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# Cognitive control, automaticity, and working memory:

## A dual-process analysis

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#### Abstract

Cognitive control is a central concept in psychology but there are few standards for its definition and measurement. This study examined relations between two approaches to cognitive control, working memory (WM) and the process dissociation (PD) procedure. Span measures were used to form groups differing in WM capacity that then performed two PD memory tasks and two attention (Stroop) tasks. Estimates of control and automaticity were computed using PD independence equations. For the memory tasks, span differences selectively affected the control estimates. For the attention tasks, span differences were isolated to the "automatic" estimates, a finding argued to reflect differences in inhibitory control and supported by correlations among the estimates, WM measures, and a measure of fluid intelligence.

## Control, Automaticity, and Working Memory: A Dual-Process Analysis

One of the most important concepts in modern psychology is that of cognitive control the ability to think and behave in accordance with one's goals and intentions while simultaneously avoiding interference from competing sources of influence. Cognitive control has been argued to be a central aspect of a wide variety of cognitive abilities, including memory (Baddeley & Hitch, 1974; Hasher & Zacks, 1979; Jacoby, 1991; Koriat & Goldsmith, 1996), attention (Kane et al., 2001; Norman & Shallice, 1986; Posner & Snyder, 1975; Shiffrin, 1988; Shiffrin & Schneider, 1977), and general fluid intelligence (Conway, et al., 2002; Engle, Tuholski, et al., 1999; Kyllonen & Christal, 1990). Cognitive control appears to be a major factor distinguishing high-achievers from under-achievers (e.g., Hitch, Towse, & Hutton, 2001), and its loss has been linked to the cognitive deficits observed in normal aging (Jennings & Jacoby, 1993), as well to the cognitive impairments observed in amnesia (Cermak et al., 1993; Schacter, Verfaellie, & Anes, 1997) and schizophrenia (Braver, Barch, & Cohen, 1999; Cohen, Braver, & O'Reilly, 1998; Kazes et al., 1999, Linscott & Knight, 2001). Thus, the concept of cognitive control appears to have wide-spread importance for explaining a variety of psychological phenomena. Yet, despite its apparent importance, there is little agreement about how best to conceptualize such control (cf. Bargh, 1999; Dennett, 1984; Jacoby, 1991; Shallice, 1994; Stuss & Alexander, 2000), what psychological mechanisms underlie it (Cohen, Dunbar, & McClelland, 1990; Dempster, 1991; Engle et al., 1999; Hasher & Zacks, 1988; Monsell, 1996; Shiffrin, 1988), and how this central aspect of cognition should be measured.

The current research attempts to integrate two major approaches to cognitive control: Engle's (2002) working memory (WM) approach and Jacoby's (1991) process dissociation (PD) approach. As described more fully below, both of these approaches have enjoyed considerable success in defining and measuring cognitive control, as well as in accounting for an impressive range of empirical results. However, their successes have been pursued in relative isolation from one another. Moreover, despite a substantial degree of theoretical overlap, no published research has attempted to compare and contrast the two approaches, to derive and test competing predictions, or to improve one or the other approaches by building on the lessons (successes and failures) of each. This research is designed to take some initial steps in these directions.

The paper is organized as follows. First, brief descriptions of the WM and PD approaches to cognitive control are provided, focusing on how each defines and measures control. These initial sections also describe selective research from the two approaches; in particular, findings from both proactive interference (PI) and Stroop tasks are described, findings that have direct relevance to the current research. The next section briefly describes similarities and differences between the approaches in terms of both theoretical orientation and general patterns of empirical results.

To briefly foreshadow the specific experiments, traditional WM span measures were used to formulate two groups differing in WM capacity and thus cognitive control. These groups then performed PD variants of memory (PI) tasks and attention (Stroop) tasks, both of which have previously been linked to WM capacity as well as to cognitive control as measured by the PD procedure. To increase the generality of the findings, as well as to test some additional predictions regarding the domain-specificity of cognitive control, both verbal and spatial versions of the PI and Stroop tasks were used, resulting in 4 separate tasks. The main experimental analyses focused on estimates of controlled and automatic processes derived from the PD independence equations.

# Working Memory as Cognitive Control

Although it has a long history (Engle & Oransky, 1999), the modern concept of WM can be traced to Baddeley (Baddeley & Hitch, 1974; Baddeley & Logie, 1999) who proposed a more dynamic conceptualization of the short-term store popularized in Atkinson and Shiffrin's (1968) "modal model" of memory (see also Cowan, 1988; Schneider & Detweiler, 1987). In particular, Baddeley suggested that short-term or primary memory (James, 1890), rather than being a static structure, is better viewed as consisting of both storage and processing components, with the latter serving as the major source of cognitive control (and thus appropriately named the "central executive"). Moreover, critical to Baddeley's conceptualization of the central executive was the notion of limited cognitive capacity, the idea that there is a limitation on the number of cognitive activities that can be performed at any one time (see Kahneman, 1973). More recently, Engle and colleagues have proposed that the central executive portion of working memory can be viewed as coextensive with the idea of controlled attention and thus, cognitive control. Consistent with this claim, they have shown that people low in WM capacity are more susceptible to interference from extraneous information on classic tasks involving cognitive control, such as verbal fluency (Conway & Engle, 1994; Rosen & Engle, 1997), dichotic listening (Conway, Cowan, & Bunting, 2001), negative priming (Conway, Tuholski, et al., 1999, Engle, Conway, et al., 1995), antisaccade (Kane et al., 2001), proactive interference (Kane & Engle, 2000; Rosen & Engle, 1998), and Stroop (Kane & Engle, 2003).

The general idea of limited-capacity controlled processes enjoys wide-spread acceptance in the WM literature, although exactly how these processes are best measured is an ongoing debate (Daneman & Carpenter, 1980; Turner & Engle, 1989; Lustig, May, & Hasher, 2001). Nevertheless, span measures appear to have gained the most wide-spread acceptance in measuring cognitive control. WM span measures are tasks with concurrent storage and processing demands. For example, a commonly used span measure, the operation-word span task (Turner & Engle, 1989), requires participants to solve simple arithmetic problems while simultaneously trying to remember a list of unrelated words. Such measures have been shown to predict group differences on a variety of cognitive measures, including reading and comprehension (Daneman & Carpenter, 1980; Daneman & Tardif, 1987; Engle, Cantor, & Carullo, 1992; Masson & Miller, 1983), reasoning (Kyllonen & Christal, 1990), language acquisition (Gathercole & Baddeley, 1993), SAT performance (Daneman & Hannon, 2001; Engle et al., 1999), and even the learning of computer programming skills (Shute, 1991). Thus, although there is some question as to the "purity" of span tasks (see Cowan, 1988; Engle, Nations, & Cantor, 1990; Engle, Tuholski, et al., 1999; Oberauer, 2001), these tasks appear to provide a very sensitive index of an individual's WM attentional capacity and thus, by theoretical implication (Engle, 2002), cognitive control.

In summary, research on short-term and working memory has evolved from being concerned with simple storage to the manipulation of information to the notion that the central executive component of WM is a domain general processor coextensive with the idea of controlled attention, fluid intelligence and, most generally, cognitive control. Moreover, span measures have arisen as the primary method for identifying differences in cognitive control. The next subsections describe research examining differences in memory and attention performance as a function of cognitive control as defined by span measures.

*Proactive Interference.* Using the traditional A-B/A-C design, Rosen and Engle (1998) had high- and low-span individuals attempt to retrieve a target (C) from a list of recently presented cue-target pairs (A-C), where the retrieval cues (A) had also been paired with different

targets in a previous list (A-B pairings). They found that low-span individuals were much more likely to show intrusions of the initial cue-target pairings (A-B) when attempting to retrieve information from the second (A-C) list. Kane and Engle (2000) replicated the larger PI effects in low-span individuals and also showed that, when placed under cognitive load, high spans exhibited PI effects similar to those shown by low spans. Engle and colleagues explained these results in terms of the role of cognitive control for maintaining access to current task goals and for preventing the intrusion of previously encountered information that interferes with such goals. When working memory capacity is low, the ability to suppress goal-irrelevant, interfering information is diminished.

*Stroop.* The Stroop (1935) effect refers to the increase in response latency (or decrease in response accuracy) to name the ink color of an incongruent color word (the word "blue" written in red ink) compared to when the word is congruent with the ink color (the word "red" written in red) or unrelated (the word "truck" written in red). A good deal of research has been done linking the Color-Word Stroop task to a variety of cognitive functions (see MacLeod, 1991 for a review). It is perhaps best known, however, as a measure of inhibitory processes (Hasher & Zacks, 1988) because accurate performance requires one to successfully perform a more controlled task (color naming) in the face of a relatively automatic (unintended) one, word reading. Consistent with a controlled attention view of WM, Kane and Engle (2003) recently found a link between WM capacity and word-reading errors in the Stroop task. Specifically, they found that when the task involved a high proportion of congruent trials (75% congruent)—thus increasing the influence of more automatic (word-reading) processes (Lindsay & Jacoby, 1994)—low-span individuals were significantly more likely than high spans to make errors on

the low-probability incongruent trials. Thus, WM capacity appears to demonstrate clear links with the ability to avoid being influenced by potent, but task-irrelevant information.

## The Process Dissociation Approach to Cognitive Control

Independent of the research on working memory, research conducted within the Process Dissociation (PD) framework (Jacoby, 1991; Jacoby, Debner, & Hay, 2001; Jacoby & Kelley, 1992; Jacoby, Toth, & Yonelinas, 1993) has also focused on the concept of cognitive control, and has provided compelling evidence that it can be separated from the more automatic processes contributing to task performance. Perhaps what best distinguishes the PD approach from other approaches is its use of an operational definition of control. In particular, control in the PD procedure is defined as the difference in performance when one is *trying to* versus *trying* not to respond in some particular way (Jacoby, 1991). Moreover, the PD approach provides an empirical strategy for quantifying this control (as well as automaticity) via the use of two experimental conditions, one where controlled and automatic processes act in concert in order to produce the same response (called the "inclusion," "facilitation," or "congruent" condition) and one where controlled and automatic processes act in opposition (called the "exclusion," "interference," or "incongruent" condition). For both of these conditions, equations are used to represent how controlled and automatic processes are combined to produce a response (essentially serving as a formal theory of performance). These two equations can then be solved algebraically to derive estimates of control and automaticity for each person. The following sections describe the PD procedure more fully, in the context of prior research on Proactive Interference (PI) and Stroop tasks.

*Proactive Interference*. Recent research using the PD framework has explored the controlled and automatic contributions to performance in a variant of the A-B/A-C PI task (Hay

& Jacoby, 1996; Jacoby, Debner, & Hay, 2001). In these studies, participants began with an initial training phase where cue words were paired with word fragments that could be completed with either of two associatively related words (e.g., bed - s ee which can be completed with either "sheet" or "sleep"). One of the two words was then presented as the solution to the fragment, and the probability of a particular response word being presented as the completion was varied across multiple presentations of that same cue-fragment pair. For example, in a condition where the proportion congruency was 75% (henceforth PC75), the high-probability response ("sheet") was paired with the cue word 75% of the time, whereas the low-probability response ("sleep") was paired with the cue only 25% of the time. For the PC50 condition, the two possible completions were presented equally often. These training conditions (which, of course, used different sets of word pairs) were designed to create "habits" of differing strength that could potentially interfere with memory for later events. Following training, participants were then placed into a more standard cued-recall paradigm in which they were presented with short lists of word pairs to remember. Critically, some of the pairs presented for study were the high-probability pairings from the prior training phase ("bed-sheet") while others were the lowprobability pairings ("bed-sleep"). Finally, participants' memory for these short lists were tested by presenting them with cue-fragment pairs ("bed -s ee") which participants were asked to complete with target words from the study list.

