WORKING MEMORY CAPACITY, PERCEPTUAL SPEED, AND FLUID INTELLIGENCE: AN EYE MOVEMENT ANALYSIS

A Thesis
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Master of Science in the
School of Psychology

Georgia Institute of Technology
December 2006

WORKING MEMORY CAPACITY, PERCEPTUAL SPEED, AND FLUID INTELLIGENCE: AN EYE MOVEMENT ANALYSIS

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Date Approved: November 14, 2006

ACKNOWLEDGEMENTS

I would like to acknowledge the efforts of several individuals during the course of this work. First, I would like to thank my advisor, Dr. Randy Engle, for his guidance and support on this project and in general throughout my graduate career. I also would like to thank my other committee members, Drs. Paul Corballis and Dan Spieler, for taking the time to listen to my questions and to offer suggestions when needed. Along the same lines, I would like to thank the other graduate students in my lab (Dr. Nash Unsworth, Rich Heitz, Jim Broadway, & Maggie Ilkowska) for their comments after various drafts and presentations of this research. I would also like to thank Aida Aguilera Martinez, as her time in the lab as a visiting researcher is why this project started when it did.

I have several family members to thank as well, including my parents (Gary & Deb), my brothers (James, Brad, Marc, & Greg), and my in-laws (Donald, Kay, & Leanne Morton), for their encouragement and interest in a topic solely because it was my research. Last, but certainly not least, the biggest thank-you of all goes to my wife, Amanda; I hope you know how much your support means to me.

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SUMMARY

Research has focused on the potential cognitive determinants of individual and developmental differences in intelligence. Two competing views influenced by information-processing theory propose important roles for the constructs of working memory capacity and perceptual speed, respectively. This study aimed to clarify the relationship between these constructs by examining the performance of younger adults who were high and low in working memory capacity on an experimental version of traditional perceptual speed tasks. The results suggested that working memory capacity is important for performance on perceptual speed tasks because of the attention and memory demands of these tasks. Eye-tracking measures corroborated the behavioral data, which suggest that individual differences on perceptual speed tasks are the result of individual differences in working memory capacity in healthy, younger adults.

CHAPTER 1

INTRODUCTION

> The centrality of the working memory capacity factor leads to the conclusion that working memory capacity may indeed be essentially Spearman's *g*. (Kyllonen, 1996, p. 73)

> Among the most meaningful ways to conceptualize mental capacity is in terms of an individual's processing speed. (Kail & Salthouse, 1994, p. 201)

> Perhaps processing speed is important for developmental differences in childhood and/or aging but not for individual differences in young adults. (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002, p. 180)

> Why is there [*sic*] strong correlation between processing speed and gF? A rational explanation is that processing speed is responsible for differences in intelligence within age groups (individual differences) but not for differences in intelligence between age groups (developmental differences). (Chang, 2004, p. 473)

The field of intelligence represents an area in which cognitive, developmental, and differential psychologists share a research interest. Recent attempts at discovering the cognitive constructs and processes responsible for the manifestation of intelligence have been heavily influenced by information-processing theory. Two examples of cognitive constructs linked to fluid intelligence (Gf) are working memory capacity (WMC) and perceptual speed (PS). The major proponents of the WMC view (Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004) have linked individual differences in WMC to Gf in healthy young adults, while the major proponents of PS as the determinant of Gf have relied mostly on evidence obtained from developmental studies (Kail & Salthouse, 1994; Salthouse, 1993b, 1996). I begin by reviewing the evidence for both theories and the basis for the current study, which attempted to clarify the nature of the interrelationships among WMC, PS, and Gf.

Review of Gf Research

In the research to be discussed, WMC and PS are treated as predictors of the criterion construct of Gf. The concept of Gf derives from work by Cattell and colleagues (Cattell, 1940, 1963; Horn & Cattell, 1966) differentiating between two types of intelligence. Crystallized intelligence (Gc) represents the knowledge that individuals acquire across the lifespan. In contrast, Gf represents the ability to adapt to novelty and to reason in situations that have not been encountered previously. Evidence for the distinction between Gf and Gc comes from studies examining the lifespan trajectory of each kind of intelligence; Gf generally increases until early adulthood and then declines over the rest of life, whereas Gc tends to gradually increase and remain intact through late adulthood (Horn & Cattell, 1966). In Carroll's (1993) reanalysis of numerous human abilities studies, he discovered that the types of tasks that typically load on Gf factors include reasoning, inferences, and matrix completion, whereas Gc tasks typically consist of vocabulary, arithmetic, and general knowledge content. Cognitive studies of intelligence have largely focused on Gf for several reasons. As mentioned above, developmental researchers are interested in Gf because of its relationship with chronological age. In addition, Gf was theorized to be less affected by differences in socioeconomic status or educational background and thus more of a "culture-fair" indicator of intelligence (Cattell, 1963). Finally, some researchers have identified Gf as being equivalent to the *g*-factor of intelligence (Gustafsson, 1984); while that may be an extreme view, Carroll (1993) did note in his three-stratum model of human intelligence that Gf was the second-order factor most dominated by *g* (p. 625). Part of the reason why Gf and *g* are viewed so similarly is that the Raven's Progressive Matrices (Ravens[1] Raven, Raven, & Court, 1998), a nonverbal, matrix completion test, is "often used as a 'marker' test for Spearman's *g*" (Jensen, 1998, p. 38). Many researchers have taken what has been termed the 'cognitive-correlates' approach to study Gf by examining the relationship between theorized cognitive components and Gf (Sternberg, 1985). Examples of this type of research can be seen in the literature examining the importance of WMC and PS.

Review of WMC Research

The working memory (WM) model proposed by Baddeley and Hitch (1974; Baddeley & Logie, 1999) argued for the existence of domain-specific buffers controlled via a domain-general central executive. This model was developed as a more dynamic system to represent the true nature of human cognition, in contrast to the conception of short-term memory (STM) as primarily a temporary store of information. The numerous roles of the central executive include coordinating, scheduling, and switching rapidly between tasks. More recent versions of the model have also included an episodic buffer as a kind of workspace for the integration of representations of different modalitites (Baddeley, 2000). Baddeley and colleagues' view of WM is similar to another prominent theory espoused by Cowan (1995, 1999, 2005), although Cowan explicitly recognizes the

[1] The general term "Ravens" us used to refer to all versions of the tests; if a specific task-task correlation is mentioned, either SPM or APM is provided to clarify whether it is the Standard or Advanced version, respectively.

interaction between memory and attention by labeling the central mechanism in his model as the focus of attention.

Another WM theory that focuses on the importance of attention is that of Engle and colleagues (Engle & Kane, 2004). Their research largely ignores the slave systems of the Baddeley model in favor of studying individual differences in the domain-general central executive. Considerable evidence for the importance of WMC to a number of cognitive, social, and psychopathological constructs has accumulated within the past 25 years (for recent reviews, see Heitz, Unsworth, & Engle, 2004; Redick, Heitz, & Engle, in press; Unsworth, Heitz, & Engle, 2005). Germane for the present work is the demonstration in factor-analytic studies that 'complex span' measures of WMC such as Operation Span (OSPAN; Turner & Engle, 1989), Reading Span (RSPAN; Daneman and Carpenter, 1980), and Counting Span (CSPAN; Case, Kurland, & Goldberg, 1982) are consistently highly correlated with Gf measures (Colom, Flores-Mendoza, Ángeles Quiroga, & Privado, 2005; Conway et al., 2002; Engle et al., 1999; Kane et al., 2004; for a recent meta-analysis, see Ackerman, Beier, & Boyle, 2005). Complex span tasks such as OSPAN are variants of memory span measures commonly included in intelligence batteries (e.g., Digit Span in Wechsler Adult Intelligence Scale-Revised; Wechsler, 1971). Instead of being given a list of digits to serially recall as in Digit Span, participants taking OSPAN would see a series of items such as the following: *IS (2 x 1) + 3 = 6 ? DOG*. Complex span tasks are also known as storage-plus-processing tests, as they all combine the recall of some items (e.g., words) while also performing a secondary processing task (e.g, math operations).

According to Engle and colleagues (Engle, Kane, & Tuholski, 1999), individual differences in WMC (as measured by OSPAN) are primarily due to differential ability to control attention in a goal-directed manner. Allocation of attention is theorized to be important to deal with switching back and forth between the processing and storage aspects of complex span tasks; to sustain current-list item information while maintenance rehearsal was prevented; and deal with previous-list items that interfere from earlier trials. Specifically, this executive attention capacity is important in situations where behavior can be guided by contextually inappropriate prepotent actions, especially if the relevant goal information is not actively maintained (Engle & Kane, 2004).

Support for the interpretation of WMC as an attention ability has been demonstrated in several 'low-level' cognitive tasks that differ dramatically in structure from the complex span tasks (for reviews, see Redick et al., in press; Unsworth, Heitz, & Engle, 2005). For example, Unsworth, Schrock, and Engle (2004) examined the relationship between WMC and performance on different versions of the antisaccade task. Participants who had previously been identified as falling within either the upper or lower quartiles of OSPAN performance (*high* and *low spans*) were instructed to make lateral eye movements in response to particular task instructions. In Experiment 1, trials were blocked into prosaccade and antisaccade conditions. On each trial, a box flashed on the left or right side of the display, and participants were instructed to either saccade toward (prosaccade) or away from (antisaccade) the blinking stimulus. Making a prosaccade was presumed to be a relatively reflexive response, whereas success on antisaccade trials would be dependent upon first stopping a reflexive prosaccade and then initiating a saccade in the opposite direction. Consistent with the interpretation that

WMC is important for response selection when a prepotent response is incorrect, low spans had longer latencies and committed more errors on antisaccade trials only (see also Kane, Bleckley, Conway, & Engle, 2001).

The block design in Experiment 1 created a task environment in which the requirement to actively maintain the goal information from trial-to-trial was unnecessary. Specifically, Unsworth et al. (2004) hypothesized that presenting prosaccade and antisaccade trials together in an intermixed design would affect WMC involvement on prosaccade performance. That is, intermixing the trial types in Experiment 2 would increase the need to keep the trial condition (and any associated stimulus-response mappings) active in order to respond correctly on each trial. As predicted, mixing prosaccade and antisaccade trials together resulted in low spans having longer latencies and making more errors on both prosaccade and antisaccade trials. These two experiments demonstrate that WMC is important to control attention in demanding situations, within the framework of goal maintenance and response-conflict resolution (Engle & Kane, 2004).

Review of PS Research

In addition to the research relating individual differences in WMC to Gf, developmental research has demonstrated that PS is also related to higher cognitive abilities. Although several different kinds of mental speed are prevalent in the psychological literature (Danthiir et al., 2005), the basic idea of human processing speed was outlined by Salthouse (1996). An individual with a faster information-processing speed is able to complete more cognitive operations within a specified amount of time, and is also more likely to utilize and update the results of previous operations before they decay below some threshold; if unrecoverable, future operations dependent on that information would be delayed until that representation has been recomputed. Salthouse and Babcock (1991) provided an application of this concept in terms of performing mental arithmetic. For example, suppose you are asked to calculate the product of 2 two-digit numbers (e.g., 23 x 14 = ?). The conventional way to solve this problem would be to multiply 23 by 4 first, multiply 23 by 10 next, and then sum the two products. An individual with a faster processing speed would compute the individual operations quicker than an individual with a slower processing speed. For the slower individual, because each product takes longer to produce, a greater amount of time would elapse between the two calculations. If enough time passes, the memory trace of the first product could decay below a critical threshold before being able to sum the products.

