The Assessment of Verbal and Visuospatial Working Memory With School Age Canadian Children

Évaluation de la mémoire de travail verbale et visuospatiale chez des enfants canadiens d'âge scolaire

KEY WORDS
WORKING MEMORY
SHORT-TERM MEMORY
ASSESSMENT
PHONOLOGICAL LOOP
CHILDREN

Ruby T. Nadler
Lisa M. D. Archibald

Abstract

This study investigated the structure of short-term and working memory in a sample of North American children between 5 and 9 years of age. The Automated Working Memory Assessment (AWMA) is a standardized test normed on a UK sample containing several tasks measuring short-term and working memory across both the verbal and visuospatial domains. A group of 178 school age Canadian children completed the 12 subtests of the AWMA. A three-factor model of working memory was supported. Performance on the different tasks was compared with the normative sample and while the same pattern of results was found, the North American sample's performance on several tasks was higher. The findings are consistent with a model of working memory characterized by domain-specific storage and domain-general processing components. Cultural differences were noted for the short-term but not working memory measures.

Abrégé

Cette étude a exploré la structure de la mémoire à court terme et de la mémoire de travail dans un échantillon d'enfants nord-américains de 5 à 9 ans. L'*Automated Working Memory Assessment* (AWMA) est un test standardisé normé sur un échantillon du Royaume-Uni contenant plusieurs tâches verbales et visuospatiales de la mémoire à court terme et de la mémoire de travail. Un groupe de 178 enfants canadiens d'âge scolaire a complété les 12 sous-tests de l'AWMA. Un modèle à trois facteurs de la mémoire de travail était supporté. La performance sur les différentes tâches a été comparée à l'échantillon normatif. Bien qu'on ait trouvé les mêmes schémas de résultats, la performance de l'échantillon nord-américain dans plusieurs tâches a été plus élevée. Les conclusions sont conformes à un modèle de mémoire de travail caractérisé par des composantes d'entreposage selon un domaine spécifique et un traitement selon un domaine général. Des différences culturelles ont été notées pour les mesures de mémoire à court terme, mais pas pour celles de mémoire de travail.

Ruby T. Nadler, Ph.D.
Western University,
Department of Psychology,
London, ON
CANADA

Lisa M. D. Archibald, Ph.D.
Western University, School of Communication Sciences and Disorders and Department of Psychology
Elborn College,
London, ON
CANADA

A considerable portion of school age children receiving speech and language services have a developmental language impairment despite largely typical neurological and emotional development and adequate educational opportunities (Tomblin et al., 1997). Many of these children struggle to learn at school across the curriculum (Leonard, 1998). Some of the effort aimed at improving our understanding of the challenges faced by these children has centred around the cognitive resources that support learning generally, and language learning in particular (Archibald & Gathercole, 2006). It follows that identifying key cognitive processes related to learning may lead to more effective assessments and interventions targeting these underlying abilities.

One cognitive system that has received considerable attention for its role in learning is working memory. Working memory is the ability to store and manipulate information across short time frames (Baddeley & Hitch, 1974; Just & Carpenter, 1992). Working memory capacity is a key indicator of cognitive performance across the lifespan; it predicts academic achievement in children (Alloway & Alloway, 2010; Bull & Scerif, 2001; De Jong, 1998; Fry & Hale, 2000; Gathercole, Brown, & Pickering, 2003; Pickering & Gathercole, 2004) and complex cognitive activities such as language comprehension and mathematical problem-solving in adults (e.g. Ackerman, Beier, & Boyle, 2005; Conway et al., 2005; Kane et al., 2007). Most theoretical models view working memory as involving both storage and processing of phonological, visuospatial (or other) information (e.g., Baddeley & Hitch, 1974; Cowan, 1999). As a result of its multifaceted nature, assessment of working memory abilities can be challenging. Alloway, Gathercole, and Pickering (2006) employed a set of automated tasks aimed at assessing storage and processing of verbal and visuospatial information with a group of children from the United Kingdom to examine theoretical models and assessment of working memory. The purpose of the present study was to provide an independent validation of these tasks with a North American group.

The most influential account of working memory is the multicomponent model of Baddeley and Hitch (1974). This model posits the existence of a central executive, which controls resources, monitors information across domains, retrieves information from long-term memory, and exerts attentional control. In addition to the central executive are two domain-specific slave systems, the phonological loop, which stores verbal information for short periods of time, and the visuospatial sketchpad, which stores visual and spatial information (see Baddeley & Logie, 1999, for a review). A fourth, recently proposed component of this system is the episodic buffer, which binds information from the different domains and subsystems into coherent chunks (Baddeley, 2000). This view of working memory is supported by several lines of evidence including studies of children (Alloway et al., 2006; Alloway, Gathercole, Willis, & Adams, 2004; Bayliss, Jarrold, Gunn, & Baddeley, 2003), adults (Kane et al., 2004), neuropsychological case studies (Jonides, Lacey, & Nee, 2005), and using psychometric approaches (Miyake & Shah, 1999). Baddeley and Hitch's tripartite theory shares many similarities with other domain-general accounts of working memory (e.g., Cowan, 1999; Engle, Tuholski, Laughlin, & Conway, 1999b). Still other accounts suggest the separation of verbal and visuospatial constructs, with no shared component (Shah & Miyake, 1996). According to Shah and Miyake (1996), working memory is served by separate verbal and visuospatial pools, each of which is capable of manipulating and keeping information active independently of the other. This model is supported by research with older children and adults (Friedman & Miyake, 2000; Jarvis & Gathercole, 2003; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001).

Working memory capacity increases gradually from early childhood to adolescence with broadly similar linear increases in factors corresponding to Baddeley and Hitch's (1974) tripartite working memory model (Gathercole, Pickering, Ambridge, & Wearing, 2004). A number of cognitive factors have been proposed to account for these developmental changes including increased processing speed (Fry & Hale, 2000), development of rehearsal strategies (Gathercole, Adams, & Hitch, 1994), and growth of long-term knowledge to support immediate memory function (Gathercole, 2006). Sex differences in short-term and working memory performance have not been reliably demonstrated, at least for children (Alloway et al., 2006). Indeed, evidence suggests identical working memory structure for male and female groups (Robert & Savoie, 2006).

