Developmental Aspects of Working and Associative Memory

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Accepted 29 November 2012

Abstract

Developmental differences between working and long-term associative memory were evaluated through a cross-sectional age difference study based on data from a memory battery’s standardization sample. The scores of 856 children and adolescents ranging from 5 to 17 years of age were compared on memory subtests that assess verbal working and long-term memory. Data were examined using curve fitting and ANOVA procedures that evaluated age group and years of age differences. The major finding was that the developmental trajectories across age differed substantially between the two memory domains. The working memory trajectory was linear until age 11, whereas the long-term memory trajectory was curvilinear with an inflection point at age 8. Both trajectories plateaued after age 11. ANOVAs produced significant interactions between tests of working and associative memory with age, supporting the view that the age trajectories had differing courses. The results are discussed in terms of neurobiological implications for the two memory systems studied.

Keywords: Learning and memory; Assessment

Working memory has been defined as a limited capacity memory system that provides temporary storage to manipulate information for complex cognitive tasks, whereas long-term memory refers to the storage and retrieval of information beyond the initial few seconds (Baddeley, 1966; Baddeley & Hitch, 1974). It is now evident that there are differences in long-term and working memory development related to their underlying neural structures and neurobiological changes throughout childhood and adolescence (Costa-Mattiloi & Sonenberg, 2008; Hötting, Katz-Biletzky, Malina, Lindenau, & Bengner, 2010). Long-term memory is encoded primarily in the medial temporal structures before diffusing throughout the cortex, whereas working memory is primarily associated with frontal and parietal regions (Fletcher & Henson, 2001; Squire, 2004; Townsend, Richmond, Vogel-Farley, & Thomas, 2010). As these regions differentially mature in typically developing youth (Bauer, 2008), it is likely that the memory abilities linked to each structure may in turn demonstrate different trajectories through early childhood and adolescence.

Regarding the developmental trajectory of working memory, studies indicate that forward and backward auditory span capacities develop in a linear fashion from about 2 to 11 or 12 years of age, at which point performance becomes asymptotic (Gathercole, 1998, 1999). There is also evidence that performance on long-term memory tasks becomes asymptotic after early adolescence, suggesting that this developmental period is a time in which certain memory components reach a maturational level (Gathercole, 1999; Schneider, Knopf, & Sodian, 2009). In contrast to the linear improvement observed with working memory span tasks, long-term verbal memory tasks appear to improve in three stages: rapidly from ages 5 to 8 years, less rapidly yet still incrementally from 9 to 11 years, and then relatively flat after 12 years (Schneider, 2002; Thaler, Allen, Cross, & Reynolds, in press). These studies therefore suggest that long-term memory and working memory components undergo different developmental trajectories in children and adolescents.
Although often studied as a unified system, there is evidence that there are separate subcomponents of working memory that are influenced by distinct neural systems (Bedwell et al., 2005; Schulze, Zysset, Mueller, Friederici, & Koelsch, 2011), which in turn are assessed by different psychometric measures. The distinction has been made between verbal and spatial working memory and different tests are used separately to evaluate these abilities, such as digit span and spatial/symbol span tasks as contained in the Wechsler intelligence and memory scales (Wechsler, 1997, 2008, 2009). There are also experimental procedures that evaluate working memory, such as the n-back task (Jaeggi et al., 2010). Long-term verbal memory has also been separated into distinct subcomponents, such as source memory and associative memory, the latter of which relies on the recall of items based on their association with other items and environmental cues (Park, Shannon, Biggan, & Spann, 2012). As a type of long-term memory, associative verbal memory is often assessed as part of neuropsychological evaluations, typically through paired-word learning and list-learning tasks. The purpose of this preliminary study was to characterize developmental changes in verbal working memory and long-term verbal associative memory in typically developing children and adolescents of varying ages.

