT data sets (i.e., 500 ms, 10 s). All RTs below 500 ms and above 10 s were removed to prevent extreme RTs from influencing the mean. Based on observational notes during testing these extreme RTs occurred due to rare interruptions. In the second phase, means and standard deviations were computed for each child's RT data set obtained after the first trimming phase. Outlier RTs ±3 SD from the mean were removed. Using this cut-off range (±3 SD) during data trimming ensured that useful data points representing the children's switching-updating times were not lost as validated by considerable pilot data. In each phase less than 2% of the RTs were removed from each data set. (It is to be noted that the updating and attention focus switching tasks were not designed to take into account accuracy on each presentation or individual update; rather count accuracy reported at the end of the trial was the outcome. Therefore, no RTs were designated as incorrect responses. All responses were considered valid since no children performing at or below chance were included in the analyses. Of interest was overall response time on switch versus non-switch presentations.)

5. Results

5.1. Preliminary Analyses. (Diagnostic measures such as histogram of errors, studentized residuals, and Cook's distance were used to examine for cases that might fall far from the regression equation. There were no outliers/influential cases. This indicated that the assumptions for the model were satisfied and the conclusions obtained from the model could be endorsed. Collinearity statistics (tolerance and variance inflation factor) indicated that there was no multicollinearity.)

5.1.1. Descriptive Statistics. Final descriptive statistics for each experimental task as well as unitary outcomes indexing predictor and outcome constructs are summarized in Table 2. Item reliability on all tasks was found to be good. On updating and attention focus switching, there was a significant difference between accuracy on low- versus high-frequency switch trials, with poorer accuracy on high-frequency switch trials for the auditory task ($M_{LF} = 12.67$, $SD = 1.77$; $M_{HF} = 10.96$, $SD = 2.76$), $t(59) = 7.75$, $p < .01$, and visual task ($M_{LF} = 13$, $SD = 1.59$; $M_{HF} = 11.85$, $SD = 2.32$), $t(60) = 5.10$, $p < .01$. For the auditory task, mean switch RT (*Mean* = 3372.29 ms, *SD* = 908.18) was significantly longer than mean non-switch RT (*Mean* = 2614.73 ms, *SD* = 688.36), $t(59) = 14.20$, and $p < .01$. Likewise, for the visual task, mean switch RT (*Mean* = 3229.51 ms, *SD* = 852.24) was significantly longer than mean non-switch RT (*Mean* = 2482.13 ms, *SD* = 654.55), $t(60) = 13.90$, $p < .01$. There was no significant difference in count accuracy for the two different stimuli (i.e., high versus low tones or big versus small squares) within each switching task ($p > .05$).

5.1.2. Correlation Analyses. Correlation analyses revealed that children's performance on all of the attention measures (sustained attention, memory updating, and attention focus switching) and verbal WM span tasks improved with age ($p < .01$). Partial correlations (controlling for age) between all experimental measures were also significant (see Table 3).

5.2. Primary Adjusted Analyses. General linear modeling (GLM) was used for model estimation with verbal WM span score as the dependent variable. The predictor variables representing updating (count accuracy), updating speed on switch (indexing both switching speed and updating speed), attention focus switching (switch cost accuracy and switch cost RT), sustained attention (overall d' prime), and age as the covariate were all entered into the model. (Speech rate which was relevant particularly to the updating and attention focus switching task was also measured for use as a covariate for all the children. However, it was observed that speech rate was not a useful covariate as it was already associated with age. That is, even without speech rate in the model the relationship of the predictors to verbal WM span, in the presence of age, remained unchanged. Speech rate was thus disregarded from any further analyses and discussion.) Univariate analysis of variance revealed that all the predictors, including age, jointly explained 57% of the variance in verbal WM span score $F(6, 52) = 11.69$, $R^2 = .57$, $p < .01$ (Table 4).

Analysis of individual parameter estimates revealed that in the presence of age and all the predictors only updating accuracy contributed significantly to unique variance in

Table 2: Descriptive statistics for all experimental tasks ($N = 61$).