Working memory capacity reliably predicts performance of both children and adults on a wide variety of complex cognitive activities. Academic achievement across the curriculum has been closely tied to working memory including mental arithmetic (e.g., Adams & Hitch, 1997; DeStefano & LeFevre, 2004), problem solving (Swanson & Beebe-Frankenberger, 2004), spelling (Kreiner, 1992), and reading comprehension (Cain, Oakhill, & Bryant, 2004). It has been suggested that working memory may play an important role in language learning given the time-dependent nature of verbal communication largely delivered through an acoustic signal of brief duration. Specifically, new word learning may be supported by the phonological loop (phonological short-term memory), especially in the early stages of language learning when the available long-term stores of lexical knowledge are small and provide less support for lexical acquisition through association (Gathercole, 2006). Sentence level processing has also been found to be linked to working memory (Montgomery, 2000). In particular, sentences that are long (Noonan, Redmond, & Archibald, 2014) or complex (Magimairaj & Montgomery, 2012) are uniquely associated with working memory because such sentences impose higher memory demands. The close associations demonstrated between working memory and language components have led to increased interest in understanding the role of working memory in children struggling to learn language.

One key to understanding working memory is developing assessment tools to accurately measure it. To this end, domain-specific tasks of short-term and working memory have been developed. Short-term and working memory tasks both impose a brief memory load but differ in whether the task also has inherent information processing requirements. The requirement to briefly store information only (without any processing demands) imposes a load on respective short-term memory systems depending on the information to be recalled. An example of a phonological short-term memory task is the serial recall of words, letters, or digits (e.g., Conrad & Hull, 1964), whereas visuospatial versions require the recall of either visual patterns or sequences of movements (e.g. Smyth & Scholey, 1996; Wilson, Scott & Power, 1987). Working memory tasks tap domain-specific short-term memory stores in the same way, but additionally impose a load on the domain-general central executive by requiring some manipulation of the information. An example of a verbal working memory task is reading span, where the participant is asked to make a meaning-based judgment (e.g. "is this sentence true or false?") for each of a series of sentences, and then to report the last word of each sentence in the order of presentation (Daneman & Carpenter, 1980). A corresponding visuospatial task is spatial span, where the participant is asked to judge the orientation of a set of letters, and then to report the sequence of degrees of rotation of the letters (Shah & Miyake, 1996).

In order to meaningfully interpret performance it is important to compare across verbal/phonological and visuospatial domains, as well as short-term and working memory demands. A pattern of low scores across both verbal and visuospatial working memory tasks despite stronger performances on corresponding short-term memory tasks would implicate weak working memory skills specific to the central executive (i.e., the common component tapped in both verbal and visuospatial working memory tasks). Poor performance in one domain (i.e., verbal or visuospatial) involving short-term memory tasks only or both short-term and working memory tasks would implicate the respective short-term memory store. For example, low scores on both phonological short-term memory and verbal working memory tasks in the context of average scores on visuospatial short-term and working memory tasks would reflect a weakness in phonological short-term memory.

Recently, standardized assessments of verbal and visuospatial short-term and working memory have been developed for use with children. The *Automated Working Memory Assessment* (AWMA; Alloway, 2007a provides multiple measures of domain-specific short-term and working memory standardized with a UK sample aged 4 to 22 years. Alloway et al. (2006) conducted confirmatory factor analyses using the data from 708 children who completed the AWMA. A three-factor model with related but separable verbal and visuospatial storage components and a shared component (i.e., the central executive) provided the best account of the data corresponding to the tripartite model of working memory proposed by Baddeley and Hitch (1974). As well, the AWMA exhibited convergent validity with concurrent clinical measures of working memory deficits (Alloway, Gathercole, Kirkwood, & Elliott, 2008). The AWMA's clinical relevance has been demonstrated in studies looking at children with Developmental Coordination Disorder (Alloway, 2007b; Alloway & Archibald, 2008; Alloway, Rajendran, & Archibald, 2009), Specific Language Impairment (Alloway & Archibald, 2008; Alloway, Rajendran et al., 2009), Attention-Deficit/Hyperactivity Disorder (Alloway, Rajendran et al., 2009), Asperger syndrome (Alloway, Rajendran et al., 2009), and also contributed to delineate a Specific Working Memory Impairment (Archibald & Joanisse, 2009; see also, Alloway et al., 2009; Gathercole et al., 2008).

The work of Gathercole and Alloway and colleagues (Alloway et al., 2006; Alloway et al., 2008; Gathercole, Alloway, Willis, & Adams, 2006), and indeed the majority of research on the developmental nature of working memory, has been conducted outside of North America. There are reasons to think that this geographic bias is not problematic. Unlike traditional knowledge-dependent measures such as vocabulary tests or tests of general knowledge, working memory tasks are considered to be processing-dependent (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Kane, & Tuholski, 1999a; Engle et al., 1999b). Processing-dependent measures are designed to be sensitive to basic learning abilities but not prior knowledge or experience. The stimuli and procedures employed in tests of working memory are designed to be unfamiliar (or equally familiar) to all subjects, preventing prior learning or experience from influencing performance. Indeed, many studies have found working memory measures to be insensitive to cultural differences. For example, performance on a short-term memory measure known as nonword repetition involving the immediate recall of multisyllabic nonword forms has not been found to differentiate white American and African American groups (Campbell, Dollaghan, Needleman & Janosky, 1997). As well Engel, Santos, and Gathercole (2008) found that a group of Brazilian children low in socio-economic-status (SES) performed comparably to a group of higher SES children on working memory measures. One interpretation of this finding is that the measures were not sensitive to differences in knowledge or prior experience typically characterizing SES groups (e.g., Blachowicz, Fisher, Ogle, & Watts-Taffe, 2006). However, not all of the reported findings are consistent with this view. Some studies investigating working memory in diverse samples have found differences (Beauchamp, Samuels, & Griffore, 1979; Ostrosky-Solís & Lazano, 2006; Reynolds, Wilson, & Ramsey, 1999). For example, Ostrosky-Solís and Lazano (2006) reported significant forward and backward digit span differences between adults in Mexico and adults in several other countries (including Austria, France, and the United States) who were matched on age and education. It is clear that the question of cultural differences in working memory measures warrants further investigation as in the current work.