We examined age differences in working memory compared with associative memory using a large, nationally representative, and stratified sample of children aged 5–17 years who were administered the Test of Memory and Learning (TOMAL; Reynolds & Bigler, 1994). The TOMAL is a well-validated battery that was designed to assess memory functioning in children and adolescents, and consists of several subtests that are conceptually linked to distinct memory domains and neural processes. Among these subtests are the digit backward (DB) and letter backward (LB) subtests, typical examples of simple backwards span tasks in which participants must mentally rotate a string of numbers and letters after it is read to them, and then immediately repeat them in reverse order. Span tasks in general are conceived as measures of attention, simple attention, and working memory. Regarding the latter domain, backwards span tasks have theoretically and psychometrically been found to be a more accurate estimate given the additional element of mental rotation involved (Ramsay & Reynolds, 1995; St Clair-Thompson, 2010). The TOMAL also has the Word Selective Reminding subtest (WSR), which is a standard test of recall of words over trials. List-learning tests are measures of associative memory in that items on ordered lists are chained together into pairwise associative units which are then chained with other units, facilitating recall (Caplan, 2005; Lewandowsky & Murdock, 1989).

This sample is the same one that was used in another examination of TOMAL subtest performance (Thaler et al., in press). Briefly, their study cluster analyzed raw TOMAL factor scores that were uncorrected for age to ascertain possible age ranges that may represent discrete periods of development in memory composites. Through cluster analysis, inspection of raw mean scores by age, and discriminant function analyses, it was determined that the age ranges 5–8, 9–11, and 12–19 had the best representation of age groups with overall different developmental trajectories. These scores were then grouped into long-term verbal, non-verbal, and short-term attention and working memory factors, and compared across the established age groups. These factors, while useful in grouping several subtests into simpler constructs, also obscured differences that may be present at the subtest level, particularly when such subtests theoretically capture discrete neurocognitive constructs. The current study differed from the other one by selecting choice subtests, rather than synthetic composites, for further analyses. These subtests are conceptually linked to working memory and associative memory, respectively, and scores were not only plotted across the 5–8, 9–11, 12–19 age groups, but also compared across individual years of age to more conclusively track developmental trajectories.

Based on the prevailing literature on both working and long-term memory (Gathercole, 1998, 1999; Schneider et al., 2009), it was hypothesized that the working memory composite would exhibit a linear developmental trajectory until early adolescence, at which point performance would plateau and become asymptotic. It was also hypothesized that the associative memory WSR subtest would exhibit a curvilinear developmental trajectory with an inflection point at age 8, and then plateaus by early adolescence. Such findings may provide direction for future hypotheses regarding the maturation of the discrete neurobiological systems underlying these cognitive measures.

**Method**

**Participants**

Participants in this study included 856 children and adolescents between the ages of 5–17 years of age ($M = 10.0$, $SD = 3.1$) drawn from the TOMAL standardization sample. Children had no history of neurological or acquired brain disorders, learning disabilities, or other disorders known to affect memory and learning. Children were 50.7% boys and 77.0% were Caucasian, 7.5% were African American, 7.7% were Hispanic, and the remaining 7.8% were other ethnicities.
Measures

The TOMAL measures selected to evaluate working and associative memory included three subtests. The DB and LB subtests require participants to recite a string of numbers or letters in reverse order to the examiner. Unlike span tasks of the Wechsler measures, the discontinue criteria for both tasks are not met after two failed trials; rather, the participant receives partial credit for recalling a portion of the span in correct position, and the task is only discontinued after a set number of completely failed trials. The WSR subtest was selected as the measure of associative verbal memory, as it is a task that requires participants to memorize a list of words with corrective reminding and then repeat this list back to the examiner. The task is repeated until every word is recalled over a series of trials or when seven unsuccessful trials have been attempted.

