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DEVELOPMENTAL TRAJECTORIES OF WORKING MEMORY FROM AGE 6 THROUGH 25 YEARS

by

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ABSTRACT

Working memory (WM) has been shown to be closely related to measures of achievement and intelligence, as well as attention, illustrating the critical role WM plays in the learning process. Understanding the typical developmental trajectory of WM is essential if professionals are to recognize and intervene when a child's WM development shows signs of delay. The current study evaluated the development of WM in a cross-sectional sample of 303 children, adolescents, and adults from ages 6 through 25 years. The study utilized a comprehensive measure of WM, assessing verbal, static visual-spatial, and dynamic visual-spatial WM capacity across various processing demands. Results provide support for previous studies indicating a linear trajectory of WM development from childhood to adolescence. However, in all but one instance (i.e. static visual-spatial WM), WM development did not show the anticipated quadratic relationship with age. The developmental trajectory of verbal WM appears to increase linearly through at least early adulthood, while the trajectory of dynamic visual-spatial WM shows a more complex relationship, with WM development declining slightly in mid-adolescence before increasing again in early adulthood. The impact of processing demand on WM development was also assessed across domains. Overall, WM development appears to be largely unaffected by processing demand, with the exception of static-visual spatial WM tasks. Implications and directions for future research are discussed.

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CHAPTER 1

INTRODUCTION

Impact of Working Memory

Working memory (WM) can be thought of as our ability to temporarily retain small portions of information for use in ongoing cognitive processes (Baddeley, 2000; Conway et al., 2005; Cowan et al., 2005). Measures of WM have been shown to be closely related to measures of achievement and intelligence (Alloway & Alloway, 2010; Oberauer, Schulze, Wilhelm, & Süß, 2005; Swanson & Siegel, 2001) as well as attention (Engle, 2002; Kane et al., 2007), illustrating the critical role WM plays in the learning process. Children with poor verbal WM capacity may struggle to follow multipart instructions, have difficulty holding information within their minds long enough to process it, and are more likely to report that their mind has wandered off-task during challenging activities (Kane et al., 2007). These difficulties are often associated with marked impairments in children's ability to complete educational assignments.

WM also plays a crucial role in the development of many important academic skills, including skill in reading and mathematics. WM is strongly associated with the development of math calculation skills (Alloway, 2006; Cowan & Alloway, 2009), as well as with mathematical word problems (Swanson & Beebe-Fankenberger, 2004). As children progress from learning single-digit multiplication to two and three-digit figures, their ability to perform mental calculations typically deteriorates as a function of their WM capacity. However, the association between WM and the development of mathematical skill seems to vary depending upon the type of math problem involved as well as the child's age. For instance, although studies have shown that verbal WM is associated with the development of math skills in young children, this association becomes less significant by the time children reach adolescence (Alloway, 2006). WM ability has also been found to be a predictor of specific learning disabilities in mathematics (Cowan & Alloway, 2009; Swanson & Siegel, 2001), with deficits in verbal WM, visual-spatial WM, and attentional processing related to lower computational skills and poor performance on word problems incorporating arithmetic (David, 2012; Siegel & Ryan, 1989; Swanson & Siegel, 2001).

The impact of children's WM capacity on educational outcomes can also be seen in the development of reading skill. Current evidence regarding WM's role in reading suggests that verbal short-term memory (STM) is significantly related to early reading achievement, primarily due to its role in the acquisition of letter knowledge and phonological processing. In particular, complex WM tasks, which involve both storage and manipulation of information, have been found to be more predictive of reading achievement than simple memory span tasks assessing storage alone (Cowan & Alloway, 2009). Yet despite its impact on the acquisition of early reading skills, deficits in WM have not been shown to be a cause of reading disabilities. Rather, its role seems to be through its impact on phonological processing. Children with reading disabilities tend to be able to recall fewer strings of letters than typically developing children (Henry, 2012) and perform more poorly on nonword repetition tasks (Rispens & Baker, 2012), supporting the idea that verbal STM is impaired in these individuals. Younger children with reading disabilities (i.e. 7-8 year olds) also show fewer similarity effects than their typically developing peers, indicating a reduced sensitivity to phonological similarities and/or differences (Siegel & Linder, 1984). In contrast, significant differences in visual-spatial STM in children with reading disabilities compared to typically developing peers have not been found, suggesting that WM's relationship with reading disabilities may be linked specifically to the verbal domain.

Given the role WM plays in achievement, it is hardly surprising that WM deficits have been linked to difficulties associated with other clinical populations as well. STM and language impairments, for instance, are highly related, with simple repetition tasks providing one of the best indicators of specific language impairment (Cowan & Alloway, 2009). Nonword repetition tasks are also particularly telling, as children with language impairments tend to score several grade levels below their peers (Archibald & Gathercole, 2006). Yet, similar to children with reading disabilities, children with language impairments typically do not show impairments in visual-spatial WM, highlighting that their WM deficits are related specifically to the verbal domain (Archibald & Gathercole, 2006).

WM deficits have also been linked to problems associated with attention deficit/hyperactivity disorder (ADHD), though the impact seems to vary depending upon the "type" of ADHD indicated. Children and adolescents with a predominantly inattentive presentation of ADHD tend to show marked deficits in WM; in fact, WM deficits are considered a hallmark of the disorder (Cowan & Alloway, 2009). Although WM deficits have been consistently linked to the predominantly inattentive presentation of ADHD, research has not yet determined whether WM deficits could be a cause of the inattentive behaviors associated with the disorder or if they are merely related. In contrast, children with ADHD who have a predominantly hyperactive presentation tend to show impairments in other aspects of executive functioning but not in WM (Cowan & Alloway, 2009).

Development of WM

Given the long-lasting and wide-ranging impacts that WM deficits can have, understanding the typical developmental trajectory of WM is essential if teachers, school psychologists, and other professionals are to recognize and intervene when a child's WM development shows signs of delay. In terms of the development of WM abilities, one of the most important and factors influencing the capacity of WM, and thus one of the most predictive, is one's age (Gathercole, 1999). Literature concerning the development of WM has consistently pointed to a linear increase in WM capacity from early childhood to adolescence (e.g. Gathercole, 1998; Gathercole, Pickering, Ambridge, & Wearing, 2004; Goldstein et al., 2014; Thaler et al., 2013). At the age of 5, for example, children are able to repeat back approximately three words in order, which increases steadily in a linear fashion, to four words by the age of 9 and five words by the age of 11 (Henry, 2012).

Research regarding the development of WM has typically focused on developmental increases in WM span. In one of the most comprehensive studies involving the development of WM across content domains, Gathercole and colleagues (2004) investigated the structure and development of WM in children and adolescents aged 4 to 15 years. The authors administered three measures of each of the three components of the Baddeley and Hitch (1974) WM model (i.e. the phonological loop, visuospatial sketchpad, and central executive). Verbal storage was measured using digit, word, and nonword recall, while visual-spatial storage was measured with tests using block tapping, mazes, and visual pattern tasks. The central executive functions were measured using complex memory span tasks, including digits backward, listening recall, and counting recall, which involve processing via the central executive as well as storage within the verbal domain (Gathercole et al., 2004). Gathercole and colleagues found evidence that the basic structure of the Baddeley and Hitch WM model was present in children from at least 6 years of age. In addition, the authors found linear increases across each of the short-term and WM components measured from 4 years of age to adolescence. There was a slight variation in the developmental trajectory of one of the components within the study (Gathercole et al., 2004), with performance on the visual pattern span task appearing to level off around 11 years of age. In contrast, the authors found that development across each of the other tasks appeared to increase linearly from age 4 to 14 years, leveling off between 14 and 15 years of age. It is notable, however, that although each of the tasks showed a linear trend in development overall, several showed periods of decline or plateau before increasing again in subsequent years. Given that Gathercole and colleagues' sample did not include individuals above the age of 15, it is possible that some of these trajectories may have continued to rise throughout later adolescence.

A more recent study by Goldstein and colleagues (2014) indicated a similar trend, with verbal WM span increasing linearly from 6 to 14 years of age, though the authors faced the same limitation regarding the ceiling of their sample's age range, which included children only to age 14. Though these findings seem to support the steady increase of WM through the age of 14, other studies regarding the development of verbal WM span have indicated an earlier asymptote around 11 or 12 years of age (Gathercole, 1998, 1999; Thaler et al., 2013). Still, although there remains some debate regarding the age at which development levels off, the initially linear trajectory of WM development from early childhood to adolescence has been well-supported.

In a recent study, Alloway and Alloway (2013) investigated the development of WM within a broad age range, including individuals from 5 to 80 years of age. Similar to previous studies, the authors found considerable growth in WM from childhood through adolescence. However, contrary to the studies described previously (i.e. Gathercole, 1998, 1999; Gathercole et al., 2004; Goldstein et al., 2014; Thaler et al., 2013), the authors found that WM performance actually peaked in 30-year olds, rather than in adolescence. A 2015 study by Isbell, Fukuda, Neville, and Vogel reported similar findings regarding the development of visual WM. The authors investigated visual WM capacity in 13, 16, and 20 year olds. Results indicated that visual WM capacity did not reach adult levels in the teenage samples, but continued to develop through adolescence and into adulthood. Thus, it remains unclear as to when the development of WM capacity ceases to increase and begins to level off.

Factors Influencing the Development of WM

Many potential explanations for the developmental increase in WM have been suggested, including an increase in articulation or speech rate, an increase in processing speed, and an increase in the space or capacity of WM storage itself (Cowan & Alloway, 2009). The development of rehearsal strategies is another possible factor that may contribute to an increase in WM capacity. Rehearsal strategies involve consciously repeating information over and over again within your mind in order to maintain the information in your mind for an extended period of time (King, 2014). Developmental differences in WM and strategy use are particularly apparent in younger ages, with rehearsal strategies not appearing to develop until around the age of 7 (Gathercole & Hitch, 1993). Prior to this age, children do not consistently use rehearsal strategies.

A developmental shift also occurs in children's visual STM around the age of 7. Children younger than the age of 7 tend to rely on visual-spatial STM (i.e. the visuospatial sketchpad) to recall visual information. When recalling items such as pictures, younger children rely on remembering the physical form of the object, rather than recoding the information into a verbal form (Palmer, 2000). In contrast, individuals over the age of 7 are more likely to recode visual information into verbal code, using verbal STM to store the information, rather than the visuospatial sketchpad (Gathercole et al., 2004; Henry, 2012; Pickering, 2001).

Different hypotheses exist as to why visual-spatial memory for items that cannot be verbally recoded also shows steady developmental increases. One possibility suggested by Isbell and colleagues (2015) is that this increase may be associated with coinciding changes in brain functioning and development that take place during adolescence. Others have suggested that the storage capacity of the visuospatial sketchpad itself may increase, that the increase in visual-spatial memory may be related to an increase in knowledge within long-term memory, or that it may be due to better functioning of the central executive (Gathercole et al., 2004). Central executive tasks have also been found to improve with age, potentially due to a decrease in the processing demands of memory tasks, which frees resources previously used in processing to be used in storage (Case, Kurland, & Goldberg, 1982). The use of additional strategic approaches to aide retention is another possible explanation for the improvement in central executive tasks (Henry, 2012).

WM Measures

A major confound in exploring the development of WM is the consideration of how specific aspects of WM measures may impact the outcomes of studies. WM tasks vary by domain (i.e., visual-spatial or verbal) as well as in the complexity of the task. As a result, different methods have been devised to measure different aspects of WM. Traditionally, the phonological loop has been assessed through measures of verbal STM, which measure the ability to recall speech-based information. These tasks can be categorized as involving storage alone (typically referred to as STM storage) or storage plus manipulation (more commonly referred to as WM). The most common measure of verbal STM storage is the digit span task (Henry, 2012), in which participants are asked to repeat a series of orally presented numbers. The length of the series is gradually increased; with the longest list the participant is able to accurately recall representing that individual’s memory span. Another common measure of verbal STM storage is word span tasks, which utilize the same procedure described previously, using words rather than numbers. These tasks are considered “simple span tasks,” as they require only storage, rather than both storage and manipulation.