The present study investigated the performance of a randomly selected group of Canadian school age children on measures of verbal and visuospatial short-term and working memory from the AWMA (Alloway, 2007a). This study had several aims. One aim of the study was to provide an independent structural analysis of the short-term and working memory components tapped by the AWMA in relation to the working memory model (Baddeley & Hitch, 1974). Findings that a domain-general factor explains a significant amount of the variation in performance on the complex span tasks across domains while the simple span tasks load on separate domain-specific factors would be consistent with Baddeley and Hitch's tripartite model. As part of the structural analysis, assessment of developmental, sex, and SES factors was planned. As in the previous studies (Alloway et al., 2006; Alloway, 2007a), age-related changes in short-term and working memory were expected across our school age sample whereas differences in sex and SES were not anticipated.

A second aim of the study was to examine the cultural sensitivity of the AWMA (Alloway, 2007a) by comparing performance of the Canadian sample to the UK results on which the study was normed. Similar raw scores across these groups would replicate previous findings (Engel et al., 2008) and lend further support to the view that working memory measures are predominantly processing-dependent and not biased by previous experience. Group differences in the raw scores, on the other hand, would be indicative of cultural differences and point to the need to continue to investigate such influences on working memory.

Method

Participants

Current sample. Participants included 178 school-aged children (96 females, and 82 males) who were randomly recruited from an unselected sample of 1605 students participating in a larger study investigating language, memory, and academic achievement in children being completed by the second author (Archibald, Oram Cardy, Joanisse, & Ansari, 2013). Twenty schools were included in the study; sixteen of the schools were located in urban areas, and four of the schools were located in rural areas in Ontario, Canada. This distribution of 80% urban and 20% rural reflects Canada's population makeup (Statistics Canada, 2006). The students ranged in age from 5 to 9 years old, corresponding with senior kindergarten to grade four in Canada. According to parental report, the majority of students (90%) spoke English as their first language. Table 1 shows the number, sex, and English-as-a-Second-Language (ESL) status of participants in each age band. Parents additionally reported the highest level of education achieved by the child's mother on a 5-point scale (1=some high school; 2=completed high school; 3=some college; 4=completed college; 5=some university/completed university), and this was employed as a proxy measure of socioeconomic status.

Historical sample. Access to the normative sample for the Automated Working Memory Assessment (AWMA; Alloway, 2007a) was provided by the test's author. The group corresponding in age to the current sample consisted of 503 school-aged children (269 females and 234 males). As above, socioeconomic status was operationalized using highest level of maternal education, and was reported on a 5-point scale with close correspondence to the scale adopted for the current sample (1 = General Certificate of Secondary Education: Foundation, 2 = General Certificate of Secondary Education: Higher, 3 = Advanced Level General Certificate of Education, 4 = vocational degree, 5 = higher degree).

Table 1. AWMA study participants

Age Group	Sex (M, F)	ESL (*n*)	*N*
5.0-5;11	9, 17	1	26
6.0-6;11	14, 21	3	35
7.0-7;11	23, 17	5	40
8.0-8;11	16, 21	5	37
9.0-9;11	20, 20	4	40
Total		18	178

Materials and Procedure

Each child completed the Automated Working Memory Assessment (AWMA; Alloway, 2007a) in an individual session in a quiet room in his or her school lasting approximately 50 minutes. The AWMA consists of 12 subtests: three tapping phonological short-term memory (*digit recall, word recall, nonword recall*), three targeting verbal working memory (*listening recall, counting recall, backward digit recall*), three aimed at visuospatial short-term memory (*dot matrix, mazes memory, block recall*), and three tapping visuospatial working memory (*odd-one-out, Mr. X, spatial span*). All of the tasks were administered using a span procedure beginning at the easiest list level (i.e., two items), increasing by one item when four out of six lists were completed correctly, and discontinued when three errors occurred at one level. Raw scores for each subtest equaled the number of lists completed accurately. All instructions and verbal stimuli were audio recordings of an adult Canadian female speaker.

Phonological short-term memory. Digit recall, word recall, and nonword recall each involve recalling a sequence of numbers, words, or non-words, respectively, in the order in which they were presented verbally by the computer program. Items were presented at a rate of one per second.

Verbal working memory. In the listening recall subtest, the child listens to a series of short sentences and has to decide whether each sentence is true or false (e.g., "Lions have four legs."), and then recalls the last word of each sentence in the exact order they were presented (e.g. "legs"). In counting recall, a series of arrays of circles and triangles is presented and the child is asked to count the number of circles in each array, and then recall the total number of circles that appeared on each trial in the correct order. In backward digit recall, sequences of numbers are presented verbally and the child is asked to recall them in the reverse order.

Visuospatial short-term memory. In dot matrix, the child is asked to point to the squares of a 4-by-4 matrix where a sequence of red dots appeared in the same order that they were presented. Mazes memory involves the presentation of a two-dimensional maze with a path drawn on it. The child is asked to retrace the path with his or her finger after the path is removed from the maze. The maze size increases across levels. Block recall is similar to the dot matrix subtest, but the child sees a board with nine cubes. An arrow appears and points to the cubes in sequence, and the child is asked to point at the cubes in the same order.

Visuospatial working memory. In the odd-one-out task, sets of three shapes in a three square matrix are shown on the computer screen, two are the same and the third one is different. The child is asked to indicate which one is the "odd one out" for each set. At the end, the child sees the matrix without any shapes and is asked to indicate where the odd shape had been in each set, in the order they had been presented. Mr. X involves the presentation of sets of two figures of men, one with a yellow hat and the other with a blue one. The Mr. X with the blue hat can appear rotated in six possible positions. The child is asked to say whether the Mr. X with the blue hat has his ball in the same hand as the Mr. X with the yellow hat. At the end of each list, a picture with six compass points appears and the child is asked to point to each location to which the ball held by the Mr. X with the blue hat had been pointing in the order they had been presented. Finally, in the spatial span subtest sets of two arbitrary but identical shapes are presented. One shape can be rotated to three possible positions and has a red dot on top of it. First, the child is asked to indicate whether the shape with the red dot is the same or the opposite to the one without the dot for each set of shapes. Then, the child is asked to point to the location where the dot on the rotating shape had been pointing for each display, in sequence.