This variant of the Proactive Interference (PI) paradigm, where the individual is trying to retrieve a target despite interference from earlier presented information (i.e., the training phase), creates the necessary conditions to obtain measures of control and automaticity. That is, in cases where the response presented in the study list was the *high-probability* completion during the initial training phase, a *congruent* condition is created, such that controlled and automatic

processes are working in concert. That is, participants could arrive at the correct response in a congruent case, either because they recollected the word from the study list (R), or because, when recollection failed (1-R), they relied on the most easily accessible response (A), the high-probability response from training. Thus, assuming independence between these controlled and automatic uses of memory, correct output of the study item can be represented by the equation R + A(1-R). By contrast, an *incongruent* condition is created when the target from the study list was the *low-probability* response during training. Here, correct responding depends on recollection of the target word from the study list because, if participants were to rely on accessibility, they would erroneously produce the high-probability response) are represented by A(1-R). The results from these two conditions can then be combined to get estimates of control and automaticity. Subtracting incongruent performance from congruent performance provides an estimate of cognitive control in the form of recollection (R). Once R is obtained, a measure of accessibility (A) can then be derived algebraically.

Using these equations to examine PI performance, Jacoby and colleagues (2001) found two critical results. First, estimates of A were significantly affected by the proportion congruency manipulation (i.e., A was larger in the PC75 training condition), but this manipulation had no reliable effect on R estimates. Conversely, age of the participants (young vs. old) was found to affect R, but not A. These findings support one of the strongest assumptions of the PD procedure, that controlled and automatic processes are independent, an issue discussed in more depth in a later section. What is important to note here is, according to the pattern of estimates, the increased errors in PI performance observed for older adults [which are similar to those shown by young adults with low WM span (Kane & Engle, 2000)] are completely due to deficits in their ability to recollect items from the study list; automatic influences from the training phase are age invariant.

*Stroop.* The PD approach has also been used to decouple the effects of word reading and color naming in Stroop performance. In particular, Lindsay and Jacoby (1994; also see Jacoby, McElree, & Trainham, 1999) manipulated the proportion of congruent and incongruent Stroop trials such that participants in a "mostly congruent" condition received 100 congruent trials and 20 incongruent trials (83% congruent or PC83), while those in a "mostly incongruent" condition received 20 congruent and 100 incongruent trials (PC17). In all conditions, the goal was to name the word's ink color, but to ignore the word itself, and a response deadline was used so that performance could be analyzed in terms of accuracy.

As in the PI studies, performance on the congruent and incongruent trials was combined to derive estimates of the controlled process of color naming (C) and the automatic process of word reading (W). That is, for the congruent trials, a correct response can be achieved simply by reading the word (W) or, where the initial word-reading response has been successfully suppressed (1-W), by engaging color-naming processes (C). Therefore, correct responding on congruent trials is represented by the equation W + C(1-W). On incongruent trials, in contrast, correct responding is dependent on the ability to name the color without being influenced by the word and is therefore expressed as C(1-W). As in the PI tasks, color-naming and word-reading estimates conformed to assumptions of independence; Lindsay and Jacoby (1994) found that increasing the number of congruent trials increased the contribution of word reading, but left color naming unchanged. By contrast, manipulating the saturation (clarity) of the ink color in which a color-word was presented affected the contribution of color-naming estimates, but had no effect on the estimates of word reading.

## WM and PD Approaches: Similarities and Differences

There are a number of similarities that motivate the comparison of the WM and PD approaches to cognitive control. First, both define control as reflecting an individual's current intentions and goals. In the WM literature, for instance, Kane and colleagues (Kane, Bleckley, Conway, & Engle, 2001) outlined a controlled attention view of working memory:

...WM capacity, the construct measured by WM span tasks, reflects the general capability to maintain information, such as task goals, in a highly active state. ...individual differences in WM capacity reflect the degree to which distractors capture attention away from actively maintaining information such as a goal state (p. 170).

Similar conceptions of control can be found in the PD literature:

...intentional control [is] the difference between performance when one is *trying to* as compared with *trying not to* engage in some act. If one is as likely to do something when trying not to do it as when trying to do it, clearly one has no control (Jacoby, Toth, & Yonelinas, 1993, p. 142).

There are also clear empirical parallels between the approaches. For example, the PD procedure has been used to illustrate selective cognitive control deficits in older adults (Jacoby, 1999; Jennings & Jacoby, 1993), individuals with closed head injuries (Schmitter-Edgecombe & Nissley, 2000), and neurologically intact, young adults who encode information under conditions of divided attention (Jacoby, 1991; 1998; Schmitter-Edgcombe, 1999). Interestingly, these same populations often demonstrate increased intrusions of irrelevant information in PI tasks (Jacoby, Debner, & Hay, 2001; Kane & Engle, 2000; Numan et al., 2000) and increased interference in Stroop tasks (Azouvi et al., 1996; Batchelor et al, 1995; Brink & McDowd, 1999; de Fockert, Rees, Frith, & Lavie, 2001; Vakil et al., 1995), patterns of performance observed in individuals with low WM span. More recently, Hedden and Park (2003) linked older adults' susceptibility to retroactive interference in working memory with decreases in the PD recollection estimate. Finally, both WM and conscious recollection have been linked to putative

control regions in the prefrontal cortex (Davidson & Glisky, 2002; D'Esposito et al., 1995; Duzel et al., 2001; Goldman-Rakic, 1987; Henson et al., 1999; Jiang et al., 2000; Shimamura, 1995, Smith & Jonides, 1999; Velanova et al., 2003).

*The PD assumption of independence.* While there are clear parallels between the Working Memory (WM) and Process Dissociation (PD) approaches to cognitive control, there are also striking differences. Perhaps the most obvious of these is the PD assumption that control and automaticity make *independent* contributions to behavior. This independence view assumes that the operation of automatic processes in no way constrains or modulates the operation of more controlled processes (and vice versa). The above dissociations support this claim by showing that it is possible to manipulate one estimate without influencing the other across a variety of experimental contexts and theoretically-derived manipulations.

However, there continues to be a debate in the literature regarding the appropriateness of independence assumptions in certain situations (Batchelder & Riefer, 1990; Bodner, Masson, & Caldwell, 2000; Curran & Hintzman, 1995; Jacoby, 1998; Joordens & Merikle, 1993; McBride, Dosher, & Gage, 2001). There are clearly situations in which relational models positing dependence between processes appear to do a better job of explaining memory performance (see Jacoby, 1998, for a dependence model of PI performance). Relevant to the current study is that, in situations where control and automaticity do not operate independently, use of the PD equations will not produce the double dissociations of the form described earlier.

Certain findings from the WM literature seem suggestive of this type of non-independent view of cognitive control. For example, Rosen and Engle (1998) found that low spans were more susceptible than high spans to intrusions of irrelevant information from prior lists in a PI paradigm and argued that it was due to low spans' inability to suppress such information.

Similarly, work by Gernsbacher and Faust (1991; also see Gernsbacher et al., 1990) found that less-skilled comprehenders (used here as a proxy for low spans) demonstrated continued activation of contextually inappropriate meanings of ambiguous words compared to more-skilled comprehenders. One interpretation of these findings is that individuals with low WM capacity (and less-skilled comprehenders) have less efficient suppression mechanisms, resulting in the increased (automatic) activation of irrelevant information. Such findings raise the possibility that, due to a *decrease* in low spans' cognitive control, they will experience a corresponding *increase* in the automatic activation, or strength, of irrelevant information. Thus, unlike aging results from the PD literature, it is not clear whether span differences can be accounted for by an independence model that posits invariance in automatic processes.

Another way that independence might be violated concerns changes in control across conditions differing in the strength of automatic (interfering) influences. For example, in the Stroop study by Kane and Engle (2003), span differences obtained only in the PC75 condition, where the to-be-ignored word could be used to produce the correct response on the majority of trials. Kane and Engle explained this result by suggesting that high spans were better able than low spans to increase their level of control (i.e., their ability to maintain the 'name the color' goal) as the automatic influences became stronger. In the context of PD, this explanation suggests that (a) estimates of cognitive control should increase across conditions for which the strength of automatic influences increases (i.e., from PC25 to PC75); and (b) changes in cognitive control across the PC conditions should be greater for high spans as compared to low spans. In contrast, the PD independence view predicts that, although low spans may indeed have less overall control than high spans, neither group should show changes in control across the PC conditions (cf. Lindsay & Jacoby, 1994). The issue of independence, then, presents a potential

division between the WM and PD approaches and provides a forum for testing competing predictions.

The locus of control in Stroop tasks. As discussed earlier, prior PD research in the memory domain (Jacoby et al., 2001) leads to the prediction that span differences in the PI task will be isolated to estimates of control; that is, low spans will show less recollection than high spans but automatic influences will remain invariant. Applying this same rationale to the Stroop task, however, leads to a theoretically implausible prediction; namely, that span differences should emerge in estimates of the controlled color-naming process, with estimates of the more automatic word-reading process being span invariant. This outcome seems unlikely given that the processes underlying color-naming do not appear to reflect the forms of control that are central in the WM literature; that is, goal maintenance and the gating (or inhibition) of distracting sources of information (Cohen, Dunbar, & McClelland, 1990; Duncan, 1990; Engle et al., 1995; Hasher & Zacks, 1988; Kane and Engle, 2003). Rather, color-naming processes seem better characterized as a measure of how accurately an individual can discriminate colors *during those* instances where they are successfully able to override the habitual word-reading response. That is, although color naming is indeed the goal in the Stroop task, estimates of this process do not appear to provide an index of how often the word-reading response is successfully overridden.

To further clarify this distinction, consider two individuals who differ in WM capacity but have a similar ability to discriminate colors. The individual with lower WM capacity will be more likely to forget the task goal and to respond impulsively on the basis of the word-reading processes than the individual with higher capacity; however, in cases where they both manage to resist the impulse to read the word, they will be equally accurate at discriminating its ink color. So, although the high-WM individual may demonstrate a greater ability to inhibit the irrelevant information, and thus would show smaller word-reading estimates, the color-naming estimates (i.e. how accurately color was named in situations where word-reading did not dominate) should be the same for the two individuals (given their equal color-discrimination abilities). Therefore, the ability to inhibit irrelevant information is not captured by the color-naming estimate, but is instead "contained" in the word-reading estimate (i.e., how often the individual is able to resist word-reading). Thus, a better prediction, consistent with the notion of goal maintenance and with previous PD aging results (Jacoby, McElree, & Trainham, 1999; Lindsay & Jacoby, 1994; Spieler, Balota, & Faust, 1996), is that there will be no span differences in color-naming estimates, but that low spans will show an *increase* in word-reading estimates reflecting their inability to override the automatic impulse to read the word.