One specific type of information-processing speed theorized to be important for cognition is PS. PS is defined as:

> *Perceptual speed* is assessed by the speed of responding (usually on paper-and-pencil tests) with simple content in which everyone would be perfect if there were no time limits. Perceptual speed tasks often involve elementary comparison, search, and substitution operations, with the test score consisting of the number of items correctly completed in the specified time. (Salthouse, 2000, pp. 35-36)

Similar PS definitions have been given as a result of psychometric research (Carroll, 1993; Ekstrom, French, Harman, & Derman, 1976). Three measures make up the PS factor in the Educational Testing Service Kit of factor-referenced cognitive tests (Ekstrom et al., 1976): Finding A's, Identical Pictures, and Number Comparison. Salthouse and colleagues (Kail & Salthouse, 1994; Salthouse, 1993b, 1996) have primarily used variants of the Number Comparison task (Letter Comparison/Pattern Comparison) as support for their view that PS is responsible for developmental differences in higher-order cognition. Although the exact content varies depending on the type of task, generally examinees are instructed to compare two stimuli and mark on the line separating them indicating whether the items are the same or different. For example, in Letter Comparison a participant may see: AFJDKZ_____AFJDMZ. Salthouse and Babcock (1991, Study 2) demonstrated that performance on two Comparison tasks accounted for all but 1.1% of the age-related performance on a WMC composite, more than that accounted for by performance on processing-only or storage-only components of the WMC tasks. Subsequent research has also shown that Comparison tasks account for a substantial proportion of the age-related variance on Gf tasks such as Ravens (Salthouse, 1993, Study 1).

In a differential study of younger adults, Ackerman and Cianciolo (2000, Study 2) found support for four related factors of PS varying along a complexity continuum: (a) Pattern Recognition, (b) Scanning, (c) Memory, and (d) Complex. Ackerman, Beier, and Boyle (2002) followed up this research by examining the pattern of relationships among the different PS subtypes with factors representing WM and *g*. In specifying the Memory and Complex factors, the authors admitted that the tasks loading onto each included "substantial demands on immediate memory" and "heightened memory loads" (p. 570), respectively. Thus, the finding that both of these PS composites were significantly correlated with WM (and *g*) is somewhat predictable. In addition, the Pattern Recognition factor, which included "tests that involve recognition of simple patterns" (p. 570), had a smaller correlation with the WM factor ($r = .23$) and did not significantly correlate with the *g* factor. More surprising are the results involving the Scanning factor, which was comprised of tasks involving "scanning, comparison, and lookup processes"

(Ackerman et al., 2002, p. 570), including two Comparison tasks. The Scanning composite was significantly correlated with both the WM composite and the *g* composite (r = .39 and .37, respectively).[2] Comparison tasks are the focus of the current study given their prominence in both the developmental research of Salthouse and colleagues and the factor-analytic results of Ackerman et al. (2002), and the lack of research explaining the cause of the relationship between performance on these tasks with WMC and Gf.

Explaining the Interrelationships Among WMC, PS, and Gf

The literature contains conflicting evidence about the nature of the interrelationships among WMC, PS, and Gf. At least part of this inconsistency can be attributed to differences in studies looking at individual differences in these constructs only within younger adults and developmental studies comparing the performance of either children or elderly adults to that of younger adults. Table 1 presents four recent studies with younger adults containing measures of WMC, PS, and Gf. Although no clear pattern emerged by examining the zero-order correlations between the various WMC and PS measures, I conducted partial correlations on these data, revealing two points of interest. First, Babcock and Laguna (1996) was the only study to demonstrate a

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[2] A different pattern emerged in Ackerman et al. (2002) when ravens APM was used as the criterion variable instead of *g*. Specifically, the WM-Ravens APM correlation was r = .48, but the Scanning-Ravens APM correlation was a nonsignificant r = .12. As previously mentioned, although Jensen (1998) stated that Ravens is often used as a *g* test, the correlations here show that the use of either a *g* composite or Ravens influences the inferences drawn related to the importance of WM and Scanning tasks in predicting intelligence. Note also that Ackerman et al. used a variety of tasks to define the WM, PS, and *g* factors. For example, the WM factor included Backward Digit Span, which previously has been found to load on a factor with other simple span tasks and not on a factor composed of complex span tasks (Conway et al., 2002; Engle, Tuholski et al., 1999). Thus, the comparison is not “apples to apples” when looking at the interrelationships among the three constructs in this study with other studies (e.g., Conway et al., 2002).

Table 1

WMC, PS, and Ravens Correlations from Studies of Young Adults

Measures			Correlations					
WMC	PS	Ravens	XY	XY.Z	XZ	XZ.Y	YZ	YZ.X
			Conway et al. (2002) [a]					
Operation	Letter	SPM	.15	.17	.20*	.22*	-.09	-.12
Reading	Letter	SPM	.15	.17	.15	.17	-.09	-.12
			Ackerman et al. (2002) [b]					
Operation	Number	APM	.26*	.25*	.24*	.23*	.09	.03
Reading	Number	APM	.24*	.23*	.23*	.22*	.09	.04
			Rogers, Hertzog, & Fisk (2000) [c]					
Computation	Number	APM	.20*	.16	.34*	.32*	.16	.10
Listening	Number	APM	.09	.05	.29*	.28*	.16	.14
			Babcock and Laguna (1996) [d]					
Computation	Letter	APM	.25*	.19*	.23*	.16	.32*	.28*
Listening	Letter	APM	.31*	.27*	.17*	.08	.32*	.29*

Note. X = WMC; Y = PS; Z = Ravens; SPM = Standard Progressive Matrices; APM = Advanced Progressive Matrices. *N*: [a] = 113; [b] = 135; [c] = 96; [d] = 134.
*$p < .05$.

significant relationship between PS and Gf after partialing out WMC. In contrast, the majority of the correlations between WMC and Gf remained significant after controlling for PS. Although these four studies varied in numerous ways regarding the administration, format, and scoring of the different tasks, this re-analysis provides preliminary support for the notion that WMC is more strongly related to Gf than PS is.

The discussion so far has demonstrated that measures of WMC, PS, and Gf are somehow related, but no mention has been made as to the mechanism(s) responsible for their interrelationships or about the processes involved in successful performance at the task level. One possibility that has been suggested by previous researchers (Conway, Kane, & Engle, 1999; Kane, Hambrick, & Conway, 2005) is that a task analysis of PS measures such as Comparison measures will reveal that there are actually varying attention and memory demands necessary for successful performance. In a similar vein, Miyake, Friedman, Rettinger, Shah, and Hegarty (2001) also noted this possibility:

> A considerable amount of executive functioning may still be required for performance on Perceptual Speed tests. . . . Perceptual Speed tests still require keeping the task goal active during performance. In addition . . . Perceptual Speed tests contain a fair amount of distracting information. (pp. 624-625)

Recall the definition of executive attention given earlier (Engle & Kane, 2004): the ability to actively maintain goal-related information in the face of interference. This ability seems especially relevant given the conclusion of French's (1951) seminal study on the PS construct that such measures are "characterized by the task of finding in a mass of distracting material a given configuration which is borne in the mind during the search" (p. 227). If Engle et al. (1999) and Kane et al. (2004) are correct in asserting that attention mediates much of the WMC-Gf relationship, then the ability to control attention should also mediate the WMC-PS connection. The prediction from this view is that WMC determines differential performance on both Gf and PS tasks because individual differences in the ability to control attention (viz., WMC) are important in both situations to varying degrees. This goes against the argument that PS is the causal factor of other cognitive abilities and developmental differences among them (Fry & Hale, 1996; Kail & Salthouse, 1994; Salthouse, 1996).

Experimental Analyses of Comparison Tasks

Although various researchers have attempted to explain performance on the Digit-Symbol Substitution Task (Wechsler, 1971), a measure commonly used to represent PS, in terms of memory, strategy, or psychomotor differences (e.g., Charness & Schultetus, 1998; Joy, Kaplan, & Fein, 2004; Piccinin & Rabbitt, 1999), Comparison tasks have not been subjected to the same level of scrutiny. However, two recent studies examining aging differences on Comparison task performance are especially relevant. Lustig, Hasher, and Tonev (2006) attempted to account for age group differences on Comparison tasks by reducing the amount of distraction present during a given comparison, in line with the Hasher and Zacks (1988) view that age-related slowing results from inhibitory deficiencies. Lustig et al. created computerized versions of Letter Comparison with different levels of distracting material. Their high distraction condition was similar to the format of paper-and-pencil Comparison tasks, in that all test items were presented in a columnar format simultaneously. In contrast, their low distraction condition presented each stimuli pair individually, thereby reducing the amount of currently irrelevant information available in the visual display. Consistent with their predictions, older adults were much faster in the low distraction condition relative to the high distraction condition, whereas younger adults' performance was unaffected by the distraction manipulation. In order to see if the computerized performance was related to the normal task administration, they correlated the computerized Letter Comparison and paper-and-pencil Pattern Comparison performance for each group (age x distraction condition). The older adults in the high distraction group had the highest correlation with Pattern Comparison ($r = -.57$), while the other three groups had roughly equivalent correlations (*r*s = -.30 to -.37). Lustig et al. interpreted this as support that age-related changes in performance on "simple" PS tasks are in fact related to inhibitory abilities that differ between younger and older adults, and that slowing is a result of the inhibitory deficiencies.

It is important to note that although Lustig et al. (2006) showed that reducing irrelevant information in the display improved older adults' performance, the younger adults were still approximately 800 ms faster than older adults in the low distraction condition. Thus, although visual distraction related to the number of irrelevant items in the display seems somewhat important for explaining age differences in PS, the remaining difference between the age groups is unexplained. In addition, Lustig et al. showed a significant Age x Target Length interaction, where the difference between the two age groups increased as the stimuli to be compared also increased from three to nine letters. This finding is not predicted if differences in distractibility were the sole mechanism responsible for impaired PS in older adults. Finally, a more convincing argument for the role of the different distraction conditions could have been made if the participants had their eye movements tracked while performing the computerized

Comparison tasks. That is, if the authors could have demonstrated that older adults in the high distraction condition made more fixations on the distracting items than the younger adults, this would have provided more concrete evidence that older adults are slowed because of their inability to inhibit irrelevant information (see Kemper & McDowd, 2006, for similar line of reasoning).

In fact, Roring (2005) did monitor eye movements in younger and older adults during performance of a computerized Number Comparison task. He found that the older adults made more overall fixations during task performance, corroborating their behavioral data showing that older adults were also slower to respond than younger adults. However, they found no reliable relationship between age and the number of "switches" (number of fixations crossing center on a given trial), although this may have been attributable to either the low number of trials used (only correct trials out of 24 total) or the small number of subjects used ($N = 26$) in their correlational analyses. In addition, the different target lengths of the stimuli were not examined as in Lustig et al. (2006).

Current Study

The basis for the current study is that both memory and attention abilities, as indexed by WMC, are important to quickly make the comparisons on PS measures such as Comparison tasks (Conway et al., 1999; Kane et al., 2005). For example, on a Comparison task with a target length of nine characters to compare, a participant would have several different ways of comparing the stimuli. One method is to try to remember all nine characters, and then move attention to the other stimulus and compare it to the representation held in memory. The ability to keep the entire nine character stimulus active in order to make the comparison depends on dealing with proactive interference that accumulates due to the similarity of the items across trials. Another method would be to chunk characters into groups of three, such that the first three characters of the first stimulus are encoded and then held in memory to compare to the first three characters of the second stimulus, and so on, until either the entire stimulus has been compared or a character that is different is encountered. In this situation, memory would be important in order to rapidly update the contents of active memory during the trial, and also to keep track of which part of the stimulus has already been compared. Control of attention would be necessary to rapidly move back and forth between the stimuli, and also to constrain focus to the current part of the stimulus that is important (e.g., encode the middle three characters and temporarily ignore the first and last three).

Changing the number of items to compare (Target Length) allowed contrasting high and low spans with varying amounts of memory load. The prediction was that as the target length of the comparison stimuli increases, the demands on attention and memory abilities will multiply, and therefore low spans would be especially slower than high spans at longer target lengths. Similar to Lustig et al. (2006), a manipulation varying the level of task-irrelevant distractors present was included by filling the blank between the target stimuli with random letters or numbers on a percentage of the trials (Distractor Type). The predicted result was that low spans would be specifically slower than high spans when the distractors were from the same category as the target stimuli.