Results

Descriptive statistics for the raw scores of the 12 subtests of the Automated Working Memory Assessment (AWMA; Alloway, 2007a) as a function of age band are provided in Table 2. Improvements in performance were seen in all cases across the age bands. Raw scores corresponding to z-score cut-offs of 1.5, 1.0, 0, -1.0, and -1.5 for each age band are presented in Appendix A.

In order to examine the sensitivity of the AWMA tasks to developmental changes in short-term and working memory, a multivariate analysis of variance (MANOVA) was conducted on the raw scores of the three subtests that correspond to each of the four different working memory components (phonological short-term memory; verbal working memory; visuospatial short-term memory; visuospatial working memory) as a function of age group (5 - 9 years) and sex (male, female) separately. Sex was maintained as a factor in the analysis in order to confirm a lack of sex differences as has been reported in previous studies (Alloway et al., 2008). The MANOVA performed on the phonological short-term memory tasks yielded a significant Hotelling's Trace (all cases) of age, F (12, 494) = 3.47, p < .001, η^2_p = .078, but no significant effect of sex, F (3, 166) = 0.37, p = .77, η^2_p = .007, and no significant interaction between age and sex, F (12, 494) = 1.50, p = .12, η^2_p = .035. The same pattern of significance was repeated in the MANOVAs performed on the visuospatial short-term memory tasks (age: F (12, 494) = 9.80, p < .001, η^2_p = .192; sex: F (3, 166) = 0.42, p = .74, η^2_p = .008; interaction: F (12, 494) = 1.07, p = .38, η^2_p = .025), and visuospatial working memory (age: F (12, 494) = 9.93, p < .001, η^2_p = .194; sex, F (3, 166) = 2.62, p = .052, η^2_p = .045; interaction: F (12, 494) = 0.65, p = .80, η^2_p = .015). The pattern was slightly different for the verbal working memory tasks, with a significant effect of age, F (12, 494) = 8.83, p < .001, η^2_p = .177, and sex, F (3, 166) = 2.98, p = .03, η^2_p = .051, but no significant interaction effect, F (12, 494) = 0.74, p = .72, η^2_p = .018. Although significant, the higher scores of the males than females overall on the verbal working memory tasks were associated with a relatively small effect size (.051). Interestingly, no main effects of sex were found for the individual verbal working memory tasks (listening recall: F (1, 168) = 2.16, p = .14, η^2_p = .01; counting recall: F (1, 168) =3.20, p = .08, η^2_p = .03; backward digit recall: F (1, 168) = 2.12, p = .15, η^2_p = .01). The age effects across all of the working memory measures reflect the increasing memory capacity of children as they get older.

Performance growth as a function of increasing age is visible in Figure 1, which plots the z-scores for each age band from 5 to 9 years of age. Scores were calculated on the basis of the entire sample of children. All of the subtests of the AWMA indicate generally similar functions, with performance increasing across each year group.

Correlations among all variables were conducted on the full age range, using the raw task scores. Zero-order correlations are displayed in the lower triangle in Table 3. The intercorrelations between measures purported to tap different working memory components were all substantial in magnitude, with rs ranging from .44 to .70 for the phonological short-term memory tasks, .43 to .58 for the verbal working memory tasks, .60 to .69 for the visuospatial short-term memory tasks, and .57 to .67 for the visuospatial working memory tasks (p < .001, all cases). Multicollinearity was assumed not to be a problem in this data set because none of the zero-order correlations were higher than .80 (Kline, 1998). However, these coefficients were inflated by the age variation in the group. A partial correlation analysis with age in months partialed out was conducted. These coefficients are shown in the upper triangle in Table 3. The intercorrelations between working memory measures was reduced after age was partialed out, and ranged from moderate to large or small to large in magnitude for all but the verbal working memory measures (rs for the latter were small to moderate in magnitude, .27 to .43). The coefficients remained moderate to large for phonological short-term memory measures, .38 to .65, and were moderate to large for visuospatial short-term memory, .43 to .57, and visuospatial working memory measures, .39 to .50. The within-construct coefficients were generally higher than between-construct coefficients, indicating good internal validity of the measures purported to tap the four subcomponents of working memory.

In order to investigate the higher order structure of the different measures in the AWMA, a principal components analysis (PCA), rotated to final solution with orthogonal rotation (varimax) was conducted on the raw scores for all 12 subtests of the AWMA. The Kaiser-Meye-Olkin measure confirmed the sampling adequacy for the analysis, KMO = .92 (Kaiser, 1970). Three factors emerged with eigenvalues in excess of Kaiser's criterion of 1.00, accounting for 52.52, 10.99, and 6.10 percent of the variance respectively, for a total of 69.61 percent of the variance. Factor loadings in

Table 2. Descriptive statistics for all working memory scores as a function of age band

	5-5;11 (*n* = 26)		6-6;11 (*n* = 35)		7-7;11 (*n* = 40)		8-8;11 (*n* = 37)		9-9;11 (*n* = 40)	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Phonological short-term memory										
Digit recall	25.31	4.67	25.86	3.60	27.55	2.93	28.32	3.64	28.90	4.61
Word recall	19.85	4.40	21.60	3.53	23.23	3.04	23.35	2.97	25.02	3.62
Nonword recall	12.88	4.09	14.31	3.98	15.45	3.70	15.70	3.22	16.93	3.79
Verbal working memory										
Listening recall	6.31	3.58	7.97	3.47	9.10	3.18	10.46	4.06	12.20	4.46
Counting recall	9.27	3.35	14.11	3.73	14.27	4.25	18.08	4.91	18.60	5.85
Bkwrd digit rec	6.50	3.33	8.63	2.75	9.57	2.41	11.05	3.54	12.10	3.27
Visuospatial short-term memory										
Dot matrix	15.27	4.67	18.57	3.32	19.47	3.51	21.43	4.28	22.35	4.11
Mazes memory	11.54	3.80	16.00	5.04	18.22	5.29	20.84	5.51	22.88	4.45
Block recall	13.35	3.02	16.69	4.01	18.08	4.60	20.41	3.72	22.13	4.83
Visuospatial working memory										
Odd one out	12.81	3.70	16.00	3.90	16.75	4.12	19.51	4.89	20.98	4.97
Mr. X	6.62	3.61	8.29	2.28	9.88	3.80	12.22	4.04	13.80	3.89
Spatial span	7.73	3.96	11.74	4.62	13.08	4.99	16.41	4.44	17.68	4.97