Some additional evidence for this perspective has been presented by Toth (1997; see also Toth, Levine, Stuss, Winocur, and Meiran, 1995) using a *spatial* variant of the Stroop task (cf. Craft and Simon, 1970; Lu & Proctor, 1995). In this task, a right- or left-pointing arrow was presented to either the right or left of a central fixation point on each trial. Participants were instructed to make right- or left-handed responses according to the direction in which the arrow pointed, but to ignore its spatial location. As in the Color-Word Stroop task, Toth demonstrated that response times on congruent trials (e.g., right-pointing arrows to the right of fixation) were significantly faster than response times on incongruent trials (e.g., right-pointing arrows to the left of fixation). Moreover, a PD analysis (using equations analogous to the ones used in Color-Word Stroop) provided evidence that the form and spatial-location information afforded by the arrow operated independently (e.g., manipulating the proportion of congruent trials significantly affected the contribution of spatial information to performance, but had little effect on the form estimate). Most important, Toth (1997) found that while there were no age differences in form estimates (when adjusted for age-related slowing), older adults produced consistently higher space estimates, consistent with the claim that older adults suffer a deficit in inhibitory processes.

To summarize, I propose that it is the up-front inhibitory mechanism that defines the control important in working memory, and that this control (or, more specifically, the lack of it) is being indexed by the word-reading and space estimates in the two Stroop tasks. If low spans possess deficits in this control similar to older adults, they should demonstrate inflations in word-reading and space estimates, but their color-naming and form estimates should be equivalent.

PD Estimates: Domain-General or Domain-Specific? In addition to the primary goals described above, the present investigation will also address an interesting secondary issue, the domain-specificity of PD estimates. In pursuit of this goal, a spatial variant of the Proactive Interference task described above was included, in addition to the three tasks already described (Verbal PI, Color-Word Stroop, and Spatial Stroop). This task is based on one used by Caldwell and Masson (2001) who had participants place 18 common household objects (e.g., a watch, a plant, a loaf of bread) in two plausible locations within a house and to remember those locations for a later test. As in the Verbal PI task used by Hay and Jacoby (1996), a training phase was used to create associations of varying strengths between the object and its locations; in the PC75 condition, participants placed an object in one location on 75% of the trials and in the other only 25%. The influence of these 'habits' on subsequent memory for specific object-location pairings was then analyzed using standard PD memory equations. The results from this Object-Location task were remarkably similar to the results from Verbal PI task: The congruency manipulation affected the automaticity (habit) estimates but had no effect on estimates of recollection, again conforming to assumptions of independence.

By including both spatial and verbal versions of the PI and Stroop tasks, it becomes possible to address questions regarding the generality of PD estimates across cognitive processes (memory vs. attention) and different types of stimuli (verbal vs. spatial). This is an interesting issue because, whereas WM capacity has been demonstrated to be a domain-general phenomenon (Engle, Tuholski, et al., 1999; Kane, Hambrick et al., unpublished manuscript), there has been little examination of this issue in the PD literature (for one exception, see Salthouse, Toth, Hancock, and Woodard, 1997). The present study will examine the relationship between PD estimates of control and automaticity from a wide range of tasks, as well as identify the relations between PD estimates, WM measures, and a measure of fluid intelligence (Ravens).

# **Overview of Experiments**

To summarize, Process Dissociation (PD) techniques have been previously employed to obtain estimates of control and automaticity in Proactive Interference (PI) and Stroop tasks. Critical to the current research is that performance in these tasks has also been shown to differentiate individuals with high vs. low WM spans. However, despite the obvious parallels between the two literatures, the PD procedure has never been used to directly examine the processes underlying performance for different WM span groups. The current research applied PD techniques to the performance of individuals varying in WM capacity for verbal and spatial variants of PI and Stroop tasks. Specifically, participants performed (a) the verbal Proactive Interference paradigm described in Jacoby, Debner, and Hay (2001), (b) a variant of the Object-Location task used by Caldwell and Masson (2001), (c) a two-color variant of the Color-Word Stroop task (Cheesman & Merikle &, 1986; Merikle, Joordens, & Stolz, 1995), and (d) the Spatial Stroop task (Toth et al., 1995). These tasks were used to address issues surrounding the configuration of processes underlying performance for the span groups (independence vs. dependence), as well as secondary issues involving the generality of PD estimates.

# Method

**Participants.** Eighty-three participants were recruited using an existing database of Georgia Tech students and volunteers from the surrounding community. Each of the participants had previously completed a standard WM span measure, Operation Span (see Methods for a detailed task description). Forty participants were selected from the top quartile of the Operation Span distribution with scores  $\geq$  19 (comprising the high span group) and 43 were selected from the bottom quartile (scores  $\leq$  9; the low span group). An additional WM span measure, Reading Span, was then used to verify these initial classifications; high spans were required to score above the median on this task and low spans were required to score below the median.<sup>1</sup> The data from eight participants were excluded from the final analyses because there was poor agreement between their span measures, and thus they could not be confidently classified as high spans or low spans. Three additional participants were also excluded, two because they performed at least one task incorrectly and one due to previous neurological trauma. Of the remaining 72 participants, 36 (19 male) were classified as high spans and 36 (13 male) were classified as low spans. The two span groups did not differ with respect to mean age (25.11 for high vs. 26.47 for low; p = .257), but the high span group did report having significantly more formal education (15.36 years vs. 13.89 years; p < .01). All volunteers received payment of \$10/hour for their participation.

**Apparatus.** The primary tasks were administered in a large room on 4 Dell PCs, with each task assigned to a different computer. E-Prime 1.0 was used to present the stimuli and to record accuracy and reaction time for all tasks. The computer used to administer the Color-Word

Stroop task was equipped with a microphone connected via a MEL response box (model 200). All computers were separated by small dividers and a sound-absorbing barrier divided the large room into two smaller workspaces so that two participants could be tested simultaneously.

General Procedure. Tasks were administered in a single three-hour session, with participants receiving a 15-minute break half way through the session. Participants were tested either individually or in groups of two, with approximately half of the high spans and half of the low spans performing the tasks individually (21 vs. 18 respectively). Prior to the testing session, all participants received a brief description of the tasks, and consent and demographic information were obtained. To minimize distraction, all participants wore headphones when performing each task and two white-noise generators were placed at either end of the room. An experimenter was present for the entire session.

Participants performed the four experimental tasks in one of two fixed orders: (1) Spatial PI  $\rightarrow$  Color-Word Stroop  $\rightarrow$  Verbal PI  $\rightarrow$  Spatial Stroop or (2) Verbal PI  $\rightarrow$  Spatial Stroop  $\rightarrow$  Spatial PI  $\rightarrow$  Color-Word Stroop. These specific orders were chosen (a) to switch which tasks occurred earlier and later in the task sequence to mitigate practice and/or fatigue effects; (b) to prevent similar tasks from occurring consecutively (i.e., the two memory and attention tasks, and the two verbal and spatial tasks); and (c) to permit group testing by staggering the tasks requiring experimenter involvement (Verbal PI and Stroop).

#### Working Memory and gF Tasks

*Operation Span (OSPAN).* Participants recalled words that were presented in the context of an arithmetic task. Each display included a math problem followed by a to-be-remembered word (e.g.,  $IS(6 \times 2) - 5 = 7$ ? *CLASS*). Participants read each math equation aloud as soon as it appeared on the screen, and then responded aloud with a "yes" or "no"

response according to whether the equation was correct. Following this response, participants read the word aloud. For example the correct response to the above example would be "Is six times two minus five equal to seven... yes... class." As soon as the participant read the word aloud, the experimenter immediately pressed a key that triggered a 200 ms blank screen, followed by another stimulus or a recall cue ("???"). When presented with a recall cue, participants tried to recall each of the words from the preceding set in the order they appeared. Set sizes ranged from 2 to 6 stimuli per trial. An individual's OSPAN score was the sum of the number of words recalled from perfectly recalled sets.

*Reading Span (RSPAN).* Participants recalled letters against a background reading comprehension task. Each display included a sentence and a to-be-remembered letter (e.g., *Whenever I drink the newspaper, I always get depressed. ? M*). When the sentence appeared participants read it aloud, verified whether it made sense, and then read the letter (e.g., "Whenever I drink the newspaper, I always get depressed... no... m.") As soon as the participant read the letter, the experimenter triggered a 250 ms blank screen, followed by another stimulus or a recall cue ("???"). When presented with the recall cue, participants tried to recall each letter from the preceding set in order. An individual's RSPAN score was the sum of the number of words recalled from perfectly recalled sets.

*Ravens Progressive Matrices (RPM).* Participants completed an abbreviated (30 item) version of the RPM task using only the odd-numbered items from the original 60-item test (Raven, Court, & Raven, 1977). Participants saw 30 patterns composed of abstract shapes and lines with a single piece missing, and were required to select, from among six presented alternatives, which piece best completed the pattern. They completed as many problems as they could in 20 minutes.

# **Primary Tasks**

The four tasks used in the current research were chosen to reflect two dimensions of interest: cognitive domain (memory vs. attention) and stimulus type (verbal vs. spatial). One task represented each unique combination of these factors, which allowed the generality of the results to be examined across a broad spectrum of measures. The general procedure for these tasks was described in the introduction, so the following sections will be used to note and explain any departures from the original paradigms, and to describe the experiments in greater detail.

Verbal PI. The procedure for this task was modeled on Jacoby, Debner, and Hay (2001) from which the critical stimuli were also obtained. Training consisted of the presentation of 20 cue-fragment pairs (e.g., "bed -s ee "), each of which appeared 20 times over the course of 5 consecutive blocks. Each fragment could be completed with either of two associatively related words (e.g., "sheet" or "sleep") and the pre-experimental likelihood of using a particular response to complete a fragment was equated across sets of pairs (see Jacoby et al., 2001). Half of the cue-fragment pairs were assigned to the PC75 condition and half were assigned to the PC50 condition. For the PC75 condition, one of the completions was presented on fifteen (75%) of the trials (the "high-probability" response), and the other was presented five times (25%, the "low-probability" response). For the PC50 condition, each of the alternatives appeared on 10 trials. Each cue-fragment pair remained on the screen for 2 seconds, followed by the presentation of the "correct" completion for 1 second. Participants were instructed to begin each trial by reading the cue aloud and then silently guessing the correct completion for the fragment. To encourage silent guessing, participants were instructed that the goal of the training phase was to improve in their ability to accurately predict the correct completion across the training blocks. They were further instructed that, following their silent guess, they were to read aloud the correct completion when it appeared on the screen. Presentation of the completion was followed by a 500 ms blank screen prior to the presentation of the next cue-target pair. Cue-target pairs were fully counterbalanced across participants, such that pairs served equally often in the two PC conditions, and the two completions served equally often as the high-probability and low-probability responses. As well, trials were freshly randomized for each participant.