Measure	M	SD	Range	Reliability*
Memory updating and attention focus switching				
Updating A (Overall acc)	23.61 (79%)	4.30	16–30	.83
Switch cost accuracy—A	1.70	1.70	−1.00–8.00	
Updating V (Overall acc)	24.89 (83%)	3.57	18–30	.84
Switch cost accuracy—V	1.15	1.75	−2.50–6.50	
Updating accuracy	**.042**	**1.81**	**−4.50–2.92**	
Switch cost accuracy	**−.018**	**1.59**	**−2.52–4.12**	
A				
Mean switch RT	3372.29	908.18	1560.89–5355.18	.97
Mean non-switch RT	2614.73	688.36	1298.22–4756.65	.98
Mean switch cost RT	757.56	413.17	−6.86–1782.91	
V				
Mean switch RT	3229.51	852.24	1473.02–5262.23	.98
Mean non switch RT	2482.13	654.55	1402.59–4229.09	.98
Mean switch cost RT	747.38	419.92	−97.42–1692.39	
Updating speed on switch	**−.028**	**1.91**	**−4.06–4.51**	
Switch cost RT	**−.014**	**1.71**	**−3.21–3.39**	
Sustained attention				
Gordon—A (hits)	36.54 (81%)	6.18	15–45	.85
d'prime (z score)	−.009	1.00	−3.72–1.40	
Gordon—V (hits)	41.31 (92%)	4.16	19–45	.85
d'prime (z score)	−.007	1.00	−5.55–.88	
Overall d'prime	**−.016**	**1.71**	**−7.58–2.27**	
Verbal working memory (WM) span				
Listening span (recall accuracy)	25.95 (65%)	6.70	11–40	.85
Counting span (recall accuracy)	23.07 (64%)	4.50	11–32	.87
Verbal WM span	**.000**	**1.71**	**−3.80–4.80**	

A: auditory stimuli; V: visual stimuli; RT: reaction time; *Cronbach's alpha coefficient of reliability. Outcomes in bold font represent unitary measures obtained by combining z-scores from the two separate tasks used for each construct.

Table 3: Bivariate and partial correlations between composite z scores of all experimental outcomes and age ($N = 61$).

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Age	1	.463**	−.310*	−.651**	−.468**	.380*	.528**
(2) Updating accuracy		1	−.651**	−.727**	−.666**	.452**	.697**
(3) Switch cost accuracy		−.603**	1	.508**	.420*	−.430*	−.465**
(4) Updating speed on switch		−.632**	.424*	1	.694**	−.611**	−.677**
(5) Switch cost RT		−.574**	.327*	.581**	1	−.441**	−.485**
(6) Sustained attention (d'prime)		.337*	−.355*	−.518**	−.322*	1	.469**
(7) Verbal working memory span		.601**	−.373*	−.517**	−.317*	.342*	1

**Correlation is significant at $\alpha = .01$ (2 tailed); *Correlation is significant at $\alpha = .05$ (2 tailed). Values below the diagonal represent partial correlations after controlling for age.

verbal WM, $B = .469$, $F(1, 52) = 9.76$, $p < .01$. For every one unstandardized unit increase in the accuracy of updating the increase in children's verbal WM span score was .469 (see Table 4). When age was removed from the model, updating speed also emerged as a significant predictor ($p < .05$) along with memory updating accuracy.

6. Discussion

Controlled attention has been emphasized in the WM literature [2, 4, 15, 20, 92], but its role has not been clearly specified [31, 93]. There appear to be two reasons for this lack of specificity. First, attention is a multimechanism construct.

Table 4: General linear model table of primary adjusted analyses predicting verbal working memory span performance using the predictor variables; updating accuracy, updating speed on switch, switch cost accuracy, switch cost RT, and d' prime (sustained attention), in the presence of age.

