THE RELATIONSHIP BETWEEN WORKING MEMORY AND INTELLIGENCE: DECONSTRUCTING THE WORKING MEMORY TASK

By

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To my significant other, Jie Zou

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LIST OF ABBREVIATIONS

GF	General fluid intelligence
PI	Proactive interference
RAPM	Raven's Advanced Progressive Matrices
STM	Short term memory
TBR	To be remembered
WM	Working memory

Abstract of Dissertation Presented to the Graduate School
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Working memory (WM) span tasks comprise short-term memory (STM) storage plus some sort of processing requirements (Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005; Engle, Kane, & Tuholski, 1999). The relationships among STM, WM, and fluid intelligence are well documented (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Christal, 1990). The correlations between WM and intelligence could be either attributed to storage, processing, or both constructs. Researchers disagree about which part is the primary contributor. We posit that disagreements in the research are driven by the variation in the WM span tasks, STM tasks, and processing tasks. The first part of the present study addresses the relative contribution of these storage and processing components in the relationship between WM and intelligence. We deconstructed the WM span task in our study to tap those constructs.

The second part of the present study explores the effect of proactive interference (PI) in the relationship between WM and intelligence. WM theories suggest individual differences in WM reflect the capability to use controlled attention to prevent PI from the environment and long-term memory (Bunting & Cowan, 2005). Low WM individuals are

more susceptible to PI (Kane & Engle, 2000). Thus, some theorists extend the controlled attention view and suggest that interference is an important component in understanding the relationship among STM, WM, and intelligence (e.g., Bunting, 2006). Furthermore, previous studies provide several practical strategies to help people overcome PI (e.g., Bunting, 2006). The present study aims to extend previous PI research so that people with low memory ability could benefit from those strategies in daily cognitive activities. Therefore, the second part of the study is a practical application for PI and WM. It could also provide theoretical insights into the WM-intelligence relationship network.

CHAPTER 1
THEROETICAL BACKGROUND

Theoretical Overview of Working Memory and Intelligence

Working memory span tasks were originally designed from the perspective of Baddeley and Hitch's (1974) theory of WM. Baddeley and Hitch address the functional importance of STM that could briefly store a limited amount of information to serve ongoing mental activity. Traditionally, STM tasks (which consist of simple span tasks) ask participants to remember and recall a list of letters or nonsense words in order to estimate the maximum amount of information a participant could store in STM (Conway et al., 2005). Baddeley and Hitch revised this task so that the new task involves simultaneous execution of two tasks. Specifically, one task requires information storage and rehearsal (as do simple span tasks, like digit span or word span), but the other involves some decision-making or recoding processes to simultaneously process additional information (for example, undertaking a digit span task while performing a reasoning test). Such WM span tasks present alternately a list of items asked to remember, such as some digits or words, and a higher-order cognitive processing task, for example, reading comprehension, mathematical calculations, or pointing out an array of shapes (Baddeley, 1998). Baddeley and Hitch (1974) concluded that a WM system with a central executive and two sub systems, visuo-spatial sketchpad and phonological loop, provides a more complete explanation of the nature of human memory and attention than the STM construct does.

After Baddeley and Hitch (1974) proposed their view of WM, numerous researchers suggested that WM capacity would be better evaluated by so called "complex" memory span tasks involving dual processing and storage tasks (Oberauer, 2005). In such tasks, participants are presented with information and they are required to process that information. Finally, they need to recall some or all of that information (Conway et al., 2005). For example, in the most commonly used reading span task (Daneman & Carpenter, 1980), participants read aloud or listen to a number of sentences and then they are asked to recall the final words of all the sentences in order.

Subsequent research provide evidence that WM and Spearman's general fluid intelligence (Gf) are related constructs (Ackerman, Beier, & Boyle, 2005; Colom, Abad, Rebollo, & Shih, 2005; Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004; Colom & Shih, 2004; Conway et al., 2002; Engle, Tuholski, et al., 1999; Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004; Kyllonen & Christal, 1990; Unsworth, Redick, Heitz, Broadway, & Engle, 2009). However, the conclusion that WM is the basis of Gf has not yet been universally accepted (Kyllonen, 1996). The most notable challenge is that processing speed accounts for the relationship between WM capacity and Gf (Fry & Hale, 1996; Jensen, 1998; Kail & Salthouse, 1994; Salthouse, 1996; Unsworth et al., 2009); some other theorists claim that STM could account for the relationship between WM and Gf and they suggest WM is very similar to STM and could be measured by STM simple span tasks (e.g., Colom et al., 2004). In contrast, other studies that try to clarify the distinction between WM and STM capacity (Conway et al., 2002; Cowan, 1995; Engle, Tuholski, et al., 1999) have supported the notion that WM, but not STM or processing speed, is strongly linked to Gf. In those later views, executive abilities and controlled attention are the primary causes for the relationship between WM complex span tasks and Gf (as well as higher-order cognition). Other theorists extend the controlled attention view and suggest inhibition control of proactive interference (PI) is an important component in the relationship between WM and Gf (Bunting, 2006). Research varies substantially in the tasks used to measure WM and intelligence. Thus, the components underlying their strong relationship remain unknown, despite the research efforts made to date.

It is clear from previous research that significant correlations exist among the measures of STM, WM, processing speed, and Gf. However, investigations of these constructs typically involve tasks for which the cognitive components are not clearly established. For example, some processing speed tasks like reading comprehension (e.g., Unsworth et al., 2009) are complicated and some are just simple perceptual processing tasks such as pattern and letter comparison tasks (e.g., Conway et al., 2002; Fry & Hale, 1996); some studies explored the relationship between WM and Gf by tasks that are lack of reliability and validity; or they sometimes used simple span tasks (i.e., that actually measure STM capacity) to measure WM, and thus underestimated the relationship between WM and intelligence (e.g., Oberauer, Süß, Wilhelm, & Wittmann, 2003). In the present study, with targeted tasks for clearly established cognitive components, we explore the relationships among WM capacity, STM capacity, processing speed (also processing accuracy), and Gf. Independent measures of processing capacity and short-term storage capacity are assessed. Thereby we examine the extent to which these components contribute unique and shared variance to Gf task performance, in order to determine their relative importance in predicting Gf. We attempt to better understand why complex span tasks correlate so well with intelligence. Relatively few studies have examined processing capacity, STM storage, WM complex span tasks performance, and Gf relationships obtained from independent tasks in the same sample (Engle, Cantor, & Carullo, 1992; Towse, Hitch, & Hutton, 2000; Turner & Engle, 1989; Waters & Caplan, 1996). This approach is also useful in that it has the potential to clarify the distinction between STM and WM constructs (Engle, Tuholski, et al., 1999).

It is important to note that Spearman's Gf may not be determined by one process or capacity, but rather by a combination of factors (Conway et al., 2002). The study is not to suggest WM capacity is Gf but rather to suggest that WM capacity might be a primary determinant of Gf. Further, it is also worth noting that we assume the causal pathway to come from WM to Gf rather than the reverse. According to Kane et al. (2004), there are several reasons to align the causal arrow this way: (1) the WM construct and the tasks derive from a rich theoretical and empirical grounding in basic cognitive, developmental, and neuroscience research. In contrast, intelligence is conceptually opaque, reflecting a mixture of various theories of intelligence. Thus the WM construct is much more tractable than Gf; (2) individual differences in WM predict differences in the performance of very basic attention tasks such as dichotic listening and Stroop tasks, in which higher-order cognitive processes such as Gf are unlikely to be involved (Conway & Kane, 2001; Engle & Kane, 2004); (3) WM is a domain-general factor. Though the tasks that measure WM also tap some domain-specific content (e.g., reading span task taps reading ability as well as WM capacity; operation span task also taps math ability), the WM latent factor derived from the variance shared by different WM tasks is domain general. However, performance on the Gf tasks may benefit from some acquired domain knowledge or task-specific experience. In sum, WM is the one parameter that correlates best with the measures of Gf. Therefore, investigating WM, and its relationship with intelligence, provides an appropriate approach towards understanding intelligence (Kane et al., 2004). In the next few sections, we discuss how different constructs (STM storage, processing, and interference) contribute to individual differences in Gf.

The Role of Storage in Working Memory and Intelligence

There are debates in the literature on the storage components in the relationship between WM and intelligence. Some theorists suggest that the storage components in WM are similar to STM, therefore WM could just be measured by STM simple span tasks, and they argue it is STM that accounts for the relationship between WM and intelligence (e.g., Colom et al., 2004). Other theorists suggest that WM should be measured by the dual processing and storage complex span tasks (e.g., Conway et al., 2005). They suggest that WM involves controlled attention but STM does not, and it is controlled attention that accounts for the relationship between WM and intelligence. Therefore, it is important to clarify the distinction between STM and WM constructs to be able to understand how each component contributes to individual differences in Gf.

Research generally views STM as simple short-term representation storage; the capacity is largely determined by the practiced skills and strategies, for example, rehearsal and chunking (Cowan, 1995; Engle, Tuholski, et al., 1999). In contrast, WM is a more complex construct because it consists of a short-term storage component as well as an attention component. Historically, simple span tasks are used to measure STM. For example, the missing digit task (Talland, 1965), which requires participant to indicate which item is missing when they hear the list for a second time, only reflects short-term storage. These simple span tasks usually lack reliability and construct validity (Dempster & Corkill, 1999). In contrast, complex span tasks are moderately or highly reliable and consistently valid (Engle & Kane, 2004) in predicting a variety of higher-level and real-world cognitive tasks.

Some theorists argue STM largely accounts for the relationship between WM and Gf. For example, Colom, Abad, Quiroga, Shih, and Flores-Mendoza (2008) suggested that a STM task could account for the relationship between WM and Gf; and controlled attention is not uniquely associated with Gf once the STM storage component is controlled. STM is related to Gf because individual differences in STM reflect the differences in acquisition or encoding strategies (Belmont & Butterfield, 1969; Cohen & Sandberg, 1977).

On the other hand, most studies suggest that WM is not just simple STM. The function of WM is to maintain STM representations in the face of concurrent processing, attention shifts, and distraction from the environment or long-term memory (Baddeley & Hitch, 1974; Conway et al., 2002; Engle, Tuholski, et al., 1999). Therefore, the extent to which a task demands WM is determined by how much it requires the focus of attention that could be vulnerable to interference. WM is a general capacity that determines cognitive processing in any domain that demands controlled attention (Conway et al., 2002; Cowan, 1995; Engle, Tuholski, et al., 1999; Lovett, Reder, & Lebiere, 1999).

Engle, Tuholski, et al. (1999) found individual differences in the performance on STM tasks are primarily due to chunking and rehearsal. They found that a latent variable derived from WM complex span tasks was correlated with Gf but the latent variable derived from STM simple span tasks was not correlated with Gf. Furthermore, when the common variance of WM latent variable and STM latent variable was removed from the WM-Gf relationship, WM still served as a significant predictor of Gf. Other studies found similar results. Kane et al. (2004) performed structural equation modeling analyses on various span tests including STM tasks, WM tasks, and Gf tests. They found that WM construct highly related to intelligence, but STM construct failed to do so.

Engle, Tuholski, et al. (1999) suggested that the link between WM and Gf is the demand of controlled attention. According to Engle, Tuholski, et al., the central executive component of WM maintains active attention to goal-relevant information and inhibits activation to goal-irrelevant information. If a task can be performed based on the automatized skills, such as rehearsal and chunking, then the WM central executive component will not be tapped, therefore individual performance on such tasks will not relate to Gf. Thus the reason complex span tasks are related to the measures of Gf is that they prevent the participant from replying on the automatized skills to perform the task. Conway and Engle (1996) suggested that the processing task plays an important role in order to make WM complex span task to demand controlled attention. Lépine, Barrouillet, and Camos (2005) suggested that the existence of processing (i.e., the extent to which processing prevents dual-task strategies and rehearsal of the to-be-remembered items) is the critical factor that makes WM span an indicator for higher-order cognition. In contrast, STM tasks can be performed using some automatic strategies. Thus, performance on those tasks will not be able to predict performance on the measures of Gf (Conway et al., 2002). Measures of Gf, such as Raven's Advanced Progressive Matrices (RAPM), also reply on the ability to maintain active attention to relevant information in the face of concurrent processing and distraction. In a detailed task analysis of RAPM, Carpenter, Just, and Shell (1990) concluded that an important aspect of RAPM was the discovery and maintenance of rules that govern the problem.