Immediately after training, participants completed 20 study-test cycles. Each study list consisted of 8 cue-target pairs (e.g., "bed - sheet", "knee - bone") and participants were instructed to remember those pairs for a subsequent test. Pairs were presented for 1 second each and were separated by a 500 ms blank screen. Three of the pairs included the high-probability (75%) completion from the prior training phase, one included the low-probability (25%) completion, and four were from the PC50 condition. Following each study list, participants' memory for that list was tested by presenting 10 cues along with their corresponding fragments (e.g., bed - s ee, knee - b n, etc.). Participants were asked to complete each fragment with the completion word presented in the immediately preceding list. Eight of the ten test fragments corresponded to targets studied in the preceding list; the remaining two "guessing" items had not been presented on the study list, but had been part of the training phase, one representing the PC75 condition and the other representing the PC50 condition. Participants were instructed that the test list would include items that were not studied and that they should respond to these items with the first appropriate completion that came to mind. Guessing items were included both as a baseline measure of habit and as a check on the success of the training phase; items from the PC75 condition were predicted to be given as the response on approximately 75% of the guessing trials, whereas items from the PC50 condition should be given on only 50% of the trials. Each critical item from training was studied a total of 8 times across all lists in a manner

that upheld the PC established for that item in training; for example, an item from the PC75 training condition appeared as a congruent item 6 times across the study lists and as an incongruent item 2 times. All items served as guessing items twice across the test lists. For all trials, the experimenter entered participants' responses into the computer.

*Spatial PI.* This task involved a simpler version of the Caldwell and Masson (2001) Object-Location task. Participants were presented with two blue boxes on the computer screen, one to the right and one to the left of a centrally presented object (e.g., a lamp, a flashlight, a shoe, etc). Participants were told that they would be presented with a series of common objects and that the goal of the task would be to place each object into one of the two boxes.

As in the Verbal PI task, participants began with a training phase, which consisted of the presentation of 20 different objects, each of which appeared 20 times. On each trial, participants were instructed to identify the object by naming it aloud and then to *silently* guess in which of the two boxes the object would be placed. The importance of guessing was emphasized as in the Verbal PI task. Two seconds after each object appeared, its "correct" location was indicated by changing the color of one of the boxes to red. Participants were instructed to indicate in which of the two boxes each object was placed (i.e., which box turned red) by pressing either the "P" (right box) or the "Q" key (left box). Following a participant's response, a 500 ms blank screen appeared, followed by the next trial. Participants were further instructed that each object would appear more than once and that, across trials, they should try to increase their ability to predict the correct location for each object. For the PC75 condition, the object was placed in one of the trials (25%, the "low-probability" response). For the PC50 condition, the object was placed in each of the boxes ten times. Object-Location pairs were fully counterbalanced across

participants such that pairs served equally often in the two PC conditions, and the two boxes served equally often as the high-probability and low-probability locations. Trials were randomized for each participant.

Immediately following training, participants received 20 study-test cycles. Each study list consisted of 8 trials where an object was paired with one particular location (e.g., the lamp would appear with a red box on the right) and participants were instructed to remember those object-location pairings. Three of those pairings included the high-probability (75%) location from the prior training phase, one included the low-probability (25%) location, and four were from the PC50 condition. Pairs (object and box) were presented for 1 second and were separated by a 500 ms blank screen. Immediately following each study list, participants' memory for that list was tested. For each test, participants saw 10 objects, one at a time, flanked on either side by a blue box (i.e., the display from training) and were asked to indicate the object's study location by pressing either the "P" key (right box) or the "Q" key (left box). Like the Verbal PI task, eight of the objects were from the immediately preceding list, whereas the remaining two objects comprised 'guessing items' that were trained but not included in the target study list. Each object was tested 8 times in a manner consistent with their earlier established PC and each item served twice as a guessing item.

*Color-Word Stroop.* Participants were tested using a two-color variant of the Stroop task (cf. Cheesman & Merikle, 1986; Merikle, Joordens, & Stolz, 1995) in which only two color words (red and blue) and two ink colors (red and blue) were used. This two-color variant is more similar to Spatial Stroop, which uses only two arrow directions (right and left) and two locations (right and left), making the estimates from the two tasks more directly comparable.

The proportion of congruent and incongruent trials was manipulated. The PC75 condition comprised 90 congruent and 30 incongruent trials, the PC25 condition comprised 30 congruent and 90 incongruent trials, and the PC50 congruent condition comprised 60 of each. Participants received three blocks of trials (one for each of the PC conditions) presented in counterbalanced order. In addition to the 120 critical trials, each block included 30 nonwords as neutral trials (e.g., "%%%%" in blue) interspersed randomly among the critical trials. Each block began with 30 buffer trials which adhered to the PC in that block and which were used to minimize interference from the associative learning established in preceding blocks and to allow performance to become stabilized. The order of trials was freshly randomized for each participant with the restriction that the PC mapping was upheld for every mini-block of 10 trials. Participants were instructed that their the goal was to name the word's ink color as quickly as possible. A microphone was used to record response latency for each trial, and the experimenter recorded accuracy by pressing the "1" key when the participant responded "red", the "2" for "blue" responses, and the "5" key for discarded trials. Discarded trials included partial responses ("bl-red"), stutters (r...r...red), and extraneous noises that inadvertently triggered the microphone (e.g., coughing, exhaling, etc.). It is important to note that, while partial responses were discarded, complete responses were scored as the first response made, even when followed immediately by a correction (e.g., "blue-red" was scored as "blue").

*Spatial Stroop.* Participants were tested using the Spatial Stroop procedure from Toth et al. (1995) where participants attempt to respond to an arrow's symbolic direction, while ignoring its spatial location. Participants were instructed to press the "P" key with their right hand as quickly as possible when the arrow pointed to the right (">") and to press the "Q" key with their left hand when they arrow pointed to the left ("<"). As in the Color-Word Stroop task described

above, each participant was exposed to three blocks of 120 trials representing the different PC conditions. For the PC75 condition, 90 of the trials were congruent and 30 of the trials were incongruent. These mappings were reversed for the PC25 block, and an equal number of congruent and incongruent trials (60 trials each) comprised the PC50 condition. Blocks were presented in counterbalanced order, and the order of trials was randomized with the restrictions that congruent and incongruent trials appeared equally often on the right and left side of fixation, and the PC mapping was upheld for every mini-block of 10 trials. As in the Color-Word Stroop task, 30 neutral trials (i.e., right- and left-pointing arrows presented at fixation) were randomly interspersed among the critical trials and 30 buffer trials (with the same PC) preceded each block to minimize interference from prior blocks and to achieve stable performance.

#### **Results and Discussion**

The results for the two memory tasks will be discussed first, followed by those for the attention tasks. Each section begins by describing observed performance (accuracy and/or RT) followed by estimates calculated using the PD equations described earlier. A final section examines correlations between the estimates from the four tasks.

#### Memory Tasks: Verbal PI.

Because the goal of this task was to examine participants' tendency to respond with either the high- or low-probability responses from training, alternative responses (i.e., those not in the response set) were not included in the statistical analyses nor were they used to compute PD estimates. Alternative responses occurred on only .083 % of the trials (i.e., high spans = .069%, low spans = .097%).

*Congruent and Incongruent Performance*. Table 1 contains the proportion of correct responses produced by high- and low-span participants in the Verbal PI task. As can be seen in

the table, performance was higher on congruent trials as compared to incongruent trials, and was higher for high spans as compared to low spans. This description was supported by a repeatedmeasures ANOVA, with Trial Type (congruent vs. incongruent) and PC (75 vs. 50) as withinsubjects factors and Span (high vs. low) as the between-subject factor, which revealed main effects of Trial Type, F(1,70) = 137.12, MSE = .009, p < .001, and Span, F(1,70) = 35.52, MSE = .023, p < .001. However, both of these main effects were qualified by reliable interactions. Trial Type interacted with PC, F(1,70) = 33.50, MSE = .013, p < .001, revealing that, relative to the PC50 condition, accuracy in the PC75 condition was higher for congruent trials, but *lower* for incongruent trials. Trial-type also interacted with Span, F(1,70) = 7.56, MSE = .009, p < .01, indicating a greater difference between congruent and incongruent trials for low spans relative to high spans. Most important, however, the three-way interaction between PC, Trial Type, and Span was significant, F(1,70) = 4.16, MSE = .013, p < .05. Looking at Table 1, it is clear that the least accurate performance obtains when low spans are required to respond to an incongruent trial in a high-congruency (PC75) context. Indeed, when directly comparing performance on incongruent trials in the PC50 and PC75 conditions, high spans did not show an appreciable change in performance, t(35) = 1.51, p = .139. However, the change for low spans is highly significant, t(35) = 4.33, p < .001. These results are a conceptual replication of the Rosen and Engle (1998) finding that low spans show greater proactive interference than high spans, but extend those findings by showing that this interference is elevated when competing responses are more strongly associated with the retrieval cue (as in the PC75 condition).

*Estimates of Control and Automaticity*. Performance on congruent and incongruent trials was used to calculate estimates of control and automaticity for each participant using the PD equations described earlier, and the means of these estimates were analyzed as a function of

Span and PC condition. Looking again at Table 1, control (recollection) was equivalent across the PC conditions, but was uniformly lower for low spans relative to high spans. These findings were confirmed by an ANOVA on the recollection estimates which found a significant effect of Span,  $\underline{F}(1,70) = 35.40$ ,  $\underline{MSE} = .045$ , p < .001, but no effect of PC condition,  $\underline{F}(1,70) = 2.05$ ,  $\underline{MSE} = .007$ , p = .156, and no interaction between the two factors,  $\underline{F}(1,70) = .93$ ,  $\underline{MSE} = .007$ , p = .339. The opposite pattern was obtained for the automaticity estimates; there was a significant effect of PC,  $\underline{F}(1,70) = 26.46$ ,  $\underline{MSE} = .023$ , p < .001, but no effect of Span,  $\underline{F}(1,70) = .76$ ,  $\underline{MSE} = .014$ , p = .386, and no interaction,  $\underline{F}(1,70) = 1.75$ ,  $\underline{MSE} = .023$ , p = .190. Thus, the PC75 training condition resulted in greater cue-target strengths than the PC50 condition, but these strengths were equivalent across the span groups. This double dissociation in the estimates as a function of WM span and PC is consistent with the claim that controlled and automatic processes made independent contributions to performance.

The proportions of high-probability responses on the guessing trials were highly consistent with the automaticity estimates produced by the PD equations (see Table 1). Similar to the automaticity estimates, analysis of guessing performance showed a main effect of PC,  $\underline{F}(1,70) = 91.98$ ,  $\underline{MSE} = .018$ ,  $\underline{p} < .001$ , but no effect of Span and no interaction ( $\underline{Fs} < 1$ ). These guessing items provide corroborating evidence that the training manipulation in this study was effective in producing differences in target accessibility. Note also that both the automaticity estimates and the guessing items produced 'probability matching', where the probability of responding with a particular set of items closely approximated the probabilities initially established for those items during training (see also Jacoby et al., 2001).