Other measures, described as “complex span tasks,” include measures such as Digit Span, found on the Wechsler Intelligence Scale for Children – Fifth Edition (WISC-V; Wechsler, 2014), and Numbers Reversed, found on the Woodcock-Johnson IV Tests of Cognitive Abilities (WJ-IV; Schrank, McGrew, & Mather, 2014). Numbers Reversed requires the participant to repeat an increasingly long list of orally presented digits in reverse order while Digit Span requires the participant to listen to a series of numbers and then repeat the numbers back in either the same order, backward, or in ascending order. Complex span tasks require both storage and manipulation, and are thus considered better measures of WM, while simple span tasks are typically seen as measuring only STM storage, rather than tapping the complexity involved in WM.

The visuospatial sketchpad is similarly assessed through measures of visual-spatial STM. One of the most common measures of spatial STM is block tapping, which measures spatial span. This task requires participants to watch the examiner tap a series of blocks and then copy the examiner's actions, tapping the blocks in the same sequence. In this instance, the individual's spatial span is considered the longest sequence that can be correctly reproduced (Henry, 2012; Pickering, 2001).

A common measure of visual STM is the pattern span task, in which the participant is shown a grid of boxes depicting a random pattern of shaded and unshaded boxes. The participant is permitted to view the grid for a short period of time and must attempt to remember which spaces were shaded and which were not. After exposure, the grid is removed and the participant has to indicate on a blank grid which spaces had previously been filled in (Henry, 2012; Pickering, 2001). Difficulty is increased by increasing the size of the grid and number of boxes to be remembered. The participant's score is determined by the highest number they are able to remember correctly. Although block tapping and pattern-span tasks are commonly used to measure visual-spatial storage, they are best described as "simple span tasks," as they require only storage, rather than storage and manipulation.

Although the importance of WM has been widely acknowledged, few comprehensive measures of WM exist. Many tests of intellectual abilities include only verbal WM measures (e.g. Woodcock-Johnson IV Tests of Cognitive Abilities (WJ-IV; Schrank et al., 2014)). As a result, measures of WM used in research do not comprehensively measure all of the WM domains (e.g. verbal, visual-spatial, including static and dynamic visual-spatial sequences) and processing demands (e.g. storage, storage with manipulation, and interference) that have been identified as important in contemporary theoretical frameworks (e.g. Baddeley, 2000; Engle, 2002; Englund, Decker, Woodlief, & DiStefano, 2014; Mammarella, Borella, Pastore, & Pazzaglia). Unfortunately, this means that researchers often fail to obtain a comprehensive assessment of an individual's WM abilities. For example, while the 2004 study by Gathercole and colleagues described previously provided one of the most comprehensive examinations of the development of WM across domains, examination of the tasks used to measure WM reveals weaknesses in the study. While the authors measured verbal, visual, and spatial STM storage, their measures of complex memory span included tasks in only the verbal domain (Gathercole et al., 2004). Thus, conclusions can only be made regarding the development of visual-spatial *STM storage* in this study, rather than visual-spatial *WM*.

In order to address the need for a comprehensive measure of WM, the WM Battery (WOMBAT) was developed. The WOMBAT is an online, multicomponent measure of WM developed for use with school-age children, adolescents, and adults (Englund et al., 2014). The WOMBAT is unique in that it measures multiple components of WM, rather than focusing solely on verbal WM tasks or solely on visual-spatial tasks as other measures do. It includes nine subtests which measure multiple WM content domains (verbal, static/simultaneous visual-spatial, and dynamic/sequential visual-spatial), as well as multiple processing demands (e.g. storage-only tasks, storage + manipulation, and storage + interference) (Englund et al., 2014). Each of the domains includes three subtests involving different processing demands.

Within the verbal domain, a digit span task, Digits Forward, measures verbal storage. Digits Backward, which includes verbal storage plus manipulation, is a complex span task measuring verbal WM, requiring individuals to repeat an increasingly long list of numbers in reverse order. Finally, Digits Forward-Interference measures verbal WM in regards to executive attention by assessing verbal storage with interference. In this subtest, participants hear a series of numbers, followed by an unrelated question which they must respond yes or no to. After responding to the question, the participants are asked to repeat the series of numbers in the same order they were presented (Englund et al., 2014).

Static (simultaneous) visual-spatial WM involves the ability to remember “static, simultaneously presented spatial locations of static stimuli” (Englund et al., 2014, p. 544). Subtests within this domain include Dots, Dots Up, and Dots-Interference. The first subtest, Dots, is a variation of the pattern-span task described previously, using dots rather than shaded squares to measure visual-spatial storage. In the Dots Up subtest, the task measures visual-spatial WM by requiring participants to remember where the original dots were and then shifting each dot up one space. Like Digits Forward-Interference, Dots-Interference is similar to Dots, except that it requires participants to answer an unrelated question prior to indicating where each dot was located (Englund et al., 2014), providing a measure of static visual-spatial WM in regards to executive-attention.

Finally, the dynamic visual-spatial domain measures the ability to remember dynamic (sequentially presented) sequences of spatial locations (Englund et al., 2014). The dynamic visual-spatial domain includes Dots Sequence, Dots Sequence-Backward, and Dots Sequence-Interference. In order to measure dynamic visual-spatial storage, the Dots Sequence subtest requires participants to remember the order in which a series of dots appeared within the grid. In the dynamic visual-spatial WM subtest, Dots Sequence-Backward again requires participants to remember the order in which dots appeared within a grid; however, the participants are asked to indicate the order the dots appeared in reverse order, beginning with the final dot and ending with the first. Finally, Dots Sequence-Interference is similar to Dots Sequence, but requires the participant to respond to an unrelated question prior to indicating the order in which the dots moved. Thus, Dots Sequence-Interference measures dynamic visual-spatial storage with interference, or dynamic visual-spatial WM-executive attention (Englund et al., 2014).

Purpose of the Present Study

Although previous research has illustrated a linear increase in WM capacity from childhood to adolescence (e.g. Gathercole, 1998; Gathercole et al., 2004; Goldstein et al., 2014; Thaler et al., 2013), few studies to date have included samples that extend into the adult years. In addition, while several studies have suggested that WM capacity increases linearly until sometime between the ages of 12 - 14 after which it levels off, other studies have suggested that WM continues to increase into adulthood (e.g. Alloway & Alloway, 2013; Isbell et al., 2015). The limited number of studies including expansive age ranges, as well as the inconsistency of previous results makes it difficult to draw conclusions as to the developmental trajectory of WM beyond the early teenage years. In addition, the failure to utilize comprehensive measures of WM in previous studies makes it difficult to draw conclusions regarding the development of WM across domains.

The primary purpose of this study is to expand upon extant literature by investigating the developmental trajectory of WM across different WM domains and processing demands in school age children, adolescents, and young adults from ages 6 through 25 years. This study asks the following questions:

(1) Does the development of various WM domains (i.e. verbal, static visual-spatial, and dynamic visual-spatial) follow a linear or nonlinear (e.g. curvilinear) trajectory from childhood through early adulthood (i.e. ages 6 – 25)?

(2) Does the developmental trajectory of these WM domains vary by processing demand (e.g. verbal STM as compared to verbal WM or verbal STM with interference)?

In regards to the first research question, based upon previous literature it is hypothesized that the development of WM will follow a curvilinear (specifically, quadratic) trajectory across WM domains such that WM development will increase steadily throughout childhood and adolescence, leveling off in early adulthood. In regards to the second research question, it is not anticipated that WM development will differ by processing demand. Thus, it is hypothesized that the development of WM will increase linearly throughout childhood and adolescence before tapering off in early adulthood, regardless of the processing demand involved.

CHAPTER 2

METHOD

Participants

Participants were selected from a newly developed online measure of WM, the WM Battery (WOMBAT). Individuals aged six through 25 years were selected from this dataset in order to assess the development of WM from childhood through adolescence and early adulthood. The WOMBAT was designed to allow individuals to complete one subtest or a number of subtests. For the purposes of this study, only those subjects with a complete profile (i.e., scores for all 9 subtests) were included in the analyses (N = 303, 146 males, 157 females, M_{age} = 14.82 (5.45), age range = 6 – 25 years). From the original dataset, a total of 54 cases fell outside of the designated age range and were excluded. An additional 261 cases were excluded due to incomplete score profiles.

Adult participants included undergraduate and graduate students recruited primarily from the Psychology department of a large pubic university in the southeast. Children were recruited from a midsize elementary school in the southeastern United States, while adolescents attended a midsize suburban high school in the southeast. More specific demographic information can be found in Table 2.1. Overall, 54.8% of participants included in the study were White, 35.3% Black, 3.3% Asian, 3.6% Latino, and 3% other. According to the 2014 U.S. Census, the racial/ethnic composition of the United States is 62.1% white (not Hispanic or Latino), 13.2% black, 5.4% Asian, 1.2% American Indian/Alaskan Native, 0.2% Native Hawaiian/Pacific Islander, and 2.5% two or more races, with 17.4% identifying as Hispanic or Latino (U.S. Census Bureau, 2015). Thus, within this sample, white, Asian, and Hispanic/Latino participants were underrepresented, while black participants were over-represented.

Measures

The WOMBAT is an online measure of WM developed by Julia Englund and Scott Decker (Englund et al., 2014) at the University of South Carolina. As described previously, the WOMBAT was designed to measure WM skills using nine subtests: Digits Forward, Digits Backward, Digits Forward Interference, Dots, Dots Up, Dots Interference, Dots Sequence, Dots Sequence Backward, and Dots Sequence Interference, each assessing a different processing demand and content domain associated with WM (see Table 2.2). The WOMBAT is administered online and has been used by a wide range of individuals, including children, adolescents, and adults, aged 6 to 77 years. Administration of the full battery progresses from storage-only tasks of verbal, static visual-spatial, and dynamic visual-spatial information to storage plus manipulation tasks in each content domain, and finally to a storage plus interference task in each domain (Englund et al., 2014). Each subtest consists of 20 items, with a total of 60 items per content domain. The WOMBAT uses Rasch modeling in order to determine individual ability level. After four consecutive errors, the subtest ends and the individual proceeds to the next subtest.

Englund and colleagues (2014) investigated the test-retest reliability, factor structure and item fit of the WOMBAT using confirmatory factor analyses and Rasch modeling. Results of the analyses provided support for the three-factor structure of the WOMBAT, indicating that it measures WM in the areas of verbal, static visual-spatial, and dynamic visual-spatial domains, with more than 98% of items contributing to measurement of those domains. Test-retest reliability (*r* = .83, range = .49 (Dots Interference) - .88 (Dots)) and internal consistency (Chronbach's α = .90, range = .66 (Dots Sequence) - .85 (Dots Backward)) results indicate that the WOMBAT has adequate reliability for early-stage research purposes; however, the authors caution that further refinement of individual items within the test is needed before it can be used for individual decision making (Englund et al., 2014). Additionally, analyses of the WOMBAT were conducted using only adolescent and adult samples indicating that further research is needed in order to ascertain that these results apply to younger populations.

Data Analyses

For the purposes of this study, a multivariate polynomial regression model was used in order to determine whether the development of various WM components follows a linear or curvilinear trajectory from childhood through early adulthood. Regression techniques are useful in predicting the outcome of one variable (e.g. WM scores) from another variable (e.g. an individual's age). Polynomial regression, which includes higher-order predictor terms in the regression model, can be used to model curvilinear relationships (Cohen, Cohen, West, & Aiken, 2003). Thus, by employing polynomial regression we are able to assess whether a nonlinear relationship might be present. Given the desire to predict multiple correlated outcomes (i.e. the development of multiple WM components), a multivariate regression model was used in order to address the primary research question while controlling for the inflation of Type 1 error rates that would arise from conducting multiple tests.