More difficult problems typically involve more rules. Thus, in order to solve difficult matrix problems, people must discover and evaluate a relevant rule and then remember that rule while searching for a second rule and so on. Therefore, the ability to maintain relevant rules in the face of concurrently searching for new features and distraction of goal-irrelevant rules is essential for successful performance on RAPM (Conway et al., 2002).

Some theorists argue that STM tasks and WM tasks reflect a common factor and have high correlations and therefore they might measure a same thing. For example, Cohen and Sandberg (1977) found that the probed recall task (i.e., a STM task) could predict WM capacity and general intelligence. Cantor, Engle, & Hamilton (1991) found that a STM word span task correlated .37 with a WM reading span task. Oberauer et al. (2000, 2003) found that simple span tasks measured the same construct (WM) as did complex span tasks. Schmiedek, Hildebrandt, Lövdén, Wilhelm, and Lindenberger (2009) found that a confirmatory factor analysis revealed a STM latent factor correlated .96 with the WM latent factor. They also found these two factors predicted Gf equally well. Thus they suggested the simple span tasks measure the WM construct as well as complex span tasks. Their finding was unique since the correlations between individual simple span tasks and individual complex span tasks were much lower (r = .14 - .51) than the correlations between latent factors.

However, Engle, Tuholski, et al. (1999) suggested that STM and WM are different constructs since STM capacity is primarily determined by the capacity of the phonological loop, but WM capacity is determined by the phonological loop capacity and the central executive functioning efficiency together. From this perspective, the commonality between STM and WM span tasks can be attributed to the phonological loop capacity (i.e., temporary short-term storage requirement), whereas the main difference can be attributed to the involvement of central executive functioning (i.e., controlled attention) in WM tasks (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). Therefore, WM span tasks are consistent with the proposal that WM = STM + controlled attention (Miyake et al., 2001). In addition, some researchers have also found that WM capacity can predict the performance on the attention tasks that require controlled processing in the face of interference (e.g., antisaccade task) but do not require heavy STM storage demands (Kane, Bleckley, Conway, & Engle, 2001; Tuholski, Engle, & Baylis, 2001). Such findings suggest that controlled attention makes the predictive power of WM span tasks greater than that of STM span tasks (Miyake et al., 2001).

Other empirical evidence also seems to provide support for the distinction between STM simple span and WM complex span tasks. For example, Cantor et al. (1991) identified two factors in the latent variable analyses: STM and WM. Engle, Tuholski, et al. (1999) found most complex span tasks loaded on the WM factor in the latent variable analyses, while most simple span tasks loaded on the STM factor. Waters and Caplan (2003) performed a factor analysis on a variety of tasks that are considered as measures of verbal and spatial STM and WM. The results were consistent with Engle, Tuholski, et al.'s results. Engle, Tuholski, et al. (1999) reported a correlation of .68 between the latent variables of WM and STM, and Conway et al. (2002) reported a correlation of .82 between these two latent variables. Conway et al. also found WM span tasks predicted Gf and higher-order cognition better than did STM span tasks.

After controlling WM, STM accounted for no unique variance in Gf. Thus, only the WM factor shares unique variance with intelligence abilities.

Because previous studies seem to provide unclear and contradicting evidence on the validation of STM simple span tasks, we are still not sure whether STM could account for the relationship between WM and intelligence. In the present study, we used a STM task that is equivalent to the storage component of the WM task, but without the processing part (as in the reading span task). The advantage of this task is that it is considered as a relatively pure indicator of short-term maintenance of information. In the previous research, people employed different STM tasks that varied in difficulty and cognitive demand. For example, some used simple probe recall tasks that require participants to recall a list of items (e.g., Cantor et al., 1991); some used backward digit span or running-memory span tasks that require a mental transformation beyond the basic short-term maintenance of the items (e.g., Broadway & Engle, 2010); and some other studies used STM simple span tasks to measure WM (e.g., Oberauer et al., 2003). To make a clear distinction, Engle, Tuholski, et al. (1999) suggested that STM tasks can be performed with the relative removal of attention from the representation of recall items, whereas WM tasks are characterized as dual tasks in that attention must be shifted between the representation of recall items and the processing component of the task. Therefore, in the present study, STM was measured by a word span task that only requires the temporary maintenance of verbal items for later recall, whereas WM was measured by a reading span task that requires sentences processing and the short-term storage of verbal items simultaneously. Our STM task can be better compared with our WM task since the two tasks involve the same STM storage processes (i.e., they are in the same domain area and have very similar content); the distinction is that the WM task adds a processing demand and thus requires controlled attention. By comparing the relationships among STM, WM, and Gf, we could investigate whether involving controlled attention in WM could increase the predictive utility of STM task alone. One of the main goals of the present study is to clarify the role of STM in the relationship between Gf and WM.

The Role of Processing in Working Memory and Intelligence

In order to clarify the debate regarding the role of processing speed in the relationship between WM and Gf, we first need to establish what “processing speed” means. Some researchers argue that processing speed accounts for the relationship between WM capacity and Gf (e.g., Unsworth et al., 2009). According to this argument, processing speed is a general mental speed capacity because processing (encoding, transforming, storing, retrieving) information within WM tasks takes time (Conway et al., 2002). The faster the processing speed, the more information can be processed in one unit of time (Unsworth et al., 2009). Thus, higher WM capacity may result from greater processing speed (Jensen, 1998; Kail & Salthouse, 1994; Salthouse, 1996). Coyle, Pillow, Snyder, and Kochunov (2011) found processing speed highly correlated with Gf. Ackerman et al. (2005) found that WM correlated significantly with a general intelligence factor (r = .70) and WM also correlated highly with processing speed in the processing task (r = .55). They explained that processing speed mediates the relationship between WM and intelligence. Salthouse and Meinz (1995) found that processing speed mediated the relationship between interference susceptibility and WM capacity. They suggested that speed of processing is usually considered an important factor in cognitive abilities. It is reasonable to argue that WM span tasks could predict higher-order cognitive performance because those span tasks are sensitive to individual differences in processing speed. High spans could perform more quickly and efficiently on the processing component of the reading span tasks, thus they could pay more attention to rehearsing the to-be-remembered (TBR) items to resist interference (Salthouse & Meinz, 1995). Similar results were also found in Carpenter and Just's (1989) study. They argued that it is the more skilled processing, not the greater storage capacity, that helps high-span participants recall more words. Moreover, Daneman and Tardif (1987) found that processing speed fully mediated the WM relationship with higher-order cognition like Gf. They explained that processing and WM storage require the same cognitive process. Unsworth et al. (2009) found processing (which was measured by the processing component of the WM tasks) partially mediated the relationship between WM and intelligence. Reaction time measured on the processing task could account for additional variance in predicting Gf (Unsworth et al., 2009).

In addition to processing speed, some researchers also suggest that processing accuracy is an important component in predicting the relationship between WM and intelligence (Unsworth et al., 2009; Waters & Caplan, 1996)). However, WM studies usually do not consider the processing task performance (e.g., Daneman & Carpenter, 1980). In the reading span task, for example, experimenters usually only score on how many letters that are correctly remembered in the correct order, not whether the sentence decision is correct or not. It is because researchers suggest that the processing task accuracy is often close to ceiling (Conway et al., 2005). Processing accuracy is generally not included in the analyses of the processing speed tasks because of the ceiling effect and lack of normality (Conway et al., 2002). Sometimes, it is necessary to use the processing task performance as an exclusion criterion. For example, researchers usually discard the entire data set for a participant if the accuracy on the processing component is below a criterion (typically, 85% as suggested by Conway et al., 2005; or 80% as used by Turner and Engle, 1989).

Unsworth et al. (2009) argued that these exclusion methods are unnecessary, since correlational research has found that participants who recall more letters or words also perform more accurately on the processing task (Daneman & Tardif, 1987; Kane et al., 2004; Salthouse, Pink, & Tucker-Drob, 2008; Waters & Caplan, 1996). Kane and his colleagues found the correlations between processing accuracy and storage were from .19 to .33. Specifically, it was lower (.19) for reading span, while for counting span and operation span they were higher (.33 and .30, respectively). Unsworth et al. (2009) found that processing accuracy was positively related to WM storage (*r* ranges from .42 to .47). They further suggested processing accuracy and processing speed should be added to the overall span estimates in order to increase the predictive power above the power deduced only from the performance on the storage component (Unsworth et al., 2009). Waters and Caplan (1996) made similar conclusions. They found that processing accuracy and processing speed partially mediated the WM relationship with Gf. Thus they suggested that processing and WM storage measure similar processes. Though they found that the sentence reading time did not correlate with sentence reading accuracy (similar results were also found in the operation span tasks, see Towse et al., 2000), they found that inspection of both processing accuracy and time could provide additional information and increase reliability when analyzing the results of complex span performance (Waters & Caplan, 1996).

However, other researchers do not find a relationship between processing accuracy and WM storage performance (e.g., Engle et al., 1992; Lépine et al., 2005; Shah & Miyake, 1996; Towse et al., 2000; Turner & Engle, 1989). They argued that the correlations between WM span estimates and processing accuracy, even if they are positively correlated, are relatively low. Furthermore, some studies found that processing (including processing speed and processing accuracy) does not affect the WM relationship with Gf and suggested that processing and WM storage tasks evaluate entirely distinct cognitive abilities (Engle et al., 1992). Conway et al. (2002) suggested that WM, but not STM or processing speed, serves as the best predictor of Gf.

Conway and Engle (1996) explained that different results on the role of processing were due to the various difficulties in the processing tasks. In the research of WM and intelligence, there are two different kinds of processing speed tasks. One kind of processing speed tasks places minimal demands on WM and the other kind places heavy demands on WM. The first kind, usually called perceptual speed, for example, contains disjunctive choice reaction time task, shape classification task, or choice reaction time. For example, participants are asked to provide a same/different judgment on two vertical arrows pointing in either the same or different directions (Conway et al., 2002). This kind of tasks places minimal demands on WM. Attention does not need to be maintained in the face of interference from concurrent processing. In fact, in a cross-sectional aging study reported by Salthouse and Meinz (1995), a processing speed score formed from simple perceptual tasks accounted for only 5% of the variance in WM tasks. Conway et al. (2002) found the measures of processing speed that place minimal demands on the maintenance of attention did not significantly predict Gf. The speed tasks they employed were digit-symbol substitution, digit and letter copying, pattern and letter comparison tasks. All of them place minimal demands on WM and attention; therefore, the demand for the maintenance of memory representation in the face of processing interference is minimal. In contrast, the other kind, usually called the speed of information processing, is the mental speed at which an individual performs basic cognitive tasks such as item identification, visual pattern searching, or simple sentence understanding. Those tasks place demands on controlled attention and WM. In the visual search task, for example, the participants are required to search for a target blue square stimulus among the distractors consisting of yellow squares and black circles (Conway et al., 2002). Since the task requires conjunctive search, it demands controlled attention (Treisman & Gelade, 1980) and WM (Tuholski et al., 2001). In Babcock's (1994) study, he categorized processing speed tasks as having either low cognitive demand or high cognitive demand; he found that the pattern of correlations between processing speed, WM, and RAPM differed depending on the complexity of the processing speed tasks (a correlation of .3 between low demand processing speed tasks and RAPM, compared to .6 between high demand tasks and RAPM).

One finding that clearly emerges from the previous studies is that the more complicated the processing speed task, the stronger the relationship between processing speed and WM, processing speed and intelligence (Jensen, 1998). The perceptual speed tests with very short response time, which are the basic conceptualizations of processing speed, do not have high correlations with WM (Ackerman et al., 2005) and also have minimal correlations with Gf. We explain the previous different findings that the more the task places demands on WM, the stronger the correlation between processing speed and Gf. Thus, it is not processing speed that predicts Gf; it is the memory and attention components of the tasks that predict Gf (Conway, Kane, & Engle, 2003; Cowan, 1995). More systematic research is needed to test this hypothesis.