# Memory Tasks: Spatial PI Task.

*Congruent and Incongruent Performance.* Table 2 shows the proportion of correct responses produced by high- and low-span participants in the Spatial PI task as a function of Trial Type and Proportion Congruency. As in the Verbal PI task, accuracy on incongruent trials was lower than congruent trials for both groups, and low spans demonstrated less accurate performance overall relative to high spans. This was supported by a repeated-measures ANOVA, with Trial Type (congruent vs. incongruent) and PC (75 vs. 50) as within-subjects factors and Span (high vs. low) as the between-subject factor, which revealed a main effect of Trial Type,  $\underline{F}(1,70) = 137.12$ ,  $\underline{MSE} = .009$ , p < .001, and Span,  $\underline{F}(1,70) = 64.53$ ,  $\underline{MSE} = .038$ , p < .001. The main effect of Trial Type was qualified by a Trial Type x PC interaction,  $\underline{F}(1,70) = 20.27$ ,  $\underline{MSE} = .007$ , p < .001; relative to the PC50 condition, accuracy in the PC75 condition was higher for congruent trials but lower for incongruent trials. However, none of the interactions involving Span were reliable; most notably, the three-way interaction was not significant in this task ( $\underline{F} < 1$ ). In sum, low spans were more likely than high spans to make errors, but this decrease in accuracy was uniform across the PC conditions.

One possible reason for the failure to find an increased span difference in the PC75 condition of this task was that training was less effective in producing strong associative learning in the low spans. Support for this explanation is provided by performance on guessing items, analyzed in the next section. Additional evidence was provided by a strategy questionnaire completed by each participant following the Spatial PI task, and which included the following questions: (1) *On a scale from 1 to 5 [1 being "very easy" and 5 being "very difficult"], how would you rate the guessing task?* (2) *Did you try to guess the correct location on each trial?* (3) *Did you become a better guesser toward the end of the guessing task?* Importantly, all 72

participants reported that they did attempt to guess the correct location on each trial (Question #2), inconsistent with the simple explanation that low spans simply did not perform the guessing task as instructed. However, low spans rated the guessing task to be slightly more difficult that the high spans (3.81 vs. 3.36), and fewer low spans perceived themselves to have improved as guessers across the 5 blocks (24/36) relative to high spans (30/36). Unfortunately, as the same questionnaire was not administered following the Verbal PI task, no definitive claims can be made about their relative difficulty. However, the questionnaire responses for this task are at least consistent with the idea that training was less effective for the low spans.

*Estimates of Control and Automaticity*. Control and automaticity estimates for the Spatial PI task are in Table 2. These data represent a statistical replication of the Verbal PI task, with the control estimate affected only by Span,  $\underline{F}(1,70) = 64.61$ ,  $\underline{MSE} = .077$ ,  $\underline{p} < .001$ , and the automaticity estimate affected only by the PC manipulation,  $\underline{F}(1,70) = 15.81$ ,  $\underline{MSE} = .015$ ,  $\underline{p} < .001$ . As before, the general pattern provides good support for the idea that low spans have less cognitive control than high spans. Here, however, there is also a marginal effect of Span on the automaticity estimates,  $\underline{F}(1,70) = 3.70$ ,  $\underline{MSE} = .017$ ,  $\underline{p} = .060$ , with low spans demonstrating less automaticity than high spans in the PC75 condition (the interaction between PC and Span was not reliable F(1,70) = 2.07,  $\underline{p} = .155$ ). As described above, these marginal differences in automaticity may be due to differences in the effectiveness of training for the two groups.

The reduced effectiveness of the training procedure for the low spans in this task is further supported by the guessing items (see Table 2). Note again that these values are similar to the PD estimates of automaticity for this task. An ANOVA examining the effects of Span and PC on guessing found that, in addition to the expected effect of PC,  $\underline{F}(1,70) = 9.37$ ,  $\underline{MSE} = .016$ , p < .005, there was a marginally significant PC x Span interaction (F(1,70) = 4.01, p = .052) pointing to the reduced effect of training for the low spans in the PC75 condition. Coupled with the questionnaire data discussed above, this pattern suggests that training was less effective for the low spans in the Spatial PI task. It also suggests that the effect of Span on automaticity estimates reflected limitations in the spatial training procedure rather than a true process difference between the span groups.

In summary, the Spatial PI data again support the claim that low spans differ from high spans primarily in their level of cognitive control, and that the level of control remains constant despite changes in the level of automatic biases.

#### Memory Tasks: Interim Conclusions.

Together, the Verbal and Spatial PI tasks provide support for the claim that low spans are more susceptible to proactive interference than high spans. For both tasks, low spans were significantly more likely to erroneously respond with the high-probability response from training. And, in the Verbal PI task, these span differences in interference were magnified when irrelevant associations from training were particularly strong (i.e., in the PC75 condition). The control estimates in both tasks demonstrated notable span differences and were contrasted by an equally large (and selective) effect of PC on automaticity. These double dissociations provide good evidence for the independent operation of control and automaticity in PI tasks.

Also note the implication of the above findings for the elevated interference observed for low spans in the PC75 congruency condition of the Verbal PI task; namely, that such elevations can be completely accounted for with an independence model of cued recall. That is, asymmetric patterns of interference in memory performance need not imply span differences in the strength of automatic biases (Jacoby et al., 2001; cf. Hasher, Quig, & May, 1997; Hasher & Zacks, 1988) nor that high (or low) spans adjust their level of control according to the strength of interfering information.

#### Attention Tasks: Color-Word Stroop.

To briefly reiterate the main goals of examining Stroop performance, I first wanted to reexamine the Kane and Engle (2003) finding that low spans produce more word-reading errors than high spans, but only in conditions where word-reading processes are particularly strong (i.e., in PC75 conditions). A second goal was to determine if that pattern of performance could be accounted for with the independence Stroop model advanced by Lindsay and Jacoby (1994). Consistent with that model, I expected the PC manipulation to have a significant effect on the word-reading estimates (increasing from PC25 to PC50 to PC75) but no effect on the colornaming estimates. The most important goal was to examine whether span differences would occur in the "controlled" color-naming estimate or the more "automatic" word-reading estimate. Assuming that the form of control targeted by WM researchers (and span measures) is the ability to override or inhibit reflexive processes, I expected the low spans to show consistently higher word-reading estimates than the high spans, reflecting their lessened ability to inhibit.

*Data trimming*. For all ensuing analyses, individual means were trimmed to exclude trials with latencies less than 200 ms and trials where the participant stuttered, gave a partial response ("bl-red"), or made an extraneous noise prior to their response (e.g., coughing, etc.). For RT analyses, in addition to trials with a latency less than 200 ms and discarded trials, trials with RTs exceeding 3 standard deviations from the mean of each condition were also excluded. Less than 2% of the trials were trimmed for both high spans (1.7%) and low spans (1.6%).

*Order analyses*. Kane and Engle (2003; also see Lowe & Mitterer, 1982) found that the magnitude and locus (accuracy vs. RT) of Stroop interference changed as a function of the order

of PC conditions. Because PC order was not fully counterbalanced in the current task, it is conceivable that it might have affected performance. To address this concern, order effects in both accuracy and latency data were examined using an ANOVA that included order as an additional between-subjects factor. For the accuracy data, there was no main effect of Order nor did it interact with any of the other variables. For the latency data, there was no main effect of Order, but the Trial Type x PC x Order interaction did achieve statistical significance,  $\underline{F}(1,70) =$ 6.99, <u>MSE</u> = .741, p < .001 with both groups showing increased congruent/incongruent differences during the first PC condition they received relative to later PC conditions. Importantly, Order never interacted with Span suggesting that the effects of order were the same for both high- and low-span individuals. Given its irrelevance to span differences, order was not included as a factor in the subsequent analyses.

*Reaction Time.* Table 3 shows RTs for correct responses as a function of Span, Trial Type, and Proportion Congruency. Note that low spans were slower to respond in all of the conditions, including the neutral baseline condition. Note also that both groups were slower to produce correct responses on incongruent trials. In support of these claims, a repeated-measures ANOVA (including neutral trials) found main effects of Span,  $\underline{F}(1,70) = 14.77$ ,  $\underline{MSE} = 89716 \text{ p} < .001$ , and Trial Type,  $\underline{F}(2,140) = 162.48$ ,  $\underline{MSE} = 3873 \text{ p} < .001$ . However, both of these effects were qualified by reliable interactions: The Trial Type x PC interaction,  $\underline{F}(4,280) = 24.63$ ,  $\underline{MSE} = 1487 \text{ p} < .001$ , reflected the modulation of performance in the congruent and incongruent trials increasing from PC25 to PC75. The Trial Type x Span interaction,  $\underline{F}(2,140) = 8.87$ ,  $\underline{MSE} = 373 \text{ p} < .005$ , resulted from the increase in response latency for low spans on incongruent trials relative to high spans. The average RTs (in milliseconds) for congruent,

incongruent, and neutral trials for high spans in this task were 492, 558, and 499 respectively, and the corresponding values for low spans were 562, 671, and 587. However, the absence of a three-way interaction between the factors ( $\underline{F}$ <1) suggests that these differences were uniform across the three PC conditions. Thus, although low spans demonstrated greater RT interference in general, there was no evidence for disproportionate interference in the PC75 condition.

To further explore the RT results, measures of interference and facilitation were examined (Table 4). Stroop interference (and facilitation) is often calculated using neutral trials (i.e., the colored percent signs) which are assumed to provide a pure measure of color naming. Other researchers (e.g., Lindsay & Jacoby, 1994; Toth et al., 1995; see also Jonides & Mack, 1984), however, consider a direct comparison of congruent and incongruent trials to be more appropriate (hereafter referred to as "difference" scores). In what follows, both methods are used such that the strongest conclusions could be based on agreement across measures.

Analyses of both the difference scores ( $RT_{incongruent}$  minus  $RT_{congruent}$ ) and interference scores ( $RT_{incongruent}$  minus  $RT_{neutral}$ ) resulted in main effects of both Span [<u>F</u> (1,70) = 14.44 for difference scores and <u>F</u> (1,70) = 4.34 for interference scores; <u>ps</u> < .05] and PC [<u>Fs</u> (2,140) = 35.73 and 17.66; <u>ps</u> < .001]; that is, interference was greater for low spans and increased across the PC conditions (from 25 to 50 to 75). Neither of the Span x PC interactions were significant (<u>Fs</u> < 1) again indicating that span differences in RT were uniform across the PC. Facilitation demonstrated a similar pattern; main effects of both Span and PC (<u>Fs</u> = 7.48 and 12.26 respectively; <u>ps</u> < .01), but no interaction factors (<u>F</u> < 1). In general, the RT data point to greater interference for low spans, but such interference is not differential across the PC conditions.

A critical, but little examined, issue in the WM literature is the effect of span-related slowing on measures of performance. That is, although low spans consistently showed increased

interference effects in the present task, they also consistently responded slower across all conditions. In the aging literature, older adults also often show increased interference effects relative to the young in attention tasks such as Stroop; however, it is widely agreed that such effects can be artificially produced by the older adults overall slower RTs. Indeed, when proportional measures of interference are calculated (i.e., measures scaled to a participant's own baseline), interference effects for older adults often disappear (Verhaeghen & Meersman, 1998). To address this issue, I computed proportional measures by dividing each participant's interference and facilitation scores by their neutral baseline score. Interestingly, however, and in contrast to findings in the aging literature, this adjustment did not change the pattern of data for any of the reported measures: Difference, interference, and facilitation scores continued to show main effects of Span and PC (ps < .05) with no interactions (Fs < 1.10). Thus, it would appear that, although low spans are consistently slower than high spans, such slowing does not account for their elevated interference in the Stroop task.