Data Inspection

Regression models assume that the relationship between the independent and dependent variables is linear and that the residuals, or error terms, are independent, homoscedastic, and normally distributed. Violation of regression assumptions may lead to biased parameter estimates and/or bias in the standard errors of the regression coefficients (Cohen et al., 2003). A thorough review of the regression diagnostics was conducted in order to check for violations of the assumptions associated with multivariate regression. The data were also inspected for out-of-range values, outliers, and missing data, as well as multicollinearity and singularity.

In order to check the regression assumptions, the univariate regression model was run for each subtest with age as a predictor. Linearity and homoscedasticity were assessed by plotting the residuals against the predicted values of the dependent variables. If the relationship is linear and homoscedastic the plot of residuals should be randomly distributed around 0. Outliers were examined using boxplots, with outliers of more than 2 standard deviations away from the mean of each subtest indicated. Independence of errors was tested by examining the Durbin-Watson statistic of the univariate regression models. The Durbin-Watson statistic provides a test for residual autocorrelation, which varies between 0 and 4, with a value of 2 meaning the residuals are uncorrelated. Values less than 1 and greater than 3 are potentially problematic. Normality was evaluated using histograms and Q-Q plots of the individual subtests as well as of the residuals. Histograms should show distributions that approximate the normal curve while Q-Q plots should show points falling on or near the diagonal line. The data were also assessed for multivariate outliers and normality using Mahalanobis distance.

Table 2.1

Demographic Characteristics

Group	*n*	Age in years *M* (*SD*)	Females (%)	Males (%)	White (%)	Black (%)	Latino (%)	Asian (%)	Other (%)
Children (ages 6-10)	102	8.15 (1.42)	53 (52.0)	49 (48.0)	54 (52.9)	37 (36.3)	8 (7.8)	0 (0.0)	3 (2.9)
Adolescents (ages 14-17)	101	15.58 (1.00)	37 (36.6)	64 (63.4)	48 (47.5)	49 (48.5)	1 (1.0)	1 (1.0)	2 (2.0)
Adults (ages 18-25)	100	20.86 (2.06)	67 (67.0)	33 (33.0)	64 (64.0)	21 (21.0)	2 (2.0)	9 (9.0)	4 (4.0)
Total	303	14.82 (5.45)	157 (51.8)	146 (48.2)	166 (54.8)	107 (35.3)	11 (3.6)	10 (3.3)	9 (3.0)

N = 303

Table 2.2

WOMBAT Structure & Subtests

	Domains		
Demands	Verbal	Static Visual-Spatial	Dynamic Visual-Spatial
STM	Digits Forward	Dots	Dots Sequence
WM	Digits Backward	Dots Up	Dots Sequence Backward
WM-Executive Attention	Digits Forward Interference	Dots Interference	Dots Sequence Interference

CHAPTER 3

RESULTS

Data Inspection

No out-of-range values or missing data were detected during the data inspection and all means and standard deviations were within reasonable limits. Univariate outliers (i.e. scores more than 2 standard deviations above the mean) were detected; however, inspection of the outliers revealed that all scores were within the specified range for each subtest. No justification to remove the outliers in question could be determined, thus all cases were included in the analyses.

The data were also assessed for linearity, homoscedasticity, independence, and normality. As anticipated, results revealed a nonlinear trend in several of the univariate models, providing additional support for the use of a polynomial regression model. Problems with non-normality in the distribution of the data were also identified and various transformations were attempted. However, transformation attempts were unsuccessful in correcting for non-normality and the original, untransformed data were used in all analyses (see Table 3.1 for descriptive statistics). The presence of multivariate outliers was also detected; however, as the univariate data could not be corrected, the multivariate outliers were also retained. No problems with independence were detected. Values of the Durbin-Watson statistic were all close to 2, with values ranging from 1.77 (Dots) to 2.06 (Dots Sequence). No problems with multicollinearity or singularity were detected. Correlations are given in Tables 3.2 and 3.3.

Regression Results

In order to investigate the developmental trajectory of WM across the specified age range (i.e. ages 6 – 25 years), multivariate polynomial regression was employed with the quadratic and cubic terms for age included in the model. In order to explore the primary research question, composite scores were created by summing each individual's subtest scores within each domain (i.e. Verbal, Static Visual-Spatial, Dynamic Visual-Spatial). Composites were then used as the dependent variables for this analysis. The test of the overall multivariate polynomial regression model, including the full (cubic) model and three domain composites, was significant (Roy's largest root = 2.23, $F(3, 299) = 222.59$, $p < .01$; see Table 3.4), indicating that age is a significant predictor of WM development. These results provided justification for further analysis of the univariate regression models.

Each of the univariate polynomial regression models investigating the development of WM across domains was significant (see Table 3.5). Contrary to the original hypothesis, a linear relationship was indicated between age and verbal WM ($t = 2.71$, $p = .007$; Figure 3.1) while the cubic relationship was significant between age and dynamic visual-spatial WM ($t = 5.45$, $p < .001$; Figure 3.2). The relationship between age and static visual-spatial WM appears to be quadratic ($t = -3.37$, $p < .001$; Figure 3.3), providing tentative support for our original hypothesis. However, the cubic relationship was also significant in this case ($t = 2.56$, $p = .01$), with a second shift in the trajectory occurring around age 20. Additional research including an expanded age range is needed to confirm these results.

In order to test the second research question, multivariate polynomial regression was again employed, with the nine WOMBAT subtests entered as the dependent variables. The test of the overall multivariate polynomial regression model, including the full (cubic) model and all nine subtests, was significant (Roy's largest root =2.33, *F*(9, 293) = 75.89, $p < .001$; see Table 3.6), indicating again that age is a significant predictor of WM development and providing justification for further analysis of the univariate regression models across subtests.

Each of the univariate polynomial regression models was significant (see Table 3.7). However, contrary to the hypothesized curvilinear trajectory across WM content domains and processing demands, results suggest that many WM components actually follow a linear trend through childhood, adolescence, and into adulthood. A linear relationship was indicated between age and Digits Backward ($t = 2.06$, $p = .04$; Figure 3.4) as well as Digits Forward Interference ($t = 2.49$, $p = .01$; Figure 3.5) and Dots Up ($t = 2.92$, $p = .004$; Figure 3.6). A linear relationship was also suggested between age and Digits Forward (Figure 3.7); however, the relationship did not reach the .05 level of significance in this model ($t = 1.93$, $p = .055$). It is noteworthy, however, that during preliminary regression diagnostics, when the quadratic and cubic terms were excluded, analyses revealed a strong linear relationship between age and Digits Forward ($p < .001$), suggesting that the addition of the higher order terms were unnecessary in this instance, and ultimately masked the linear relationship between age and Digits Forward.

A quadratic relationship was indicated between age and Dots ($t = -2.54$, $p = .01$; Figure 3.8); however, contrary to the original hypothesis, no other models showed a quadratic relationship. The cubic relationship was significant between age and Dots

Interference ($t = 2.70$, $p = .007$; Figure 3.9), Dots Sequence ($t = 4.70$, $p < .001$, Figure 3.10), Dots Sequence Backward ($t = 4.02$, $p < .001$, Figure 3.11), and Dots Sequence Interference ($t = 4.43$, $p < .001$, Figure 3.12). Complete results for the univariate polynomial regression models across subtests can be found in Table 3.7.

Overall, results revealed significant relationships with age, including linear, quadratic, and cubic relationships across both WM domains and processing demands. Results for the verbal WM components (Digits Forward, Digits Backward, and Digits Forward Interference) indicated R^2 values ranging from .40 - .54, suggesting that age accounts for a large proportion of the variance in these components. Results for the static visual-spatial components (Dots, Dots Up, and Dots Interference) indicated R^2 values ranging from .42-.50, again suggesting that differences in age account for a large proportion of the variance in the components. However, results for the dynamic visual-spatial WM components (Dots Sequence, Dots Sequence Backward, Dots Sequence Interference) revealed R^2 values ranging from only .13 -.20, suggesting that while age does account for a significant amount of variance in these components, it is not the primary determinant of developmental growth in these abilities.

Table 3.1

Descriptive Statistics

Variable	*M* (*SD*)	Range	Skew	Kurtosis
Age	14.82 (5.45)	6 – 25	-0.09	-1.15
Digits Forward	8.88 (2.75)	2.0 – 18	0.15	0.30
Digits Backward	6.53 (3.11)	0.1 – 20	0.92	3.35
Digits Forward Interference	6.60 (3.16)	0.1 – 20	0.53	2.18
Dots	12.05 (3.52)	0.1 – 20	-0.99	2.21
Dots Up	9.72 (4.21)	0.1 – 19	-0.37	-0.49
Dots Interference	12.92 (4.15)	0.1 – 20	-1.09	0.86
Dots Sequence	8.69 (2.75)	0.1 – 15	-1.11	1.24
Dots Sequence Backward	7.65 (3.09)	0.1 – 16	-.0.65	0.18
Dots Sequence Interference	7.73 (3.28)	0.1 – 17	-0.72	0.33
Verbal Domain Composite	22.02 (8.09)	4.1 – 57	0.51	1.75
Static Visual-Spatial Domain Composite	34.69 (10.49)	3.1 – 58	-0.61	0.07
Dynamic Visual-Spatial Domain Composite	24.07 (7.61)	0.3 – 46	-0.67	0.50

Note. Possible subtest scores ranged from 0 - 20 possible points. The actual range of observed scores is indicated above. Composite scores indicate the total of the 3 subtests in each domain; thus scores range from 0 – 60 possible points. Scores of 0 were coded as .1 for analyses.

Table 3.2

Correlation Matrix of Subtests with Age

	Age	DF	DB	DFI	Dots	DU	DI	DS	DSB	DSI
Age	1.00	-	-	-	-	-	-	-	-	-
DF	0.73	1.00	-	-	-	-	-	-	-	-
DB	0.64	0.70	1.00	-	-	-	-	-	-	-
DFI	0.62	0.68	0.73	1.00	-	-	-	-	-	-
Dots	0.58	0.57	0.52	0.47	1.00	-	-	-	-	-
DU	0.61	0.53	0.51	0.47	0.66	1.00	-	-	-	-
DI	0.62	0.58	0.57	0.54	0.66	0.68	1.00	-	-	-
DS	0.31	0.36	0.33	0.36	0.51	0.46	0.51	1.00	-	-
DSB	0.29	0.34	0.41	0.36	0.43	0.47	0.53	0.53	1.00	-
DSI	0.23	0.26	0.30	0.31	0.43	0.41	0.48	0.58	0.51	1.00

Note. All correlations are significant at the $p < .001$ level. DF = Digits Forward, DB = Digits Backward, DFI = Digits Forward Interference, DU = Dots Up, DI = Dots Interference, DS = Dots Sequence, DSB = Dots Sequence Backward, DSI = Dots Sequence Interference.

Table 3.3

Correlation Matrix of Domain Composites with Age

	Age	Verbal	Static Visual-Spatial	Dynamic Visual-Spatial
Age	1.00	-	-	-
Verbal	0.73	1.00	-	-
Static Visual-Spatial	0.69	0.67	1.00	-
Dynamic Visual-Spatial	0.33	0.45	0.64	1.00

Note. All correlations are significant at the $p < .001$ *level.*

Table 3.4

Overall Multivariate Polynomial Regression Results across Domain Composites

Multivariate Test	Effect	*F*	*df*(num, den)	*p*
Wilk's Λ	0.27	57.43***	(9, 722.97)	< 0.001
Pillai	0.82	37.75***	(9, 879)	< 0.001
Hotelling-Lawley	2.38	78.15***	(9, 887)	< 0.001
Roy's Θ	2.23	222.59***	(3, 299)	< 0.001

Note. ***$p < .001$

Table 3.5

Univariate Polynomial Regression Results across Domain Composites

Subtest		*B* (*SE*)	*t*	*F*(3,299)	R^2
Verbal	Intercept	-10.30 (6.94)	-1.49	126.2***	0.56
	Age	4.36 (1.61)	2.71**		
	Age^2	-0.19 (0.11)	-1.67		
	Age^3	0.003 (0.002)	1.30		
Static Visual-Spatial	Intercept	-27.66 (8.79)	-3.15**	136.7***	0.58
	Age	9.85 (2.04)	4.83***		
	Age^2	-0.48 (0.14)	-3.37***		
	Age^3	0.008 (0.003)	2.56*		
Dynamic Visual-Spatial	Intercept	-36.88 (8.66)	-4.26***	28.37***	0.22
	Age	12.69 (2.01)	6.31***		
	Age^2	-0.81 (0.14)	-5.79***		
	Age^3	0.017 (0.003)	5.45***		

Note. **p* < .05, ***p* < .01, ****p* < .001.