Variables in the model	B	95% confidence interval		F	p
		Lower bound	Upper bound		
Age	.019	−.008	.046	1.94	.170
Updating accuracy	.469	.168	.770	9.76	.003
Updating speed on switch	−.225	−.543	.092	2.03	.160
Switch cost accuracy	.025	−.234	.285	.038	.845
Switch cost RT	.129	−.134	.392	.964	.331
D' prime	.097	−.141	.334	.668	.417

$F(6, 52) = 11.69$, $R^2 = .57$, $p < .01$. When age was removed from the model, updating speed on switch also emerged as a significant predictor along with accuracy of updating, $F(5, 53) = 13.41$, $R^2 = .56$, $p < .05$.

Determining which mechanism(s) are relevant to specific cognitive activities requires careful theoretical and empirical examination. Second, deployment of specific mechanisms depends on the nature of the cognitive task [20, 31, 93]. We examined three attention mechanisms (memory updating, attention focus switching, and sustained attention) and their relation to children's verbal WM performance. We selected these mechanisms because of their theoretical relevance.

6.1. Influence of Memory Updating and Attention Focus Switching on Verbal WM Span. First, performance patterns similar to those reported in the previous literature were obtained in the present study regarding memory updating and attention focus switching [25, 59]. Even the youngest children (7-years old) were able to perform memory updating and attention switching, but they were slower doing so than their older counterparts, as evidenced by the significant correlation between age and updating speed.

With respect to explaining verbal WM span, the results clearly showed that accuracy of memory updating, but not speed of memory updating, is a critical determinant of children's WM span. That memory updating accuracy was a significant contributor to the children's WM performance resonates well with the recent adult literature. Recall that the adult literature also argues that the ability to accurately update memory with the correct item brought into the focus of attention plays an important role in WM performance [13, 17, 26, 49, 94–96]. Also recall that more recent formulations of WM emphasize that retrieval of contents in WM involves switching attention from items that are already in the focus of attention to those that are currently activated but need retrieving so they might be brought back into the focus of attention [13, 26, 94, 95, 97, 98].

That children's accuracy of memory updating and not speed of updating is a robust predictor of verbal WM performance is consistent with findings reported in the literature [49]. Similar to the Unsworth and Engle [49] study, secondary analyses in the present study showed that, controlling for age, there was a linear relationship between speed of updating (on both non-switch and switch presentations) and accuracy of memory updating ($r = -.427$, $p < .001$ and $r = -.632$, $p < .001$, resp.). That is, children who were more accurate to update were also faster to update. A speed-accuracy tradeoff thus was not responsible for reducing the impact of updating speed on children's verbal WM performance.

Like adults [49], the children demonstrated switch costs, an index of attention focus switching. The children's mean switch RTs were longer than their mean non-switch RTs. This finding suggests that retrieving an item already in the focus of attention is less attention demanding than retrieving an item outside the current focus of attention. In conventional WM span tasks such as those used in the present study, the processing activity and the items to be recalled are interleaved with each other. During processing, executive attention resources are invoked and in order to refresh items to be recalled there is a need to switch attention from the processing activity to storage in order to refresh those items. That is, during processing, the items to be recalled lie just outside the focus of attention and hence they need to be brought back into the focus of attention to be refreshed for recall.

Accuracy of updating also suffered as the demand for frequent attention switches increased, suggesting that more frequent switching of attention is disruptive to children's memory updating process. This is in line with studies suggesting that increasing the pace of the processing component or controlling processing time on WM tasks (e.g., [13]) disrupts the switching process making children more vulnerable to errors (i.e., children may switch to the incorrect element) and preventing more retrievals. Increasing such disruptions therefore places a burden on the attention switching process and thus leads to poorer WM performance.

Shared variance could be one of the factors that caused speed of updating to be nonsignificant in the presence of the other predictors. Faster updating speed was closely associated with greater updating accuracy (indirectly reducing the retention interval during which decay was possible), which was, in turn, related to verbal WM span. Finally, without age in the model, both updating accuracy and updating speed contributed unique variance to WM in the presence of all other predictors. These findings suggest that there are age-related improvements in updating speed that contribute to better verbal WM performance.

Switch cost variables were included in the model to represent the attention switching construct over and above updating accuracy and updating speed. Switch cost accuracy represented the difference in accuracy between high- and low-frequency switch trials. Switch cost RT reflected the difference in response time between switch versus nonswitch presentations. Neither switch cost variable contributed any unique variance to verbal WM span in the presence of the other predictors. Switch cost RT may have failed to contribute unique variance because of its shared variance with updating speed.