In addition to obtaining accuracy and response time (RT) data on these tasks, another advantage of the computerized administration of the Comparison tasks was to permit eye-tracking during performance. In this study, several eye-movement patterns could be informative as to the locus of impaired performance on Comparison tasks. For example, if low spans' performance is specifically impaired by longer target lengths as predicted, finding that low spans make more back-and-forth switches between the target stimuli would provide evidence that low spans groups chunk fewer characters at a time than high spans. In addition, if low spans are more likely to be affected by the presence of irrelevant distractors, the eye-movement data should indicate that low spans make more fixations in the region between the target stimuli than the high spans do.

The goal of the current study was to specify more precisely the role of WMC in the performance of two commonly used PS tasks as a means to explain the relationship between these constructs and with Gf. Participants were administered paper-and-pencil and computerized versions of different complex span, Comparison, and reasoning tasks. In addition, eye-tracking during computerized versions of the Comparison tasks was included to help determine more precisely the locus of slower PS performance in relation to individual differences in WMC in healthy, younger adults.

CHAPTER 2

METHOD

Participants

All participants first completed a standard screening session in a previous visit to our lab consisting of three computerized WMC tasks and a computerized version of 12 RSPM problems. Each of these tasks is described in detail in Appendix A. Participants were dichotomized into high- and low-span groups based on a z-score composite of performance on the three WMC tasks.

Fifty-four participants (22 high spans and 32 low spans) were recruited from various Atlanta area colleges and universities and from the community at large via flyers and newspaper advertisements. All participants were between the ages of 18 and 35 years, with normal or corrected-to-normal eyesight based on performance on a Snellen acuity chart. Overall, each participant was tested individually for two sessions (screening and current study), with each session lasting approximately one hour. All participants were compensated with either one class credit or a $20 check at the end of each session.

Apparatus and Materials

On the computerized Comparison tasks, E-Prime (Schneider, Eschman, & Zuccolotto, 2002) was used to administer the experiment, collect responses, and record accuracy and RT. Stimuli were presented via a 19-inch monitor.

Eye movement data were recorded using the Applied Sciences Laboratory E-5000 eye-tracker (Bedford, Massachusetts). The eye-tracking camera was mounted directly below the computer screen displaying the stimuli and positioned so that the left eye of each participant was used for recording. The camera operates via infrared light projecting from the center of the camera lens directly into the participant's pupil. The eye-tracking system has a sampling rate of 60 Hz, enabling eye position and pupil dilation to be recorded every 16.7 milliseconds (ms). Participants used a chinrest to maintain a fixed distance from the computer screen and to prevent unnecessary head movements. Eye position, fixation, fixation durations, and inter-fixation durations were calculated using the EYENAL software distributed with the eye-tracking system.

Procedure

All participants completed the two sessions in the same order. After completing the screening session, qualifying participants were scheduled for the second session, in which they completed separate paper-and-pencil versions of Letter and Number Comparison, the paper-and-pencil Shipley Abstract Reasoning task, and the computerized Comparison task.

Before beginning the computerized Comparison task, participants were instructed about how the eye-tracking system recorded their eye movements and told to minimize head movements during the actual experiment. The eye-tracking system was calibrated to the participant's pupil using a nine-point display representing a three by three grid covering the computer screen. After calibration, participants saw an instruction screen letting them know which of six possible conditions (Target Type x Target Length) the upcoming block of trials was going to be (e.g., Letter x 3). Before the first block, the experimenter informed the participant that there were three types of items that could be between the letters or numbers to compare: (a) a blank line, similar to that completed in the paper-and-pencil tasks; (b) random letters or numbers from the different character type; and (c) random letters or numbers from the same character type (representing None, Different, and Same Distractor Types, respectively). Each instruction screen also included a display with an example stimulus of the type to be encountered in the upcoming block, which was always two matching items separated by Same distractors (e.g, ABCQILCIEABC). This screen was always followed by a second instruction screen informing the participants that they should press the right button (*m* key covered with a blue sticker) if the letters/numbers match, and the left button (*z* key covered with a green sticker) if the letters/numbers do not match. Participants were instructed to be as fast as possible. The participants then completed six practice trials before each block, with accuracy and RT feedback after each trial.

Participants were explicitly instructed that they must maintain fixation on the central dot (1 cm x 1 cm white plus sign) before a trial would begin. Each trial was initiated by requiring participants to hold fixation on a central dot that appeared for 600-2200 ms, varying unpredictably in 100 ms increments. At the end of this variable foreperiod, fixation position was again checked, and if fixation was not on the central dot, the fixation screen remained and was checked very 50 ms until the participant fixated on the central dot. After the fixation period ended, the stimulus display appeared and remained onscreen until participants responded or 10 seconds (s) had passed, whichever occurred first. After responding, a blank screen appeared for 1500 ms before the central fixation dot appeared again to start a new trial. During practice, trials that were not responded to within 10 s were followed by a feedback screen stating, “No response detected.”

After completing the six practice trials before the first block, participants were given the opportunity to ask any questions, and were informed that they would not receive feedback on the experimental trials. Immediately before beginning the experimental trials on each block, participants were reminded to limit their head movements as much as possible. Each block of trials ended with the appearance of the nine-point calibration screen, indicating that the participant could rest and also to check eye-tracking and recalibrate, if necessary, before starting the next block. During the computerized task, the experimenter remained in the room to monitor the eye-tracking camera position and adjust the camera for slight head movements during the task. The computerized task lasted approximately 45 minutes.

Each trial was randomly generated before the study so that each participant saw the same stimuli, but presented in a random order both in terms of the blocks and the trials within a block. Constraints on the random generation were such that any nonmatch trial was created by changing the identity of one letter or digit. The within-subjects variables (see below) combined to form 36 different kinds of trials, with nine presentations of each kind of trial. Therefore, each of the six blocks had 54 trials, making 324 total trials for each participant.

Design

The design of the computerized Comparison task was a 2 (Span: High vs. Low) x 2 (Target Type: Letter vs. Number) x 3 (Target Length: 3 vs. 6 vs. 9) x 3 (Distractor Type: None vs. Different vs. Same) x 2 (Trial Type: Match vs. Nonmatch) mixed factorial design, with Span as a between-subjects variable, Target Type and Target Length as blocked within-subjects variables, and Distractor Type and Trial Type as intermixed within-subjects variables.

Eye-Movement Data Preparation

Eye data was first examined individually for the number of trials in which a "Loss" occurred either due to eye blinks, head movements, or variable pupil constriction. In addition, fixations were plotted to determine the accuracy of calibration across the experimental session. Eye data was aggregated into fixations using the software program accompanying the eye-tracking system. First, individual samples were combined into fixations according to the default settings, with a fixation defined as six consecutive samples within 1 degree of visual angle. Fixations were then labeled according to their position on the screen for the different areas-of-interest (AOIs) used to examine the eye data. For example, the simplest analysis was based on an AOI that separates the computer display into two equal halves, establishing a vertical line at center by which to count the number of times that fixation crosses center in a given trial (switches). An additional AOI was used to separate the display into three equal sections: two representing each side of the stimuli being compared and another representing the area between the stimuli, in order to examine the amount of fixations that occur in this middle region corresponding to the various distractor conditions. Because the E-Prime program was written to crosstalk with the eye-tracking software and mark in code when critical trial events occurred (e.g., stimulus onset and response), only trial-relevant fixations were included in the analyses of the eye movement data.

CHAPTER 3

RESULTS

The computerized Comparison task accuracy, RT, and eye-movement analyses were done separately for each target type (letter/number) and for trials with no distractors versus the different distractor (different/same) conditions. A 3 x 2 x 2 (Target Length x Trial Type x Span) mixed analysis of variance (ANOVA) was used on all trials without distractors, whereas a 3 x 2 x 2 x 2 (Target Length x Distractor Type x Trial Type x Span) mixed ANOVA was used on all distractor trials.

All analyses were conducted using .05 as the probability of a Type I error. Only correct trials from the computerized Comparison tasks entered the RT analyses. In addition, 0.3% of the trials was lost due to blinks and/or temporary loss of tracking, and was thus removed from the analyses; analyses including these trials produced the same results. Because the focus of the study was the influence of WMC on Comparison performance, the text results concentrate on significant Span effects; full ANOVA results are presented in Appendix B to support the description of the results.

Criteria for Exclusion of Participants

Data from 20 participants (16 low spans and 4 high spans) were excluded from the final dataset for various reasons: (a) 2 low spans due to physical eye problems; (b) 2 participants due to interference from colored contacts (1 low span and 1 high span, respectively); (c) 6 low spans due to dim pupils that prevented eye-tracking calibration; (d) 6 participants due to poor eye-tracking (4 low spans and 2 high spans, respectively); and (e) 4 participants due to low accuracy in the computerized Comparison tasks (3 low spans and 1 high span, respectively). Therefore, the final results are based on 16 low spans and 18 high spans with suitable eye data. There were no age differences between the final span groups, $F(1, 32) < 1$.

Additional Measures

Descriptive statistics for all of the additional WMC, PS, and Gf measures are provided in Table 2. Note that by definition, the span groups were chosen based on their position in the upper and lower quartile of the WMC distribution, so high spans not surprisingly showed better performance on all three WMC tasks. In addition, on the Gf measures the high spans scored significantly higher than low spans on the RSPM subset and the Shipley Abstract Reasoning test. Finally, the high spans scores' were marginally higher on both the paper-and-pencil Letter and Number Comparison tasks. An in-depth analysis of the errors made on these tasks, given in Appendix C, did not reveal any significant effects involving WMC, but the results are presented to contrast with the computerized Comparison trials without distractors.

Error Rates

Letter Comparison

An examination of the blank trials in Figure 1 showed that although errors increased as target length increased, the span groups did not differ in the number of errors committed. Inspection of the distractor trials again revealed no effect of WMC, but both groups made more errors as target length increased and on trials with distractors that were also letters.

Table 2

High and Low Span Group Mean Scores on Additional Measures

Measure	High Spans (*n* = 18)	Low Spans (*n* = 16)	*p*-value
Operation Span	67.22 (5.28)	39.75 (10.80)	< .01
Symmetry Span	34.50 (3.90)	19.00 (7.47)	< .01
Reading Span	67.39 (6.18)	34.94 (11.25)	< .01
Letter Comparison	12.75 (2.56)	10.94 (2.77)	.06
Number Comparison	15.64 (3.06)	13.94 (2.57)	.09
Ravens	10.18 (1.33)	8.40 (2.32)	.01 [a]
Shipley Abstraction	16.06 (1.35)	13.31 (3.14)	< .01

Note. *SD* is given in parentheses. See Appendix A for scoring procedures for each task.
[a] = 17 high spans/15 low spans.

Number Comparison

Figure 2 displays the pattern of errors on Number Comparison. Looking first at trials without distractors, none of the effects, including WMC, were significant. On distractor trials, although the span groups did not differ in the number of errors committed, overall participants made more errors as target length increased and on trials with random numbers as the distractors.

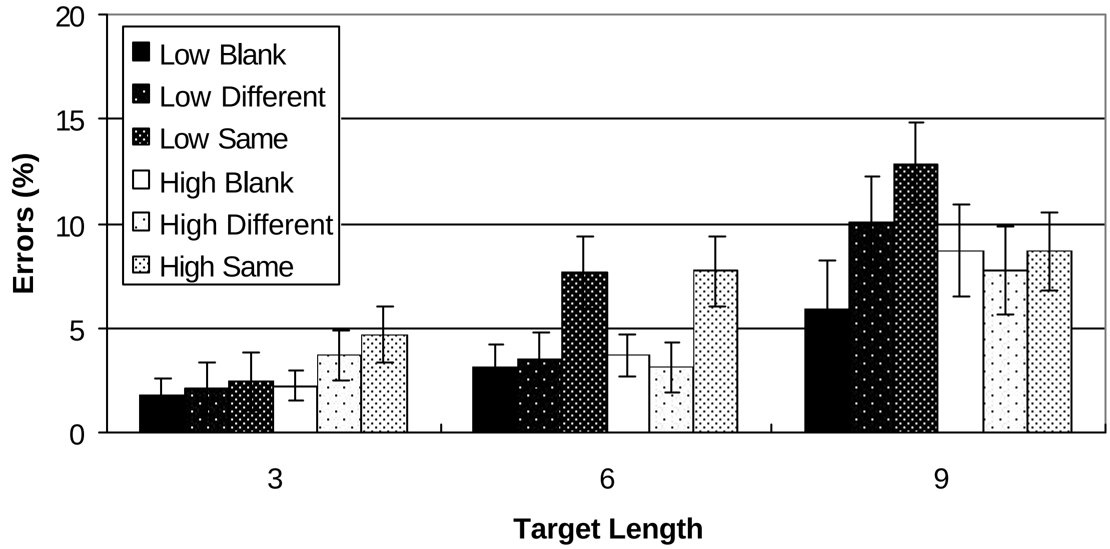

Figure 1. Computerized Letter Comparison error rates for each span group as a function of target length and distractor type.