Table 3.6

Overall Multivariate Polynomial Regression Results across Subtests

Multivariate Test	Effect	*F*	*df*(num, den)	*P*
Wilk's Λ	0.24	19.49***	(27, 850.51)	< 0.001
Pillai	0.89	13.79***	(27, 879)	< 0.001
Hotelling-Lawley	2.54	27.30***	(27, 869)	< 0.001
Roy's Θ	2.33	75.82***	(9, 293)	< 0.001

Note. ***$p < .001$

Table 3.7

Univariate Polynomial Regression Results across Subtests

Subtest		*B* (*SE*)	*t*	*F*(3,299)	R^2
Digits Forward	Intercept	-0.04 (2.42)	-0.02	114.8***	0.54
	Age	1.08 (0.56)	1.93		
	Age^2	-0.04 (0.04)	-1.08		
	Age^3	0.00 (0.00)	0.88		
Digits Backward	Intercept	-4.54 (3.01)	-1.51	76.91***	0.44
	Age	1.44 (0.70)	2.07*		
	Age^2	-0.06 (0.05)	-1.15		
	Age^3	0.00 (0.00)	0.75		
Digits Forward Interference	Intercept	-5.72 (3.16)	-1.81	66.31***	0.40
	Age	1.83 (0.73)	2.49*		
	Age^2	-0.09 (0.05)	-1.74		
	Age^3	0.00 (0.00)	1.47		
Dots	Intercept	-6.22 (3.45)	-1.80	73.18***	0.42
	Age	2.90 (0.80)	3.63***		
	Age^2	-0.14 (0.06)	-2.54*		
	Age^3	0.00 (0.00)	1.92		
Dots Up	Intercept	-9.03 (4.09)	-2.21*	76.23***	0.43
	Age	2.77 (0.95)	2.92**		
	Age^2	-0.13 (0.07)	-1.90		
	Age^3	0.00 (0.00)	1.38		

Table 3.7 (continued)

Subtest		*B* (*SE*)	*t*	*F*(3,299)	R^2
Dots Interference	Intercept	-12.42 (3.80)	-3.27**	98.56***	0.50
	Age	4.17 (0.88)	4.73***		
	Age^2	-0.21 (0.06)	-3.45***		
	Age^3	0.004 (0.001)	2.70**		
Dots Sequence	Intercept	-11.70 (3.17)	-3.69***	25.15***	0.20
	Age	4.18 (0.74)	5.68***		
	Age^2	-0.26 (0.05)	-5.11***		
	Age^3	0.005 (0.001)	4.70***		
Dots Sequence Backward	Intercept	-11.70 (3.68)	-3.18**	17.69***	0.15
	Age	3.99 (0.85)	4.68***		
	Age^2	-0.25 (0.06)	-4.27***		
	Age^3	0.005 (0.001)	4.02***		
Dots Sequence Interference	Intercept	-13.47 (3.95)	-3.41***	14.38***	0.13
	Age	-4.52 (0.92)	4.93***		
	Age^2	-0.30 (0.06)	-4.62***		
	Age^3	0.006 (0.001)	4.43***		

Note. **p* < .05, ***p* < .01, ****p* < .001.

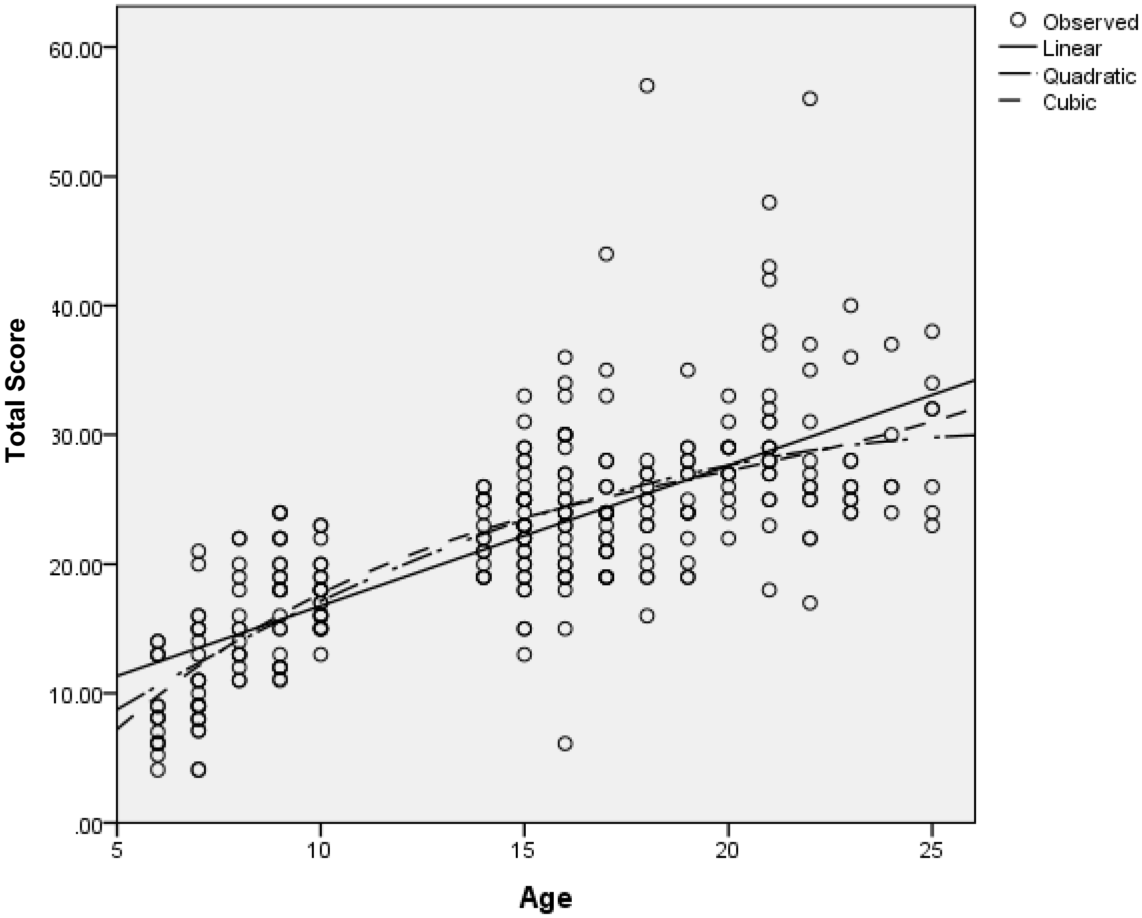

Figure 3.1 Developmental Trajectory of Verbal WM Domain. Possible subtest scores ranged from 0 - 20 possible points. Composite scores indicate the total of the 3 subtests in each domain; thus scores range from 0 – 60 possible points. Scores of 0 were coded as .1 for analyses.

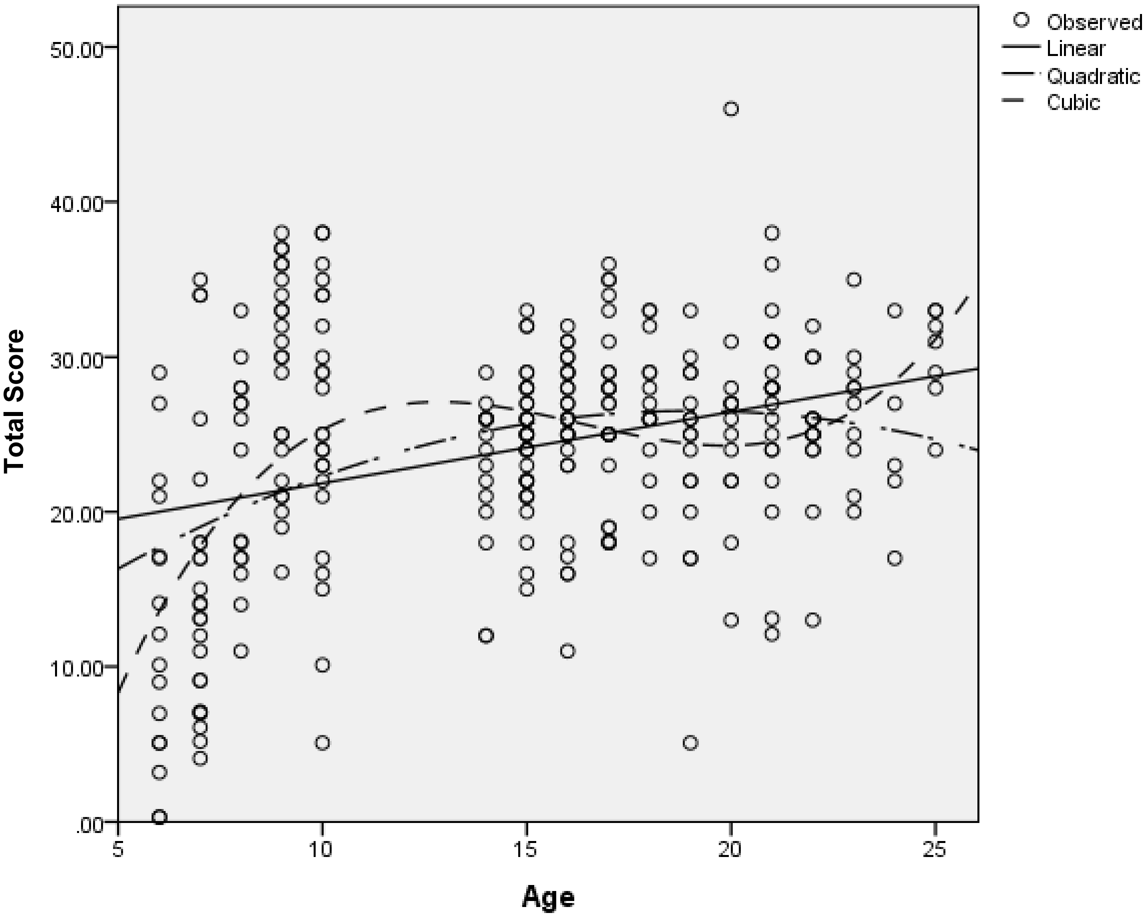

Figure 3.2 Developmental Trajectory of Dynamic Visual-Spatial WM Domain. Possible subtest scores ranged from 0 - 20 possible points. Composite scores indicate the total of the 3 subtests in each domain; thus scores range from 0 – 60 possible points. Scores of 0 were coded as .1 for analyses.