In sum, researchers have not reached agreement on a core set of processing speed tasks. Some researchers used very simple processing tasks (e.g., Conway et al., 2002; Fry & Hale, 1996), some used more complicated processing tasks (e.g., Babcock, 1994), and some researchers obtained the processing capacity estimates during the WM task (e.g., Towse & Hitch, 1995; Unsworth et al., 2009) instead of measuring the processing performance independently of the complex span task. We posit that disagreements in the research of WM and Gf are driven by the variation in the nature of the processing speed tasks (Carpenter, Just, & Shell, 1990; Conway et al., 2002; Engle, Tuholski, et al., 1999; Fry & Hale, 1996; Jensen, 1998; Kail & Salthouse, 1994; Kyllonen, 1996; Kyllonen & Christal, 1990; Salthouse, 1996; Unsworth et al., 2009). These are the gaps in the literature.

Therefore, in the present study, we incorporated targeted processing speed tasks (i.e., that control for the type of processing) to explore the relationships between WM, STM, processing speed (also processing accuracy), and Gf. The processing capacity was measured by a sentence-processing task that is equivalent to the processing component of the reading span task but does not require participants to store any of the information. The performance on the sentence-processing task could be better compared with our WM reading span task since they involve the same processing components (i.e., they are in the same domain area and have very similar content); the only distinction is that the reading span task has some additional storage demands. We used a sentence-processing task because it measures information-processing speed, which is considered as a property of the WM system (Colom et al., 2008). The task design in our study avoided tapping simple perceptual speed constructs. As previously reviewed, some researchers used the perceptual speed task performance to indicate information processing speed. Those studies measured processing speed by tasks that do not tap directly the construct of interest (Colom et al., 2008). For example, Conway et al. (2002) used several psychometric speed tests widely known as measures of perceptual speed (Carroll, 1993). On the other hand, information processing speed may or may not correlate to perceptual speed, but information processing speed should tap minimal short-term storage requirements (Colom et al., 2008). While in Unsworth et al.'s (2009) study, they used the performance on the processing components of the WM tasks to indicate the processing capacity. Though the processing performance during the dual-task situation could indicate how the processing task is performed in conjunction with the recall task, it might implicate some additional temporary storage requirements (Colom et al., 2008; Towse & Hitch, 1995; Unsworth et al., 2009). Thus in the present study, we measured the reading speed independently of the reading span task, therefore it is considered to tap information processing speed but also avoids any storage requirements. Thus this single-task (processing-only) performance could be considered as a relatively pure indicator of information processing capacity. Therefore it would be better able to clarify the distinction in the literature about the role of processing in the relationship between WM and Gf. It also helps to explore whether processing components could add predict power of WM to account for Gf.

The Role of Interference in Working Memory and Intelligence

Controlled attention theory suggests that the central executive component of the WM system is responsible for the relationship between WM and intelligence (Engle, Kane et al., 1999). Individual differences in WM reflect the capability to use controlled attention to prevent interference from the environment and the items stored in long-term memory (Bunting & Cowan, 2005; Bunting, Conway, & Heitz, 2004). Kane and Engle (2000) suggested that greater susceptibility for low spans to proactive interference is due to an inability to use controlled attention to counteract the effect of PI on the recall in memory tasks like STM and WM tasks. Thus, some theorists extend the controlled attention view of WM and further suggest that interference is an important component in the relationship among STM, WM, and intelligence (e.g., Bunting, 2006). Furthermore, PI theories provide practical implications to help people overcome PI in the memory tasks. Thus, the present study also aims to find ways to reduce the influence of PI; therefore people with low memory ability could benefit from those strategies in daily cognitive activities.

Generally speaking, PI refers to difficulty in remembering a new item that is similar to items previously learned (Lustig, May, & Hasher, 2001). In Tuholski et al.'s (2001) controlled attention study, they found that performance differences between high- and low-span individuals emerged only when the distractor task was similar to the target material. Thus, high- and low-span individuals differ in PI susceptibility. Conway and Engle (1994) also found that low spans slowed down on retrieving items from a list if the items appeared more than once on the TBR lists (i.e., PI increased because of the similarity of the lists), but high spans showed no differences in performance. Thus they suggested that low spans are more sensitive to interference effects than high spans.

Studies also find WM predict performance on tasks that require suppression of irrelevant associations (e.g., Engle & Oransky, 1999; Rosen & Engle, 1998). Thus, a key ability measured by the WM span tasks might be the ability to combat interference (Whitney, Arnett, Driver, & Budd, 2001). Kane et al. (2004) suggested that the executive attention capability in WM maintains memory representations (e.g., action plans, goal states, or environmental stimuli) in an active and accessible state, while WM span tasks disturb such active maintenance by inducing PI that accumulates over trials, which makes long-term memory retrieval more difficult and slower (e.g., Lustig, May, et al., 2001).

Many early findings in STM research suggest the PI might also be a source of simple span differences (e.g., Dempster, 1985; Jensen, 1964; Rosner, 1972). For example, Dempster and Cooney (1982) found that individuals with low STM spans had higher PI effects than high spans. Later work on complex span tasks by Rosen and Engle (1998) demonstrated that participants with high WM span gave better performance on a PI task than those with low WM span did. Kane and Engle (2002) found that low-WM individuals were more vulnerable to PI. Kane and Engle (2000) found that the high and low span groups recalled equivalently numbers of items on the first trial, and their performance gradually decreased on the following trials. The trend of decreasing in performance for the low-span group was more dramatic compared to the high-span group (Kane & Engle, 2000). This is consistent with the view that the PI effect is greater for low-span individuals.

People frequently experience forgetting from PI in their daily life. Research has shown that PI is correlated with the number of pervious items and the time between learning and retrieval (Greenberg & Underwood, 1950; Underwood & Ekstrand, 1967). Prior information causes the most interference when the newly learned information or the situational context is similar (Underwood, 1957). High-span individuals have better inhibitory control and are less affected by similarity-based interference than low-span individuals. Either prior items (Lustig, May, et al., 2001; May et al., 1999) or prior laboratory experience (Lustig & Hasher, 2002) could lead to similarity-based interference which gives rise to performance decrements (decreased accuracy and slower probed recognition reaction times).

PI may cause forgetting and hurt performance in STM and WM tasks. Evidence from early work with STM simple span measures suggests that simple span tasks encourage the buildup of interference when TBR items are highly similar (Conrad & Hull, 1964; Postman & Underwood, 1973). For example, span scores in an auditory version of reading span task are lower when letter sequences include acoustically similar letters than when they consist of acoustically dissimilar letters. Moreover, researchers also propose that simple span estimates decrease when the items from the lists are drawn from the same category (e.g., digits) compared to when they come from two different categories such as digits and words (Young & Supa, 1941). Other studies with complex span suggest that span estimates become lower when highly similar types of information are employed in both the processing and storage components of the task (e.g., two verbal tasks—verify sentences and remember words), relative to when highly distinct materials are employed for the processing versus storage components (e.g., a spatial processing task and a verbal memory storage task; Shah & Miyake, 1996).

PI plays a major part in determining span estimates. Empirical evidence shows that PI builds from trial to trial in WM span tasks (e.g., Bunting, 2006; Dempster, 1992; Lustig, May, et al., 2001; May et al., 1999; Whitney et al., 2001). WM span tasks contain multiple trials, which consist of many highly similar stimuli, like digits, letters, and words, and there is no break or release from PI between trials (Bunting, 2006). Under these conditions, it is difficult to discriminate relevant items from prior items in active WM and long-term memory (Bunting, 2006). The recall on each trial requires only the items in the most recent information and thus this makes it more probable to buildup PI from previous trials, for example, the second trial suffers PI from the first trial, and the third trial suffers PI from the first and second trials and so forth (Bunting, 2006; Keppel & Underwood, 1962). Keppel, Postman, and Zavortink (1968) also showed that the increase in PI with additional trials was able to persist across the length of a STM simple span task. In the original reading span task (Daneman & Carpenter, 1980), the sentences are grouped into sets, with different set sizes ranging from 2 to 5 sentences. Participants begin with the easiest trials (e.g., those with two sentences) and proceed step by step to the most difficult ones (e.g., those with six or seven sentences). High span scores correspond to the success in trials with high memory loads (e.g., 5 sentences). Yet, if we reconsider from PI theories, since the participants are presented set sizes from smaller to larger size and meanwhile interference is accumulated, those trials with largest size sets not only mean the greatest memory loads but also imply the greatest interference (Lustig, May, et al., 2001). Therefore, individuals more vulnerable to interference will be differentially impaired for large sets, and in this way, differences in the ability to combat interference also contribute to differences in span estimates

(Bunting, 2006; Lustig, May, et al., 2001; May et al, 1999). This buildup of PI could be particularly significant for individuals with relatively weaker ability to suppress items from previous trials, like older adults in Lustig, May, et al.'s study.

Researchers have tried to find ways to reduce the influence of PI, therefore low STM, low WM, and old adults could benefit from those strategies in daily memory activities. According to Lustig, May, et al. (2001), several ways to reduce the influence of PI include adding distinctive breaks between each trial to enhance the temporal distinctiveness between trials, changing presentation order, and decreasing similarity between trials (e.g., Underwood, 1957; Wickens & Cammarata, 1986; Wickens & Gittis, 1974). Lustig, May, et al. administered the reading span task in two formats purported to vary in their level of interference: half of the participants performed the span task in the standard, ascending format (beginning with set size 2 and progressing toward larger sets), and the other half completed the span task in a descending format (beginning with the largest sets and moving ahead gradually to smaller sets). They assumed that the descending format is an interference-reducing format, since the most difficult trials are presented first, so that they could be completed without the possibility of interference buildup from the smaller set-size trials. They found that old adults could benefit from the descending format. May et al. (1999) created distinctive breaks between each trial and thus reduced PI built across previous trials. They found that both young and older groups increased their span estimates from this manipulation, but the older adults increased more dramatically. Wickens, Born, and Allen (1963) demonstrated that changing the type of TBR items (e.g., from words to digits) released participants from interference. Other studies showed that reducing similarity among

TBR items also tended to increase STM scores (e.g., Shah & Miyake, 1996). Bunting (2006) adopted Wickens et al.'s (1963) manipulation and found out changing the TBR items from words to digits within or across trials alternatively in WM tasks released PI; not doing so permitted PI buildup. Thus, those above strategies are advantages for those most susceptible to the effects of interference, such as older adults in Lustig, May, et al.'s (2001) study.

However, Bunting (2006) found that it was scores from PI-buildup trials, not PI-release trials, which correlated well with a Gf test like RAPM. Therefore, it is consistent with theories that suggest interference is a critical component of WM (Lustig, Hasher, & Toney, 2001; May et al., 1999). Other supporting evidences for this view come from experimental manipulations of interference-relevant variables within the span task and the relationship between interference susceptibility and overall STM and WM span task performance (e.g., Chiappe, Hasher, & Siegel, 2000; Conway & Engle, 1994; Dempster, 1981; Dempster & Cooney, 1982; Jensen, 1964; May et al., 1999; Rosen & Engle, 1998; Rosner, 1972). It is consistent with the theorists suggesting that controlled attention is a crucial part in WM to predict intelligence. Memory tasks generally require participants to use controlled attention to maintain short-term representations in the face of PI built up from the previous trials (Bunting, 2006). Controlled attention is an important component of Gf as we previously reviewed. Thus, PI-reduced situations should decrease the correlations between memory span tasks and intelligence (Bunting, 2006).

There are still gaps in the literature. Previous research has concentrated on older adults because they are more vulnerable to PI (e.g., Lustig, Hasher, et al., 2001; May et al., 1999). The present study examines whether similar strategies benefit young adults. If so, then students with memory issues may benefit from implementing these strategies in their daily cognitive activities.