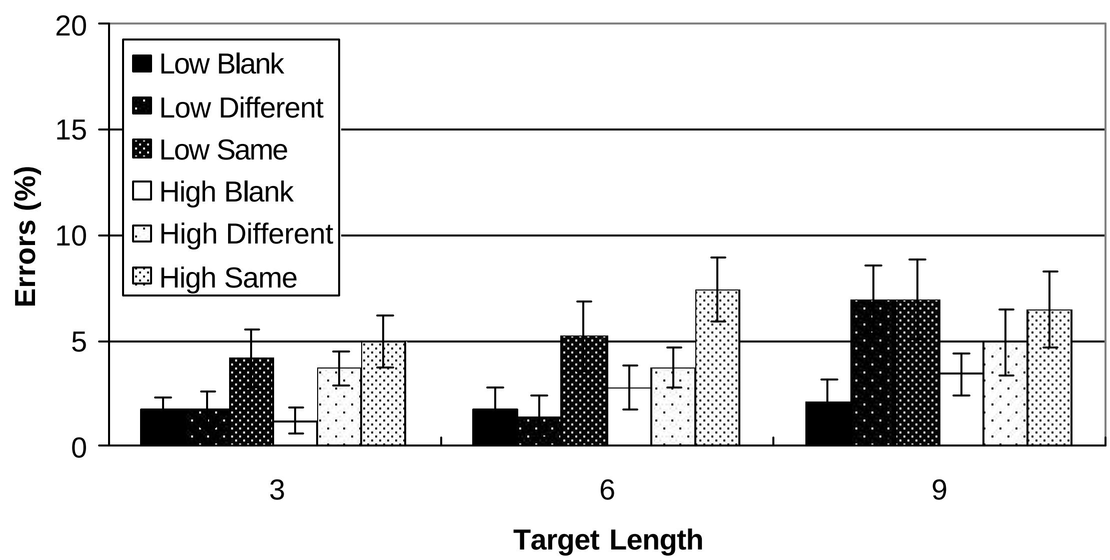

Figure 2. Computerized Number Comparison error rates for each span group as a function of target length and distractor type.

Correct RT

Letter Comparison

Mean Letter Comparison RTs are presented in Figure 3. Examining the no distractor trials revealed that low spans were slower than high spans, and that responses were slower as target length increased. Notably, the Target Length x Span interaction was significant; the advantage for high spans versus low spans was 226, 580, and 975 ms for target lengths of three, six, and nine, respectively.

Looking at the distractor trials indicated again that low spans were slower than high spans, responses were slower as target length increased, and responses were slower on trials with letters as distractors. As predicted, the WMC main effect was qualified by a Target Length x Span interaction, and a Distractor Type x Span interaction. As can be seen in Figure 3, the advantage for high spans compared to low spans increased as the target length increased, and low spans were further impaired by the similar (letter) distractors compared to the dissimilar (number) distractors. In addition, a Trial Type x Span interaction indicated that low spans were even slower on match trials than nonmatch trials compared to high spans.

Number Comparison

Mean Number Comparison RTs are presented in Figure 4. Looking at trials without distractors revealed that low spans were slower than high spans, and that responses were slower as target length increased. Overall, low spans were 319 ms slower than the high spans. In contrast to the Letter Comparison results, none of the interactions involving WMC were significant, although the Trial Type x Span interaction suggested that low spans were slower on match versus nonmatch trials compared to high spans.

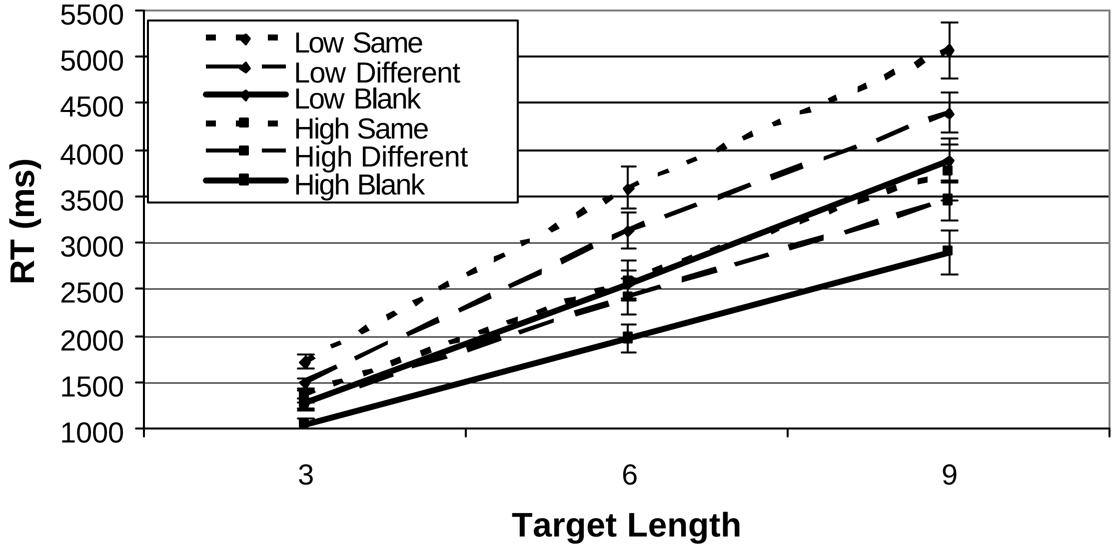

Figure 3. Computerized Letter Comparison mean RT for each span group as a function of target length and distractor type.

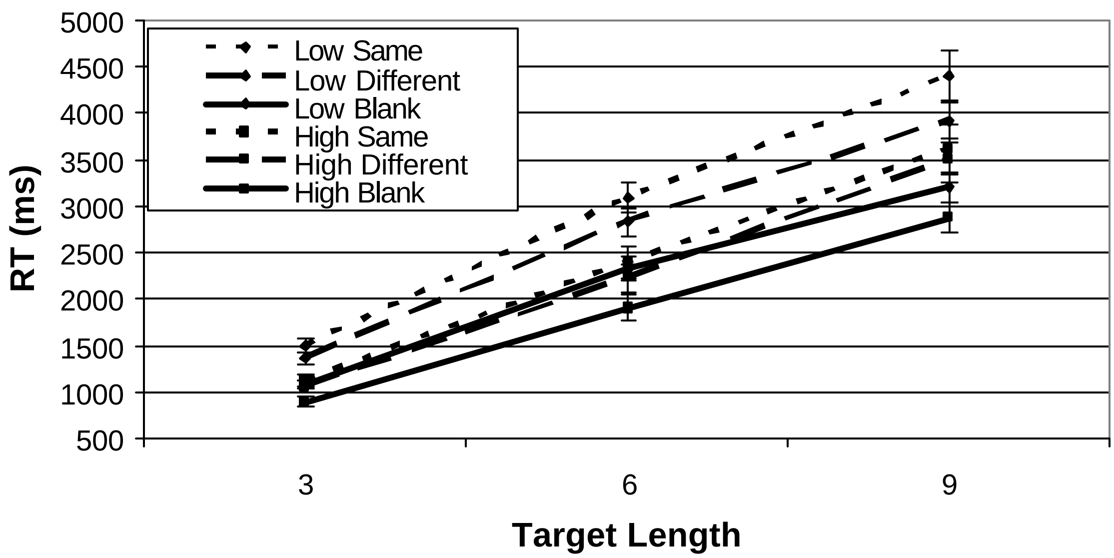

Figure 4. Computerized Number Comparison mean RT for each span group as a function of target length and distractor type.

Inspection of the trials with distractors indicated that low spans were slower than high spans, responses were slower as target length increased, and responses were slower with random numbers as the distractors. Importantly, the effect of WMC was qualified by significant Distractor Type x Span interaction; low spans were further impaired by similar distractors compared to high spans. In addition, a Trial Type x Span interaction indicated that low spans were slower on match than nonmatch trials compared to high spans.

Overall Fixations

Letter Comparison

Figure 5 displays the number of overall fixations on the computerized Letter Comparison task; low spans made more fixations than high spans, and fixations increased as the target length increased. Again consistent with predictions, a significant Target Length x Span interaction revealed that low spans made 0.41, 0.71, and 1.48 more fixations than high spans at target lengths of three, six, and nine, respectively.

Examination of trials with distractors in Figure 5 showed that low spans made more overall fixations than high spans, the number of fixations increased as target length increased, and more fixations occurred on trials with similar letters as distractors. However, a significant Target Length x Span interaction indicated again that low spans made more overall fixations as the target length increased, and a significant Distractor Type x Span interaction indicated that low spans made more fixations than high spans, especially when the distractors were more similar to the targets.

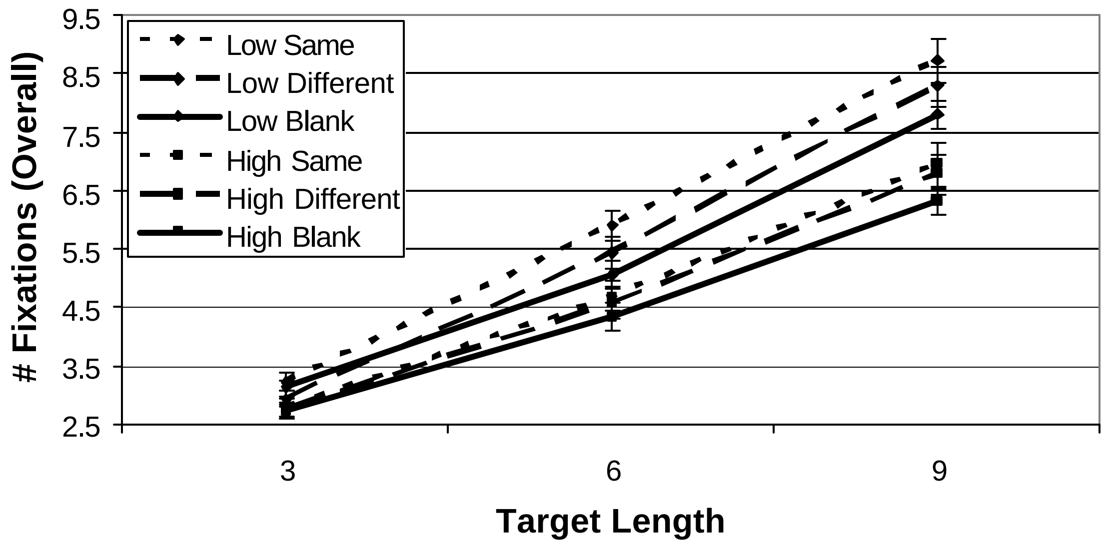

Figure 5. Computerized Letter Comparison number of overall fixations for each span group as a function of target length and distractor type.