*Accuracy.* The accuracy data for the Color-Word Stroop task are included in Table 3. Note that errors were most pronounced on incongruent trials and in the PC75 condition, and that this was especially the case for low spans. These descriptions were supported by a repeated-measures ANOVA, which revealed main effects of Trial Type,  $\underline{F}(2,140) = 85.24$ ,  $\underline{MSE} = .009$ ,  $\underline{p} < .001$ , PC,  $\underline{F}(2,140) = 24.55$ ,  $\underline{MSE} = .002$ ,  $\underline{p} < .001$ , and Span,  $\underline{F}(1,70) = 15.35$ ,  $\underline{MSE} = .007$ ,  $\underline{p} < .001$ . The first-order interactions between PC and Span,  $\underline{F}(2,140) = 3.95$ ,  $\underline{MSE} = .002$ ,  $\underline{p} < .005$ ,  $\underline{p} < .001$ , and Trial Type and PC,  $\underline{F}(4, 280) = 32.37$ ,  $\underline{MSE} = .002$ ,  $\underline{p} < .001$ , but all were qualified by an interaction between the three factors,  $\underline{F}(4, 280) = 3.50$ ,  $\underline{MSE} = .002$ ,  $\underline{p} < .01$ . Similar to the Verbal PI task, low spans made considerably more word-reading errors on incongruent trials in the PC75 condition relative
to the high levels of accuracy achieved by both groups in the other conditions. These findings support Kane and Engle's (2003) claim that low spans are more susceptible to errors on incongruent trials when goal maintenance is made difficult by a high-congruency context.

Evidence for this increased susceptibility of low spans to error under high-interference conditions remains evident regardless of how one calculates interference. Table 4 depicts facilitation (congruent-neutral), interference (neutral-incongruent), and difference (congruentincongruent) scores as a function of span and PC condition. An ANOVA of the difference scores revealed main effects of both PC, F(2,140) = 36.87, MSE = .004, p < .001, and Span, F(1,70) = 16.95, MSE = .013, p < .001, but, more importantly, the Span x PC interaction was significant, F(2,140) = 4.38, MSE = .005, p < .05: Low spans demonstrated greater interference relative to high spans in the PC75 condition compared with the other two PC conditions. Looking at the table, the differential interference between high and low spans increased across the PC manipulations from PC25 (.03) to PC50 (.07) to PC75 (.10). Interference scores produced a similar pattern of differences; however, while the main effects of PC, F(2, 140) =34.61, MSE = .003, p < .001, and Span, F(1,70) = 17.55, MSE = .014, p < .001, were again significant, the Span x PC interaction was only marginal for this measure, F(2,140) = 3.05, MSE = .003, p = .065. Still, it is clearly the case that interference is greater for the low span group and that there is a definite tendency for that interference to increase under conditions of high interference. In contrast to the interference measures, there was no observable facilitation in this task, and no group differences obtained (p = .315).

**PD Estimates.** In order to generate estimates of the probabilities of color-naming and word-reading, a post-hoc deadline procedure was used in which the cumulative probability of a correct response in the neutral, congruent, and incongruent conditions was computed for each

100 ms interval from 200 to 1000 ms (Lindsay & Jacoby, 1994; Salthouse et al., 1997; Spieler et al., 1996; Toth, 1997). The results of this analysis are displayed in Figure 1 for both high span (left panel) and low spans (right panel). Notice that the probabilities increase with time, and that there are clear span differences such that the functions are shifted to the right for low spans illustrating the generally slower responding of this group across all conditions. The most pronounced shift appears to occur for incongruent trials consistent with the idea that low spans experienced particular interference in this condition.

The congruent and incongruent data summarized in Figure 1 were used to compute estimates of the probability of color-naming (C) and word-reading (W) for each participant at each successive interval using the Stroop equations presented earlier. The resultant estimates are illustrated in Figure 2 (solid lines for high spans, broken lines for low spans). Note the relatively monotonic increase in the color-naming estimate for both span groups. Note also the rise and subsequent fall of the word-reading estimates, demonstrating that automatic processes tend to have their largest effect near the beginning of a trial, but then taper off as responses become increasingly driven by more controlled processes. Finally, note the clear process dissociation observed in these functions. That is, the C estimates are consistently lower in the low spans but equivalent across the PC conditions. In contrast, the magnitude of the W estimates varies according to the strength of the PC manipulation (i.e., PC75 > PC50 > PC25) and are consistently higher in the low spans.

To better examine this double dissociation, an ANOVA was performed on the estimates from the 600-ms interval (see Table 5). This interval was chosen because it allowed the largest number of trials to be examined while performance was still clearly off ceiling (< .80). For the color-naming estimates, only the main effect of Span achieved significance,  $\underline{F}(1,70) = 14.06$ , <u>MSE</u> = .223 <u>p</u> < .001; neither the main effect of PC nor the PC x Span interaction were reliable (<u>Es</u> < 1.05) consistent with the findings from the earlier memory tasks. Also consistent with the memory findings, the estimates of W were significantly affected by PC, <u>F</u>(2,140) = 46.98, <u>MSE</u> = .013 <u>p</u> < .001. However, contrary to those earlier automaticity estimates, W estimates in the Stroop task were also significantly affected by Span, <u>F</u>(1,70) = 13.94, <u>MSE</u> = .043 <u>p</u> < .001, with low spans demonstrating higher word-reading estimates across all conditions. Taken at face value, these results suggest that, relative to high spans, low spans show both decreases in the more controlled, color-naming processes, as well as increases in the more automatic, word-reading processes

However, as with the interference and facilitation measures described earlier, interpretation of these PD estimates is complicated by the slower responding of the low span group. An additional analysis attempted to take these response-speed differences into account by computing "relative post-hoc deadlines" (Salthouse et al., 1997; Toth, 1997). That is, for each participant, RTs were computed at the point where he or she achieved a neutral-trial accuracy of .10, .20, .30, .40, .50, .60, .70, .80, .90, and 1.00. These RTs were then used as post-hoc deadlines for assessing probability correct on congruent and incongruent trials. Performance in these conditions was then used to compute estimates of color-naming and word-reading. The resultant color and word functions are depicted in Figure 3. With this method, the color estimates revealed relatively uniform linear functions no longer differentiated by Span. However, word estimates continue to show curvilinear functions separated according to PC and Span. Table 5 shows representative estimates for the interval where neutral performance reached .70. An ANOVA of the color-naming estimates revealed no main effect of Span or PC and no interaction. By contrast, the corresponding ANOVA for word-reading estimates revealed main effects of both PC,  $\underline{F}(2,140) = 64.62$ ,  $\underline{MSE} = .014 \text{ p} < .001$ , and Span,  $\underline{F}(1,70) = 12.38$ ,  $\underline{MSE} = .036 \text{ p} < .005$ , with low spans showing consistently higher word-reading estimates across all conditions (differences of .07, .10, and .10 in the PC25, PC50, and PC75 conditions respectively; interaction term,  $\underline{F} < 1$ ).

As a check on the validity of the estimates, correlations between the estimates and neutral-trial performance at the 600-ms interval were conducted (see Lindsay & Jacoby, 1994). The rationale was that performance on neutral trials (colored percent signs) should provide a relatively pure measure of color-naming abilities. Thus, if PD color-naming estimates provide a valid index of color-naming processes, they should correlate highly with neutral-trial performance. By contrast, word-reading estimates (which include no word information) should demonstrate much weaker relationships. Consistent with these predictions, color-naming estimates correlated very highly with neutral trials for both high spans ( $\underline{rs} = .92$  to .93;  $\underline{ps} < .$  001) and low spans ( $\underline{rs} = .85$  to .92;  $\underline{ps} < .$  001). By contrast, none of the correlations between word-reading and neutral performance were significant for either group ( $\underline{rs} = .29$  to .13; n.s.). These correlations are consistent with the earlier claim that color-naming estimates measure the efficacy of color-naming processes.

In summary, the results from the Color-Word Stroop task revealed deficits in both accuracy and RT for low spans across all conditions. Low spans showed a significant increase in automatic (word-reading) errors, relative to high spans, in the PC75 condition, replicating Kane and Engle's (2003) finding that performance is particularly poor for low spans in conditions where the context does not continuously support the "name-the-color" goal. As well, low spans showed greater interference in RT across conditions, a pattern that remained even after performance was adjusted for the low spans' overall slower responses. Perhaps most

importantly, unlike the memory tasks where span differences emerged solely in the control estimate (recollection), span differences in Stroop performance emerged in the more automatic, word-reading estimates. This is consistent with the earlier claim that the control indexed by WM span measures is not captured by the color-naming estimate, but is instead contained in the word-reading estimate; that is, the increased word estimates for the low-span group appear to indicate their lessened ability to inhibit irrelevant word information in this task.

### Attention Tasks: Spatial Stroop.

As with Color-Word Stroop, all analyses reported for the Spatial-Stroop task were based on each participant's trimmed data. The trimming procedure was identical to that used for the Color-Word Stroop task and resulted in less than 2% of the trials being eliminated for both high spans and low spans (1.2% and 1.7%, respectively).

Effects of order of PC conditions were again analyzed as a potential source of variability in this task using an ANOVA with Order as a between-subjects factor. Significant Order x PC x Trial Type interactions were obtained for both the accuracy data,  $\underline{F}(8,264) = 3.29$ ,  $\underline{MSE} = .002$ ,  $\underline{p} > .001$ , and the RT data,  $\underline{F}(8,264) = 2.18$ ,  $\underline{MSE} = 867$ ,  $\underline{p} > .029$  pointing to a general modulation of performance as a function of order. As before, however, Order did not interact with Span (all Fs < 1.2) suggesting that order effects were relatively uniform across the groups and thus likely didn't contribute to any observed span differences.

*Reaction Time.* Table 6 contains the RTs for correct responses in the Spatial Stroop task. Of interest here is that low spans were slower than high spans across all PC conditions and were particularly slow on incongruent trials. These findings were supported by an ANOVA which revealed main effects of Trial Type, PC, and Span (ps < .005), each of which was qualified by two higher-order interactions, the same interactions observed in the Color-Word Stroop task:

The PC x Trial Type interaction,  $\underline{F}(4,280) = 60.50$ ,  $\underline{MSE} = 887$ ,  $\underline{p} > .001$ , reflects the increasing difference in performance between congruent and incongruent trials from PC25 to PC75. The Trial Type x Span interaction,  $\underline{F}(2,140) = 7.41$ ,  $\underline{MSE} = 2323$ ,  $\underline{p} > .005$ , is due to the disproportionate increase in RT on incongruent trials for low spans; the average response latency (in ms) for congruent, incongruent and neutral trials, respectively, was, 427, 462, and 418 for high spans and, 512, 577, and 503 for low spans. Note, as well, that the difference in RT for neutral trials is reliable, t (70) = 4.18, p < .001, replicating the general slowing for low spans in this task. The three-way interaction was not reliable ( $\underline{F}$ <1), indicating that the higher interference effects for the low spans were uniform across the PC conditions.

As before, difference scores, interference scores, and facilitation scores were calculated (see Table 7). Both measures of interference (difference and interference scores) demonstrated main effects of PC ( $\underline{Fs} = 92.88$  and 40.42 respectively; ps < .001) and Span ( $\underline{Fs} = 7.99$  and 10.61 respectively; ps < .01), but neither demonstrated a significant interaction between the two (ps = .860 and .241 respectively); as with the overall data, there was no evidence for differential interference across the PC conditions for the two groups. Facilitation scores showed only a main effect of PC (F= 32.43 p < .001), suggesting that, as with Color-Word Stroop, the span groups did not demonstrate differential facilitation. Finally, to account for the potential effects of slowing in low spans, proportional measures of interference and facilitation were computed. This adjustment did not change the statistical pattern of results for any of the measures.