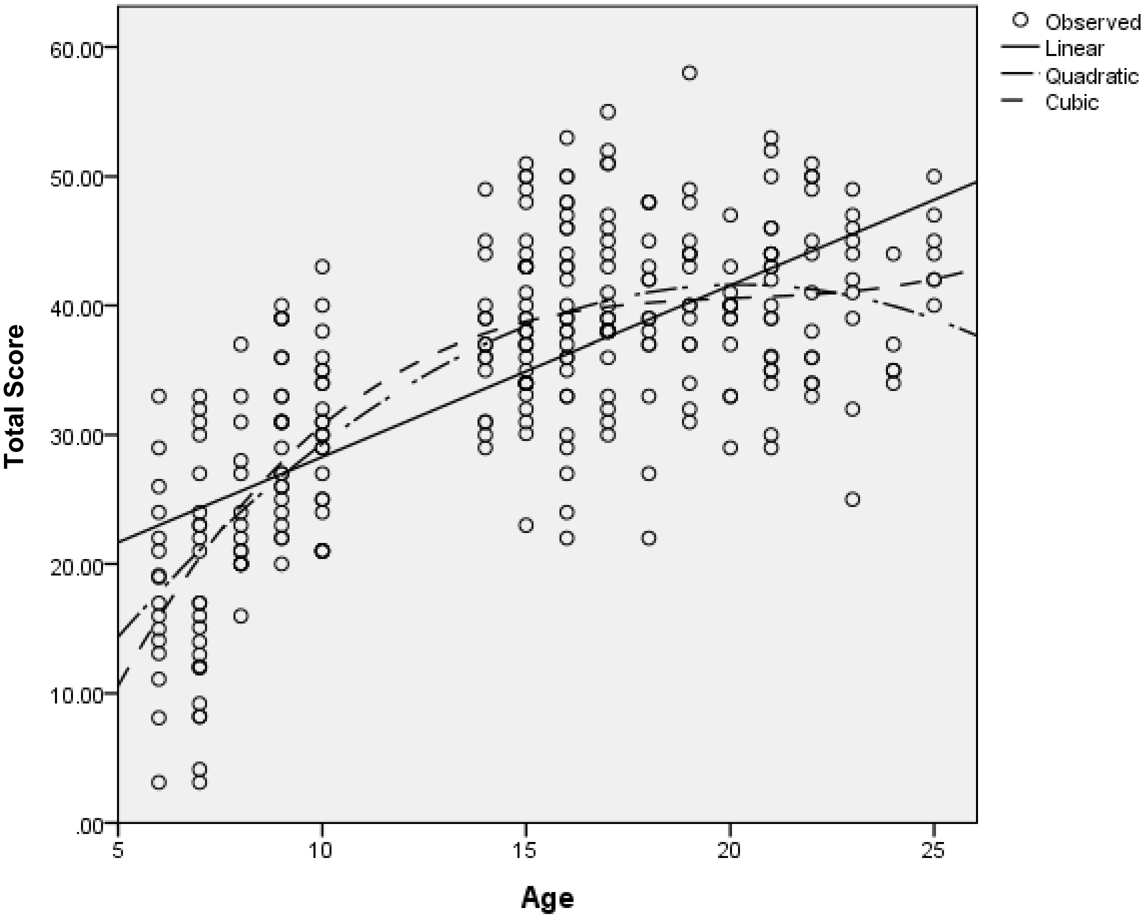

Figure 3.3 Developmental Trajectory of Static Visual-Spatial WM Domain. Possible subtest scores ranged from 0 - 20 possible points Composite scores indicate the total of the 3 subtests in each domain; thus scores range from 0 – 60 possible points. Scores of 0 were coded as .1 for analyses.

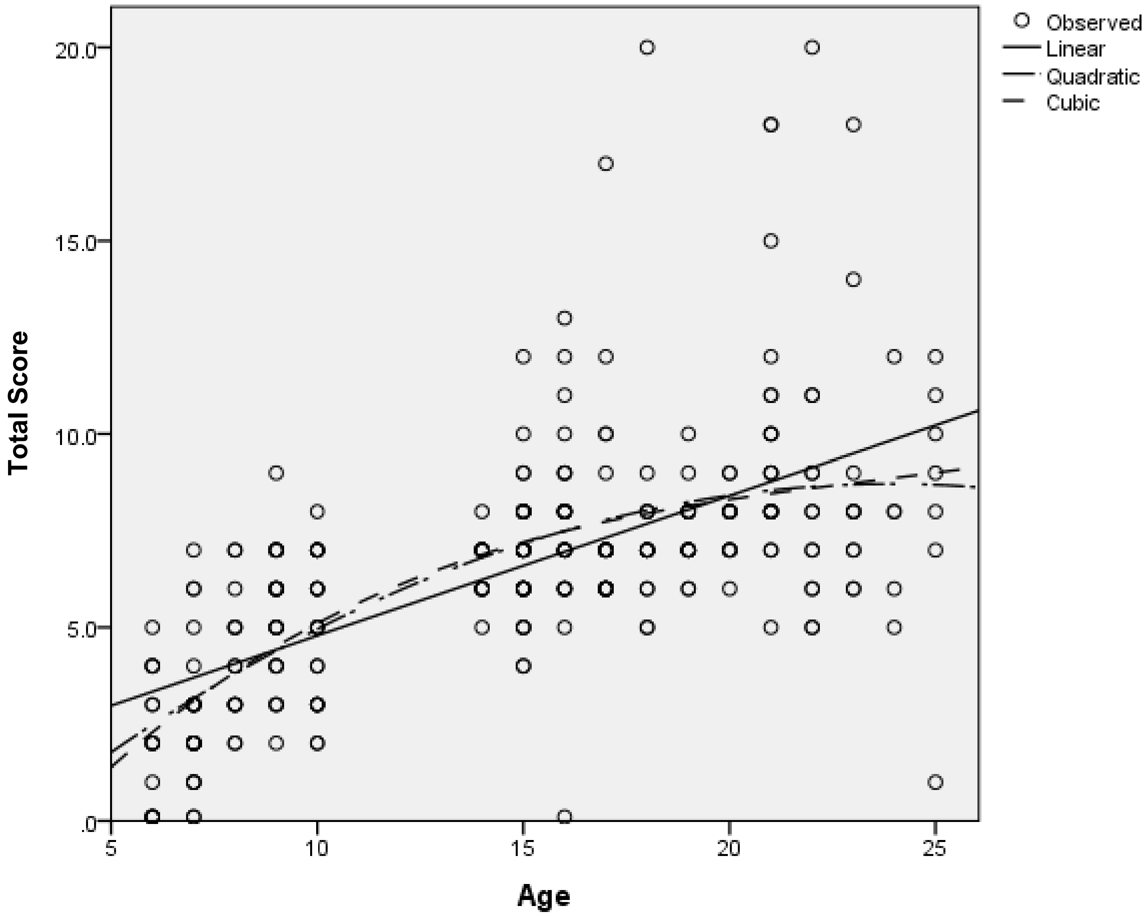

Figure 3.4 Developmental Trajectory of Digits Backward (i.e. Verbal WM). Possible subtest scores ranged from 0 - 20 possible points. Scores of 0 were coded as .1 for analyses.

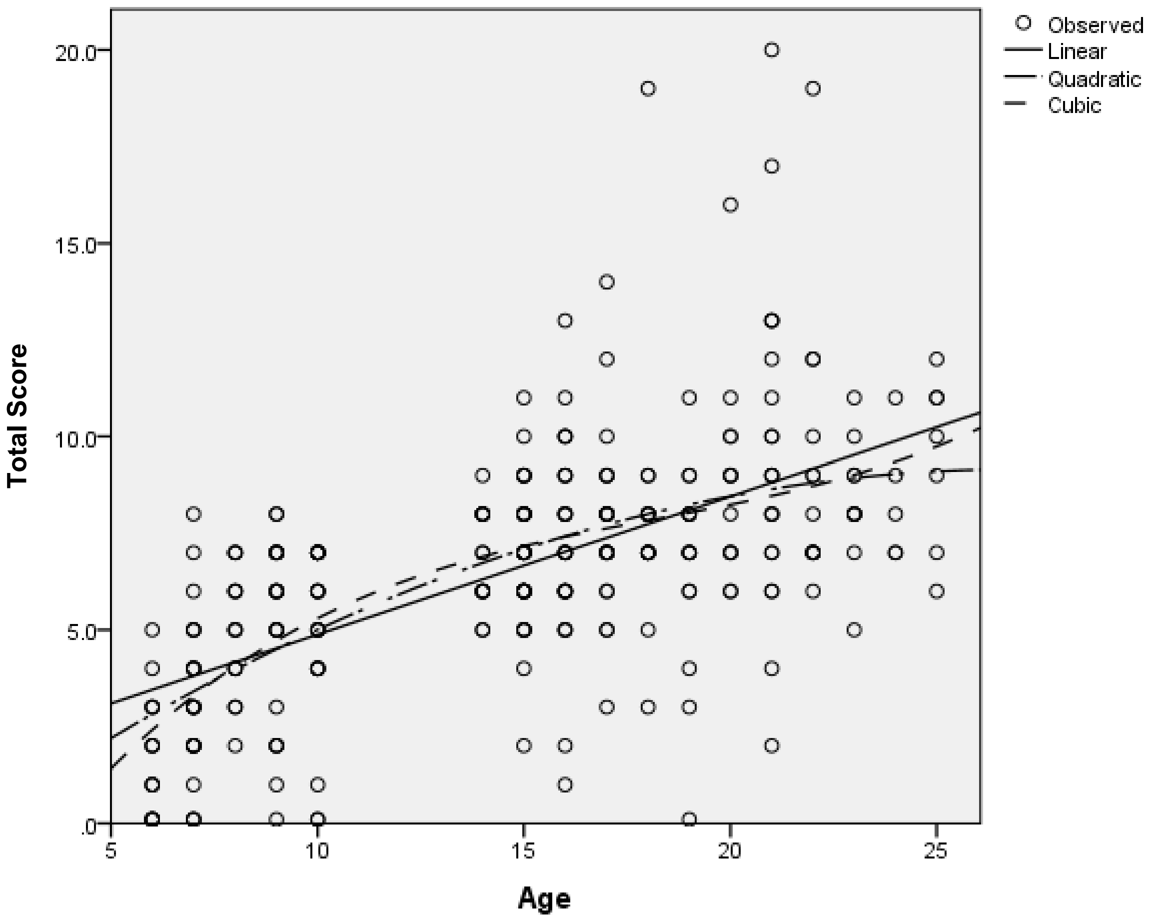

Figure 3.5 Developmental Trajectory of Digits Forward Interference (i.e. Verbal WM-Executive Attention). Possible subtest scores ranged from 0 - 20 possible points. Scores of 0 were coded as .1 for analyses.

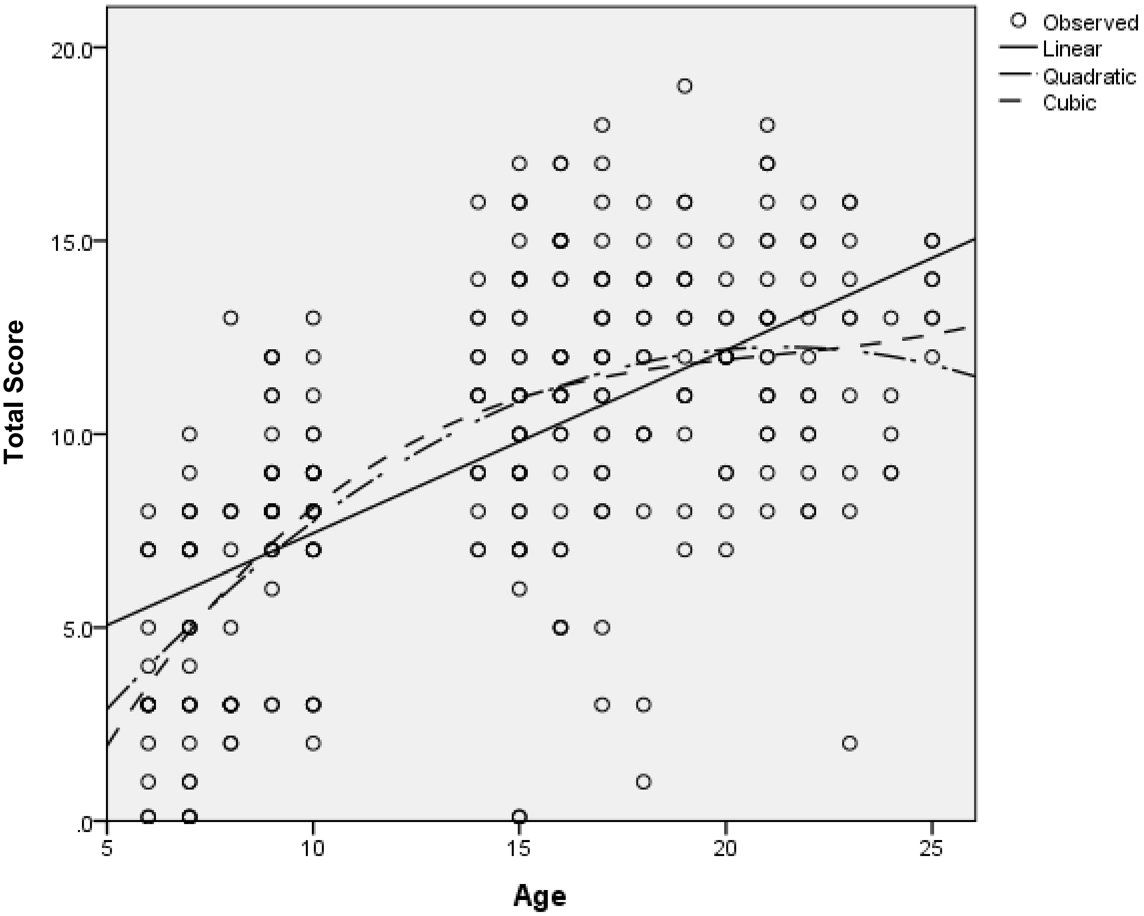

Figure 3.6 Developmental Trajectory of Dots Up (i.e. Static Visual-Spatial WM). Possible subtest scores ranged from 0 - 20 possible points. Scores of 0 were coded as .1 for analyses.