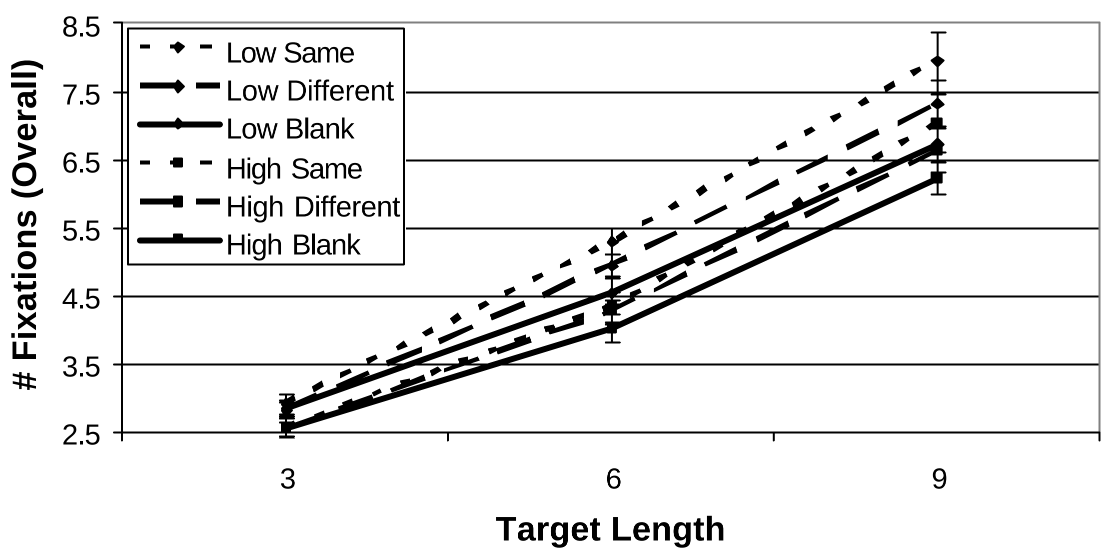

Figure 6. Computerized Number Comparison number of overall fixations for each span group as a function of target length and distractor type.

Number Comparison

The number of overall fixations in Number Comparison is presented in Figure 6. An examination of Number Comparison trials without distractors showed that low spans made more overall fixations than high spans, and that more fixations occurred as the target length increased. In contrast to the Letter Comparison results (but consistent with the Number Comparison RT results), the Target Length x Span interaction was not significant.

Looking next at Number Comparison trials with distractors in Figure 6, the low spans made more fixations than high spans, the number of fixations rose as target length increased, and more fixations occurred on trials with similar number distractors compared to letter distractors. Similar to the analyses of Number Comparison trials without distractors, none of the interactions involving WMC were significant.

Number of Switches

Letter Comparison

The next analysis of the eye-tracking data divided the computer display into equal halves using a vertical line that passed through the central fixation. Thus, the number of times on a given trial that consecutive fixations occurred on either side of center was taken to be the number of switches from one target to the other. Figure 7 displays the number of switches in the various conditions of the Letter Comparison task. An examination of the results indicated that low spans made more switches than high spans, and the number of switches increased as the target length increased. As predicted, a significant Target Length x Span interaction revealed that low spans made 0.26, 0.37, and 0.70 more switches than high spans at target lengths of three, six, and nine, respectively.

Looking at Figure 7 at the Letter Comparison trials with distractors indicated that low spans made more switches than high spans, and the number of switches increased as target length increased, although the main effect of Distractor Type was not significant. Importantly, these findings were qualified by significant interactions involving WMC, including Target Length x Span, and Distractor Type x Span. In line with the findings with no distractors, the low spans made more switches than high spans, and the difference grew as target length increased. In addition, the high spans showed no difference in the number of switches for the different distractor types, but low spans made more switches when the distractors were more similar to the targets.

Number Comparison

Figure 8 presents the number of switches on Number Comparison trials. Inspection of the figure indicated that on trials without distractors, more switches occurred on longer target lengths, and for low spans compared to high spans. None of the interactions involving WMC were significant, although the Trial Type x Span interaction indicated a trend toward low spans making relatively more switches on match trials compared to nonmatch trials, whereas the number of switches high spans made did not differ as a function of trial type.

As can be seen in Figure 8, on Number Comparison trials with distractors, low spans made more switches than high spans, more switches occurred at longer target lengths, and more switches occurred on trials with numbers as distractors. A significant Target Length x Span interaction, as can be seen in Figure 8, indicated that low spans switched 0.18, 0.37, and 0.76 more than high spans at target lengths of three, six, and nine, respectively.

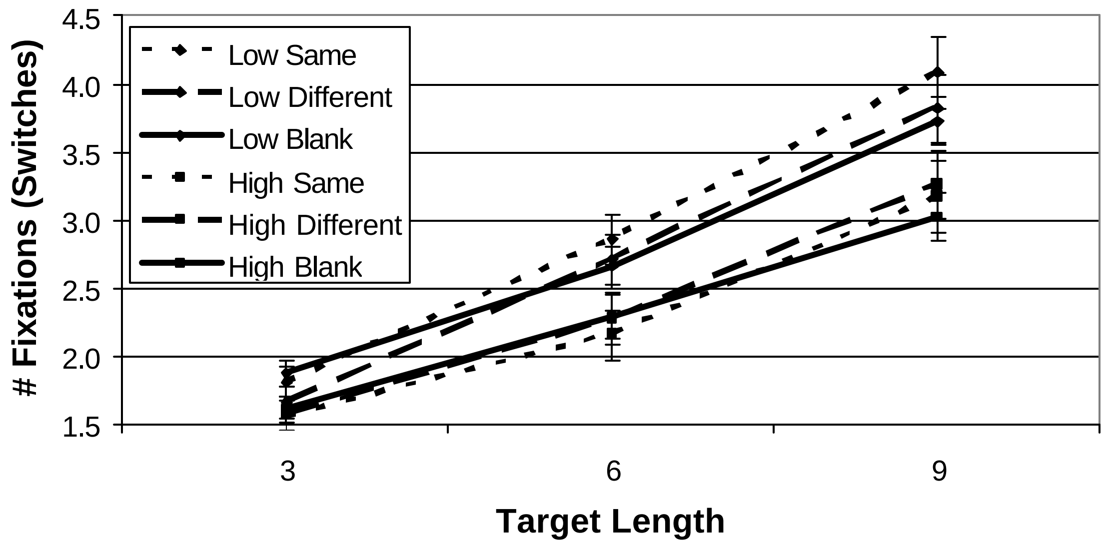

Figure 7. Computerized Letter Comparison number of switches for each span group as a function of target length and distractor type.

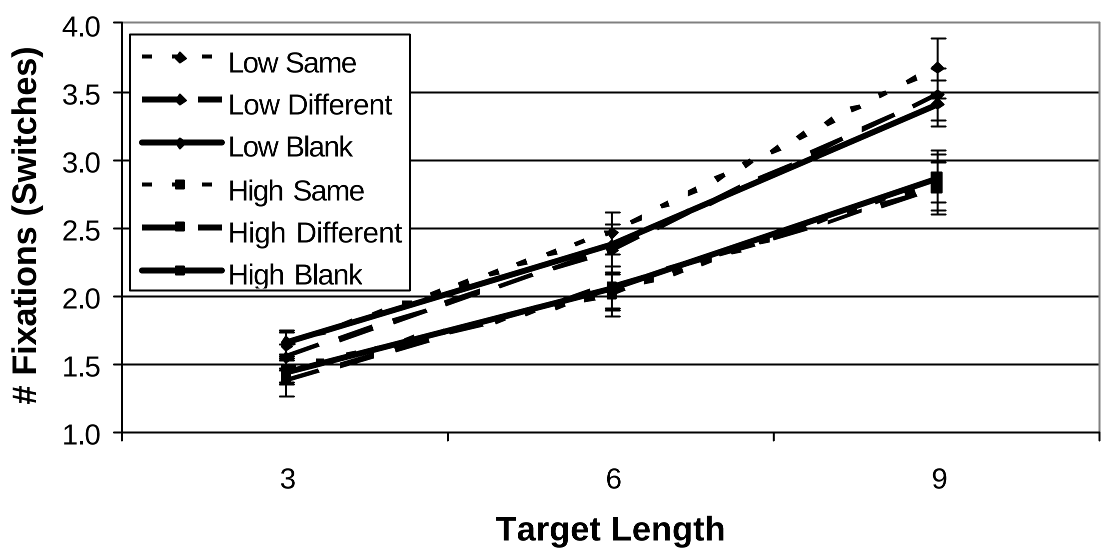

Figure 8. Computerized Number Comparison number of switches for each span group as a function of target length and distractor type.

Central Fixations

Letter Comparison

In order to examine the role of the presence of distractors upon performance, a central AOI was created using the boundaries of the central blank line or distractor stimuli. As expected, the high and low spans did not differ in the amount of fixations to the central region when no distractors were present (Table 3). However, looking at the Letter Comparison trials with distractors indicated that low spans made more fixations to the distractor region, and more central fixations occurred when the distractors were more similar to the targets. Importantly, the Distractor Type x Span interaction was significant; as seen in Table 3, low spans made more overall fixations to the intervening distractors, and they made even more fixations when the distractors were more similar to the targets.

Number Comparison

The number of central fixations, also presented in Table 3, was examined for Number Comparison trials. Similar to the analyses in Letter Comparison, the span groups did not differ in central fixations when there were no distractors. However, an inspection of Number Comparison trials with distractors in Table 3 indicated that low spans made more central fixations when distractors were present than high spans, and that more central fixations occurred for similar distractors. In contrast to the results with Letter Comparison, the type of distractor did not interact with WMC.

Table 3

High and Low Span Mean Number of Fixations in Central AOI

Letter Comparison			
		Distractor Type	
Span Group	None	Different	Same
High Spans	.29 (.06)	.43 (.07)	.44 (.07)
Low Spans	.41 (.06)	.65 (.08)	.76 (.08)

Number Comparison			
		Distractor Type	
Span Group	None	Different	Same
High Spans	.21 (.04)	.39 (.05)	.45 (.06)
Low Spans	.30 (.04)	.60 (.06)	.69 (.07)

Note. Standard error of the mean given in parentheses. *N* = 18 high spans/16 low spans.

Computerized and Paper-and-Pencil Comparison Relationship

In order to examine the extent to which conclusions about the computerized Comparison tasks inform us about the traditional paper-and-pencil Comparison tasks, the computerized trials without distractors were combined across Target Length and Trial Type and correlated with the paper-and-pencil scores for both types of Comparison tasks. The versions of Letter Comparison were significantly correlated, $r(34) = -.66$, $p < .01$, as were the versions of Number Comparison, $r(34) = -.68$, $p < .01$. These results suggest that inferences drawn from performance of the computerized tasks generalize to the paper-and-pencil versions, given the high correspondence between the separate formats.

Finally, the eye-movement data were used as a covariate in re-analyses of the paper-and-pencil and computerized trials without distractors. First, looking at the paper-and-pencil tasks, an analysis of covariance (ANCOVA) was conducted separately on the Letter and Number Comparison scores, with Span as a between-groups factor, and the number of fixations on blank trials of computerized Letter and Number Comparison, respectively, as the covariate. The main effect of Span for both paper-and-pencil tasks was not significant, both *F*'s < 1. The same analyses were conducted separately using the RT data from blank trials for Letter and Number Comparison. The ANCOVA results indicated that the main effect of Span was no longer significant for either task after including the number of fixations as a covariate: Letter Comparison, $F(1, 31) = 1.80$, $p = .19$, ?^{2} = .06; Number Comparison, $F(1, 31) = 1.15$, $p = .29$, ?^{2} = .04. Accounting for the number of fixations reduced the span group RT difference by 57% and 58% in Letter and Number Comparison, respectively.

CHAPTER 4

DISCUSSION

The goal of this study was to elucidate the relationship between WMC and PS, two cognitive constructs argued to be important for the development and magnitude of Gf. Ascertaining this relationship has been hindered by inconsistent results obtained from developmental studies comparing children or older adults to younger adults and from differential studies of younger adults. Adding to the uncertainty is the complex nature of the PS construct and the scarce amount of experimental work establishing the task parameters affecting performance on these tasks. The current study attempted to resolve these issues by comparing healthy younger adults that varied in WMC, thereby avoiding the potential cohort differences of developmental research. In addition to the traditional paper-and-pencil PS tasks, computerized versions were also administered in order to determine the importance of eye movements on performance of PS tasks. A speed account of performance on Comparison and other PS tasks contends that high and low scorers on these tasks perform them in the same manner, but slower individuals take more time to execute the cognitive processes involved. In contrast, a WMC account posits that individual differences in WMC represent a combination of active maintenance and controlled attention abilities, and performance on PS tasks is dependent to some extent on these abilities. Therefore, a WMC account argues that PS tasks such as Comparison may be performed differently by individuals who differ in these memory and attention abilities, and thus measurements of eye movements should reveal differential patterns for high and low scorers.