excess of .40 on the rotated factor matrix are shown in Table 4. The seven measures that loaded most highly on Factor 1 were the dot matrix, mazes memory, block recall, odd-one-out, counting recall, Mr. X, and spatial span measures. These measures were considered visuospatial tasks, with the exception of counting recall. The visuospatial short-term memory tasks (dot matrix, mazes memory, block recall) and the visuospatial working memory tasks (odd-one-out, Mr. X, spatial span) all require short-term memory for visuospatial material while the working memory measures additionally require the processing of visuospatial information. Even the counting recall task requires the counting of shapes in an array, and may have tapped visuospatial abilities. Overall, tasks loading on Factor 1 tapped visuospatial short-term memory. The measures that loaded most highly on Factor 2 were word recall, digit recall, and nonword recall. These are all measures of phonological short-term memory, and represent the phonological short-term memory composite of the AWMA. Interestingly, none of the verbal working memory tasks had loadings greater than 0.4 on Factor 2 (listening recall = .253; counting recall = .318, backwards digit recall = .361). The measures that loaded most highly on Factor 3 are listening recall, Mr. X, backward digit recall, and spatial span. These measures all have a large processing

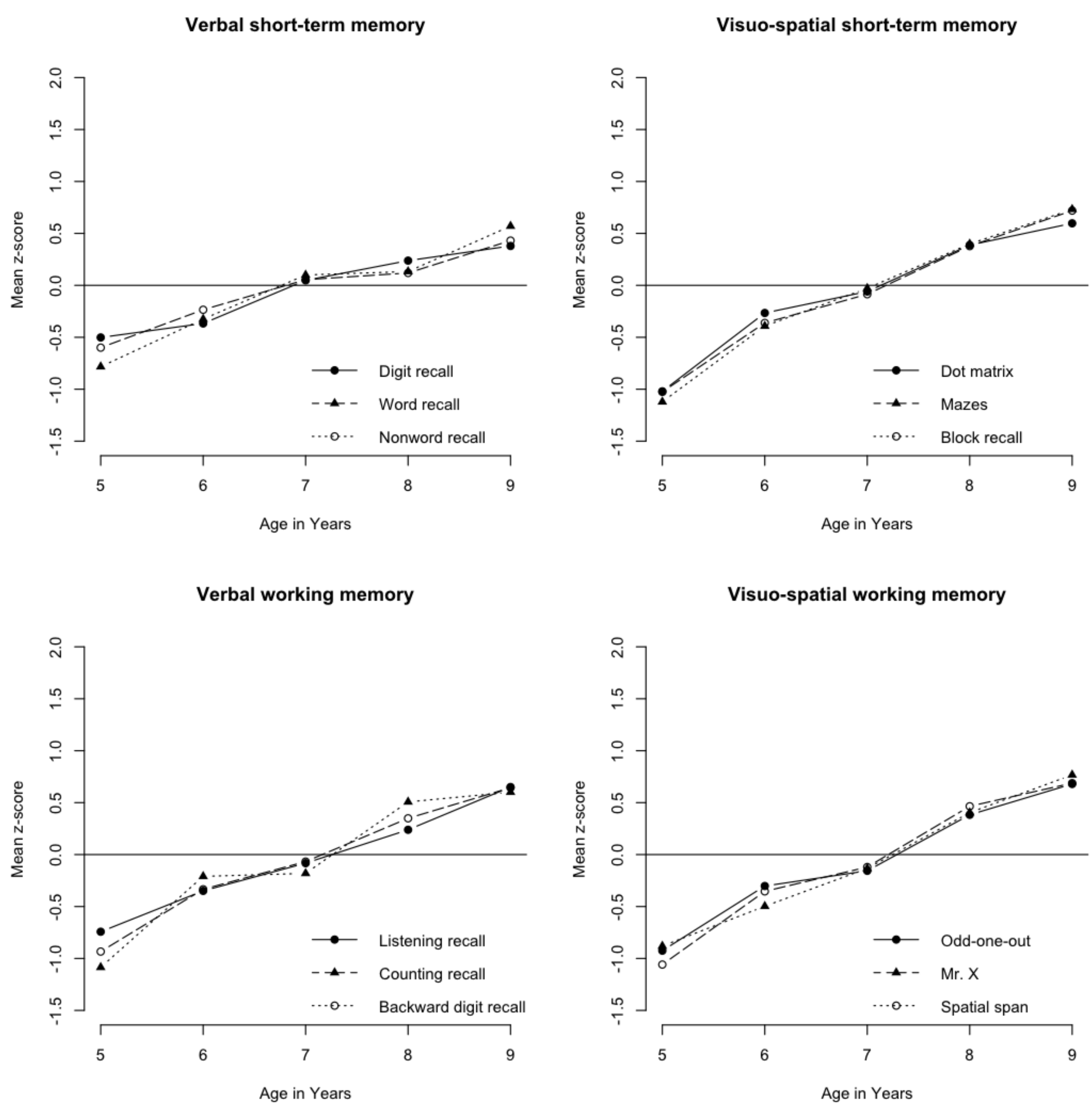

Figure 1. Mean z-scores as a function of age for each of the 12 subtests, grouped by task type.

load. Notably, two of the working memory measures did not load on this processing factor (odd-one-out, counting recall).