In our present study, in order to test whether release from PI could benefit young adults with low memory ability, we created three conditions in STM and WM tasks: an ascending condition, a descending condition (similar to Lustig, May et al.'s conditions, 2001), and a changing TBR items condition (we adopt the manipulations from Bunting, 2006). The present study helps to provide practical applications that can be used to aid people in daily memory activities. Additionally, comparing the amount of PI across different conditions, the relationships between Gf and STM, Gf and WM could be examined. We expect release from PI should attenuate the relationships between STM and Gf, WM and Gf in general. Those analyses have not been thoroughly conducted in the previous literature. Our present study aims to address those issues.

CHAPTER 2
THE PRESENT STUDY

Thus far, the following gaps in the WM literature have been identified: A lack of consensus regarding the type of processing speed and STM tasks, and disagreement regarding which component in the WM tasks accounts for the relationship between WM and intelligence. In PI and WM research, very few previous studies examined the PI effect and its relationship with intelligence in young adults. Therefore, we still do not know what accounts for the relationship between WM and Gf. This is the primary question of interest in the present study.

This study addresses the gaps discussed above by using targeted processing and STM tasks for which the cognitive components are clearly established. We try to demonstrate the importance of the dual processing and storage demand of WM complex span tasks by contrasting their predictive utility of Gf with STM span tasks and processing-alone tasks. Additionally, we try to demonstrate the importance of PI in STM and WM by contrasting the relationships between span estimates in different PI-reduced conditions and Gf.

We want to test the following hypotheses: (1) Gf correlates more strongly with WM than STM. Processing accuracy and processing speed could account for shared variance in the relationship between WM and Gf; and (2) Descending and changing TBR items conditions could improve STM and WM task performance compared to ascending condition; and (3) Descending condition could improve performance on more difficult trials (i.e., trials that require participants to recall more words, or later trials that have more PI) in STM and WM tasks compared to ascending condition; and (4) People with low STM ability could benefit from those PI-reduced conditions (i.e., descending condition and changing TBR items condition) in the WM tasks; and (5) The relationships between Gf and STM, Gf and WM in the descending condition and changing TBR items condition would be weaker than those relationships in the ascending condition.

CHAPTER 3
METHODS

Design

A between-subjects design was adopted. Upon arriving at the laboratory, participants were randomly assigned by the experimenter based on the sign-up order to one of the three groups: ascending difficulty condition, descending difficulty condition, or changing TBR items condition. We deconstructed the WM tasks to STM tasks and processing tasks in each condition (i.e., the recall component in the WM task became the STM task; the processing component in the WM task became the processing speed task). In the ascending difficulty condition, participants were asked to finish a WM task, a STM task, and a processing task (sentence verification) in which trials increased in difficulty as the tasks progresses (i.e., easiest trials first, then gradually increasing to more difficult trials). In the descending difficulty condition, participants were asked to finish these same tasks but the most difficult trials were presented first, then gradually decreasing to easier trials. In the changing TBR items condition, participants were asked to finish a modified reading span task (i.e., the TBR items in the reading span task were matrices alternated with words), and a word span task alternated with the matrix span task (the matrix span task was adopted from Kane et al.'s study, 2004), and a sentences verification task in the ascending format. A between-subject design was adopted to help to minimize the practice and/or fatigue effect built up from similar WM tasks. In all conditions, the participants were asked to finish a Gf task (RAPM) to examine the changes in the relationships between Gf, STM, and WM performance in the three conditions.

Participants

There were 228 participants in this study. Thus, there were 76 participants in each of the three conditions. They were undergraduate students from the University of Florida who participated for credits toward a course requirement. Among them, 188 were females and 40 were males.

Materials and Procedures

All tasks were administered in a single session lasting approximately 1 hour. The participants first completed a consent form when they arrived at the laboratory. All participants completed the tasks in the following order: the intelligence task (RAPM), STM task, sentence processing task, and finally the reading span task. Participants could choose to take an optional 1-minute rest break between tasks. This order of task provided the following pragmatic benefits that participants began with the simpler STM version and processing version before they attempted the more complex WM version, thus saving the time for practice trials in WM tasks.

All the participants were first required to finish a same intelligence task. Then, depending on their assigned conditions, they completed different formats of STM, processing, and WM tasks. Participants who were assigned to the ascending condition were first required to finish the intelligence task, then a STM task that was ordered in ascending difficulty, then a processing task in ascending difficulty, and finally the reading span task in ascending difficulty. Participants who were assigned to the descending condition were first required to finish the same intelligence task as well, then a STM task that was ordered in descending difficulty, then a processing task in descending difficulty, and finally the reading span task in descending difficulty. Participants who were assigned to the changing TBR items condition were first required to finish the same intelligence task, then a STM task that the TBR items were alternated between words and matrices. Then they finished a processing task, which was the same processing task in the ascending condition. Finally they finished a reading span task that the TBR items were alternated between matrices and words, but the processing component remained to be the same sentence verifications as in the reading span task of the ascending condition. We presented more detailed descriptions of each task below.

In all tasks, the set size referred to the number of items to be recalled during each trial. Following three practice trials with a set size of 2, three trials of each set size were tested. In all the tasks, participants in the same condition received the exact same order and content of the task materials. Except where noted, all TBR items appeared in black on a white background, centered on the computer screen. Recall was signaled by the visual presentation of a question immediately following the last TBR item in a trial. Participants took as much time as needed to recall the items in each trial, but they could not return to prior trials once the next trial starts.

WM Tasks

Reading span task ascending difficulty condition

Participants in this condition were required to finish a reading span task in ascending order. Participants read sentences while trying to remember some unrelated words. Daneman and Carpenter (1980) originally developed the reading span task to assess WM during reading. This task was chosen because previous studies (e.g., Lustig, May, et al., 2001) used a similar reading span task to manipulate PI. PI was shown to increase when the processing tasks (reading sentences made up of words) interfere with the storage tasks (remembering words).

Participants first read all the instructions about the reading span task on the computer screen. Before beginning the experimental trials, participants completed a practice session. Participants were required to read a sentence and determine whether the sentence made sense (e.g., “We were fifty lawns out at sea before we lost sight of land.”) while also remembering a word presented after the sentence decision. Participants were instructed to comprehend as quickly as possible and then press the space bar to move on to the next screen. On the next screen the participants were required to press either a “Y” or “N” to indicate whether the sentence made sense or not (“Y” represented yes and “N” represented no). There were 10 to 15 words in each sentence. After participants gave their responses they were presented with an unrelated word for 1 s asking participants to remember. These words had one or two syllables and were presented in a lowercase font. After that, the next sentence appeared for participants to indicate whether it made sense or not, then the participants were presented with another unrelated word, and so forth. No word appeared more than once in the task. A blank screen lasting 0.5 s separated the presentation of each sentence and word. At the end of a series of sentence/word combination sets, participants were asked to type all the words they recalled from each set in the presented order, with a space between the words, on the computer screen. After typing the words, participants pressed “ENTER” to move on to the next trial. The practice session combined the sentence verification task with the TBR items, mirroring the experimental trials. In the experimental trials, half of the sentences made sense while the other half did not. The computer recorded the participants’ accuracy (i.e., correct or incorrect sentence decision), processing time to read each sentence, and the words they typed. If a participant took more than 10 seconds to comprehend a sentence, the program automatically moved on and counted that sentence decision as an error. Participants completed three practice trials, each of set-size two. After participants completed all of the practice sessions, the program advanced to the experimental trials. These trials consisted of three trials of each set-size, with the set-sizes ranging from three to seven combinations of words and sentences. This made for a total of 75 words and sentence combinations. WM capacity was scored by the total number of words that participants recalled correctly from each trial.

In the ascending format, participants started with three trials of the three sentences/words combination set, and then three trials of set size four, and gradually increased to three trials of set size seven. This entire task took about 20 minutes to finish.

Reading span task descending difficulty condition

Participants assigned to the descending condition were asked to finish the reading span task in descending format. The material was the same as in the reading span ascending condition, but participants started with three trials of the seven sentences/words combinations after the practice trials, and then three trials of set size six, and gradually decreased to three trials of set size three. This task took about 20 minutes to finish.

Reading span alternated with matrix span task

Participants assigned to the changing TBR items condition were asked to finish a modified reading span task (i.e., the TBR items in the reading span task were matrices alternated with words). We adopted the matrix span task from Kane et al.’s (2004) study. The processing component was the same as in the reading span ascending condition. The difference from the ascending condition was that half of the TBR items were words (i.e., similar to the storage component in the ascending version of the reading span task) and half were red-square locations (i.e., the matrix span task). In the matrix span trials, participants recalled sequences of red-square locations within successive matrices. A sequence of 4 X 4 matrices (5 cm X 5 cm) each presented 1 of the 16 squares in red, and each appeared for 1 s. Set size ranged from three to seven matrices. Red-square locations never repeated within a trial; each of the 16 red squares appeared approximately equally often in the whole task. There were 15 trials in total, with eight trials of sentences/words combinations and seven trials of sentences/squares combinations. Before the beginning of the real trials, participants were given three practice trials.

The trial was presented in ascending order; participants started with three trials of the smallest set size and gradually increased to three trials of larger set size. The TBR items were alternated from words to matrices across sets. In other words, participants received one trial of sentences/words combinations and then one trial of sentences/matrices combinations alternatively. Specifically, for example, the first trial they received was three sentences/words combinations, and the participants were required to recall the three words at the end of the trial; the second trial they received was three sentences/matrices combinations, and they were required to recall the positions of red squares in the matrices at the end of the trial; the third trial they received was three sentences/words combinations; the fourth trial was increased to four sentences/matrices combinations; the fifth trial was increased to four sentences/words combinations and so forth. The details of each trial were presented in Table 3-1. The fourteenth trial they received was increased to seven sentences/matrices combinations so participants were required to recall seven positions of red squares in the matrices at the end of the trial. Finally the fifteenth trial (i.e., the last trial) consisted of seven sentences/words combinations and participants were required to recall seven words at the end of the trial.

Table 3-1. Reading span trials in the changing TBR items condition

Trials	Details	Recall
1	Three words/sentences combinations	Three words
2	Three matrices/sentences combinations	Three matrices
3	Three words/sentences combinations	Three words
4	Four matrices/sentences combinations	Four matrices
5	Four words/sentences combinations	Four words
6	Four matrices/sentences combinations	Four matrices
7	Five words/sentences combinations	Five words
8	Five matrices/sentences combinations	Five matrices
9	Five words/sentences combinations	Five words
10	Six matrices/sentences combinations	Six matrices
11	Six words/sentences combinations	Six words
12	Six matrices/sentences combinations	Six matrices
13	Seven words/sentences combinations	Seven words
14	Seven matrices/sentences combinations	Seven matrices
15	Seven words/sentences combinations	Seven words

We chose this task because changing the types of TBR items could release participants from PIs (Bunting, 2006). We chose changing TBR items from words to squares because words and squares were considered as in the different domain areas. One had verbal content and the other one had spatial content. It could effectively reduce the item similarity and thus reduce PI.

In the recall session, participants typed the words in the sentences/words combination trials on the computer screen, similar to the ascending condition of the reading span task. In the sentences/squares trials, participants saw a blank 4 X 4 matrices on the computer screen, and they were asked to click the locations of the red squares in the correct order on the computer screen corresponding to the red squares in the previous presentation. The computer recorded the participants' accuracy (i.e., correct or incorrect sentence decision), processing time to read each sentence, the words they typed, and the matrix positions they clicked. WM capacity was scored by the total number of words and matrix positions that participants recalled correctly from each trial. This whole task took about 20 minutes to finish.

STM Tasks

Word span task ascending condition

Participants recalled sequences of one- and two-syllable words that were presented in a lowercase font for 1 s each, with a 500-ms blank screen between each word. Set sizes ranged from three to seven words (for 15 trials total). No word appeared more than once in the task. Participants typed the words on the computer screen they recalled from each trial in the order that the words were presented previously (see the word span task Kane et al. used in 2004). Participants started with three trials of the three words set, and then three trials of the four words set, and gradually increased to three trials of the seven words set.