The results were consistent with these predictions in several ways. First, the high spans scored higher on the Ravens and Shipley measures of Gf, consistent with previous correlational work (Engle, Tuholski et al., 1999; Conway et al., 2002; Hambrick, 2003; Kane et al., 2004; Ackerman et al., 2002; Unsworth & Engle, 2005; Unsworth, Heitz, Schrock, & Engle, 2005). The paper-and-pencil Comparison results were suggestive of a positive relationship between WMC and PS, although this evidence was somewhat weaker in the case of Number Comparison. Note that WMC appears to be related more strongly to Gf than to PS; this stands in contrast to claims by some previous researchers (Ackerman et al., 2002; Kyllonen & Christal, 1990; but see Conway et al., 2002).

Notably, the results from the computerized Comparison tasks supported several predictions regarding the relationship of WMC to PS. On the trials with no distractors, which were most similar to the paper-and-pencil versions, the high spans were 594 ms faster on Letter Comparison and 319 ms faster on Number Comparison. However, after accounting for the differential number of overall fixations, the span groups were no longer significantly different for either task. This result suggests that instead of an overall slower rate of perceptual extraction and/or cognitive processing, high and low scorers on PS tasks may instead be completing them in different ways. Given the high level of correspondence between the paper-and-pencil and computerized versions of the Comparison tasks, these findings also shed light on the performance of traditional PS measures.

Other evidence against a basic speed account was obtained as well. For example, in the computerized Letter Comparison a significant interaction between WMC and the length of the target stimuli revealed that the difference between the high and low spans grew as the target length increased. Lustig et al. (2006) found a similar interaction of target length and group on a computerized Letter Comparison task in their study of younger and older adults. These findings are expected because individuals low in WMC are more likely to have (a) a smaller scope of attention (Cowan et al., 2005); (b) problems updating the contents of the focus of attention, partially due to interference within and across trials (Bunting, 2006) (c) difficulty actively maintaining items over an interval (Payne, 2003); and (d) trouble maintaining the order of memory representations (Unsworth & Engle, 2006). In support of this view, the eye-tracking data indicated the same Target Length x Span interaction in both the number of overall fixations and the number of switches back and forth between the target stimuli. These results indicate that memory and attention abilities are important for performance on tasks that are theorized to measure PS.

In addition, the distraction manipulation demonstrated the role of selective attention in Comparison performance. In both task versions low spans' performance was impaired by the presence of distracting stimuli, and low spans were even slower when the distracting stimuli were from the same category as the targets. These results are similar to previous research (Heitz & Engle, in press; Redick & Engle, 2006) showing that WMC is important to selectively attend to goal-relevant information and filter out related distractors. Evidence from the eye-tracking data showed that in both versions low spans were more likely to fixate the irrelevant distractor stimuli, and in the Letter Comparison version a significant Distractor Type x Span interaction indicated that low spans were even more likely to fixate in the intervening region when the distractors were random letters. Similar to the results in Lustig et al. (2006), the distractibility manipulation specifically impaired the individuals who have difficulty dealing with interference.

A few limitations of the current work need to be resolved with future research. First, the distinction between Letter and Number Comparison versions was unexpected, as the exact content of the comparisons is not generally thought to be important. However, the differences between the span groups were more robust in both the paper-and-pencil and computerized Letter Comparison version. Although unanticipated, previous research with complex span tasks similar to those employed in this study has shown higher correlations with Letter Comparison than Number Comparison (D. Z. Hambrick, personal communication, February 23, 2006). In this study, Number Comparison consistently showed better performance, in terms of higher scores in the paper-and-pencil tasks and faster mean RTs in the computerized tasks. Interestingly, research has shown that performance is better on Digit Span compared to Letter Span tasks (e.g., Colom, Shih, Flores-Mendoza, & Ángeles Quiroga, 2006). One likely explanation is that most individuals are more familiar with random number strings such as phone numbers or mental calculations compared to the frequency with which random letter strings are encountered in day-to-day activity. Although PS has been treated as a domain-general construct, future work should investigate the possible domain-specific relationships among WMC, PS, and Gf.

Another potential limitation is the interpretation that more switches back and forth between stimuli for the low spans represent impaired memory abilities for these individuals (either more forgetting or smaller chunk sizes). A different explanation that would also be consistent with more switches is that the low spans engage in a cautious strategy of checking their answers before responding, and thus low spans are slower (and make more switches) due to strategic differences. One way to examine this possibility is to compare performance for the different trial types (match vs. nonmatch) at the longest target length. On nonmatch trials, more cautious performers might be expected to exhaustively search the two target strings even when the different character occurs in the first or second serial position (e.g., *OFKZDSVLR*_____*NFKZDSVLR*). Cautious performers would be expected to show more similar performance on match and nonmatch trials, while individuals not engaging in the checking strategy would be expected to respond quicker (and maker fewer switches) on nonmatch versus match trials. An examination of trials without distractors at a target length of nine revealed that both high and low spans were faster on nonmatch compared to match trials in Letter and Number Comparison, but neither Span x Trial Type interaction was significant: Letter Comparison, $F(1, 32) < 1$; Number Comparison, $F(1, 32) = 2.21$, $p = .15$. The same analyses conducted on the number of switches corroborate the RT results: Letter Comparison, $F(1, 32) < 1$; Number Comparison, $F(1, 32) = 1.63$, $p = .21$. Although these findings go against the argument that high and low spans use different strategies, there were not enough trials in the current experiment to analyze performance for nonmatch trials based on the serial position of the nonmatching character.

Finally, some other issues are being investigated in a follow-up study. An argument could be made that including the distractor manipulation changed the way that participants performed all trials, including those without distractors. Thus, in the latest study only trials without distractors are presented to participants, eliminating this potential concern and coming closest to representing the paper-and-pencil Comparison tasks. Second, the target lengths used in the current study were three, six, and nine, which are the same as those used in the most common version of the paper-and-pencil Comparison tasks. However, systematically varying the target length may demonstrate that WMC differences do not occur at a target length of one, but they do occur as the memory load increases and individual differences in active maintenance of serial position and/or the size of the focus start to affect Comparison performance. Finally, although the current study has focused on individual differences, the main evidence for the PS-as-primitive view comes from developmental research. Although individual differences and developmental changes in abilities are often discussed somewhat interchangeably, relatively few studies have explicitly examined individual and developmental differences simultaneously to determine whether the same mechanism is responsible for both (e.g., Oberauer, 2005). The new study includes this design in order to unite the two areas of research and provide clarification about whether the PS argument is only applicable to explanations of developmental changes.

In addition, investigations of the underlying neural networks responsible for the relationship among WMC, PS, and Gf are possible with today's neuroimaging techniques. Rabbitt et al. (2006) showed that different brain regions are responsible for the aging performance decline seen in speed and intelligence tasks, casting doubt that speed is the underlying construct responsible for intelligence. Future work should include examinations of healthy younger adults and additional measures of WMC in order to provide converging evidence about the relationship among these constructs.

CHAPTER 5

CONCLUSION

The current work systematically investigated performance on two Comparison tasks used as measures of PS in the developmental literature. Chronometric and eye-tracking data on computerized versions of these tasks revealed that individual differences in WMC are important for performance on these PS measures, but this relationship is the result of the memory and attention demands on these "simple" tasks. Taken together, these results point toward an interpretation that individual differences in WMC are important in situations requiring the ability to selectively control attention and maintain information, including some tasks originally theorized to measure PS.

APPENDIX A

DESCRIPTION OF ADDITIONAL WMC, PS, AND GF MEASURES

In addition to the main experiment, all of the participants were tested on the various WMC, PS, and Gf measures in the same order across the two sessions.

WMC Measures

Span groups were determined by a *z*-score composite on three WMC tasks. All tasks are automated and based on traditional WMC tasks. All tasks were of the same variety: a processing task interleaved with to-be-remembered (TBR) items to be serially recalled. All participants practiced the task components in the same order: storage only, processing only, processing and storage. Although the same fixed pool of TBR items was used within a task, a TBR item was not allowed to repeat within a set. The correct response for the answer aspect of the processing task was approximately equiprobable. All tasks were scored by taking the correct number of items recalled in the correct serial position and summing across all sets (total number correct; see Conway et al., 2005 for discussion of scoring methods).

In order to limit the amount of rehearsal in which a participant could potentially engage, processing time was calibrated individually for each task by presenting participants with 15 processing-only practice trials to calculate a mean processing time. A time limit was imposed on the processing part of experimental trials by taking the individual's mean processing time and adding two standard deviations to that amount; if participants had not indicated a response to the processing part of the trial before that time limit is met, the TBR item was immediately presented, and the trial was marked as a speed error. Participants could also incorrectly respond to the answer part of the processing task, which would be marked as a processing error. In order to be included in the current study, participants had to maintain at least 80% accuracy on the processing components of the WMC tasks.

During the recall phase, participants marked the box next to the items that were presented in the previous set. As a box was marked, the serial position of the response (e.g., 1, 2, 3) was shown in the chosen box. If a participant cannot remember a certain item, they could select the *blank* box to indicate the serial position of the item that could not be recalled. Participants clicked *Exit* when completed with the recall portion of the current set. Three forms of feedback were presented for 2000 ms on the following screen: (a) Recall accuracy on the previous set, given in terms of the number of items recalled in the correct order out of the total number of items presented; (b) the number of processing errors made during the previous set; and (c) the cumulative processing accuracy is presented in the upper right corner as a reminder that participants needed to maintain an overall level of accuracy in order to participate in future studies.

Operation Span (Unsworth, Heitz, Schrock, & Engle, 2005; based on Turner & Engle, 1989)

Participants were presented with simple math operations composed of three single digits and two separate operations (e.g., (1*2) + 1 =?). After mentally computing the answer, participants were instructed to click on the screen to advance to the answer part of the trial. Participants were presented with a number and instructed to click either *TRUE* or *FALSE* if the number presented on the screen matched the number from the mental calculation. Immediately after responding, a single letter was presented for 800 ms, after which another math operation was presented, depending on the current set size.

After all of the TBR items for the current set had been presented, the participant was shown a fixed grid of letters from which all TBR items were randomly drawn (F, H, J, K, L, N, P, Q, R, S, T, & Y). Three sets of each list length (3-7) were presented randomly, for a maximum possible score of 75.

Symmetry Span (based on Kane et al., 2004)

Participants were presented with figures that were either vertically symmetrical or asymmetrical. After making a symmetry judgment, participants were instructed to click on the screen to advance to the answer part of the trial. Participants were asked if the previous matrix was symmetrical and instructed to click either *TRUE* or *FALSE*. Immediately after responding, a single box in a four by four grid was highlighted in red and presented for 650 ms, after which another figure was presented, depending on the current set size. After all of the TBR items for the current set had been presented, participants were shown a blank four by four grid matching that shown when the TBR items were presented. They then clicked in serial order the boxes that were highlighted in the previous set. Three sets of each list length (2-5) were presented randomly, for a maximum possible score of 42.

Reading Span (based on Daneman & Carpenter, 1980)

Participants were presented with figures that were either vertically symmetrical or asymmetrical. After making a symmetry judgment, participants were instructed to click on the screen to advance to the answer part of the trial. Participants were asked if the previous matrix was symmetrical and instructed to click either *TRUE* or *FALSE*. Immediately after responding, a single box in a four by four grid was highlighted in red and presented for 650 ms, after which another figure was presented, depending on the current set size. After all of the TBR items for the current set had been presented, participants were shown a blank four by four grid matching that shown when the TBR items were presented. They then clicked in serial order the boxes that were highlighted in the previous set. Three sets of each list length (2-5) were presented randomly, for a maximum possible score of 42.