Comparison between Canadian and British Samples. The current results were compared to the normative sample for the AWMA collected in the North Eastern region of the United Kingdom. A multivariate analysis of variance (MANOVA) was conducted with culture (Canadian versus British) as a fixed variable, and the 12 AWMA subtests as dependent variables. Two covariates were added to the model: age (total months), SES (maternal education). By including these variables as covariates, observed group differences could be attributed to the between-group cultural factor rather than differences in age or SES across

Table 3. Correlations between all memory scores; partial correlations (controlling for age in months) in upper triangle

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Age (months)	-----												
2. Digit recall	0.34	------	**0.65**	**0.38**	**0.30**	**0.28**	**0.37**	0.17	0.17	**0.31**	0.25	0.11	0.20
3. Word recall	0.42	0.70	-----	**0.53**	**0.29**	**0.28**	**0.33**	0.11	0.13	0.22	0.17	0.18	**0.31**
4. Nonword recall	0.30	0.44	0.59	-----	0.22	**0.39**	0.23	0.19	0.24	0.30	**0.32**	0.16	**0.32**
5. Listening recall	0.46	0.41	0.43	0.33	------	**0.28**	**0.27**	0.18	0.17	0.23	**0.30**	**0.29**	**0.29**
6. Counting recall	0.55	0.41	0.44	0.48	0.46	------	**0.43**	**0.37**	**0.41**	**0.40**	**0.56**	**0.36**	**0.47**
7. Backward digit recall	0.50	0.47	0.46	0.34	0.43	0.58	-----	0.24	**0.27**	**0.30**	**0.33**	**0.28**	**0.28**
8. Dot matrix	0.51	0.31	0.30	0.31	0.37	0.55	0.43	-----	**0.43**	**0.57**	**0.49**	**0.34**	**0.34**
9. Mazes Memory	0.60	0.34	0.40	0.36	0.40	0.60	0.49	0.60	------	**0.48**	**0.42**	0.24	**0.38**
10. Block recall	0.56	0.43	0.40	0.40	0.43	0.58	0.49	0.69	0.65	------	**0.45**	**0.29**	**0.43**
11. Odd-one-out	0.52	0.38	0.35	0.42	0.47	0.68	0.50	0.62	0.60	0.61	------	**0.39**	**0.42**
12. Mr. X	0.58	0.28	0.37	0.30	0.48	0.56	0.48	0.54	0.50	0.52	0.57	------	**0.50**
13. Spatial span	0.58	0.36	0.47	0.43	0.48	0.64	0.48	0.54	0.60	0.61	0.59	0.67	------

Note. All zero-order correlations (bottom triangle), p < .001; First-order correlations (upper triangle): all values in bold, p < .001.

the samples. The MANOVA yielded a significant Hotelling's Trace (all cases) of culture, F (12, 575) = 57.69, $p < .001$, η^2_p = .546, SES, F (12, 575) = 5.19, $p < .001$, η^2_p = .098, and age, F (12, 575) = 59.04, $p < .001$, η^2_p = .552. Follow-up univariate ANOVAs were conducted and a Bonferonni adjustment was employed to control against Type I error rates for multiple comparisons, thus a significance level of 0.004 was used. The ANOVAs revealed that the Canadian sample achieved significantly higher scores on the phonological short-term memory subtests (e.g. digit recall, word recall, nonword recall; $p < .001$, all cases), but not the verbal working memory subtests (e.g. listening recall, counting recall, backward digit recall; $p > .05$, all cases). On the visuospatial short-term memory composite the Canadian sample had higher scores on the dot matrix, F (1, 586) = 14.19, $p < .001$, η^2_p = .024 and mazes memory, F (1, 5) = 6, $p < .001$, η^2_p = .105, subtests but did not differ on block recall, F (1, 586) = 1.93, p = .17, η^2_p = .003. On the visuospatial working memory composite the Canadian sample obtained higher scores than the British sample on the odd-one-out, F (1, 586) = 49.59, $p < .001$, η^2_p = .078 and Mr. X, F (1, 586) = 16.04, $p < .001$, η^2_p = .027, subtests but did not differ on spatial span, F (1, 586) = 3.16, p = .08, η^2_p = .005. The discrepancy between standard scores based on the Canadian vs. normative sample for the Canadian sample appear in Appendix B. Average discrepancies mirror the results of the ANOVA with large discrepancies for the phonological short-term memory, dot matrix, mazes memory, odd-one-out, and Mr. X subtests, and smaller discrepancies for the verbal working memory, block recall, and spatial span subtests. Discrepancies tended to be larger for the younger than older age groups with scores based on the Canadian sample being, on average, 9.2 points higher (SD = 3.7).

Table 4. Factor loadings based on a principal components analysis with varimax rotation for 12 subtests from the Automated Working Memory Assessment (N=178)

Rotated Component Matrix	Component		
	1	2	3
Dot matrix	0.819		
Mazes memory	0.784		
Block recall	0.781		
Odd-one-out	0.733		
Counting recall	0.666		
Spatial span	0.633		0.460
Word recall		0.838	
Digit recall		0.795	
Nonword recall		0.746	
Listening recall			0.789
Mr. X	0.542		0.636
Backwards digit recall			0.513

Note. Factor loadings < .40 are suppressed.

Discussion

This study investigated the performance of a group of Canadian children between the ages of 5 and 9 years randomly selected from a large database on measures of phonological and visuospatial short-term and verbal and visuospatial working memory from the Automated Working Memory Assessment (AWMA; Alloway, 2007a). All measures demonstrated significant developmental increases. There were no reliable sex differences. Although males scored significantly higher on the verbal working memory composite, no sex differences were found on the individual subtests comprising this composite. Results of the principal components analysis completed on all subtests revealed a three-factor structure accounting for nearly 70% of the variance. Visuospatial short-term and working memory measures loaded on Factor 1, and phonological short-term memory measures, on Factor 2. Both verbal and visuospatial working memory measures loaded on Factor 3. Correlational analyses were consistent with this factor structure. The pattern of findings were consistent with those reported for the UK sample on which the AWMA was normed, however the Canadian sample achieved higher raw scores even when adjusted for age and maternal education on the phonological short-term memory measures, and two each of the visuospatial short-term (dot matrix; mazes recall) and working memory (odd-one-out; Mr. X) subtests.

These findings reflect considerable consistency with results reported previously. Age-related improvements in short-term and working memory have been observed in many past studies (e.g., Alloway, Gathercole, & Pickering, 2006; Hulme, Thomson, Muir, & Lawrence, 1984). While the nature of the developmental changes in working memory have been the matter of some debate, evidence largely supports an increase in the efficiency of the working memory components (Gathercole, 1999; Jenkins, Myerson, Hale, & Fry, 1999 Luciana & Nelson, 1998; Luna, Garver, Urban, Lazar & Sweeney, 2004; Pickering, 2001). One factor that interacts with memory efficiency is an increase in the long-term knowledge base. Performance is better when recalling familiar items such as words than unfamiliar items such as nonwords (Gathercole, 1995) or novel shapes or locations. Consistent with this view, raw scores tended to be higher in the present study (see Table 2) for short-term memory tasks with familiar items (i.e., digit recall) than unfamiliar items (e.g., nonword recall, mazes memory).