That the switch cost variables did not contribute unique variance to verbal WM performance has important implications for current models of developmental WM. While accuracy of memory updating is closely associated with verbal WM performance, attention switching per se is not. These findings, first, suggest that attention focus switching is in and of itself an incomplete contributor to verbal WM performance. Rather it is what the WM system does right *after* the switch which is more important, namely, update memory with a proper count. Age-related improvements in memory updating speed subsumed both speed of switching to an item outside the focus of attention and the ability to update memory following a switch. Therefore, with regard to switching, it is primarily the age-related improvement in the speed of switching and memory updating which contribute to developmental verbal WM performance. These findings are timely given the emphasis on attention switching in several WM models [13, 14, 26, 49, 58, 99] in that relative to the switching mechanism the memory updating mechanism is a more robust predictor of children's verbal WM performance. The role of attention switching is primarily mediated by the joint age-related improvement in speed of switching and speed of memory updating.

6.2. Influence of Sustained Attention on Verbal WM Span. We hypothesized that sustained attention should be required over the course of each processing and retrieval episode across multiple trials of the WM tasks. Results of the GLM showed that contrary to our hypothesis, sustained attention failed to contribute any unique variance to verbal WM span, even though it was linearly related to span. Item recall thus appears to predominantly require a refreshing mechanism to reactivate items in memory. Thus, attention refreshing/item updating seems to be more functionally equivalent to attention focus switching [13] than sustained attention.

To further examine the weak relation of sustained attention to verbal WM span, partial correlations between sustained attention and each of the two measures of WM were computed. Controlling for age, sustained attention (composite score) correlated significantly with counting span ($r = .462$, $p < .001$) but not with listening span ($r = .111$, $p > .05$). The differential correlation pattern may reflect the nature of the unique processing demands of each task. The counting span task may have instantiated sustained attention given the rapid and continuous nature of its processing activity. Recall that the children were presented in rapid succession different series of dots on the computer screen with the requirement of having only to count (and remember) the number of dots on each screen. The pace of the task was rather quick, with each new screen of dots being presented immediately after the child finished counting. The continuous and fluid nature of each trial may have invited significant vigilance. By contrast, it might be argued that the listening span task was performed in a less continuous, "fluid" fashion. The children heard sets of sentences and judged the truth value of each one. Making a correct response entailed multiple and different processes, including comprehending the input sentence, making a semantic-pragmatic evaluation of its real-world meaning, and performing a motor response. The task structure and performance demands may have elicited a greater use of attention mechanisms other than sustained attention, for example, switching, inhibition.

The interpretation that the nature of the processing episode may influence the attention control processes used is consistent with recent arguments put forth in the WM literature [100]. For instance, Towse and Cowan [100] have argued that complex memory span tasks are multifaceted and that attention control functions could be involved in different ways in different WM tasks. For example, reading span involves more inhibitory mechanisms while operation span with word recall invokes greater controlled attention since the processing and storage elements are distinct [100]. The relation of WM span to cognition is thus complex [101] and therefore the use of multiple tasks and latent variable analyses to assess WM is recommended [51]. The above finding is also important because it speaks to the issue of WM training in children. Recent studies report that executive functions can be improved with training [37–41]. Better understanding attention mechanisms of WM allows for better understanding of (a) aspects that may or may not improve with training and (b) what aspects may transfer to other cognitive skills based on the nature of the tasks used during training and while evaluating transfer effects [43].

7. Conclusion

The purpose of the study was to investigate the relative contributions of memory updating, attention focus switching, and sustained attention to children's verbal WM performance. Memory updating accuracy emerged as the single unique predictor of verbal WM span. Memory updating speed (that included attention focus switching speed) also was a contributor but was mediated by age. However, neither attention focus switching, as indexed by switch cost, nor sustained attention played a significant role in explaining verbal WM performance in the presence of the other predictors. Overall, results support the view that children employ active attention mechanisms to facilitate WM performance (e.g., [102]). Understanding the relative contribution of attention mechanisms allows for convergence of theoretical models of WM, better understanding of the predictive value of WM to higher-order cognition, and explaining improvements or deficits in children's WM.