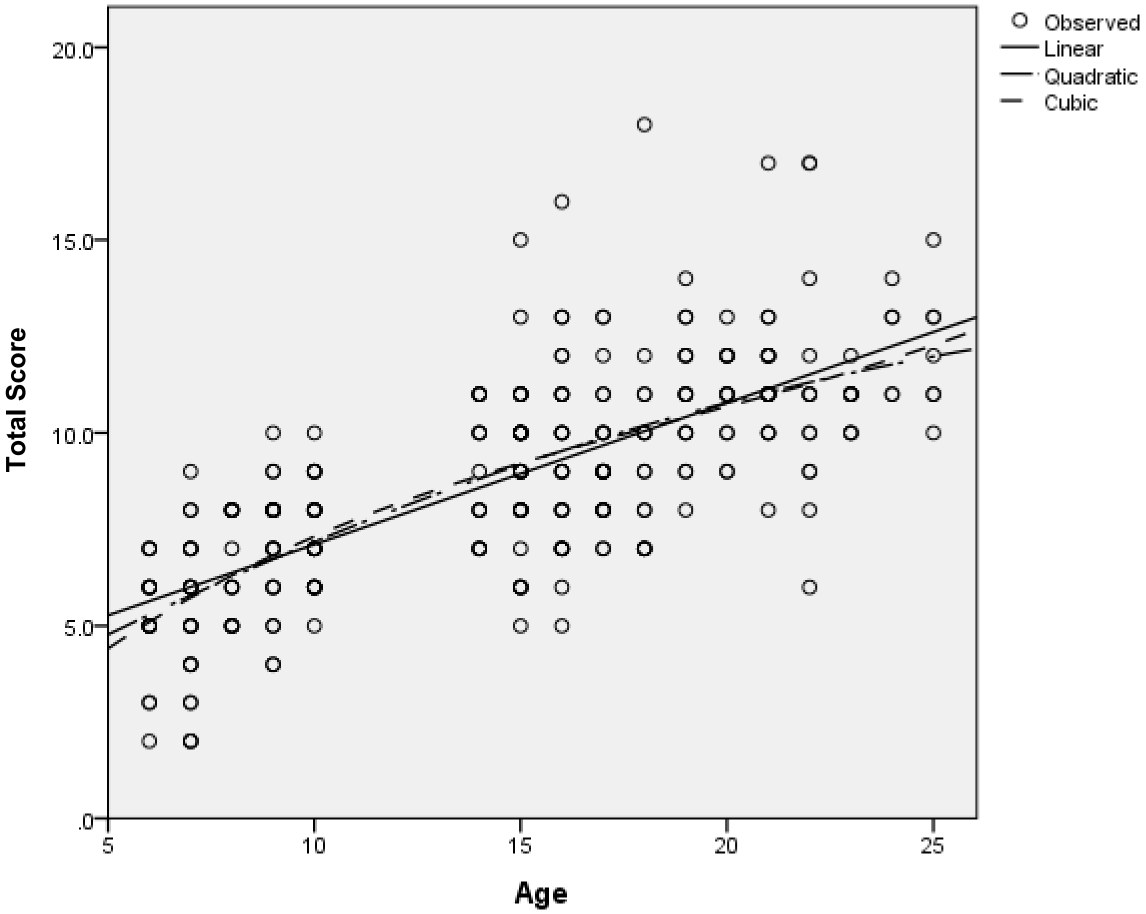

Figure 3.7 Developmental Trajectory of Digits Forward (i.e. Verbal STM). Possible subtest scores ranged from 0 - 20 possible points. Scores of 0 were coded as .1 for analyses.

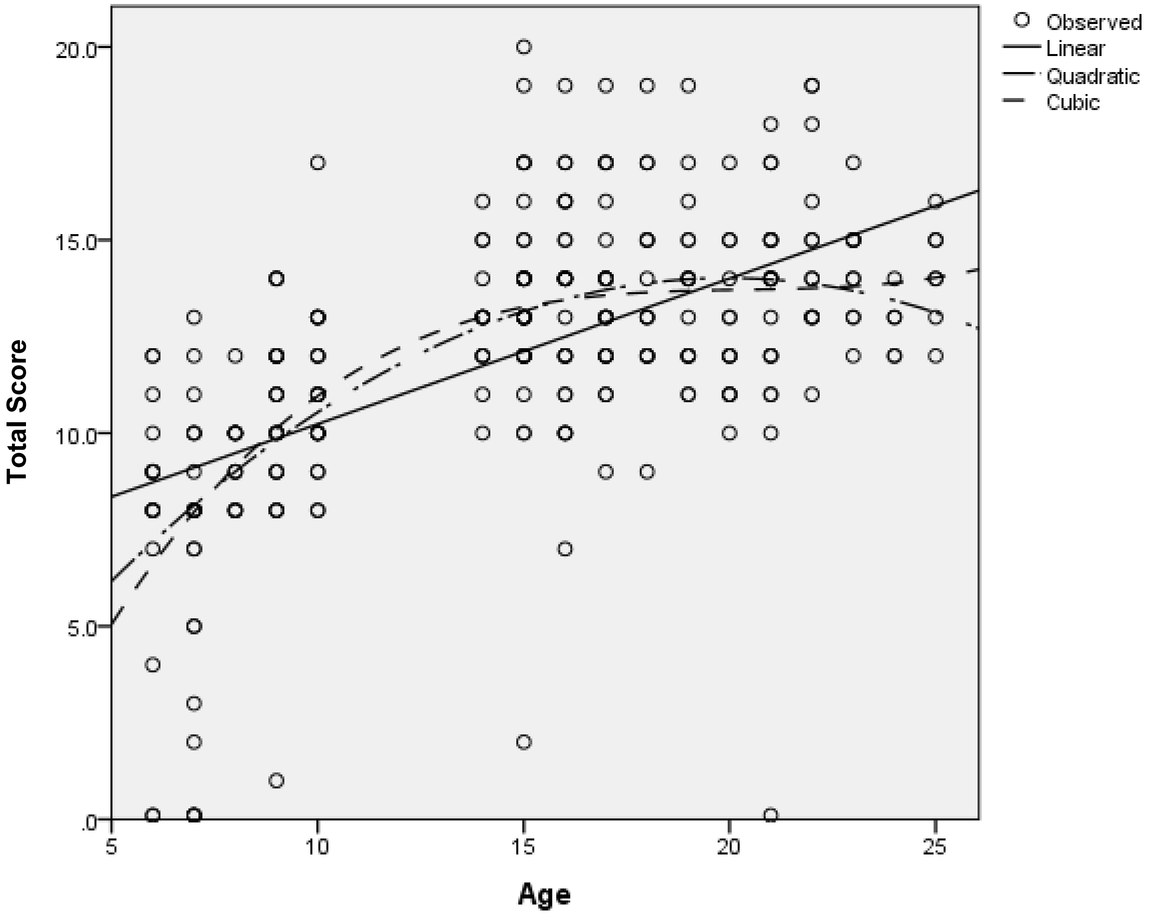

Figure 3.8 Developmental Trajectory of Dots (i.e. Static Visual-Spatial STM). Possible subtest scores ranged from 0 - 20 possible points. Scores of 0 were coded as .1 for analyses.

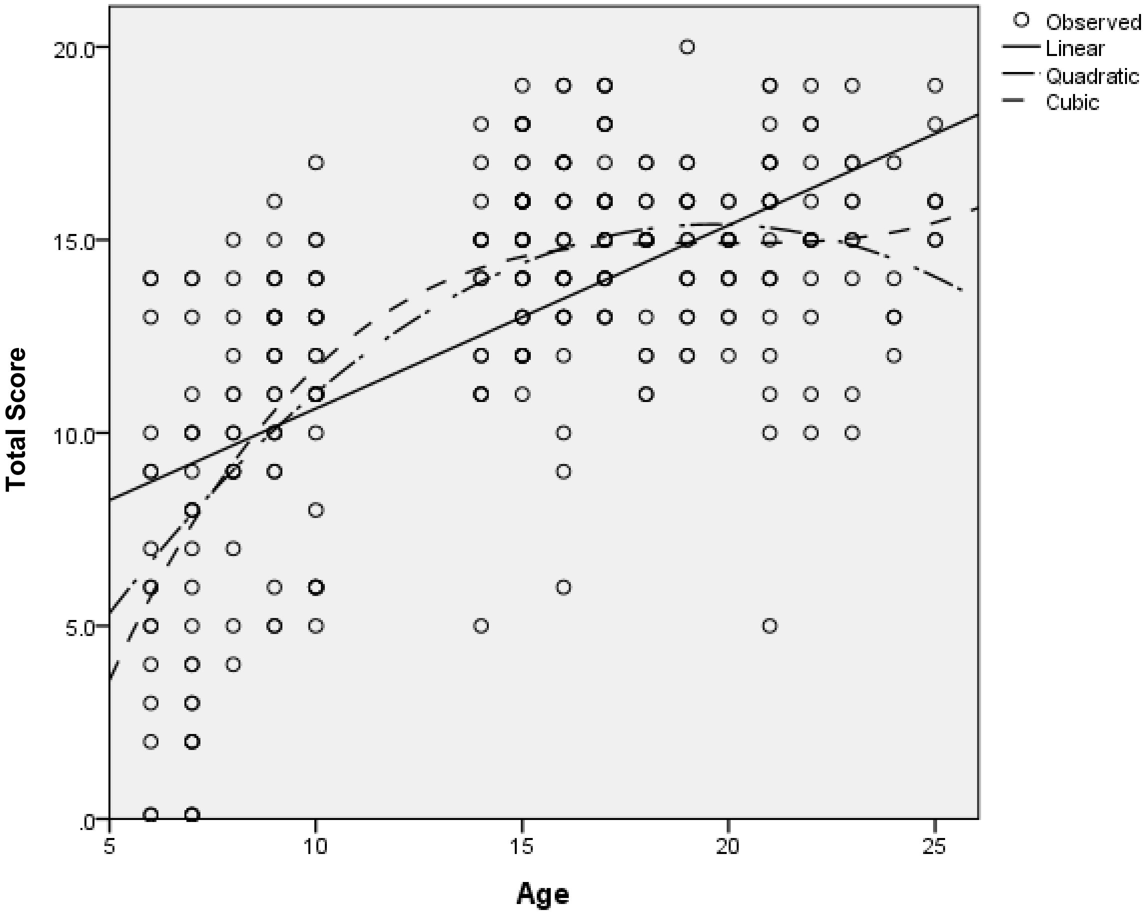

Figure 3.9 Developmental Trajectory of Dots Interference (i.e. Static Visual-Spatial WM-Executive Attention). Possible subtest scores ranged from 0 - 20 possible points. Scores of 0 were coded as .1 for analyses.