The word span task mirrored the storage component of the reading span task, but participants did not need to simultaneously read sentences as they would do in the reading span task. They only needed to do the storage component. The words were of equal letters to the reading span task and were of similar difficulty levels. The computer recorded the words they typed. STM capacity was scored by the total number of words that participants recalled correctly from each trial.

This task was chosen because we wanted it to be as similar as possible as if participants would experience in the storage component of the reading span task, but without any processing component. Therefore there was no trade-offs between processing and storage component as in the WM tasks. Thus this STM task performance could be a pure indicator of short-term verbal storage capacity. This task took about 5 minutes to finish.

Word span task descending condition

The material was the same as in the word span ascending condition, but participants started with three trials of the seven words set, and then three trials of the six words set, and gradually decreased to three trials of the three words set. This task took about 5 minutes to finish.

Word span alternated with matrix span task

In the changing TBR items condition, participants got half of the word span trials and half of the matrix span trials. There were 15 trials totally, with eight trials of word span and seven trials of matrix span. The trial was presented in the ascending order; participants started with three trials of the smallest set size and gradually increased to three trials of larger set size. The TBR items were alternated from words to matrices across sets. In other words, participants received one trial of word span, and then one trial of matrix span, and then one trial of word span and so on, in such an alternative way. We chose this task because we wanted the participants to receive similar trials as if they would experience in the storage components of the reading span task alternated with matrix span task condition, but without any processing components. Therefore there was no trade-offs between processing and storage component as in the WM tasks. Thus this STM task could be a pure indicator of short-term storage capacity for verbal and spatial contents.

In the matrix span trials, participants recalled sequences of red-square locations within successive matrices just as they did in the storage component of the reading span task alternated with the matrix span task version. A sequence of 4 X 4 matrices (5 cm X 5 cm) each presented 1 of the 16 squares in red, and each appeared for 1 s with 500-ms interstimulus blank screen. Set sizes ranged from three to seven matrices (for 15 sets total). Red-square locations never repeated within one trial; each of the 16 squares appeared in red approximately equally often in the task. In the recall, participants saw a blank 4 X 4 matrices on the computer screen, and they were asked to click the locations of the red squares on the computer screen corresponding to the red squares in the display. As in the sentences/words combination trials, participants attempted to reproduce the sequence of red-square locations in the correct order (see the matrix span task Kane et al. used in 2004). The computer recorded the red-square locations they clicked. STM capacity was scored by the total number of words and matrix positions that participants recalled correctly from each trial. The whole task took about 5 minutes to finish.

Processing-Alone Tasks

Sentence verification task in ascending format

Participants in the ascending condition and in the changing TBR items condition received this processing task in ascending format. The sentence verification task mirrored the processing component of the reading span task but participants did not need to recall words as they would do in the reading span task. They only needed to do the sentence-processing component. Both of the processing components in the reading span task and the sentence verification task had equal number of sets and equal number of nonsense and sense sentences. The sentences were of equal length to the reading span task and the same number of words per sentence. And the sentences were also of similar difficulty levels using the Flesch-Kincaid Grade Level readability scale.

This task was chosen because we wanted it to be as similar as possible as if participants would experience in the processing component of the reading span task, but without any STM load. Therefore there was no trade-offs in the cognitive resources between processing and storage component as in the WM tasks. Thus this processing task could be a pure indicator of information processing speed and processing accuracy on the sentence comprehension.

In the ascending format, participants started with three trials of the three sentences set with a 0.5-second blank screen between the sentences, and a 1-second break between the trials, and then three trials of the four sentences set with the same break between the trials, and then gradually increasing to the seven sentences set; just as if they would experience in the ascending format of the reading span task, but only the processing component. Specifically, participants were required to read a sentence and determine whether the sentence made sense (e.g., “Andy was stopped by the policeman because he crossed the yellow heaven.”). Participants were instructed to comprehend as quickly and accurately as possible whether the sentence made sense or not; after comprehending the sentence, participants then pressed the space bar to move on to the next screen. On the next screen, the participants were required to press either a “Y” or “N” to indicate whether the sentence made sense or not. After the participants gave their responses, the next sentence showed up, and so forth. There were 75 sentences (15 trials) totally. There were also three practice trials before the real trials. The practice trials were just like the real trials, but had only two sentences in each trial. The time to read the sentence and make a sentence decision were recorded. If participants spent more than 10 seconds to read the sentence, this sentence would automatically count as an error and continued to the next sentence, just as participants would experience in the reading span tasks. This task took about 5 minutes to finish.

Sentence verification task in descending format

Participants assigned to the descending condition received this sentence verification task in descending format. The materials and instructions were the same as in the ascending condition. But the participants started with three trials of the seven sentences set with a 1-second break between the trials, and then three trials of the six sentences set with the same break between the trials, and then gradually decreasing to three trials of the three sentences set; just as if they would experience in the descending format of the reading span task. This task took about 5 minutes to finish.

Intelligence Task

RAPM (Raven's Advanced Progressive Matrices). In all of the three conditions, participants received this task. The RAPM is a measure of abstract reasoning (Raven, Raven, & Court, 1998). This task was chosen because it was considered as a widely accepted standardized measure of Gf. From previous studies, RAPM has moderate correlations with different types of WM tasks. This version of the RAPM is a widely used brief paper and pencil version that consists of 12 items (Bors & Stokes, 1998; Conway et al., 2002; Unsworth et al., 2009). Each item consists of a matrix of geometric patterns with the bottom-right pattern missing. Participants were instructed to select from among eight alternatives the one that correctly completed the overall series of matrix patterns. Items were presented in ascending order of difficulty (i.e., the easiest item was presented first and the hardest item was presented last). A participant's score was the total number of correct solutions. Participants received two practice problems before the real trials. Participants were asked to finish this task in a limited time (typically 20 minutes as suggested by Bors and Stokes).

CHAPTER 4
RESULTS

Descriptive Statistics

The total number of correct solutions on the Raven's Advanced Progressive Matrices was considered as an indicator of Gf.

In all of the three conditions, the total number of items recalled on the storage portion of the task (WM recall) was reported. The total number of the correctly recalled items in STM tasks was reported (STM recall); the proportion correct on the sentence verification of the processing-alone task was reported (processing-alone accuracy); and we reversely coded the average processing time (in units of milliseconds) on the sentence comprehension in the processing-alone task as speed of processing (processing-alone speed).

Descriptive statistics across three conditions were presented in Table 4-1. Descriptive statistics in each condition were presented in Tables 4-2, 4-3, and 4-4. Skewness and kurtosis values were reported to ensure that each score was approximately normally distributed (i.e., skewness < 2 and kurtosis < 4; see Kline, 1998). Processing-alone accuracy scores had higher kurtosis values and it also showed ceiling effects (Conway et al., 2005; Unsworth et al., 2009). Therefore, processing accuracy was removed from the analyses because of lack of normality. It is consistent with previous studies that processing accuracy in the processing speed tasks usually has ceiling effects therefore it is usually excluded from the processing speed task analyses (Conway et al., 2002; 2005).

All the data were screened for both univariate and multivariate outliers. Univariate outliers were defined as cases more than 3.5 standard deviations from the mean.

Multivariate outliers were examined by calculating Mahanalobis' d^2. None of the cases in the data were deemed outliers.

Table 4-1. Descriptive statistics across three conditions

Measures	Range	*M*	*SD*	Skewness	Kurtosis
RAPM	1 - 12	6.72	2.39	-0.18	-0.39
WM recall	19 - 71	44.48	10.81	0.01	-0.45
STM recall	38 - 72	56.92	6.86	-0.18	-0.53
Processing-alone speed	-529382 – -153551	-290800.00	62306.10	0.66	0.84
Processing-alone accuracy	62 - 75	72.86	2.03	-1.71	5.04

Table 4-2. Descriptive statistics for ascending condition

Measures	Range	*M*	*SD*	Skewness	Kurtosis
RAPM	1 - 12	6.71	2.51	-0.14	-0.52
WM recall	23 - 67	42.63	10.44	0.12	-0.61
STM recall	39 – 66	54.72	6.46	-0.17	-0.67
Processing-alone speed	-529567 – -172342	-289460.00	59321.93	0.82	2.23
Processing-alone accuracy	67 - 75	73.08	1.70	-1.07	1.19

Table 4-3. Descriptive statistics for descending condition

Measures	Range	*M*	*SD*	Skewness	Kurtosis
RAPM	1 - 11	6.74	2.29	-0.31	-0.16
WM recall	23 - 71	44.72	12.02	0.10	-0.54
STM recall	38 - 70	58.14	6.52	-0.30	-0.10
Processing-alone speed	-494327 – -190534	-286913.00	64192.09	0.73	0.51
Processing-alone accuracy	63 - 75	72.68	2.08	-1.74	5.00

Table 4-4. Descriptive statistics for changing TBR items condition

Measures	Range	*M*	*SD*	Skewness	Kurtosis
RAPM	1 - 12	6.71	2.40	-0.11	-0.36
WM recall	19 - 65	46.09	9.69	-0.27	-0.01
STM recall	40 - 72	57.87	7.12	-0.18	-0.71
Processing-alone speed	-468632 – -154107	-296107.00	63773.96	0.49	0.43
Processing-alone accuracy	62 - 75	72.83	2.29	-1.88	5.68

Pooled Correlation Analyses

Pooled correlation analysis controlling for three treatment groups was conducted to compare the correlations between Gf and STM, Gf and WM. We hypothesized that Gf correlates more strongly with WM than STM; processing speed could account for shared variance in the relationship between WM and Gf. We found that Gf correlated .35 with WM ($p < .01$) while Gf correlated .21 with STM ($p < .01$). The correlation coefficients for all measures were presented in Table 4-5. Moreover, after controlling WM, STM accounted for non-significant amount of variance in Gf (R^2 remained to be .12). Steiger's (1980) test showed that these two correlation coefficients were statistically different ($z = 2.41$, $p < .05$). The result is consistent with our hypothesis. Moreover, in Table 4-5, we also found that processing speed correlated with WM, STM, but not Gf ($r = .20$, $p < .01$; $r = .29$, $p < .01$; $r = .04$, *ns*, respectively). Partial correlation between WM and Gf when processing speed was controlled was significantly different from zero ($r = .35$, $p < .01$). Therefore processing speed could not account for shared variance in the relationship between WM and Gf.

Table 4-5. Pooled correlation coefficients

Measures	1	2	3	4
1. RAPM (Gf)	--			
2. WM recall	.35**	--		
3. STM recall	.21**	.57**	--	
4. Processing-alone speed	.04	.20**	.29**	--

**$p < .01$.

Comparison of R^2

To explore the contribution of processing speed in WM with Gf, we compared R^2. We hypothesized that processing speed could account for shared variance in the relationship between WM and Gf. A series of regression analyses was carried out to obtain R^2 values from different combinations of the predictor variables. We tested two hypothesized models: (1) Gf was regressed on WM; (2) Gf was regressed on WM and processing speed. We found that adjusted R^2 remained the same in the second model compared to the first model (adjusted R^2 = .12). Therefore we concluded that processing speed could not add predictive power of the WM tasks to Gf.

We also compared the corresponding models in each condition. The results in the three conditions were similar: adjusted R^2 remained to be .04 in the ascending condition, .12 in the descending condition, and .22 in the changing TBR items condition. Therefore we did not account for treatment in this analysis.

Comparing Means

T-test analyses were conducted to compare the performance difference between the treatment groups. We hypothesized that the descending and changing TBR items conditions could improve STM and WM task performance compared to the ascending condition. The difference between the ascending and descending conditions is the order of difficulty; and the difference between the ascending and changing TBR items conditions is the TBR items. But the difference between the descending and changing TBR items conditions could be due to either the order or the TBR items, therefore we were not interested in the difference between the descending and changing TBR items conditions. Thus we only used *t* -test to compare the performance between the ascending and descending conditions, and the performance between the ascending and changing TBR items conditions. Based on the same reasons, we did not compare the descending and changing TBR items conditions in the regression analyses described below.