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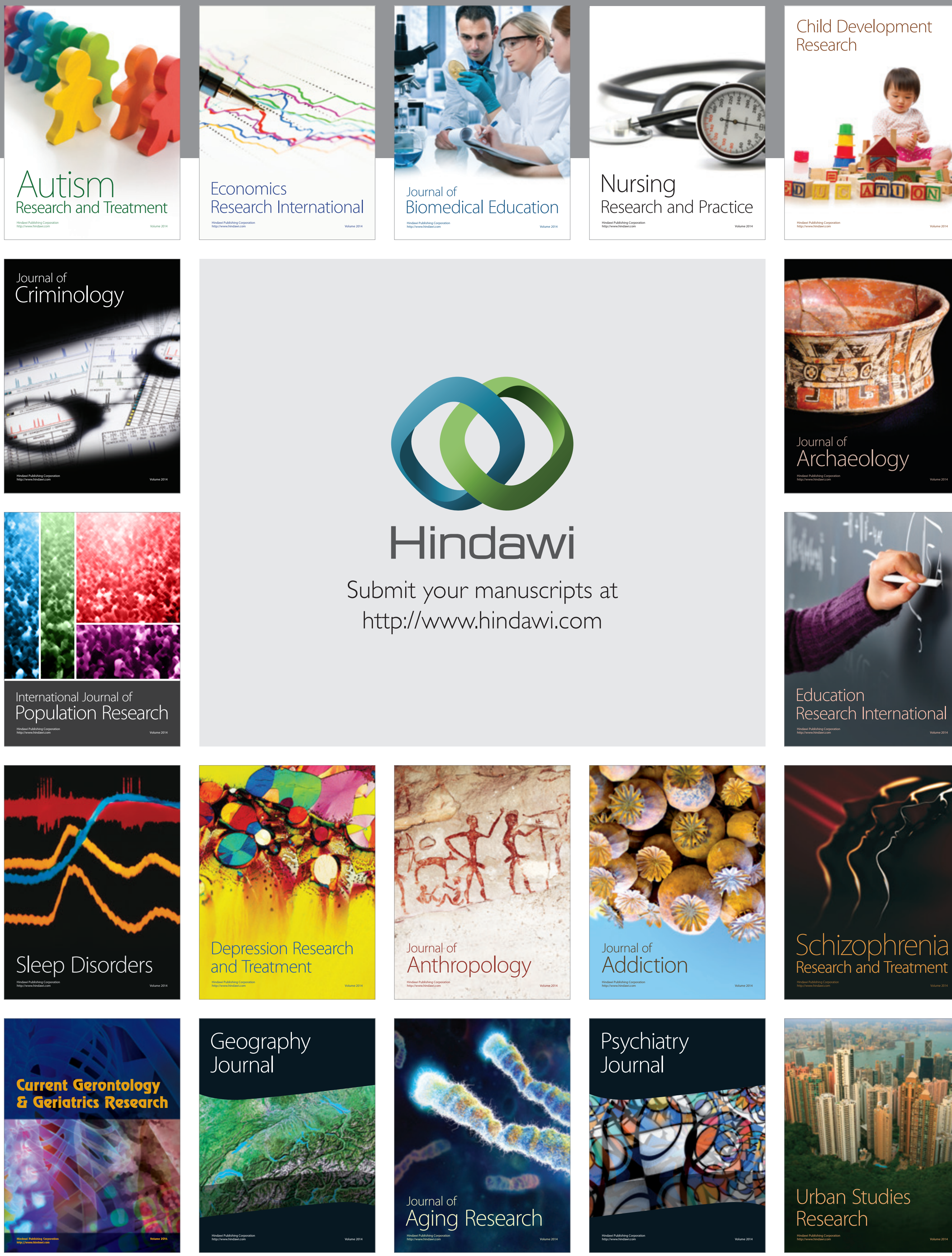
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