The results are also consistent with Baddeley and Hitch's (1974) tripartite model of working memory. The three-factors identified in our principal components analysis map readily to the three components described by Baddeley and Hitch. Factor 1 included all of the short-term and working memory tasks tapping visuospatial skills, as well as counting recall. The common demand posed by these tasks is visuospatial processing and short-term memory. Although the counting recall task requires verbal labeling, the circles must be located prior to counting thereby posing some visuospatial processing. Clearly, then, Factor 1 corresponds to Baddeley and Hitch's visuospatial sketchpad. Factor 2 included the phonological short-term memory measures corresponding to the phonological loop. Interestingly, none of the factor loadings for the verbal working memory subtests exceeded 0.4 for this factor despite their requirement for retention of verbal information. It may be that the processing demands of these tasks were sufficiently high that children were unable to expend resources on storage. The final factor was associated with both visuospatial (Mr. X, spatial span) and verbal (listening recall, backwards digit recall) working memory tasks. In addition to their domain-specific storage demands, these tasks pose processing demands across domains. Thus, Factor 3 corresponds to the domain-general central executive. Two of the working memory tasks did not load on this factor (odd-one-out, counting recall) possibly because their low processing demands (locating an odd shape from three, counting) did not consistently constrain performance.

The cultural differences observed in the present study, as reflected by higher raw scores for the Canadian sample than the normative UK sample, were unexpected. Nevertheless, previous research has reported variable results with regard to the cultural sensitivity of working memory assessments, with some studies reporting differences between groups (Beauchamp et al., 1979; Ostrosky-Solís & Lazano, 2006; Reynolds et al., 1999), and others reporting no differences (Campbell et al., 1997; Engel, Santos & Gathercole, 2008). The current study found differences between Canadian and UK performance on the AWMA, with the Canadian sample exhibiting higher performance than the UK sample on several subtests. Interestingly, consistent differences across all measures testing one component were found only for the phonological short-term memory composite. The phonological short-term memory measures included digit and word recall, both of which tap prior knowledge. It may be that the current sample had a greater knowledge base to support recall in these tasks. This suggestion, however, would not explain the difference found on the nonword recall task because the nonwords would be equally unfamiliar to both samples. It may be that pedagogical differences in the respective school systems provided some phonological processing advantage to the Canadian sample that facilitated nonword encoding and recall. Importantly, however, any advantage in storing verbal information did not lead to an advantage on the verbal working memory measures. This finding suggests that performance on the verbal working memory tasks was constrained by the processing demands associated with these tasks, and that these processing demands are not influenced by cultural differences.

The groups also differed on two of the visuospatial short-term (dot matrix, mazes memory) and working memory tasks (odd-one-out, Mr. X). These tasks are all associated with our visuospatial short-term memory factor with only the Mr. X task having been observed to load additionally on the domain-general processing factor in our factor analysis. Reasons for a visuospatial short-term memory advantage in our Canadian sample are less clear. It may be that other influences not measured here differed between the two samples such as experience with visuospatial processing. For example, our groups may have differed in time spent playing popular video games, which has been found to influence visual memory (Ferguson, Cruz, & Rueda, 2008).

One limitation of the present study is the sample size. Normative data is usually based on cohorts of 100 per age band. The present study included 26 to 40 children per age band. As a result, the margin for error in estimating the population performance is greater. Given that the current findings represent a replication of previous results for the most part, the smaller sample size may not be particularly problematic. However, the comparisons across the cultural samples warrant cautious interpretation given the smaller size of the Canadian sample.

Clinical Implications

Given the possible discrepancy between standard scores based on the two cultural samples compared in the present study, caution is warranted when applying the published AWMA norms across cultures. The present findings call for the development of North American norms for the AWMA, as has been provided for numerous other tests including the *Clinical Evaluation of Language Fundamentals, 4th edition* (Semel, Wiig, & Secord, 2003) and the *Woodcock-Johnson Tests of Cognitive Abilities, 3rd edition* (Woodcock, McGrew, & Mather, 2001).

Nevertheless, examining the relative scores across the verbal and visuospatial and short-term and working memory composites of the AWMA still has clinical utility. Such comparisons provide information about whether the child is challenged more by phonological/verbal than visuospatial material (as evidenced by poor performance on the phonological short-term and verbal working memory composites but not the corresponding visuospatial composites) or by working than short-term memory tasks (as evidenced by poor performance on the verbal and visuospatial working memory but not corresponding short-term memory composites). It might be expected that phonological/verbal deficits would have a more language-specific impact than a domain-general working memory impairment, although language processing deficits would be expected in the latter case as well (Noonan et al., 2014).

Conclusion

In this study, a North American sample of children aged 5 to 9 years completed measures of phonological and visuospatial short-term and verbal and visuospatial working memory from the Automated Working Memory Assessment (AWMA; Alloway, 2007a). Results replicated previous findings of a developmental increase for all measures, and a three-factor structure to explain the variance in performance. Consistent with Baddeley and Hitch's (1974) tripartite working model, nearly 70% of the variance was explained by domain-specific short-term memory stores for either phonological or visuospatial material and a domain-general processing resource. The current sample achieved higher raw scores than the UK normative sample for this test on the phonological and visuospatial short-term memory tasks; however, the working memory tasks were not influenced by cultural differences.

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Acknowledgements

This work was supported by a National Science and Engineering Research Council of Canada discovery grant to the second author. The valuable assistance of participating school personnel and families is gratefully acknowledged. The authors are grateful to Dr. Tracy Packiam Alloway for providing access to the normative UK sample for the Automated Working Memory Assessment (Alloway, 2007a), and to Pearson, Clinical Assessment for test access.

Authors' Note

Correspondence concerning this article should be addressed to Lisa M. D. Archibald, Western University, School of Communication Sciences and Disorders, Elborn College, Room 1510. London, ON N6G 1H1 CANADA. Email: larchiba@uwo.ca.