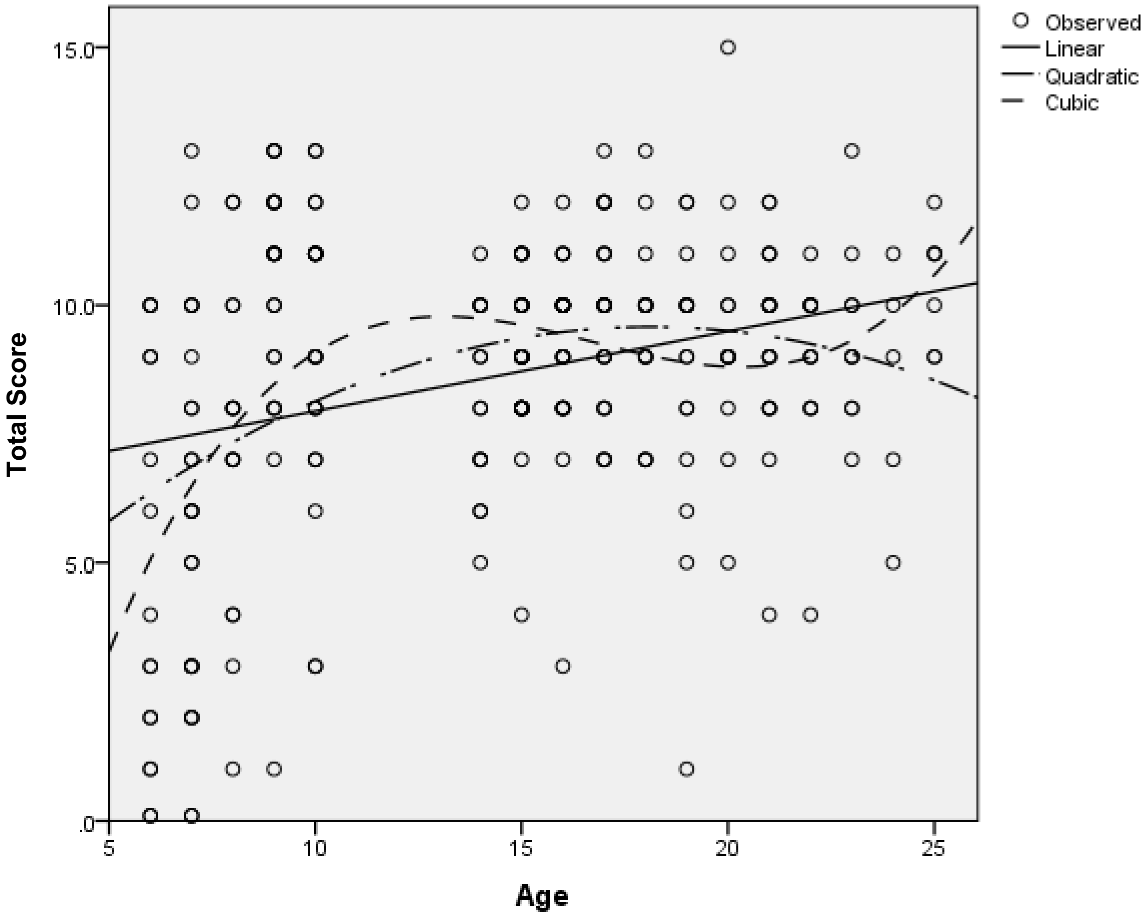

Figure 3.10 Developmental Trajectory of Dots Sequence (i.e. Dynamic Visual-Spatial STM). Possible subtest scores ranged from 0 - 20 possible points. Scores of 0 were coded as .1 for analyses.

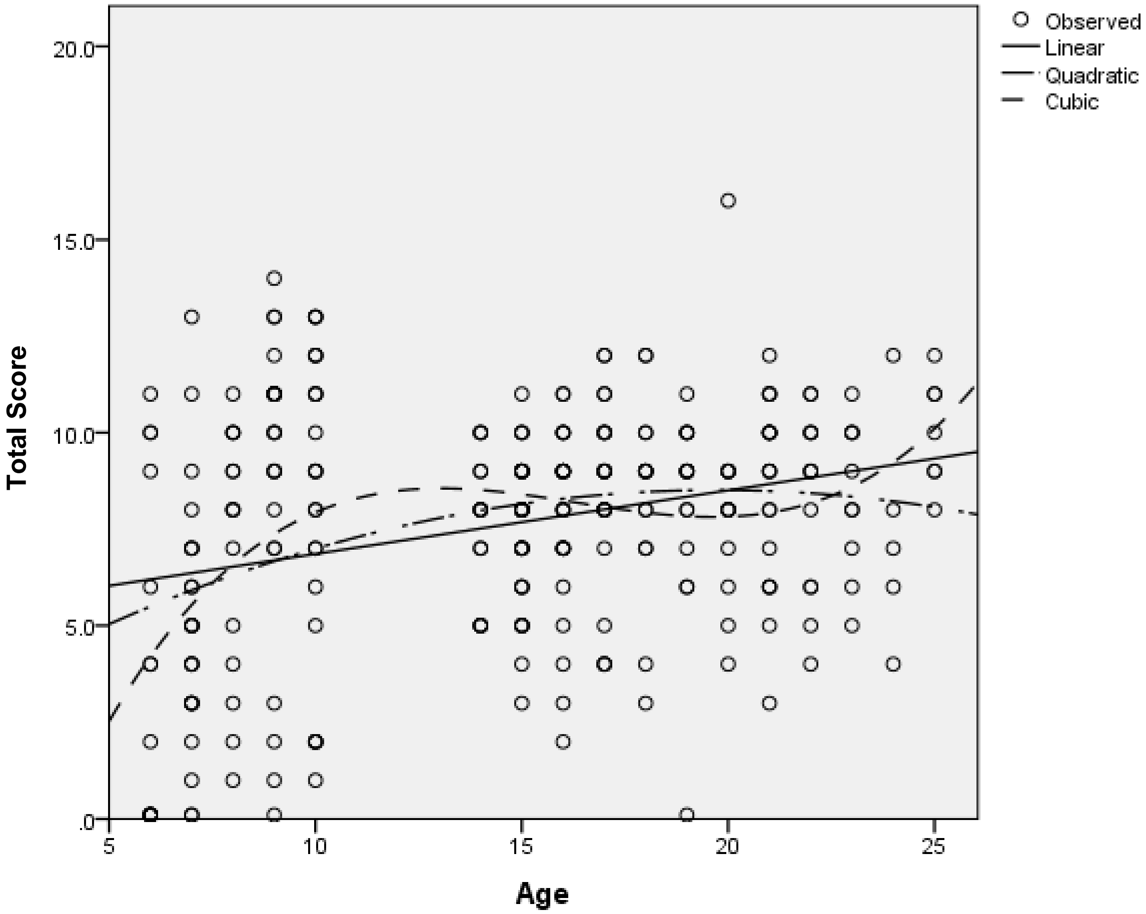

Figure 3.11 Developmental Trajectory of Dots Sequence Backwards (i.e. Dynamic Visual-Spatial WM). Possible subtest scores ranged from 0 - 20 possible points. Scores of 0 were coded as .1 for analyses.

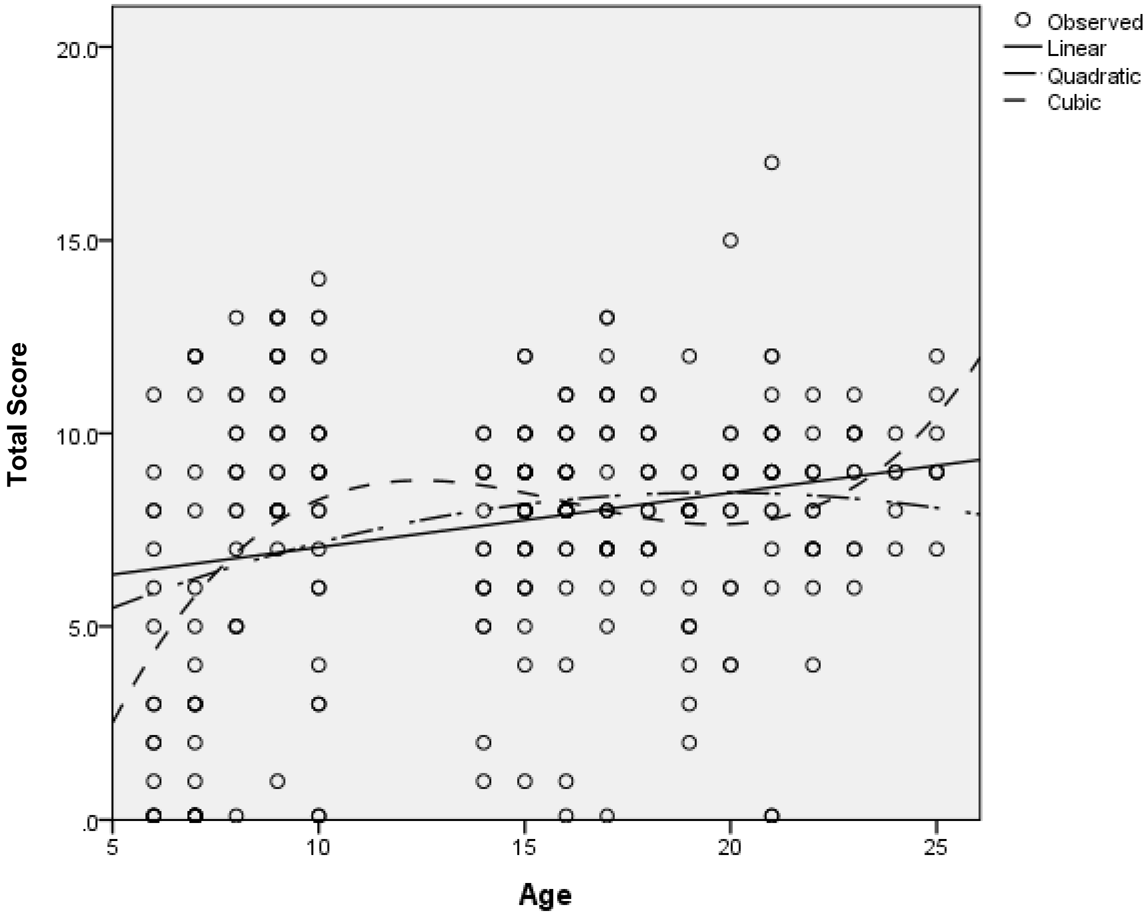

Figure 3.12 Developmental Trajectory of Dots Sequence Interference (i.e. Dynamic Visual-Spatial WM-Executive Attention). Possible subtest scores ranged from 0 - 20 possible points. Scores of 0 were coded as .1 for analyses.

CHAPTER 4

DISCUSSION

This study investigated the developmental trajectory of WM across domains, including verbal WM, static visual-spatial WM, and dynamic visual-spatial WM from ages 6 through 25 years. The study was designed to contribute to the current literature by examining the development of WM across a broad age range, utilizing a comprehensive measure of WM ability which encompassed the full spectrum of the WM domains identified by current theoretical frameworks. The study also investigated whether the development of WM varies depending upon the specific processing demand involved in a given task. Based upon previous literature, it was hypothesized that the development of WM would show a curvilinear trajectory with WM skills increasing in a linear fashion across all domains from childhood through adolescence, ultimately tapering off in early adulthood. It was not anticipated that WM development would differ by processing demand; thus, a quadratic relationship was anticipated across subtests as well.