PS Measures

The paper-and-pencil tasks were very similar and vary only in the type of item (letters vs. numbers) to compare. Each participant was given general instructions as to the nature of the task, completed three practice items, and was given the opportunity to ask questions before beginning the real task. Participants were instructed to compare the letters or numbers on each side of the blank line, and then write an *S* in the blank if they were the same or a *D* if they were different. Participants were instructed that there were two pages of items to compare with a time limit of 30 s for each page, and that they were to make their responses as rapidly as possible. The experimenter signaled when to turn the page to begin the task, and simultaneously started a stopwatch to provide exactly 30 s on each page. The score was the number of items correct minus the number incorrect in order to account for guessing.

Letter Comparison (based on Salthouse & Babcock, 1991)

Consonants grouped into three, six, or nine were randomly distributed throughout each page of the task. Half of the 24 stimuli randomly distributed throughout each page were nonmatch problems, created by randomly changing the identity of one of the consonants in the problem.

Number Comparison (based on Salthouse & Babcock, 1991)

Digits grouped into three, six, or nine were randomly distributed throughout each page of the task. Half of the 24 stimuli randomly distributed throughout each page were nonmatch problems, created by randomly changing the identity of one of the digits in the display.

Gf Measures

Two different reasoning tasks were administered, one in the first session as part of our normal screening, and one in the second session after completing the eye-tracking experiment. The score for each task was the number of items correct.

RSPM subset (Unsworth, Heitz, et al., 2005; based on Raven, Raven, & Court, 1998)

Participants were given five minutes to complete a computerized subset of 12 trials from the RSPM. These 12 problems provide a mix of items from sets A-E of the RSPM and are formed by combining shapes and patterns across rows and columns. Participants were given general instructions about the nature of the task and then given two practice problems with the correct answer given. Participants were instructed to use the mouse to choose among the six or eight alternatives presented below each problem and click on the response that best completes the overall pattern. The program did not advance to the next problem until a response had been made. The computer program logged the accuracy for each problem. A re-analysis of data used in Unsworth, Heitz, et al. (2005) showed that the correlation between automated Operation Span and the computerized RSPM subset administered here was consistent with other complex span-Raven research ($r = .38$).

Shipley Abstract Reasoning (Hambrick & Engle, 2002; based on Zachary, 1986)

Participants were given a paper-and-pencil task and told that they would be presented with various letters, words, and numbers, and that they should use the relationships between the items given in each problem to infer what should go in the blank provided to best complete the overall series. The answer to each item was a letter, word, or number, and thus contrasted with the visuospatial content of the RSPM subset. They were presented with one practice problem with the correct answer choice, and then were given four minutes to work on the 20 problems on the following page.

APPENDIX B

COMPLETE ANALYSIS OF VARIANCE RESULTS FROM COMPUTERIZED COMPARISON TASKS

Accuracy: Letter Comparison without Distractors

Span (S)	*F*(1, 32) < 1		
Target Length (TL)	***F*(2, 64) = 7.41**	**partial $?^2$ = .19**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 8.42**	**partial $?^2$ = .21**	***p* < .01**
S × TL	*F*(2, 64) < 1		
S × TT	*F*(1, 32) < 1		
TL × TT	***F*(2, 64) = 7.21**	**partial $?^2$ = .18**	***p* < .01**
S × TL × TT	*F*(2, 64) < 1		

Accuracy: Letter Comparison with Distractors

Span (S)	*F*(1, 32) < 1		
Target Length (TL)	***F*(2, 64) = 18.69**	**partial $?^2$ = .37**	***p* < .01**
Distractor Type (DT)	***F*(1, 32) = 10.82**	**partial $?^2$ = .25**	***p* < .01**
Trial Type (TT)	*F*(1, 32) = 2.37	partial $?^2$ = .07	*p* = .13
S × TL	*F*(2, 64) = 2.83	partial $?^2$ = .08	*p* = .07
S × DT	*F*(1, 32) < 1		
S × TT	*F*(1, 32) < 1		
TL × DT	*F*(2, 64) = 1.82	partial $?^2$ = .05	*p* = .17
TL × TT	*F*(2, 64) < 1		

DT × TT	***F*(1, 32) = 19.00**	**partial ?^{2} = .37**	***p* < .01**
S × TL × DT	*F*(2, 64) < 1		
S × TL × TT	*F*(2, 64) = 1.73	partial ?^{2} = .05	*p* = .19
S × DT × TT	*F*(1, 32) = 1.32	partial ?^{2} = .04	*p* = .26
TL × DT × TT	***F*(2, 64) = 5.82**	**partial ?^{2} = .15**	***p* < .01**
S × TL × DT × TT	*F*(2, 64) < 1		

Accuracy: Number Comparison without Distractors

Span (S)	*F*(1, 32) < 1		
Target Length (TL)	*F*(2, 64) = 1.10	partial ?^{2} = .03	*p* = .34
Trial Type (TT)	*F*(1, 32) = 3.19	partial ?^{2} = .09	*p* = .08
S × TL	*F*(2, 64) < 1		
S × TT	*F*(1, 32) < 1		
TL × TT	*F*(2, 64) = 2.36	partial ?^{2} = .07	*p* = .10
S × TL × TT	*F*(2, 64) < 1		

Accuracy: Number Comparison with Distractors

Span (S)	*F*(1, 32) < 1		
Target Length (TL)	***F*(2, 64) = 3.75**	**partial ?^{2} = .11**	***p* < .05**
Distractor Type (DT)	***F*(1, 32) = 8.21**	**partial ?^{2} = .20**	***p* < .01**
Trial Type (TT)	*F*(1, 32) = 1.57	partial ?^{2} = .05	*p* = .22
S × TL	*F*(2, 64) = 1.63	partial ?^{2} = .05	*p* = .20
S × DT	*F*(1, 32) < 1		
S × TT	*F*(1, 32) = 3.48	partial ?^{2} = .10	*p* = .07
TL × DT	*F*(2, 64) = 2.06	partial ?^{2} = .06	*p* = .14

TL × TT	*F*(2, 64) = 1.75	partial $?^2$ = .05	*p* = .18
DT × TT	*F*(1, 32) < 1		
S × TL × DT	*F*(2, 64) < 1		
S × TL × TT	*F*(2, 64) = 1.33	partial $?^2$ = .04	*p* = .27
S × DT × TT	*F*(1, 32) < 1		
TL × DT × TT	*F*(2, 64) < 1		
S × TL × DT × TT	*F*(2, 64) < 1		

Correct RT: Letter Comparison without Distractors

Span (S)	***F*(1, 32) = 10.97**	**partial $?^2$ = .26**	***p* < .01**
Target Length (TL)	***F*(2, 64) = 187.96**	**partial $?^2$ = .86**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 19.87**	**partial $?^2$ = .38**	***p* < .01**
S × TL	***F*(2, 64) = 5.31**	**partial $?^2$ = .14**	***p* < .01**
S × TT	*F*(1, 32) = 1.47	partial $?^2$ = .04	*p* = .24
TL × TT	***F*(2, 64) = 25.09**	**partial $?^2$ = .44**	***p* < .01**
S × TL × TT	*F*(2, 64) < 1		

Correct RT: Letter Comparison with Distractors

Span (S)	***F*(1, 32) = 11.80**	**partial $?^2$ = .27**	***p* < .01**
Target Length (TL)	***F*(2, 64) = 223.11**	**partial $?^2$ = .88**	***p* < .01**
Distractor Type (DT)	***F*(1, 32) = 70.16**	**partial $?^2$ = .69**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 80.92**	**partial $?^2$ = .72**	***p* < .01**
S × TL	***F*(2, 64) = 5.58**	**partial $?^2$ = .15**	***p* < .01**
S × DT	***F*(1, 32) = 11.27**	**partial $?^2$ = .26**	***p* < .01**
S × TT	***F*(1, 32) = 5.48**	**partial $?^2$ = .15**	***p* < .01**

TL × DT	***F*(2, 64) = 7.37**	**partial ?^{2} = .19**	***p* < .01**
TL × TT	***F*(2, 64) = 44.87**	**partial ?^{2} = .58**	***p* < .01**
DT × TT	*F*(1, 32) = 1.20	partial ?^{2} = .04	*p* = .28
S × TL × DT	*F*(2, 64) < 1		
S × TL × TT	*F*(2, 64) = 2.43	partial ?^{2} = .07	*p* = .10
S × DT × TT	*F*(1, 32) = 1.93	partial ?^{2} = .06	*p* = .17
TL × DT × TT	*F*(2, 64) < 1		
S × TL × DT × TT	*F*(2, 64) < 1		

Correct RT: Number Comparison without Distractors

Span (S)	***F*(1, 32) = 5.05**	**partial ?^{2} = .14**	***p* < .05**
Target Length (TL)	***F*(2, 64) = 303.98**	**partial ?^{2} = .91**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 11.14**	**partial ?^{2} = .26**	***p* < .01**
S × TL	*F*(2, 64) < 1		
S × TT	*F*(1, 32) = 3.98	partial ?^{2} = .11	*p* = .06
TL × TT	*F*(2, 64) = 28.30	partial ?^{2} = .47	*p* < .01
S × TL × TT	*F*(2, 64) = 1.73	partial ?^{2} = .05	*p* =.19

Correct RT: Number Comparison with Distractors

Span (S)	***F*(1, 32) = 7.43**	**partial ?^{2} = .19**	***p* = .01**
Target Length (TL)	***F*(2, 64) = 268.28**	**partial ?^{2} = .89**	***p* < .01**
Distractor Type (DT)	***F*(1, 32) = 24.46**	**partial ?^{2} = .43**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 26.54**	**partial ?^{2} = .45**	***p* < .01**
S × TL	*F*(2, 64) = 1.16	partial ?^{2} = .04	*p* = .32
S × DT	***F*(1, 32) = 4.70**	**partial ?^{2} = .13**	***p* < .05**

S × TT	***F*(1, 32) = 4.44**	**partial ?^{2} = .12**	***p* < .05**
TL × DT	*F*(2, 64) = 2.79	partial ?^{2} = .08	*p* = .07
TL × TT	***F*(2, 64) = 36.68**	**partial ?^{2} = .53**	***p* < .01**
DT × TT	*F*(1, 32) < 1		
S × TL × DT	*F*(2, 64) = 1.84	partial ?^{2} = .05	*p* = .17
S × TL × TT	*F*(2, 64) = 3.03	partial ?^{2} = .09	*p* = .06
S × DT × TT	*F*(1, 32) < 1		
TL × DT × TT	*F*(2, 64) < 1		
S × TL × DT × TT	*F*(2, 64) < 1		

Overall Fixations: Letter Comparison without Distractors

Span (S)	***F*(1, 32) = 14.59**	**partial ?^{2} = .31**	***p* < .01**
Target Length (TL)	***F*(2, 64) = 389.69**	**partial ?^{2} = .92**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 47.83**	**partial ?^{2} = .60**	***p* < .01**
S × TL	***F*(2, 64) = 6.83**	**partial ?^{2} = .18**	***p* < .01**
S × TT	*F*(1, 32) = 1.68	partial ?^{2} = .05	*p* = .21
TL × TT	***F*(2, 64) = 30.10**	**partial ?^{2} = .49**	***p* < .01**
S × TL × TT	*F*(2, 64) = 1.07	partial ?^{2} = .03	*p* = .35

Overall Fixations: Letter Comparison with Distractors

Span (S)	***F*(1, 32) = 11.25**	**partial ?^{2} = .26**	***p* < .01**
Target Length (TL)	***F*(2, 64) = 379.76**	**partial ?^{2} = .92**	***p* < .01**
Distractor Type (DT)	***F*(1, 32) = 21.39**	**partial ?^{2} = .40**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 150.64**	**partial ?^{2} = .83**	***p* < .01**
S × TL	***F*(2, 64) = 7.33**	**partial ?^{2} = .19**	***p* < .01**