Comparing the ascending condition and descending condition, we found that the STM scores increased 3.42 points out of 75 (*SE* = 1.06) in the descending condition compared to the ascending condition [$t(150) = 3.24$, $p < .01$]. This part of the result is consistent with our hypothesis. However, in WM task, the result was not significant [$t(150) = 1.15$, *ns*], which is not consistent with our hypothesis.

Comparing the ascending condition and changing to-be-remembered items condition, we found that the STM scores increased 3.15 points out of 75 (*SE* = 1.11) in the changing TBR items condition compared to the ascending condition [$t(150) = 2.85$, $p < .01$]. The WM scores increased 3.46 points out of 75 (*SE* = 1.63) in the changing TBR items condition compared to the ascending condition [$t(150) = 2.12$, $p < .05$]. The results of the changing TBR items condition are consistent with our hypotheses.

Multilevel Analyses

Multilevel analyses were conducted to compare the ascending condition and the descending condition. We hypothesized that the descending condition could improve performance on more difficult trials (i.e., trials that require participants to recall more words, or later trials that have more PI) in STM and WM tasks compared to the ascending condition. We did not compare the changing TBR items condition with the ascending condition here because the changing TBR items condition had both words and matrix trials while the ascending condition only had words trials; therefore we had much fewer corresponding words trials to compare.

In the following hypothesized model, P was the expected proportion of correctly recalled words in each trial, TMT was the treatment condition (0 = ascending condition, 1 = descending condition), TRIAL was the serial number of the trial (15 trials in total), and SIZE was the number of words to be remembered in each trial (ranging from 3 to 7 in our experiment). This model was used in both STM and WM tasks.

Level 1: Logit $P(\text{Y} = \mathit{1}) = \pi_{0i} + \pi_{1i} * \mathit{TRIAL} + \pi_{2i} * \mathit{SIZE}$

Level 2: $\pi_{0i} = \beta_{00} + \beta_{01} * \mathit{TMT} + \gamma_{0i}$

$\pi_{1i} = \beta_{10} + \beta_{11} * \mathit{TMT} + \gamma_{1i}$

$\pi_{2i} = \beta_{20} + \beta_{21} * \mathit{TMT} + \gamma_{2i}$

Based on the reliability estimates and significance levels, the combined model results for STM were: Logit $P(\text{Y} = \mathit{1}) = 5.94 + 0.21 * \text{TMT} – 0.85 * \text{SIZE}$. All coefficients were significantly different from zero. For TMT, $t(173) = 3.32$, $p < .01$; for SIZE, $t(174) = -36.45$, $p < .01$. The results indicated that the descending condition would benefit performance. The slope for treatment was 0.21, therefore, comparing the descending condition to the ascending condition, the odds ratio for correct word recall was $e^{0.21} = 1.23$, indicating an increase in the probability of correctly recalling words from the ascending condition to the descending condition.

The combined model results for WM were: Logit $P(\text{Y} = \mathit{1}) = 3.15 – 1 * \text{TMT} + (0.2 * \text{TMT} – 0.52) * \text{SIZE}$. All the variables were significant from zero. For TMT, $t(150) = -4.26$, $p < .01$; for SIZE, $t(150) = -23.03$, $p < .01$; for TMT and SIZE interaction term, $t(150) = 5.47$, $p < .01$. The results indicated that if the set size was larger than 5, the descending condition would benefit performance. For example, for a set size of 7, the simple slope for TMT was (0.2 * 7 - 1) = 0.4. Therefore, comparing the descending condition to the ascending condition, the odds ratio for correct word recalled was $e^{0.4 * 1} = 1.49$, indicating an increase in the probability of correctly recalling words from the ascending condition to the descending condition. The results are consistent with our hypotheses.

Regression Analyses

Reading Span Tasks: Ascending Condition vs. Descending Condition

Linear regression analysis was used to determine whether STM capacity and PI condition (the ascending or descending condition, indicated by “TMT” in the equation) could estimate the performance on the storage component of the reading span task (indicated by “WM recall” in the equation). We hypothesized that people with low STM ability could especially benefit from those PI-reduced conditions in the WM tasks. Therefore, we were also interested in whether there was an interaction between STM and PI conditions. PI conditions were dummy-coded in the regression model (0 as ascending condition and 1 as descending condition). All variables were entered into the model in a single step. WM recall was regressed on STM, TMT, and their cross product. The hypothesized equation was: WM recall = $a + b_1$ * STM + b_2 * TMT + b_3 * STM * TMT.

As indicated by the previous studies, low STM and low WM individuals were more vulnerable to PI; and the PI-reduced version of WM tasks could increase the span estimates (Lustig et al., 2001; May et al., 1999). Moreover, WM capacity correlated with STM capacity (Kane et al., 2004). Thus STM capacity could moderate the PI effect on the WM tasks.

The result suggested that STM predicted WM ($\beta = 0.54$, $p < .01$). However, the treatment and the interaction terms were not significant ($\beta = -0.55$, *ns*; $\beta = 0.53$, *ns*, respectively). When we removed the interaction term, the treatment effect was still not significant (β = -0.05, *ns*). Therefore we concluded that the descending condition could not improve overall WM performance. This is not consistent with our hypothesis.

Reading Span Tasks: Ascending Condition vs. Changing TBR Items Condition

A similar linear regression analysis was used to determine the effect of STM and PI conditions on the reading span task performance as in the previous regression analysis comparing the ascending condition and descending condition. All the other analyses were similar except that the ascending condition was coded as 0 and changing TBR items condition was coded as 1. Changing TBR items would decrease PI, as indicated by the previous studies (Bunting, 2006). The result suggested that STM, treatment, and their interaction predicted WM (β = 0.67, p < .01; β = 1.74, p < .01; β = -1.65, p < .01, respectively). Therefore, we concluded that all the participants benefited from the changing TBR items condition (WM recall increased); however, lower STM individuals tended to improve their performance more dramatically than higher STM individuals did. As STM capacity became lower (lower than 62 out of 75), participants were more likely to benefit from the reduced PI condition. This is consistent with our hypothesis.

Correlation Analyses

Previous studies of PI (Bunting, 2006; Lustig et al., 2001; May et al., 1999) suggested that WM performance on PI-buildup version correlated more with intelligence than PI-reduced version. We also hypothesized that the ascending version of the STM and WM tasks accounts for more variance in RAPM than the descending version and changing TBR version do.

To test this hypothesis, we first compared the residual variances of STM and WM across conditions to make sure that they were of similar size. Then we obtained correlation coefficients between STM, WM, and Gf in each condition (see Table 4-6 for correlation coefficients results in the three conditions). Then we used Fisher's *Z* test to test if those correlation coefficients were significantly different. However, we found that none of the correlation coefficients were significantly different. The observed correlations between Gf and memory tasks also did not decrease in PI-reduced conditions. This is not consistent with our hypothesis.

Table 4-6. Correlation coefficients in three conditions (ascending / descending / changing TBR Items)

Measures	1	2	3
1. RAPM (Gf)	--		
2. WM recall	.24* / .37** / .48**	--	
3. STM recall	.00 / .25* / .31**	.57** / .60** / .55**	--

*$p < .05$. **$p < .01$.

CHAPTER 5
DISCUSSION

The Relationship Between Gf and WM

Our primary research interest is to explore what accounts for the relationship between Gf and WM. We found that Gf had higher correlations with WM than STM (r = .35 compared to .21). We used a novel method to explore the relationships by deconstructing the WM task. Processing accuracy and processing speed were measured alone in a separate task; therefore they were pure indicators of information processing ability. However, processing speed correlated with WM but not RAPM (r = .20 and .04, respectively): the faster the processing speed, the higher the WM. Our results are consistent with Conway et al.'s (2002) findings that WM, but not STM or processing speed, is a relatively better predictor of Gf (also see Carpenter et al., 1990; Colom et al., 2008; Engle, Tuholski, et al., 1999; Kyllonen, 1996; Kyllonen & Christal, 1990). Our results are not consistent with Unsworth et al.'s (2009) findings that processing speed partially accounts for the relationship between WM and intelligence (also see Fry & Hale, 1996; Jensen, 1998; Kail & Salthouse, 1994; Salthouse, 1996). Processing speed did not add predictive power above what was accounted for by WM in Gf (adjusted R^2 remained the same). This part of result is also not consistent with Unsworth et al.'s findings (also see Waters & Caplan, 1996).

To better compare our results with other studies that explored similar constructs, we summarize the results from selected studies in the following tables (Tables 5-1, 5-2, and 5-3). We list the tasks they used and the correlations they found between Gf and WM, Gf and STM, Gf and processing speed, WM and processing speed. In the following tables, unless otherwise noted, Gf was all measured by RAPM. Table 5-1 lists the WM tasks that different studies used and their correlations with Gf. Table 5-2 lists the STM tasks in selected studies and their correlations with Gf. Table 5-3 lists the processing speed tasks used and their correlations with Gf and WM. We include all the memory tasks labeled as WM tasks by the original authors (including simple span tasks and complex span tasks from various content domains) in Table 5-1; and all the memory tasks labeled as STM tasks by the original authors in Table 5-2. In these tables, we could see that researchers vary a lot in the measures. For example, in Ackerman, Beier, and Boyle's (2002), Colom et al.'s (2004, 2008), de Jonge and de Jong's (1996), and Miyake et al.'s (2001) studies, they used a lot of simple span tasks to measure WM, thus underestimated the relationship between Gf and WM.

Regarding the relationship between processing speed and Gf, some results from previous studies are consistent with the claim that the difficulty of processing speed tasks accounts for the relationship between Gf and processing (Conway et al., 2002). The more complicated the processing speed task, the stronger the relationship between processing speed and WM, processing speed and intelligence (Conway et al., 2002; Jensen, 1998). In Ackerman et al.'s (2002) results, we could see that more complex processing speed tasks (memory speed and complex speed tasks) correlated more with Gf than simple processing speed tasks (scanning speed and pattern recognition speed tasks) did. Similar results were also found in Sternberg and Gastel's (1989) study, they found a correlation of .32 between a sentence verification speed task and Cattell intelligence test, compared to a correlation of .04 between a finding A test (i.e., a simple motor perceptual speed task) and Cattell intelligence test. de Jonge and de Jong (1996) found a correlation of .32 between sentence reading speed and Gf, compared to a correlation of .11 between pseudo word recognition speed and Gf.

Moreover, in Table 5-3, we could find that the correlations between processing speed and Gf are generally low, compared to the correlations between processing speed and WM, WM and Gf. For example, Ackerman et al. (2002) found RAPM correlated only .25 with the processing speed latent variable (derived from all the processing speed tasks in their study), but WM factor correlated .70 with RAPM. In addition, they found WM factor correlated .55 with processing speed factor. Thus Ackerman et al. suggested that processing speed only accounts for subtle variances in Gf compared to WM. In our results, we also found that processing speed correlated more with WM than Gf. It is consistent with previous research that the relationship between processing speed and intelligence is much weaker than that between WM and processing speed (Fry & Hale, 2000; Miller & Vernon, 1996). For example, Fry and Hale (1996) found a correlation of .55 between WM latent variable and processing speed latent variable, compared to a correlation of .12 between Gf latent variable and processing speed latent variable (similar results were also found by Ackerman et al., 2002; Colom et al., 2004; Kyllonen & Christal, 1990; and Miyake et al., 2001).

Furthermore, in Table 5-3, the processing speed tasks that have higher correlations with WM tasks tend to also have higher relationships with Gf. For example, in Ackerman et al.'s (2002) results, more complex processing speed tasks (memory speed and complex speed tasks) had higher correlations with WM and also Gf, than that of simple processing speed tasks (scanning speed and pattern recognition speed tasks). It is consistent with our previous claim that the more the task places demands on

WM, the stronger the correlation between processing speed and Gf. It is not processing speed that predicts Gf; it is the memory and attention components of the tasks that predict Gf (Conway, Kane, & Engle, 2003; Cowan, 1995).