APPENDIX A

Raw scores corresponding to Z-score cut offs for each Automated Working Memory Assessment Subtest by age group.

Z-Score	5 years	6 years	7 years	8 years	9 years
Digit Recall					
1.5	32.32	31.26	31.95	33.78	35.82
1.0	29.98	29.46	30.48	31.96	33.51
0	25.31	25.86	27.55	28.32	28.90
-1.0	20.64	22.26	24.62	24.68	24.29
-1.5	18.31	20.46	23.16	22.86	21.99
Word Recall					
1.5	26.45	26.90	27.73	27.81	30.45
1.0	24.25	25.13	26.23	26.32	28.64
0	19.85	21.60	23.23	23.35	25.02
-1.0	15.45	18.07	20.23	20.38	21.40
-1.5	13.25	16.31	18.73	18.90	19.59
Nonword Recall					
1.5	19.02	20.28	21.00	20.53	22.62
1.0	16.97	18.29	19.15	18.92	20.72
0	12.88	14.31	15.45	15.70	16.93
-1.0	8.79	10.33	11.75	12.48	13.14
-1.5	6.75	8.34	9.90	10.87	11.25
Listening Recall					
1.5	11.68	13.18	13.87	16.55	18.89
1.0	9.89	11.44	12.28	14.52	16.66
0	6.31	7.97	9.10	10.46	12.20
-1.0	2.73	4.50	5.92	6.40	7.74
-1.5	0.94	2.77	4.33	4.37	5.51

Counting Recall					
1.5	14.30	19.71	20.65	25.45	27.38
1.0	12.62	17.84	18.52	22.99	24.45
0	9.27	14.11	14.27	18.08	18.60
-1.0	5.92	10.38	10.02	13.17	12.75
-1.5	4.25	8.52	7.90	10.72	9.83
Backwards Digit Recall					
1.5	11.50	12.76	13.19	16.36	17.01
1.0	9.83	11.38	11.98	14.59	15.37
0	6.50	8.63	9.57	11.05	12.10
-1.0	3.17	5.88	7.16	7.51	8.83
-1.5	1.51	4.51	5.96	5.74	7.20
Dot Matrix					
1.5	22.28	23.55	24.74	27.85	28.52
1.0	19.94	21.89	22.98	25.71	26.46
0	15.27	18.57	19.47	21.43	22.35
-1.0	10.60	15.25	15.96	17.15	18.24
-1.5	8.27	13.59	14.21	15.01	16.19
Mazes Memory					
1.5	17.24	23.56	26.16	29.11	29.56
1.0	15.34	21.04	23.51	26.35	27.33
0	11.54	16.00	18.22	20.84	22.88
-1.0	7.74	10.96	12.93	15.33	18.43
-1.5	5.84	8.44	10.29	12.58	16.21
Block Recall					
1.5	17.88	22.71	24.98	25.99	29.38
1.0	16.37	20.70	22.68	24.13	26.96

0	13.35	16.69	18.08	20.41	22.13
-1.0	10.33	12.68	13.48	16.69	17.30
-1.5	8.82	10.68	11.18	14.83	14.89
Odd-one-out					
1.5	18.36	21.85	22.93	26.85	28.44
1.0	16.51	19.90	20.87	24.40	25.95
0	12.81	16.00	16.75	19.51	20.98
-1.0	9.11	12.10	12.63	14.62	16.01
-1.5	7.26	10.15	10.57	12.18	13.53
Mr. X					
1.5	12.04	11.71	15.58	18.28	19.64
1.0	10.23	10.57	13.68	16.26	17.69
0	6.62	8.29	9.88	12.22	13.80
-1.0	3.01	6.01	6.08	8.18	9.91
-1.5	1.21	4.87	4.18	6.16	7.97
Spatial Span					
1.5	13.67	18.67	20.57	23.07	25.14
1.0	11.69	16.36	18.07	20.85	22.65
0	7.73	11.74	13.08	16.41	17.68
-1.0	3.77	7.12	8.09	11.97	12.71
-1.5	1.79	4.81	5.60	9.75	10.23

APPENDIX B

Average discrepancy between standard scores based on the current sample vs. the test's normative sample

	5-5;11 (*n* = 26)		6-6;11 (*n* = 35)		7-7;11 (*n* = 40)		8-8;11 (*n* = 37)		9-9;11 (*n* = 40)		Total (*n* = 178)	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Phonological short-term memory												
Digit recall	21.4	0.83	9.1	7.6	8.2	6.2	9.8	1.6	4.6	2.4	9.8	6.9
Word recall	16.8	3.8	11.7	5.5	14.2	5.2	5.6	3.8	7.4	4.8	10.8	6.2
Nonword recall	24.0	3.4	18.7	2.7	21.8	12.6	14.1	4.7	13.9	4.6	18.1	7.9
Verbal working memory												
Listening recall	17.8	6.2	8.6	2.3	4.2	3.1	3.3	6.3	2.9	3.0	6.6	6.7
Counting recall	8.7	1.1	10.7	1.3	2.5	2.4	8.9	2.1	1.8	3.5	6.2	4.4
Bkwrd digit rec	10.5	0.5	3.6	2.5	0.1	5.3	1.1	2.0	-1.7	5.0	2.1	5.4
Visuospatial short-term memory												
Dot matrix	12.7	1.8	15.4	2.9	4.6	2.3	7.1	1.4	2.2	5.9	7.9	6.0
Mazes memory	10.4	4.6	11.7	2.2	3.1	1.7	1.4	1.9	6.3	5.2	6.2	5.2
Block recall	6.6	4.1	5.3	3.3	-2.4	1.9	0.5	4.6	1.1	2.5	1.8	4.6
Visuospatial working memory												
Odd one out	19.8	5.2	15.8	5.5	11.6	4.3	14.2	3.7	11.1	3.2	14.1	5.2
Mr. X	19.0	4.3	11.7	4.6	15.0	3.2	9.8	3.5	12.2	3.5	13.2	4.8
Spatial span	14.6	2.5	6.9	5.2	5.8	1.9	8.5	2.4	6.7	3.0	8.1	4.3