S × DT	***F*(1, 32) = 6.31**	**partial ?^{2} = .17**	***p* < .05**
S × TT	*F*(1, 32) < 1		
TL × DT	*F*(2, 64) < 1		
TL × TT	***F*(2, 64) = 52.21**	**partial ?^{2} = .62**	***p* < .01**
DT × TT	*F*(1, 32) < 1		
S × TL × DT	*F*(2, 64) < 1		
S × TL × TT	*F*(2, 64) < 1		
S × DT × TT	*F*(1, 32) < 1		
TL × DT × TT	*F*(2, 64) = 1.91	partial ?^{2} = .06	*p* = .16
S × TL × DT × TT	*F*(2, 64) < 1		

Overall Fixations: Number Comparison without Distractors

Span (S)	***F*(1, 32) = 4.87**	**partial ?^{2} = .13**	***p* < .05**
Target Length (TL)	***F*(2, 64) = 390.12**	**partial ?^{2} = .92**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 20.75**	**partial ?^{2} = .39**	***p* < .01**
S × TL	*F*(2, 64) < 1		
S × TT	*F*(1, 32) = 1.07	partial ?^{2} = .03	*p* = .31
TL × TT	***F*(2, 64) = 27.66**	**partial ?^{2} = .46**	***p* < .01**
S × TL × TT	*F*(2, 64) < 1		

Overall Fixations: Number Comparison with Distractors

Span (S)	***F*(1, 32) = 5.86**	**partial ?^{2} = .16**	***p* < .05**
Target Length (TL)	***F*(2, 64) = 295.56**	**partial ?^{2} = .90**	***p* < .01**
Distractor Type (DT)	***F*(1, 32) = 17.82**	**partial ?^{2} = .36**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 113.35**	**partial ?^{2} = .78**	***p* < .01**

S × TL	*F*(2, 64) = 1.32	partial ?^{2} = .04	*p* = .28
S × DT	*F*(1, 32) = 2.22	partial ?^{2} = .07	*p* = .15
S × TT	*F*(1, 32) < 1		
TL × DT	***F*(2, 64) = 4.75**	**partial ?^{2} = .13**	***p* < .05**
TL × TT	***F*(2, 64) = 43.69**	**partial ?^{2} = .58**	***p* < .01**
DT × TT	*F*(1, 32) < 1		
S × TL × DT	*F*(2, 64) < 1		
S × TL × TT	*F*(2, 64) < 1		
S × DT × TT	*F*(1, 32) < 1		
TL × DT × TT	*F*(2, 64) < 1		
S × TL × DT × TT	*F*(2, 64) < 1		

Switches: Letter Comparison without Distractors

Span (S)	***F*(1, 32) = 6.48**	**partial ?^{2} = .17**	***p* < .05**
Target Length (TL)	***F*(2, 64) = 157.80**	**partial ?^{2} = .83**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 31.07**	**partial ?^{2} = .49**	***p* < .01**
S × TL	***F*(2, 64) = 3.06**	**partial ?^{2} = .09**	***p* = .05**
S × TT	*F*(1, 32) = 2.31	partial ?^{2} = .07	*p* = .07
TL × TT	***F*(2, 64) = 23.61**	**partial ?^{2} = .43**	***p* < .01**
S × TL × TT	*F*(2, 64) < 1		

Switches: Letter Comparison with Distractors

Span (S)	***F*(1, 32) = 4.93**	**partial ?^{2} = .13**	***p* < .05**
Target Length (TL)	***F*(2, 64) = 139.18**	**partial ?^{2} = .81**	***p* < .01**
Distractor Type (DT)	*F*(1, 32) = 2.34	partial ?^{2} = .14	*p* = .07

Trial Type (TT)	***F*(1, 32) = 136.46**	**partial ?^{2} = .81**	***p* < .01**
S × TL	***F*(2, 64) = 3.14**	**partial ?^{2} = .09**	***p* = .05**
S × DT	***F*(1, 32) = 10.80**	**partial ?^{2} = .25**	***p* < .01**
S × TT	*F*(1, 32) < 1		
TL × DT	*F*(2, 64) < 1		
TL × TT	***F*(2, 64) = 28.33**	**partial ?^{2} = .47**	***p* < .01**
DT × TT	*F*(1, 32) = 2.88	partial ?^{2} = .08	*p* = .10
S × TL × DT	*F*(2, 64) < 1		
S × TL × TT	*F*(2, 64) < 1		
S × DT × TT	*F*(1, 32) = 2.06	partial ?^{2} = .06	*p* = .16
TL × DT × TT	*F*(2, 64) = 1.36	partial ?^{2} = .04	*p* = .26
S × TL × DT × TT	*F*(2, 64) < 1		

Switches: Number Comparison without Distractors

Span (S)	***F*(1, 32) = 4.90**	**partial ?^{2} = .13**	***p* < .05**
Target Length (TL)	***F*(2, 64) = 135.70**	**partial ?^{2} = .81**	***p* < .01**
Trial Type (TT)	***F*(1, 32) = 17.72**	**partial ?^{2} = .36**	***p* < .01**
S × TL	*F*(2, 64) = 1.53	partial ?^{2} = .05	*p* = .23
S × TT	*F*(1, 32) = 3.43	partial ?^{2} = .10	*p* = .07
TL × TT	***F*(2, 64) = 30.11**	**partial ?^{2} = .49**	***p* < .01**
S × TL × TT	*F*(2, 64) < 1		

Switches: Number Comparison with Distractors

Span (S)	***F*(1, 32) = 6.07**	**partial ?^{2} = .16**	***p* < .05**
Target Length (TL)	***F*(2, 64) = 122.19**	**partial ?^{2} = .79**	***p* < .01**

Distractor Type (DT)	**$F(1, 32) = 6.80$**	**partial ?^{2} = .18**	**$p < .05$**
Trial Type (TT)	**$F(1, 32) = 89.61$**	**partial ?^{2} = .74**	**$p < .01$**
S × TL	**$F(2, 64) = 3.71$**	**partial ?^{2} = .10**	**$p < .05$**
S × DT	$F(1, 32) = 2.62$	partial ?^{2} = .08	$p = .12$
S × TT	$F(1, 32) = 1.44$	partial ?^{2} = .04	$p = .24$
TL × DT	$F(2, 64) < 1$		
TL × TT	**$F(2, 64) = 46.45$**	**partial ?^{2} = .59**	**$p < .01$**
DT × TT	$F(1, 32) < 1$		
S × TL × DT	$F(2, 64) < 1$		
S × TL × TT	$F(2, 64) = 1.06$	partial ?^{2} = .03	$p = .35$
S × DT × TT	$F(1, 32) < 1$		
TL × DT × TT	$F(2, 64) = 1.12$	partial ?^{2} = .03	$p = .33$
S × TL × DT × TT	$F(2, 64) < 1$		

Central Fixations: Letter Comparison without Distractors

Span (S)	$F(1, 32) = 2.15$	partial ?^{2} = .06	$p = .15$
Target Length (TL)	**$F(2, 64) = 22.79$**	**partial ?^{2} = .42**	**$p < .01$**
Trial Type (TT)	$F(1, 32) = 2.25$	partial ?^{2} = .07	$p = .14$
S × TL	$F(2, 64) < 1$		
S × TT	$F(1, 32) < 1$		
TL × TT	$F(2, 64) = 1.69$	partial ?^{2} = .05	$p = .19$
S × TL × TT	$F(2, 64) < 1$		

Central Fixations: Letter Comparison with Distractors

Span (S)	**$F(1, 32) = 7.00$**	**partial ?^{2} = .18**	**$p < .05$**

Target Length (TL)	***F*(2, 64) = 5.61**	**partial ?^{2} = .15**	***p* < .01**
Distractor Type (DT)	***F*(1, 32) = 7.13**	**partial ?^{2} = .18**	***p* < .05**
Trial Type (TT)	*F*(1, 32) = 3.42	partial ?^{2} = .10	*p* = .07
S × TL	*F*(2, 64) < 1		
S × DT	***F*(1, 32) = 4.45**	**partial ?^{2} = .12**	***p* < .05**
S × TT	*F*(1, 32) < 1		
TL × DT	*F*(2, 64) = 1.25	partial ?^{2} = .04	*p* = .29
TL × TT	*F*(2, 64) = 1.31	partial ?^{2} = .04	*p* = .28
DT × TT	*F*(1, 32) < 1		
S × TL × DT	*F*(2, 64) = 1.02	partial ?^{2} = .03	*p* = .37
S × TL × TT	*F*(2, 64) < 1		
S × DT × TT	*F*(1, 32) < 1		
TL × DT × TT	*F*(2, 64) < 1		
S × TL × DT × TT	*F*(2, 64) < 1		

Central Fixations: Number Comparison without Distractors

Span (S)	*F*(1, 32) = 2.32	partial ?^{2} = .07	*p* = .14
Target Length (TL)	***F*(2, 64) = 8.72**	**partial ?^{2} = .21**	***p* < .01**
Trial Type (TT)	*F*(1, 32) = 1.10	partial ?^{2} = .03	*p* = .30
S × TL	*F*(2, 64) < 1		
S × TT	*F*(1, 32) < 1		
TL × TT	*F*(2, 64) < 1		
S × TL × TT	*F*(2, 64) < 1		

Central Fixations: Number Comparison with Distractors

Span (S)	***F*(1, 32) = 7.51**	**partial ?^{2} = .19**	***p* = .01**
Target Length (TL)	***F*(2, 64) = 4.85**	**partial ?^{2} = .13**	***p* < .05**
Distractor Type (DT)	***F*(1, 32) = 11.56**	**partial ?^{2} = .27**	***p* < .01**
Trial Type (TT)	*F*(1, 32) < 1		
S × TL	*F*(2, 64) < 1		
S × DT	*F*(1, 32) < 1		
S × TT	*F*(1, 32) = 1.21	partial ?^{2} = .04	*p* = .28
TL × DT	*F*(2, 64) < 1		
TL × TT	*F*(2, 64) < 1		
DT × TT	*F*(1, 32) = 3.98	partial ?^{2} = .11	*p* = .06
S × TL × DT	*F*(2, 64) = 1.54	partial ?^{2} = .05	*p* = .22
S × TL × TT	*F*(2, 64) < 1		
S × DT × TT	*F*(1, 32) < 1		
TL × DT × TT	*F*(2, 64) < 1		
S × TL × DT × TT	*F*(2, 64) < 1		

Note. Significant effects are given in **bold**.

APPENDIX C

ERROR ANALYSES OF PAPER-AND-PENCIL COMPARISON MEASURES

A detailed examination of the errors committed in the paper-and-pencil PS measures was conducted using a 3 x 2 x 2 (Target Length x Trial Type x Span) mixed ANOVA separately for Letter and Number Comparison. Looking first at Letter Comparison revealed significant main effects of Target Length, $F(2, 64) = 5.75$, partial $?^2 = .15$, and Trial Type, $F(1, 32) = 16.09$, partial $?^2 = .34$, but no significant effect of Span, $F(1, 32) < 1$. These effects were qualified by a significant Target Length x Trial Type interaction, $F(2, 64) = 4.93$, partial $?^2 = .13$. On match trials, target length had no effect on the small number of errors committed, $F(2, 66) < 1$, while on nonmatch trials, the number of errors increased as target length also increased, $F(2, 66) = 6.57$, partial $?^2 = .17$. None of the interactions involving Span approached significance (all *F*'s < 1).

Comparable results were obtained from Number Comparison. Significant main effects of Target Length, $F(2, 64) = 4.03$, partial $?^2 = .11$, and Trial Type, $F(1, 32) = 5.56$, partial $?^2 = .15$, were found, but no effect of Span, $F(1, 32) < 1$, was obtained. The significant main effects were qualified by a Target Length x Trial Type interaction, $F(2, 64) = 3.21$, partial $?^2 = .09$. On both match and nonmatch trials, the number of errors increased as target length increased, $F(2, 66) = 3.49$, partial $?^2 = .10$, and $F(2, 66) = 4.07$, partial $?^2 = .11$, respectively. None of the interactions involving Span approached significance (all *F*'s < 1).

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