Data Analysis

Raw scores uncorrected for age were examined in order to evaluate the impact that age may have on subtest performance. These scores were standardized into z-scores and a composite score combining digits and letters backward subtests (BWS) was combined. Z-scores also allowed the BWS and WSR scores to be directly compared with each other. Scores were calculated by subtracting each of the subtests by its mean and dividing it by the standard deviation, essentially standardizing raw scores relative to performance within the sample. Data were initially analyzed using a curve fitting procedure. Years of age data were treated graphically to allow for a year by year inspection of the developmental patterns. Scatterplots were obtained and fitted with curves for linear and quadratic effects and with Loess curves. Loess or local regression curves were used to evaluate the possibility that the age curve did not fit a typical linear or quadratic effect. It is not necessary to specify any particular function to fit a model to the data. Preliminary curve fitting analyses for linear and quadratic functions did in fact indicate that the corresponding regression lines for the two tests were essentially identical with what was found for the Loess curves and so we used those curves for all subsequent analyses.

In order to obtain quantitative statistical analyses of the data shown in the curves, the sample was divided into three age ranges that had been identified through statistical means using cluster analysis, described in detail in Thaler and colleagues (in press) to represent three distinct periods of memory development in children and adolescents. Cluster analysis was selected in that study as a statistical method for examining the data because it can test the similarity of performance on memory components across children of different ages, with the rationale that ages with relatively similar performance reflect a period of stable memory function. When performance characteristics abruptly shift at a specific age, this likely reflects a developmental point or inflection at which memory improves. Application of discriminant function analysis evaluating several cluster solutions indicated that a three cluster solution clearly separated substantially different cognitive profiles.

Age groups were analyzed with ANOVA to allow for statistical interpretation of the main findings. The three age groups showing optimal separation were 5–8, 9–11, and 12–17 years, and served as the between-subjects variable in a mixed-model ANOVA with Age Group as the between-subjects factor and a repeated measures Memory variable consisting of the BWS and WSR z-scores as the repeated measure. Thus, this Memory variable was used to compare relative performance between these scores across the age groups. Significant main and interaction effects were examined, with the assumption that significant interaction effects would represent distinct changes in working memory versus associative memory that are influenced by age. The purposes of this analysis were those of determining whether there are significantly different patterns of age differences between verbal working and associative memory found in a large, stratified normative sample using a well-established battery. This analysis was initially performed using the age groups as the between-subjects variable and was repeated using actual age in years.

Results

The Loess curves showing the relation between age in years and scores on the TOMAL WSR and BWS scores are presented in Fig. 1. In the case of the WSR score, there is a large inflection after age 8 and a smaller one after age 11, at which point the curve plateaus. These breaking points are similar to those that were produced by the cluster analysis (Thaler et al., in press) and suggest that there are marked changes in developmental trajectories around ages 9 and 12, respectively. For the BWS score, the curve the pattern is linear from ages 5 to 11 years, and then there is a similar plateau after age 11. In other words, no inflection point was present after age 8 for the working memory composite as there was for the associative memory composite and the growth trajectory flattened around age 12. Curve fitting procedures for linear and quadratic estimates yielded essentially the same curves as were found for the Loess solution, and so only the Loess solution is presented here.

Inspection of the figure also suggests that at the younger age range, children performed relatively poorer on the WSR subtest compared with the BWS score in absolute z-score terms. This relationship changed in the middle age range, at which children
performed better on the WSR subtest. Differences in relative performance between the WSR and BWS variables evened out in the older age range, suggesting that through adolescence, children develop equivalent levels of ability in working and associative memory. Paired sample $t$-tests with a Bonferroni correction set at 0.017 confirmed that in the younger age range, WSR was poorer than BWS—$t(301) = 12.59, p < .001$—in the middle age range, WSR was better than BWS—$t(371) = 7.12, p < .001$—and no such differences were present in the older age range—$t(181) = 0.72, p = .47$.

Results of the ANOVAs are presented in Table 1. The mixed-model ANOVA comparing age groups found a significant main effect. However, the main effect for the memory system was not significant. Interestingly, a large interaction effect was found for Age Group × Memory System, confirming that age range differentially influenced performance on the two memory subtests. In order to obtain a more refined analysis by age without consideration of the three age groups, a second mixed-model ANOVA was run (see Table 1). Similar to the Age Group analysis, there was a significant main effect for Years of Age, as well as a significant Years of Age × Memory System interaction effect. Again, no effect for Memory System was found.