On the other hand, this conclusion might still not be well supported by some other studies. In Conway et al.’s (2002) results, they found processing speed latent variable did not significantly predict Gf since their measures of processing speed place minimal demands on memory and attention. However, in our study, we used a measure, the sentence verification task, which places some demands on memory and attention instead of relying totally on the automatic strategies compared to Conway et al.’s tasks. But we still cannot find a relationship between Gf and processing speed. Previous theorists suggested that the differences in the results about the relationship between Gf and processing speed might be due to the various tasks they used. Conway et al. suggested that in some studies that found a high correlation with Gf, the speed tasks might tax the WM system. Fry and Hale (1996) used relatively complex tasks and they found a higher correlation between Gf and processing speed than the correlation results in Conway et al.’s studies. However, in Salthouse’s (1996) study, they carefully chose relatively “simple” perceptual speed tasks but still found a high correlation between Gf and processing speed. Given our results, we suggest that except for the difficulty and reliability of the processing speed tasks, prior studies that found a high relationship between Gf and processing speed may be due to different samples they used, similarity in the content materials of Gf and processing speed tasks, or different statistical procedures.

Regarding the samples in the studies exploring the relationships between Gf and processing speed tasks, we found that some studies used cross-age samples. Therefore, the correlations between Gf and processing speed might be very high if they did not control age. For example, Salthouse (1994) found the correlations between processing speed tasks and RAPM were from .46 to .49. However, after controlling age, the correlations dropped to around .21 to .26. Fry and Hale (1996) found a correlation of .61 between processing speed latent variable and Gf, but after controlling age, the correlation dropped to .12; furthermore, after controlling both age and WM, the correlation dropped to .04. In Conway et al.'s (2002) discussion, they addressed the distinction between individual differences in cognitive ability and developmental differences in cognitive ability. There are evidences to suggest that processing speed is an important factor underlying developmental differences in cognitive ability in childhood (Coyle et al., 2011; Fry & Hale, 1996, 2000) and in aging (Salthouse, 1994, 1996). Conway et al. suggested that it is possible that the factors that account for developmental differences in cognitive ability do not match the factors that account for individual differences in cognitive ability in young adults. Perhaps processing speed is important for developmental differences in childhood or aging but not for individual differences in young adults, like college students in our sample.

In Tables 5-1, 5-2, and 5-3, we could find that although the correlations have been found to vary widely, depending on the methods of measuring processing speed and intelligence, the reliabilities of these measures, and the population of interest, the correlations between WM and Gf are generally larger than the correlations between STM and Gf, or processing speed and Gf. Furthermore, if the test content materials were in the spatial/visual images domain, the correlations would generally be larger than those in the experiment using verbal test content materials since the content materials in Gf tests (e.g., RAPM) are usually in the spatial/visual images domain. This suggests that higher correlations might be due to the highly similar content domain rather than the similar cognitive mechanisms. For example, Jurden (1995) found that the counting span task (a spatial-figural counting WM task) correlated more with RAPM (also a figural task) than the reading span task did (r = .43 compared to r = .20, respectively); Schmiedek et al. (2009) found that the rotation span and the counting span tasks correlated more with Gf than the reading span task did (r = .32 and .41 compared to .20, respectively); Conway et al. (2002) also found that the counting span correlated more with RAPM than the reading span and the operation span tasks did (r = .38 compared to .15 and .20, respectively). In the relationship between STM and Gf, Bayliss et al. (2003) found that the Corsi block span task (a visual STM task) correlated more with RAPM than the digit span task did (r = .62 compared to .17). Colom et al. (2008) also found that the Corsi block span task correlated more with Gf than the forward digit span and the forward letter span tasks did (r = .45 compared to .30 and .39). In the relationship between processing speed and Gf, Unsworth et al. (2009) found that the symmetrical pattern decision speed correlated more with RAPM than the sentence verification speed did (r = .41 compared to .32).

Moreover, there are several studies reporting stronger relationships at the latent variable level among Gf, STM, WM, and processing speed (Ackerman et al., 2002, 2005; Colom et al., 2004, 2005, 2008; Colom & Shih, 2004; Conway et al., 2002; Engle, Tuholski, et al., 1999; Kane et al., 2004; Kyllonen & Christal, 1990; Miyake et al., 2001;

Unsworth et al., 2009). Researchers used latent variable analyses and generally obtained higher correlations between latent constructs than the correlations between the observed variables of individual tasks. For example, in Kyllonen and Christal's study, they found a correlation of .80 - .90 between Gf and WM latent variables, and a correlation of 0.25 - 0.37 between Gf and processing speed latent variables. Those correlation coefficients were much higher than the correlations of individual tasks presented in Table 5-1 and Table 5-3. Similar results were also found in Colom et al.'s (2004) study, they found a correlation of .76 between Gf and processing speed latent variables. However, the correlations of individual tasks were much lower (from .10 to .24). Furthermore, in Colom et al.'s (2004) study, they found a correlation of .93 between Gf and WM latent variables (although they used STM simple span tasks to measure WM). The correlations of individual tasks were also much lower (from .12 to .32). Similarly, in Hambrick's (2003) result, the correlation between Gf latent variable and WM latent variable was .71, but the correlations of individual tasks were from .21 to .23.

We would like to point out that, compared to other studies, the correlations between individual processing tasks and Gf in Unsworth et al.'s (2009) study were exceptionally high. They found a high relationship between processing accuracy and Gf, processing speed and Gf. But they measured processing in the WM tasks (i.e., how much time participants spent on the WM tasks and the sentence verification accuracy in the WM tasks). Therefore, their measures of processing might not be pure indicators of processing since the processing components in the WM task might tap some short-term storage requirements and some trade-off strategies between storage and processing requirements. Furthermore, there was no report of outlier removal procedures in their study. They also transformed the processing accuracy data using arcsin transformation because of high skewness and high kurtosis of processing accuracy. This transformation is not commonly used in the research of processing speed. In addition, they used variance partitioning analysis (also called communality analysis) to explore the shared and unique contribution of processing speed and processing accuracy to Gf. This type of analysis is debunked several years ago. Therefore their results of high correlations between Gf and processing might be due to unusual statistical procedures.

In sum, our results are consistent with prior work that WM and STM are highly correlated but separable (Kane et al., 2004). WM is more closely related to Gf and reasoning than STM is (Cohen & Sandberg, 1977; Colom et al., 2008; Conway et al., 2002; Engle, Tuholski, et al., 1999; Kane et al., 2004; Schmiedek et al., 2009), especially when the measures of STM and WM are clearly distinguishable. This argument is well supported by several large-sample, latent-variable studies (Kane, Hambrick, & Conway, 2005). WM tasks correlate strongly with each other and with a wide range of cognitive abilities, and WM and Gf share substantial variance that is independent of STM (Kane et al., 2004). Our findings are consistent with the view that WM and STM span tasks require some shared executive and storage-rehearsal processes but WM span tasks require additional executive processes (i.e., controlled attention) to deal with their dual-task demands, whereas STM tasks may elicit additional rehearsal processes that are disrupted by the processing task in WM span (Kane et al., 2004). WM tasks involve short-term storage and processing components. We deconstructed the two components to individual STM and processing speed tasks. But

STM and processing speed tasks cannot predict as much variance in Gf as WM tasks can. Therefore WM tasks involve more than just the combination of STM and processing speed tasks do. It is in accordance with our hypothesis that WM requires more controlled attention than STM does, and it is controlled attention that drives the correlations between WM and Gf (Kane et al., 2005).

In conclusion, we agree with the statement of Conway et al. (2003) that “WM and Gf are indeed highly related, but not identical” (Conway et al., 2003, p. 547). WM, but not STM or processing speed, is a predictor of Gf (Conway et al., 2002).

Our research used a novel method to explore the relationship between Gf and WM (i.e., deconstruct the WM task). It has theoretical implications for processing speed research. Some theories emphasized the role of processing speed in children’s cognitive development because it is thought to relate to fluid intelligence (Coyle et al., 2001; Jensen, 1998). For example, Coyle et al. (2011) suggested that increases in Gf in childhood or adolescence can be attributed to increases in mental processing speed. On the other hand, decreases in Gf in old adults can be due to decreases in processing speed (e.g., Fry & Hale, 1996). In contrast, our results suggest that processing speed seems not to relate to Gf. It suggests that overemphasizing on processing speed might be unnecessary.

Our study also has limits. We only deconstructed one WM task, namely, the reading span task, to analyze the connections between each component in the reading span task and RAPM. We do not know if similar results would also be found in other WM tasks, like operation span task and symmetrical span task. It would be better to use latent variable analysis in future studies to explore the relationship between Gf and WM.

Because there is no single task used to measure WM capacity as a pure indicator, the span estimate may be contaminated by task-specific variance and not able to reflect all relevant contents of WM. Individual differences in domain-specific ability can account for difference in WM span score estimated in a different domain (Salthouse, Mitchell, Skovronek, & Babcock, 1989; Swanson & Sachse-Lee, 2001; Wilson & Swanson, 2001). Previous researchers found that verbal and spatial tasks had dramatically different difficulty. For example, Daneman and Tardif (1987) compared accuracy for different span tasks including verbal, numerical and spatial tasks. They used a verbal processing task that required higher levels of domain-specific knowledge than a typical WM task did (e.g., the processing component required participants to generate low-frequency words). The mean processing accuracies for the same processing tasks were different in the WM tasks that required different storage components: verbal (78% correct), numerical (87% correct) and spatial (96% correct). Therefore, independent of participants' WM capacity, it seems that the domain-specific demands of these tasks influenced the span estimates and thus affected the correlation between WM and higher-order cognition (Kane et al., 2004). It is likely that one test can only measure partially specific cognitive abilities (Salthouse, 1990) and the performance is mismatched with different tasks. For example, the operation span task is used to measure WM capacity, but it also reflects mathematical ability. Similarly, the reading span task measures WM capacity and verbal ability among other factors. Indeed, Conway et al. (2005) suggested researchers should consider using latent variable analysis to measure WM capacity when the study has a battery of WM tasks. For example, several studies derived a latent variable, WM capacity, from the common variance among reading span, operation span, and counting span (e.g., Conway et al., 2002; Engle, Tuholski, et al., 1999; Kane et al., 2004).

Furthermore, researchers found that a latent variable representing WM capacity from a battery of tests (Kane et al., 2004; Kyllonen, 1994; Suß, Oberauer, Wittman, & Wilhelm, 2000; Suß, Oberauer, Wittman, Wilhelm, & Schulze, 2002) accounted for considerably greater variance in fluid intelligence or reasoning ability than estimated just by the observed variable from individual single task. Oberauer et al. (2003) found that the mean correlation of 12 individual tasks (including storage and processing tasks and coordination tasks) with the reasoning ability (in BIS reasoning scale) was $r = .47$. But after aggregating those tasks, the correlation between an overall composite of WM capacity and reasoning increased to .75. Lewandowsky, Oberauer, Yang, and Ecker (2010) used a battery of four WM tasks (a reading span task, an operation span task, a spatial short-term memory task, and a memory updating task) to get a common WM factor. Those four tasks were chosen from two content domains and two functional aspects of WM in order to provide heterogeneous measures of WM capacity, thus reducing unwanted variance (Lewandowsky et al., 2010). They found that the correlations between the latent variable of WM and RAPM were higher and more stable across studies (ranged from .37 to .44) than the correlations from the individual observed variables (ranged from .15 to .34). It is consistent with Conway et al.'s (2003) claim that "several latent variable analyses suggest that WM accounts for at least one third and perhaps as much as one half the variance in g" (p. 511).

Therefore, a latent variable derived from multiple indicators of WM is more reliable and valid than a single task (Conway et al., 2005). When using only one single task to indicate WM, we do not have the information about which processes embedded in the task are responsible for the correlations with other types of higher-order cognition (Kane et al., 2004). Therefore, psychometric constructs such as WM capacity are best measured by multiple tasks that differ in functional or content levels but share theoretically critical requirements (Kane et al., 2004).

Similarly, we only used one measure to indicate Gf. Although RAPM is widely used, high-quality estimates of Gf may not be derived only from a single nonverbal reasoning scale. Rather, Gf would be better estimated if it were generated from the average across multiple tests of differing formats, contents, and processes (Ackerman et al., 2005).