Overall, then, the Spatial-Stroop task revealed a pattern of performance that was generally similar to that found in the Color-Word Stroop task: Low spans took longer in all conditions to produce a correct response, and this difference was especially pronounced on

incongruent trials where low spans took much longer to override irrelevant, spatial information; that is, low spans showed greater RT interference than high spans.

Accuracy. The accuracy data for the Spatial Stroop task are also included in Table 6. These results replicate the finding in the memory tasks and the Color-Word Stroop task that incongruent performance is generally less accurate than congruent performance; both high- and low-span participants were more likely to make errors when the arrow's directional information and its spatial information were in conflict. This was supported by a repeated-measures ANOVA including Trial Type (congruent, incongruent, and neutral) and PC (25, 50, and 75) as within-subjects factors and Span (high vs. low) as the between-subjects factor, which revealed only a significant main effect of Trial Type, F(2,140) = 84.16, MSE = .005, p > .001. This main effect was qualified by a Trial Type x PC interaction, F(4,280) = 48.50, MSE = .002, p > .001; congruent and incongruent performance was moderated by PC, with the most notable decrement observed for incongruent trials in the PC75 condition (where incongruent trials occurred relatively infrequently making it difficult to maintain the task goal). In contrast to the previous tasks, however, there were no span differences in accuracy nor any interactions with Span (all Fs < 1). Therefore, while spatial information was clearly interfering with performance in this task, it was doing so similarly for the two span groups. This pattern obtains regardless of whether one calculates difference scores, facilitation scores, or interference scores (see Table 7); in all cases, there was a clear effect of PC (all p's < .001), but no reliable effects of Span. These results fail to support the hypothesis that low spans are more susceptible to interference that high spans, at least with respect to accuracy. Unlike with Color-Word Stroop, span differences in this spatial task were restricted to the RT data.

PD Estimates. Estimates of form- and space-based processing were generated using the same post-hoc deadline procedure used for Color-Word Stroop. That is, congruent, incongruent, and neutral performance were examined as a function of response time for each 100 ms interval between 200 and 1000 ms. As shown in Figure 4, the resulting functions were quite similar to those observed for the Color-Word Stroop task: Participants showed increased accuracy with time in all conditions, the functions for low spans were shifted to the right for all conditions indicating a general slowing in their responses, and this shift was particularly pronounced for incongruent trials pointing to the possibility of greater interference in this condition. PD estimates computed from these data are shown in Figure 5. Again similar to Color-Word Stroop, the form estimates showed monotonic increase over time for both groups, while the space estimates showed a corresponding rise and fall. Form estimates were consistently lower for the low-span group while space estimates were consistently higher. Using the same selection rule used for Color-Word Stroop (i.e., the value based on the most trials but with overall performance still clearly off ceiling) the 500-ms interval was chosen to take a closer look at the PD estimates (see Table 8). An ANOVA of the form estimates revealed a main effect of Span, F(1,70) =19.57, MSE = .195 p < .001, illustrating the same group differences obtained in Color-Word Stroop. In this task, however, there was also a significant effect of PC on the form estimates, F(2,140) = 8.88, MSE = .013 p < .001. This is an unusual finding given that none of the other tasks demonstrated an effect of PC on the more controlled processes. One possible explanation is that, of the four main tasks in this study, this is the only one where a high number of participants in the PC25 conditions (27 high-spans and 17 low spans) and, to a lesser degree the PC50 condition (6 high spans and 2 low spans) actually responded faster and more accurately on *incongruent* trials, thereby producing negative space estimates. Because the space estimates are

used in the denominator of the equation for form, the resultant form estimates are likely underestimated. The space estimates replicated the findings from the Color-Word Stroop task; they were significantly affected by both PC,  $\underline{F}(2,140) = 174.32$ ,  $\underline{MSE} = .013 \text{ p} < .001$ , and Span,  $\underline{F}(1,70) = 11.19$ ,  $\underline{MSE} = .050 \text{ p} < .005$ ; that is, the estimates increased from PC25 to PC50 to PC75, and were consistently elevated in the low spans across conditions (interaction term,  $\underline{F}<1$ ).

To examine span differences in the estimates adjusted for the baseline RT differences, the relative post-hoc deadline procedure introduced for the Color-Word Stroop task was used. The resulting form and space estimates are shown in Figure 6. As in Color-Word Stroop, the resultant form estimates showed similar, linearly increasing functions, while the space estimates continued to show differences as a function of PC conditions, although the span differences were notably reduced. Indeed, a closer inspection of a single interval (.70) supports these general claims (see Table 8). An ANOVA of the form estimates revealed no main effects and no interaction. The corresponding ANOVA for the space estimates revealed a significant effect of PC, F(2,140) = 231.45, MSE = .018 p < .001, but the effect of Span, although showing a trend toward elevated scores in the low spans, did not reach significance (p = .12). Thus, the adjustment for slowing appears to have eliminated span differences in the Spatial Stroop task, consistent with the idea that the greater interference effects in the low spans were predominantly due to general slowing. Alternatively, the less "capturing" effect of spatial information in this task (suggested by the smaller RT interference effects in PC50, as compared to Color-Word Stroop) may have made span differences more difficult to detect.

As with Color-Stroop, the validity of the estimates was investigated by correlating them with neutral-trial performance (centrally-presented arrows; see Toth et al., 1995). Arrows presented at fixation contain no space information and thus should provide relatively pure

measures of responding on the basis of form. Thus, if form estimates provide valid measures of form-based responding, they should correlate highly with performance on neutral trials; space estimates, on the other hand, should produce much weaker correlations. Consistent with these predictions, form estimates at the 500-ms interval correlated highly with neutral trials from this interval for both high spans ( $\underline{rs} = .90$  to .93;  $\underline{ps} < .001$ ) and low spans ( $\underline{rs} = .90$  to .93;  $\underline{ps} < .001$ ). By contrast, correlations between space estimates and neutral performance were not significant ( $\underline{rs} = .19$  to .03), with the exception of a *negative* correlation for high spans in the PC75 condition ( $\underline{r} = -.40$ ;  $\underline{p} < .05$ ) for which I have no explanation. Overall, though, these correlations support the notion that form estimates provide a relatively pure index of form-based processing.

## Interim Conclusions: Attention Tasks.

The main conclusions for the attention tasks were as follows. First, low spans were reliably slower than high spans in all conditions. Second, low spans exhibited greater RT interference than high spans in both tasks; however, although both groups showed increases in interference across the PC conditions (from PC25 to PC75), the increase was statistically the same for the two groups. Third, low spans showed lower overall accuracy than high spans; however, in contrast to the RT measures, the span effect reliably increased in the PC75 condition of Color-Word Stroop (Kane & Engle, 2003) and was numerically, but not reliably, larger in Spatial Stroop. Finally, PD estimates adjusted for slowing showed span differences only in the "automatic" word-reading estimates of Color-Word Stroop (low spans > high spans). This same pattern also obtained in the Spatial Stroop, but the difference failed to reach significance.

### **Correlational Analyses.**

Pearson correlations were used to assess relationships among the PD estimates from the various tasks, as well as the two WM measures (OSPAN and RSPAN) and the measure of fluid

intelligence (Ravens Progressive Matrices) described earlier. As discussed in the introduction, these analyses were motivated by the finding that performance on WM span measures correlates strongly with performance on other WM measures and measures of higher-order cognition (Engle, Tuholski, et al., 1999; Kane, Hambrick et al., unpublished manuscript)

Few studies have examined the predictive relations among PD estimates and their relation to other measures of cognition. Salthouse et al. (1997) found a small, but significant, correlation between the control estimates in their two PD tasks (cued recall and spatial Stroop). These estimates also loaded strongly on a "common factor" that they related to "deliberate, strategic processes." In contrast, the automaticity estimates from their tasks showed a weaker, nonsignificant relation to each other and showed no, or a slightly negative, loading on the common factor. Using these findings as a guide, *positive* correlations were expected among the control estimates from the present two memory tasks, as well as between those estimates, the WM measures, and Ravens. Further, based on the assumption that inhibitory control is being captured by the word-reading and space estimates in the attention tasks, *negative* correlations between these estimates and the other control measures were predicted. Finally, weaker correlations were expected for the automaticity estimates from the memory tasks, and for the discriminability measures (color naming and form processing) from the attention tasks.

Looking first at the memory measures (Table 9), the strongest pattern of relations to emerge was clearly among the control estimates, with the largest correlations occurring for conditions within the same task. The correlation between control estimates for the PC50 and PC75 conditions was .822 for Verbal PI and .908 for Spatial PI; cross-task correlations were smaller but still highly reliable ranging from .513 and .569. Thus, aside from a few moderate, unexpected correlations involving the automaticity estimates from the Spatial task (for which I have no explanation), the main finding from this analysis was that an individual's level of control in one memory condition provided a relatively strong indicator of his or her control in another, whereas the relationship among the automaticity measures was weaker and much less consistent.

Looking next at the attention tasks (Table 10), relatively strong correlations were found among the color-naming estimates from the three Color-Word Stroop PC conditions (see rows 7-9). In contrast, the form estimates from Spatial-Stroop (rows 10-12) failed to exhibit any significant within-task correlations. Unlike the memory tasks, the "automatic" estimates from the two attention tasks [word-reading (rows 1-3) and space (rows 4-6)] showed a relatively consistent pattern of within-task correlations (with only one of six failing to reach the .05 level). These correlations likely reflect the engagement of similar word-reading (in Color-Word Stroop) and spatial processing abilities (in Spatial Stroop) across the PC conditions. Note, however, that domain-general inhibitory control could also contribute to such positive relations.

In contrast to the relatively strong and consistent correlations obtained within the memory and attention domains, there were relatively few reliable correlations across the two domains (and thus no table is included)<sup>2</sup>. This suggests little overlap in the processes contributing to memory and attention performance. There were, however, a set of *negative* correlations (ranging from -.238 to -. 353; p < .05) between word-reading estimates from the PC50 condition in Color-Word Stroop and the four control estimates from the PI tasks. Although tentative, these correlations are consistent with the suggestion that inhibitory control is a necessary component of episodic recollection (Hasher & Zacks, 1988; Jacoby, 1999). Overall, however, the PD estimates did not display the domain-generality that typically characterizes theories of WM capacity (Engle et al., 1999).

The most important correlations were those that directly addressed the issue of whether PD estimates of control reflect the kind of control examined in the WM literature. To examine this issue, process estimates from the four experimental tasks were correlated with performance on the WM span tasks and Ravens (Table 11). With few exceptions, the pattern of correlations was quite clear: The control measures from the memory tasks demonstrated strong *positive* relationships with the three criterion measures, with all possible correlations being significant and ranging from .45 to .67. Perhaps even more notable, the word-reading estimates from the three criterion measures. These findings are consistent and reliable negative correlations with the three criterion measures with two of the main hypotheses under investigation in this study; namely, that (a) the form of control isolated by WM span measures is indeed being indexed by the PD procedure, but (b) that it is measured by the control estimates from the memory tasks and the putatively automatic estimates from the attention tasks.