**Table 1.** Results of mixed model analyses of variance (ANOVA) for age and memory system.

<table>
<thead>
<tr>
<th>ANOVA and effects</th>
<th>$F$</th>
<th>df</th>
<th>$p$</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Age Group ANOVA$^a$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age Group</td>
<td>590.43</td>
<td>2, 853</td>
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<td>0.581</td>
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<td>Memory system</td>
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<td>1, 853</td>
<td>.82</td>
<td>0.0001</td>
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<tr>
<td>Age Group × Memory System</td>
<td>114.32</td>
<td>2, 853</td>
<td>&lt;.001</td>
<td>0.211</td>
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<tr>
<td>2. Age in years ANOVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age in years</td>
<td>107.45</td>
<td>12, 843</td>
<td>&lt;.001</td>
<td>0.601</td>
</tr>
<tr>
<td>Memory System</td>
<td>0.34</td>
<td>1, 853</td>
<td>.56</td>
<td>0.001</td>
</tr>
<tr>
<td>Age in years × Memory System</td>
<td>20.03</td>
<td>12, 843</td>
<td>&lt;.001</td>
<td>0.222</td>
</tr>
</tbody>
</table>

$^a$Note: Age groups are those identified in Thaler and colleagues (in press) and include children who are 5–8, 9–11, and 12–17 years.
The interaction between memory system and age in years is likely represented by the inflection point at the middle age in years going from a rapid acceleration to a plateau for the WSR subtest, with a very linear pattern for the BWS score through the middle ages until it abruptly plateaus in early adolescence. Thus, repeating this analysis with actual ages resulted in the same findings. These results are clearly illustrated in Fig. 2 which contains a plot of the interaction. It can be seen that the curve for the BWS composite is linear until it becomes asymptotic at age 12, whereas there appear to be an additional inflection at age 9 for the WSR subtest.

These results indicate that in a large, representative healthy sample, tests of working and associative memory have different trajectories across ages, with working memory showing a linear pattern until age 12, at which point performance becomes asymptotic, and associative memory showing a curvilinear pattern demonstrating rapid acceleration until age 9, and then a slower acceleration until age 12, at which point it also is followed by a plateau. Inflection points noted in the Loess curve for the WSR subtest supports the division into age groups previously suggested by a cluster analysis.

Discussion

This study was conducted to describe the development of verbal working memory in contrast to associative memory in typically developing children and adolescents ranging in age from 5 to 17 years. The study was based on subtests from the TOMAL standardization sample that measure verbal working and associative memory. Results indicated that the age difference trajectories differed between the WSR subtest, a measure of associative memory, and the BWS composite, a measure of verbal working memory. For the associative memory task, the trajectory was found to be curvilinear, rapidly accelerating up until about age 9, then slowly but steadily increasing to about age 12, and then plateauing afterwards. In contrast, the working memory measure had a markedly linear trajectory across ages up until age 12, after which it also was asymptotic.

Fig. 2. Memory system by age interaction effects.
For the purpose of statistical analyses, ages were divided into age groups with children 5–8 years old constituting the youngest group, children 9–11 placed in the middle group, and children and adolescents above 11 in the oldest group. While the division into age groups may be viewed as somewhat arbitrary, it is supported by cluster analyses by Thaler and colleagues (in press) as well as research examining the development of memory abilities (Gathercole, 1999; Schneider, 2002). The division was also justified by curve-fitting results that fit with the traditional distinction made among younger children, older children, pre-adolescents, and adolescents. It would appear that the cognitive abilities required for associative memory memory mature earlier in life than those needed for working memory with those needed for associative memory rapidly increasing between ages 5 and 8 before slowing between ages 9 and 11, while those needed for working memory require a more gradual developmental trajectory during this period. From a clinical perspective, these findings suggest that neurological insults within the 5–8 year time frame may be particularly hindering to developing associative memory abilities. Findings also suggest that after early adolescence, working and associative memory abilities have reached maturational levels and so any neurological insult may affect these domains but not interfere with typical development. Results therefore provide a refinement to memory assessment that allows for evaluation of memory impairment from the standpoint of developmental considerations, and suggest that different forms of memory develop with differing trajectories.