Although previous research has investigated the development of WM, results have been inconsistent due in part to limitations in study design (e.g. inclusion of a limited sample age range, failure to include a comprehensive array of WM measures). While previous results have differed regarding the age at which WM ability peaks, they have typically been in agreement regarding the quadratic nature of WM development. However, results of the current study reveal that the development of WM actually varies depending upon the domain in question. While static/simultaneous visual-spatial WM appears to follow the anticipated quadratic trajectory, the development of verbal WM follows a linear course through early adulthood. Dynamic/sequential visual-spatial WM development also deviates from the anticipated quadratic trajectory, appearing to go through multiple periods of growth and decline. These results were surprising and contrary to our original hypothesis that WM development would show an initially linear trajectory before leveling off in early adulthood, regardless of WM domain or processing demand. Following, we discuss how these results fit within the existing literature, as well as possible explanations and implications for these findings.

WM Development across Domains

As noted, results of this study reveal that verbal WM follows a linear developmental trajectory from childhood through at least early adulthood (see Figure 3.1). While this finding coincides with the first part of our hypothesis regarding a linear increase in WM capacity from childhood through adolescence, the hypothesis that development would then taper off in early adulthood was not supported. This result appears to support previous literature indicating a linear trend in WM development from childhood to adolescence (e.g. Gathercole, 1998; Gathercole et al., 2004; Goldstein et al., 2014; Thaler et al., 2013). However, contrary to the authors' conclusions that the development of WM increases only to approximately age 12 – 14, the results of this study indicate that Verbal WM continues to develop into early adulthood and possibly beyond. This finding provides additional support for Alloway and Alloway's 2013 study, which found that the development of WM continues to increase well into adulthood.

Results of the investigation regarding the development of static visual-spatial WM across ages 6 through 25 years appear to provide preliminary support for the hypothesis that WM development follows a quadratic/curvilinear trajectory, increasing in a linear fashion from childhood through adolescence before tapering off in early adulthood. The strongest relationship in this model appeared to show a quadratic trend, with development increasing linearly until approximately age 18, at which point it seemed to plateau. However, the model also suggests the possibility of a cubic relationship, with the trajectory appearing to increase again sometime after age 20 (see Figure 3.3). Given that this increase appears to be quite small and the sample included individuals only to age 25, additional research is needed to confirm whether the development of static visual-spatial WM is in fact quadratic, or if the cubic model would provide a better fit.

The hypothesis regarding the development of dynamic visual-spatial WM was also not supported. Rather than the quadratic relationship that was hypothesized, results indicate that the overall trajectory appears to follow a cubic path. While development did show an initially linear trend before subsequently dropping off around ages 12 to 13, development appeared to increase again after age 20 (see Figure 3.2). These results extend previous findings which have indicated an initially linear trajectory of visual-spatial WM development until age 11 – 14 (e.g. Gathercole, 1998; Gathercole et al., 2004), while providing preliminary support for the recent findings by Isbell and colleagues (2015) which indicated that the development of visual-spatial WM appears to continue into adulthood. Additional analyses including expanded age ranges are needed to clarify these results.

There are several possible explanations as to why the results of this study differ from those reported by previous studies. First, a majority of the literature regarding WM development has focused on children and adolescents. As was noted previously, the results of the current study confirm previous findings regarding the initially linear development of WM from childhood to adolescence. However, it appears that the authors were premature in concluding that development peaks in adolescence. Given the restricted age range included in most studies, it is possible that previous studies may have witnessed similar trends if older adolescents and young adults had been included in the samples.

Additionally, some studies have included samples with a discrete age group within each of the developmental phases (i.e. childhood, adolescence, and adulthood), rather than a comprehensive sample of individuals across all ages. For example, Isbell and colleagues (2015) investigated visual-spatial WM capacity in individuals aged 13, 16, and 23 years, with results of the study indicating that development appears to continue into adulthood. Given the discrete age groups utilized, however, it is unlikely that the authors would have been able to detect subtle shifts in the developmental trajectory which may have indicated possible quadratic or cubic relationships, as were found in the current study.

Another explanation for these results relates to the specific domains measured. Although this study included a comprehensive measure of WM across domains, previous studies have typically focused on solely on verbal or visual-spatial WM components. Few studies have investigated static and dynamic visual-spatial WM trajectories independently. Given that the results of the current study regarding static visual-spatial WM development were consistent with previous findings regarding a quadratic trend in the development of visual-spatial WM, it is possible that WM tasks used in previous research have focused more on static visual-spatial WM than dynamic visual-spatial WM. The results of this study may begin to fill this gap.

Finally, although the results of the present study show that verbal WM follows a linear trajectory, it should be noted that our results extend only to age 25. It is possible that, given a broader age range, the anticipated quadratic relationship may have become apparent in subsequent years. For instance, while our results provide additional support for Alloway and Alloway's (2013) findings regarding the development of verbal WM into adulthood, the authors noted a peak in development within one's 30s indicating that the developmental trajectory of verbal WM was ultimately quadratic, despite its initially linear trend.

Impact of Processing Demand

A secondary goal of this study was to investigate whether the developmental trajectory of each WM domain varies by processing demand. It was again hypothesized that the development of WM would follow a curvilinear (i.e. quadratic) trajectory with WM skills increasing in a linear fashion from childhood through adolescence, ultimately tapering off in early adulthood. Results for subtests within the verbal domain were consistent with those of the overall composite, with both Digits Backward (verbal WM) and Digits Forward Interference (verbal WM-executive attention) indicating a linear trend. While the relationship between Digits Forward (verbal STM) and age did not reach significance at the .05 level, analyses conducted during preliminary data inspection indicated a strong linear relationship for that component as well, suggesting that the use of the cubic model ultimately masked the relationship. Overall, these results suggest that verbal WM development follows a linear trajectory through early adulthood, regardless of processing demand.

In contrast, results for the static visual-spatial subtests varied by processing demand (i.e. STM, WM, or WM-executive attention). The STM subtest (Dots) showed the hypothesized quadratic relationship, similar to that seen in the overall domain composite. However, the WM subtest (Dots Up) followed a linear developmental trajectory, while the WM-executive attention subtest (Dots Interference) showed a possible cubic relationship. Thus, the developmental trajectory of static-visual spatial WM appears to vary substantially depending upon which processing demand is used. The reason for these differences is unclear. As was noted previously, there were several potential problems with the data regarding possible outliers and abnormal distributions that were unable to be corrected prior to analysis. It is possible that the variation seen across subtests in this domain reflects artifacts of the data. Additional research is needed to clarify these results.

Investigation of the dynamic visual-spatial subtests revealed results consistent with those of the overall composite. All three subtests, Dots Sequence (dynamic visual-spatial STM), Dots Sequence Backward (dynamic visual-spatial WM), and Dots Sequence Interference (dynamic visual-spatial WM-executive attention), showed curvilinear trajectories, similar to that seen in the dynamic visual-spatial composite. Overall, these results suggest that the development of dynamic visual-spatial WM follows a cubic trajectory, with development appearing to increase from childhood to early adolescence, then declining in adolescence and increasing again in early adulthood. As hypothesized, this pattern did not vary across processing demands, although it was contrary to our original hypothesis that development would approximate a quadratic relationship. However, as indicated previously, though age accounted for a significant amount of the variance across the verbal and static visual-spatial tasks, with R^2 ranging from approximately .40 to .50, it did not appear to be highly related to the dynamic visual-spatial tasks which had R^2 values ranging from only .13 to .20. This suggests that while dynamic visual-spatial WM does vary to some extent by age, age is not the primary predictor of these abilities.

Implications

Results of this study hold both theoretical and practical implications. From a theoretical standpoint, the difference in developmental trajectories across WM domains provides support for theoretical frameworks which have identified multiple related but distinct components within the WM construct. The differing developmental trajectories evidenced across verbal, static visual-spatial, and dynamic visual-spatial WM suggest that these tasks are in fact measuring different abilities. As static and dynamic measures of visual-spatial WM have not typically been included in developmental research, these results provide important evidence for the preliminary support for the future inclusion of static and dynamic visual-spatial WM measures in the comprehensive assessment of WM ability.

It is unclear what causal mechanism might be at play within WM development that might predict the variation in developmental trends seen across individual components. In order to understand and confirm these results, it will be important for future studies to not only replicate these results, but to investigate potential causal explanations for the differing developmental trajectories of each WM component. For instance, we know that the brain goes through substantial maturational changes during childhood and adolescence. Can changes in brain development explain coinciding changes in the development of WM? Are there other neurological features or cognitive abilities that show similar patterns of development? What impact, if any, does education or environment have on the development of WM? These questions will be important to consider in future research.

The results of this study also have important practical implications in terms of test development and measurement. These findings provide additional support for the inclusion of tasks that will assess WM across verbal, static visual-spatial, and dynamic visual-spatial domains. At present, commonly used measures of cognitive abilities (e.g. the WISC-V, WJ IV) typically under represent visual-spatial WM, providing an incomplete picture of an individual's WM abilities. If static and dynamic visual-spatial WM abilities continue to be distinct from one another in future research, it will be important for future measures of WM to include these as individual domains. In addition, understanding the anticipated developmental trajectory of WM is critical when conducting norms or calculating standard scores. Thus, confirmation of these results is needed in order to ensure correct application within future test development.

Finally, these results can help to inform assessment and intervention practices in schools, leading to more effective interventions and improvements in academic achievement. As noted previously, WM capacity has been repeatedly shown to have a substantial impact on learning and educational outcomes, with deficits linked to impairments in key academic skills such as reading and mathematics. The impact of WM deficits depends upon the affected WM domain. For instance, deficits in visual-spatial

WM have been linked to difficulties in various types of mathematical skills and problem solving, while deficits in verbal WM are associated with difficulties in reading and mathematics as well as disorders such as ADHD and specific language impairment. Understanding the developmental trajectory of different WM domains is essential not only to identify children with WM deficits, but also to inform the selection of appropriate interventions or accommodations.

Limitations and Future Directions

Several limitations regarding this study should be considered when interpreting these results. As mentioned previously, outliers and violations of normality were present across the majority of the WM subtests. While useful in modeling curvilinear relationships, polynomial regression models can be highly influenced by outliers, particularly when minimal data are available in the tails of the distribution (Cohen et al., 2003). Unfortunately, the majority of the subtests included outliers and/or skewed distributions. This suggests the need for additional data collection in order to attempt to normalize these distributions. Additional studies are needed to confirm these results.

In addition to problems with the distribution of the data, it should be noted that the sample was obtained primarily from one geographic region. Additional data should be obtained from a broader geographic area in order to generalize these results. It was also noted previously that, while initial analyses showed adequate reliability of the WOMBAT for use with adolescent and adult populations, further analyses are needed to confirm its reliability in younger populations. Thus, the results for children included in this sample should be interpreted with caution. Additionally, while the sample size was relatively large (N = 303), unfortunately, no data were available for individuals aged 11-13, thus additional data is also needed to confirm the results among this age group.

Conclusion

The current study extends previous research which has noted a linear trend in WM development from childhood through adolescence, and provides further support for recent studies indicating that WM continues to develop into adulthood (e.g. Alloway & Alloway, 2013; Isbell et al., 2015). Though WM deficits are common in children with learning disabilities and pose significant hurdles for these children in terms of their academic achievement, they are also invisible and may go unnoticed or ignored in the classroom. In light of the impact of WM capacity on academic achievement, it is important that children with impairments in WM be identified early so that potential interventions and/or accommodations can be put into place. Understanding the typical developmental trajectory is an important component in being able to identify and intervene when WM deficits arise. In addition, while the development of WM from childhood through adolescence has consistently pointed to a linear trajectory, the developmental trajectory of WM from late adolescence and into adulthood remains unclear. It will be important for future research to attempt to replicate these results with broader age ranges in order to determine at what point in development, if any, WM truly plateaus or begins to decline. Understanding the typical trajectory of WM development and/or decline is essential if we are to employ interventions that attempt to improve WM capacity or alternately ward off age-related decline.

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