In conclusion, the current project clearly suggests a strong link between measures of WM and measures of Gf. Exploring these relationships yields important theoretical insights into individual differences in cognition. Speed tasks that place some demands on working memory still do not predict Gf. More research is needed to address the notion that controlled attention underlies performance on WM tasks as well as tests of Gf.

Proactive Interference in WM

The second part of our study explored the effect of proactive interference in WM. PI makes it difficult to discriminate between relevant items and prior items in long-term memory and active WM. We used two PI-reduced strategies (i.e., changing the presentation order to descending difficulty and changing TBR items alternatively) to explore the effect of PI in the relationship between WM, STM, and Gf.

We hypothesized that descending condition could improve STM and WM performance. This hypothesis was confirmed by a *t*-test and a multilevel analysis revealing that the descending condition improved on STM and WM tasks. Previous studies only used *t*-test to find that the descending condition could benefit old people but not young adults. Here we also used a multilevel analysis and found that the descending condition could especially benefit young people in more difficult trials on the STM and WM tasks.

We hypothesized that the changing TBR items condition could improve STM and WM. This hypothesis was confirmed by *t*-test analyses showing significantly higher performance for the changing TBR items condition in the STM and WM task. Therefore it suggests that PI could be reduced by changing TBR items alternatively. A follow-up regression showed an interaction between STM and treatment condition that participants with low memory (i.e., got a STM score smaller than 62 out of a total 75) could benefit more from the changing TBR condition in the WM task. Therefore people with lower STM could especially benefit from the changing TBR items condition.

Furthermore, we hypothesized that the descending condition and changing TBR items condition could reduce the relationship between Gf (as measured by RAPM) and WM/STM. This hypothesis was not confirmed in either condition. Our results are not consistent with previous findings that PI-reduced conditions could reduce the variances that WM accounts for in Gf (Bunting, 2006), and we also did not find these results in STM tasks.

Generally, WM tasks require participants to use controlled attention to maintain access to memory representations in the face of proactive interference and mandatory shifts of the secondary processing task (Kane et al., 2005). High and low WM span individuals differ in the performance of attention-control tasks such as dichotic listening, Stroop, and antisaccade tasks (Engle & Kane, 2004). High WM individuals often can better control over thoughts and actions than do low WM individuals. And it is controlled attention that drives the correlations between WM and Gf. Thus we predicted that PI-reduced conditions in our study (i.e., require less controlled attention) reduce the relationship between WM and Gf, and thus make the cognitive mechanism different.

In addition, although STM tasks involve less controlled attention compared to WM, STM tasks also require participants to inhibit proactive interference. WM tasks reflect temporary memory storage plus controlled processing, but STM tasks cannot be considered as reflecting temporary memory storage with no executive involvement or controlled attention (Colom et al., 2004; Colom, Abad, Rebollo, Flores-Mendoza, & Botella, 2002; Süß, Oberauer, Wittman, Wilhelm, & Schulze, 2002). WM tasks measure attention-control abilities and other abilities as well (e.g., storage, processing skills, rehearsal strategies). Although WM tasks are more influenced by controlled attention than by storage and rehearsal, the reverse seems true for STM tasks. Both WM and STM tasks measure executive attention control and STM storage to some degree (Kane et al., 2004). We argue that WM is tied to attention control than STM, we mean that WM's predictive power reflects primarily, but not uniquely, variance attributable to controlled attention. STM tasks also require participants to use controlled attention to prevent PI that buildups from the previous trials. That is why we hypothesized that PI-reduced conditions could weaken the relationship between Gf and WM, as well as Gf and STM.

However, in our results, we did not find PI-reduced versions of WM and STM tasks significantly account for less variance in Gf. The observed correlations between Gf and memory tasks also did not decrease in PI-reduced conditions. These unexpected results were not without explanations. First, the PI manipulation in our study did not affect all potential sources of PI, including the attention shifts between the storage and the processing requirements in the WM tasks, which may not have been completely effective. Second, reading span is a dual task, and the predictive utility of reading span is due to contributions from both component tasks. The PI manipulations in our experiment made it easier to remember the TBR items in the storage component, but the nature of the processing component was not manipulated. Lépine et al. (2005) suggested that the nature of the processing is the most important factor in making WM tasks predictive of Gf. In the current experiment, engaging in the processing component of reading span still demanded controlled attention; hence, the correlations between Gf and WM in different conditions failed to be significantly different. Third, in both STM and WM tasks, it is possible that our manipulations were not strong enough to catch the changes of controlled attention. Proactive interference is built up because participants have difficulty in remembering a new item that is similar to items previously learned. The PI effect also varies as a function of the stimulus type, the number of prior items, and time between storage and retrieval (Bunting, 2006). Since there were only 15 trials in the experiment, it is possible that PI had not yet strongly built up. Future studies could consider using longer experiment (i.e., more trials) to build up more PI, therefore the effect of PI-reduced manipulations could be more significant.

Very few previous studies have demonstrated that the buildup and release of PI in memory tasks influence the predictive utility of the task (Bunting, 2006). It seems that future work will be needed to determine the role of controlled attention in the relation between PI in memory tasks and Gf, or whether such differential relationship findings are just not easily replicable.

In sum, our results on PI provide practical implications that people with low memory ability could benefit from those PI-reduced strategies in their daily memory activities. People could change the memory list to descending difficulty, or change the to-be-remembered materials alternatively in order to prevent proactive interference. However, the descending difficulty strategy is not as effective as the changing to-be-remembered items strategy according to our results. Future research is needed to explore how these strategies could be applied effectively in the educational settings.

Theoretically, we found individuals with lower memory ability could especially benefit from our PI-manipulation strategies. Individual with greater STM ability and attentional capacity (i.e., larger and more focus on TBR materials) can hold more items in the focus of attention and immune to PI. According to the controlled attention view, TBR materials are maintained in an active state with the help of attention (Engle, Tuholski, et al., 1999; Lépine et al., 2005). One of the greatest challenges for attention is to combat PI, as shown in our experiment. Hence, individual differences in susceptibility to the interference effect in our experiment could be explained by differences in the capacity of attention. However, future research is still needed to address the role of controlled attention in the relation between PI in memory tasks and Gf.

Table 5-1. Correlations between multiple measures of WM and RAPM from selected studies

Studies	WM tasks	*N*	*r*
Ackerman et al. (2002)	ABCD order	135	.36
	Alpha span		.38
	Backward digit span		.37
	Computation span		.24
	Figural-spatial span		.32
	Spatial span		.38
	Reading span		.23
Cohen & Sandberg (1977)	Running memory span slow	80	.59
	Running memory span fast		.56
Colom et al. (2004)	Counter	198	.32
	Sentence-verification		.29
	Line formation		.12
Colom et al. (2008)	Alphabet	111	.44
(Using Primary Mental Abilities to	Computation span		.50
test Gf)	Letter rotation		.41
Conway et al. (2002)	Reading span	120	.15
	Operation span		.20
	Counting span		.38
de Jonge & de Jong (1996)	Word span	289	.20
(Using Figural Analogical	Digit span		.21
Reasoning Test to test Gf)	Reading span		.20
	Computation span		.16
	Star counting		.19
Engle, Tuholski, et al. (1999)	Reading span	133	.28
	Operation span		.34
	Counting span		.32
Hambrick (2003)	Computation span	187	.23
	Reading span		.21
Jurden (1995)	Reading span	52	.20
	Counting span		.43
Kane et al. (2004)	Reading span	236	.35
	Operation span		.32
	Counting span		.25
	Symmetrical span		.39
Kyllonen & Christal (1990)	Grammatical reasoning	723	.35
Study 1	Numerical assignment		.54
(Using Armed Services	Digit span		.32
Vocational Aptitude Battery to test Gf)	Mental Arithmetic		.40
Miyake et al. (2001)	Letter rotation	167	.26
(Using Tower of Hanoi to test Gf)	Dot matrix		.24

Table 5-1. Continued

Studies	WM tasks	*N*	*r*
Schmiedek et al. (2009)	Reading span	96	.20
	Counting span		.41
	Rotation span		.32
Unsworth et al. (2009)	Reading span	138	.52
	Operation span		.49
	Symmetrical span		.51

Table 5-2. Correlations between multiple measures of STM and RAPM from selected studies

Studies	STM tasks	*N*	*r*
Bayliss et al. (2003)	Digit span	75	.17
	Corsi block span		.62
Cohen & Sandberg (1977)	Probed recall (first three)	80	-.03
	Probed recall (middle three)		.30
	Probed recall (last three)		.46
Colom et al. (2008)	Forward letter span	111	.39
(Using Primary Mental Abilities to test Gf)	Forward digit span		.30
	Corsi block span		.45
Conway et al. (2002)	Four versions of word span	120	.05-.10
Engle, Tuholski, et al. (1999)	Backward span	133	.27
	Dissimilar forward span		.19
	Similar forward span		.21
Kane et al. (2004)	Word span	236	.25
	Letter span		.33
	Digit span		.26
	Arrow span		.54
	Matrix span		.42
	Ball span		.53
Schmiedek et al. (2009)	*N*-back slow	96	.31
	N-back fast		.28
	Alpha span slow		.29
	Alpha span fast		.36
	Memory updating slow		.30
	Memory updating fast		.23

Table 5-3. Processing speed tasks, and the correlations between processing speed and RAPM, processing speed and WM from selected studies

Studies	Processing speed tasks	*N*	*r* with Gf	*r* with WM
Ackerman et al. (2002)	Scanning speed:	135		
	Name comparison		-.01	.02-.24
	Number sorting		.25	.23-.39
	Number comparison		.09	.06-.35
	Noun-pair		.22	.12-.44
	Pattern recognition:			
	Finding a and t		-.02	.05-.19
	Mirror reading		.23	.08-.32
	Summing to 10		-.01	.10-.31
	Canceling symbols		-.01	-.10-.17
	Memory speed:			
	Naming symbols		.18	.18-.37
	Divide by 7		-.11	-.10-.16
	Coding		.19	.12-.29
	Digit/symbol		.24	.20-.37
	Complex speed:			
	Sentence reading		.50	.14-.40
	Directional reading		.33	.16-.40
Bayliss et al. (2003)	Visual search	75	.35	.25-.53
	Verbal search		.37	.12-.57
Colom et al. (2004)	Rectangle or triangle filling	198	.10	.07-.34
	Vowel-consonant filling		.17	.09-.42
	Odd-even filling		.24	.16-.41
Colom et al. (2008)	Letter comparison	111	.25	.12-.23
(Using Primary Mental	Digit comparison		.31	.09-.19
Abilities to test Gf)	Arrow comparison		.21	.11-.17
Conway et al. (2002)	Digit-symbol substitution	120	-.08	-.06-.05
	Digit and letter copying		-.01	.05-.19
	Pattern comparison		.03	.16-.19
	Letter comparison		-.09	.13-.15
de Jonge & de Jong (1996)	Sentence reading speed	289	.32	.13-.27
(Using Figural Analogical Reasoning Test to test Gf)	Pseudo word speed		.11	.08-.27
Fry & Hale (1996)	Disjunctive arrow reaction	214	.12	.55
	Shape classification			
	Visual search			
	Abstractor matching-to-sample			

Table 5-3. Continued

Studies	Processing speed tasks	*N*	*r* with Gf	*r* with WM
Kyllonen & Christal (1990) Study 1 (Using Armed Services Vocational Aptitude Battery to test Gf)	Coding speed	723	.19	.07-.26
	Numerical operations		.27	.03-.28
Miyake et al. (2001) (Using Tower of Hanoi to test Gf)	Identical pictures	167	.15	.16-.24
	Hidden patterns		.27	.30-.39
Salthouse (1994)	Boxes and digit copying	246	.26	--
	Letter and pattern comparison		.21	
Sternberg & Gastel (1989) (Using Cattell Culture-Fair Test of g to test Gf)	Sentence verification	50	.32	--
	Finding A		.04	
Unsworth et al. (2009)	Math operation	138	.41	.24-.37
	Symmetrical decision		.41	.29-.43
	Sentence verification		.32	.31-.34

Note. Dashes indicate the results were not reported.

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