It is well understood that verbal working memory is primarily mediated by a network of circuits within the frontoparietal regions (Østby, Tamnes, Fjell, & Walhovd, 2011; Takeuchi et al., 2011). The structural development of these regions is characterized by synaptic pruning and the thinning of gray matter (Østby et al., 2011). It may be that the steady improvement of performance on the DB span task reflects a constant rate of developmental change at the neuronal level in developing children. By early adolescence, cognitive performance on short-term working memory tasks may have peaked and reached levels held constant through adulthood. This is an interesting comparison to more complicated listening span working memory tasks, which continue to develop through late adolescence and early adulthood (Gathercole, 1999), and is likely tied to continued neurodevelopment of the frontal regions. Our findings also support that associative memory develops rapidly in the early years, which may in part be due to the functional maturity of the temporal-cortical network by the second year of life (Bauer, 2008). As this region has already reached maturity by the time children enter school, children may benefit from environmental and educational cues in the early school years (Schneider et al., 2009), which in turn reflects the rapid improvement in associative memory during early childhood. By early adolescence, children have acquired memory strategies for organization of information for consolidation (Bauer, 2008). It appears from our results that this represents a peak level of associative memory performance through mid to late adolescence, although additional studies are required to support this hypothesis.

With regard to identifying a neurobiological basis for these results, as a preliminary suggestion we would refer to a study of the relation among cognitive function, age, and magnetic resonance spectroscopy (MRS) findings done previously by our group (Goldstein et al., 2009). In this study, healthy, normal children ranging in age from 6 to 18 years were tested with a battery of cognitive tests and an MRS procedure that yielded numerous metabolic and structural variables. Differences were found among ages on several of these variables along with differences on the cognitive tests. The MRS variable that tracked the cognitive changes most closely was the high-energy phosphate metabolite phosphocreatine (PCr). The age curve corresponded closely for the curve representing a single memory index derived from the Wide Range Assessment of Memory and Learning (WRAML), a test that is quite similar to the TOMAL. This domain score was an index incorporating the results of the WRAML Picture Memory, Design Memory, Verbal Learning, Story Memory and Number/Letter subtests, and the curve identified inflection points at approximately 9.5 and 12 years, which is comparable with our inflection points identified at 9 and 12 years. In their study, a distinction was not made between types of memory, and the MRS findings were for the whole brain, and not specific regions, which may explain the slight differences in identified inflection points. However, it provided evidence that there was a strong association between a brain metabolite involving energy utilization and cognitive ability. The capability is now available to obtain MRS results from specific brain regions, and with this capability, it would be possible to test working and associative memory specifically in association with age differences in PCr and possibly other metabolites for specific brain regions. This research could identify the pattern of possibly different forms of age-related change in specific aspects of memory as they relate to metabolic changes, and could help to determine if these change patterns differ across the major brain regions.

Perhaps the major limitation of this study was that it was restricted to verbal memory, and did not consider spatial memory. The reason spatial memory was not considered was that it was not clear that the TOMAL contains subtests that make the clear distinction between working and associative memory that is made for verbal memory. Future research may investigate these issues further by using non-verbal tasks designed to specifically assess working and associative memory abilities. In addition, the three age group model identified in Thaler and colleagues (in press) requires more validation, though this study appears to support the initial findings. Another limitation is the cross-sectional nature of the study. A longitudinal follow-up of these results may provide additional support for the established findings, and might also examine how environmental factors might influence individual trajectories.
**Funding**

This research was supported by the Mental Illness Research, Education, and Clinical Center (MIRECC) VISN-IV, Pittsburgh, PA, and by the Medical Research Service, Department of Veterans Affairs.

**Conflict of Interest**

No conflict of interest.

**Acknowledgements**

The VISN IV Mental Illness Research, Education, and Clinic Center (MIRECC), VA Pittsburgh Healthcare System and the Medical Research Service, Department of Veterans Affairs are acknowledged for support of this research.

**References**