#### **General Discussion**

The goal of the current research was to integrate two approaches to the study of cognitive control, the process dissociation (PD) approach of Jacoby and colleagues and the working memory (WM) approach of Engle and colleagues. In pursuit of this goal, the performance of high- and low-span groups was compared on PD variants of two memory tasks (Verbal and Spatial PI) and two attention tasks (Color-Word and Spatial Stroop). Overall, the results from these tasks were quite clear in suggesting that the control processes measured by the PD procedure have much in common with the forms of control operating in WM tasks. This commonality is even more noteworthy when it is recognized that the WM-span groups were formed on the basis of performance of what are effectively *short-term memory* tasks (in the literal sense of requiring only retention for a short period of time); yet, these groups showed

theoretically consistent process dissociations in estimates of *long-term memory* and in *attentional* (Stroop) performance. Correlations between process estimates, WM measures, and a measure of fluid intelligence (Ravens) further supported the idea that cognitive control as measured by the two approaches are tapping similar mechanisms. The present results thus offer promise both for integrating disparate approaches to cognitive control and, more generally, for more clearly defining and measuring this important concept.

The following two sections briefly discusses the implications of the present results for the PD and WM approaches to cognitive control. A final section notes some of the theoretical issues that could be informed by more fully integrating the two approaches.

## Implications of the current findings for the PD approach to cognitive control.

How did comparing high- and low-span participants inform the use of the PD procedure? In terms of the memory tasks, the most obvious implication is that the PD approach can be successfully extended to a new population. Prior PD research has revealed a number of factors that can selectively influence estimates of cognitive control, including full versus divided attention at encoding (Gruppuso et al., 1997; Jacoby, 1991; 1998; Jacoby et al., 1993; Schmitter-Edgecombe, 1999), study time (Jacoby, 1998), study repetition (Jacoby, 1999), response speed (Toth, 1996a; Yonelinas & Jacoby, 1995), head injury (St.Marie et al., 1996; Toth, 1996b; Schmitter-Edgecombe & Nissley, 2000), and the age of participants (Jennings & Jacoby, 1993). The present results extend this list to include differences in WM capacity. Examining patterns of recollection across various experimental manipulations in this way helps to more precisely define which cognitive processes are being measured by the PD recollection estimate.

The fact that span, aging, and attention exert similar selective effects on recollection suggests that these variables may be operating through a common mechanism. One candidate

for such a mechanism is the binding of mnemonic information at encoding. Hasher and Zacks (1988; see also Chalfonte & Johnson, 1996; Mitchell et al., 2000) speculated that older adults show greater interference than the young because they are less able to inhibit irrelevant information from entering working memory at encoding, resulting in this irrelevant information being bound with the target event. A similar binding explanation has been used to explain increased interference in low spans (Conway & Engle, 1994) and low memory performance as a function of divided attention (Wheeler & Treisman, 2002).

In terms of the attention tasks, the present study found that span effects emerged entirely in the word-reading estimates for the Color-Word Stroop task; a pattern also seen, albeit not significantly, for the spatial-location estimate from the Spatial Stroop task (after adjusting for span-related slowing in both cases). These findings are consistent with theorizing on goal neglect and inhibitory control (see Introduction, as well as Kane & Engle, 2003; Hasher & Zacks, 1988; Lindsay & Jacoby, 1994; Spieler et al., 1996) and support the earlier claim that the form of control emphasized in the WM literature-and ostensibly measured by WM span tasks-is being indexed by the more "automatic" estimate in Lindsay and Jacoby's (1994) twoprocess Stroop model. As evidence for this claim, the word-reading estimates demonstrated consistent reliable correlations with the WM span measures as well as with Ravens (ranging from -.35 to -.39). Note, however, these correlations were also consistently weaker than those found between these criterion measures and the memory control estimates. One possible explanation of this difference is that the PD estimates of inhibitory control (i.e., the word-reading and spatial-location estimates) may have been diluted by true word-reading (or spatial) processes, as well as by associative learning processes driven by the PC manipulation which was also reflected in these estimates. Coupled with recent claims that there may be multiple forms of control operating in the Stroop task—goal neglect and conflict resolution (see Kane & Engle, 2003)—this possibility suggests that a three (or more) process model may be necessary to accurately index inhibitory control in Stroop-like tasks.

Some evidence suggesting the need for a three-process model was provided Toth and colleagues (1995) in the context of the Spatial Stroop task. Based on the asymmetric effects of proportion-congruency (PC) on both reaction times and PD process estimates, they argued that an arrow's spatial location triggered two separable automatic influences. One influence reflected the associative learning induced by the PC manipulation (which they termed "associative automaticity"), while the other was a more "impulsive" response that was insensitive to the PC manipulation ("non-associative automaticity"). It is this latter, non-associative, component that I believe reflects the goal neglect discussed in the WM literature and which may provide a purer measure of inhibitory control. Future PD research should examine the ability of three-process models to separate capture processes from those involved with associative learning.

A final implication of the present results for the PD approach concerns the possibility that PD estimates can be successfully employed as individual difference measures (see also Salthouse et al., 1997). As noted in the introduction, span measures have been used to predict everything from laboratory memory tasks to computer-program learning. The strong correlations between the PD control estimates and the WM measures (ranging from .45 to .67) suggest that PD estimates could also be used to predict performance on these and other tasks requiring cognitive control. Indeed, PD control estimates from the Verbal and Spatial PI tasks correlated with performance on Ravens (from .52 to .67) at levels that were in the same general range as (and not statistically different from) those found for Operation Span (.75) and for Reading Span (.64).

### Implications of the current findings for the WM approach to cognitive control

The most obvious implication of the present results for the WM approach is that PD estimates can be successfully employed as a source of converging evidence for measuring cognitive control. Future research should be directed at comparing the two measures of control, as well as their ability to predict performance in different task domains. At a more speculative level, the close correspondence between PD estimates and span measures suggests a broader definition of what constitutes a measure of WM capacity. That is, consistent with Engle's (2002) claim that WM capacity is coextensive with controlled attention, it may be that any task requiring the maintenance of a goal in the face of competing information can potentially yield an informative measure of WM capacity. The present results suggest that the PD procedure can potentially be used to extract such a measure, regardless of whether the target task involves short-term storage with concurrent processing demands (cf. Baddeley & Hitch, 1974).

A related benefit of applying PD logic to the study of WM-based control is that span differences can be examined at the process level and not just at the task level. An interesting goal of future research will be to apply PD procedures directly to WM-span tasks. By focusing on processes, PD offers a useful tool for testing hypotheses about how cognitive control is operating. As an example, consider the increased mnemonic interference shown by low spans in situations where competing, irrelevant information is strong or "prepotent" (such as in the PC75 conditions of the present study). As noted earlier, possible interpretations of this pattern include the notion that inhibitory deficits result in unusually strong automatic biases in low spans (cf. Hasher & Zacks, 1988), or that high spans are able to more efficiently modulate control processes as automatic influences become stronger (Kane & Engle, 2003). PD estimates from the present experiments supported neither of these alternatives (see also Hedden & Park, 2003), and instead suggested that the low span's increased interference was entirely attributable to reduced control in the presence of unchanged automatic processes. Although this conclusion must obviously be verified by additional work, the point is that the PD procedure offers WM researchers a way to move from task-based to process-based hypothesis testing.

# Toward a better understanding of cognitive control: A synthesis of PD and WM.

Perhaps the most exciting aspect of the present research is its suggestion that our understanding of cognitive control can be enhanced by combining the strengths of the WM and PD approaches, and by integrating their traditionally disparate research domains. One of the more important theoretical contributions of the PD approach is its emphasis on defining and measuring cognitive control in the context of the more automatic processes operating in a task (Jacoby, 1991), and its ability to allow hypotheses regarding cognitive control to be tested at the process level, rather than the task level. In return, the WM approach to cognitive control helps tie PD measures more closely to attention (Cowan, 1995; Engle, 2002; Kane et al., 2001), as well as to underlying neural mechanisms (Kane & Engle, 2002; Smith & Jonides, 1999). The present experiments provide an initial foundation for building closer links between these mechanisms and the PD approach to control.

Additional theoretical questions regarding cognitive control may also benefit from the continued integration of the WM and PD approaches. One question in particular that may benefit from this integration is understanding <u>how</u> high spans use their normally functioning control processes to prevent the intrusion of irrelevant information. Jacoby, Kelley, and McElree (1999) distinguish between two general modes of cognitive control, early selection and late correction. *Early selection* involves using control to constrain retrieval or attentional set such that only appropriate responses come to mind. Thus, cognitive control is used early in

information processing to gate out irrelevant information and to prevent it from reaching consciousness or gaining access to the response system. This is contrasted with a late-correction mode where control is used to correct for (or "edit") inappropriate responses that have already come to mind automatically (cf. Devine & Monteith, 1999). Thus, the distinction between earlyselection and late-correction modes of control elucidates the various ways that control processes might operate to minimize the influences of more automatic ones; however, it makes no specific claims regarding the cognitive and neural mechanisms that might underlie these forms of control.

Kane and Engle (2003) recently argued that two control mechanisms might underlie span differences in attention tasks. The first mechanism is goal maintenance, where task goals are maintained in an active, accessible state so that responding can be appropriately constrained to task-relevant behaviors. The second mechanism is competition resolution, which involves resolving conflicts between competing sources of information on incongruent trials. Goal maintenance and competition resolution bear a striking similarity to the early-selection and latecorrection modes of cognitive control described by Jacoby and colleagues. Most interesting is that Kane and Engle linked their control mechanisms to specific brain regions. Goal maintenance was argued to be a function of the dorsolateral prefrontal cortex, whereas competition resolution was linked to anterior cingulate functioning. Integrating these two theoretical perspectives leads to the hypothesis that individuals in an early-selection mode will show much less anterior cingulate activation than those in a late-correction mode. More generally, combining the process-oriented PD approach with the WM approach which has typically emphasized individual differences and neural mechanisms is a powerful tool for testing various hypotheses regarding cognitive control at different levels of analysis. The continued integration of these two approaches will undoubtedly be a fruitful one.

### References

- Atkinson, R. C. & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes.(In K. W. Spence & J. T. Spence (Eds.), <u>The psychology of learning and</u> <u>motivation: Advances in research and theory</u> (Vol. 2, pp. 89—195). New York: Academic Press.
- Azouvi P., Jokic, C., Van der Linden, M., & Marlier, N. (1996). Working memory and supervisory control after severe closed-head injury: A study of dual-task performance and random generation. Journal of Clinical & Experimental Neuropsychology, 18, 317-337.
- Baddeley, A. D. & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), <u>The psychology of learning and motivation</u> (Vol. 8, pp. 47–89). New York: Academic Press.
- Baddeley, A. D. & Logie, R. H. (1999). Working memory: The multiple component model.(In A. Miyake & P. Shah (Eds.), <u>Models of working memory: Mechanisms of active</u> <u>maintenance and executive control</u> (pp. 28–61). New York: Cambridge University Press.
- Bargh, J. A. (1999). The cognitive monster: The case against the controllability of automatic stereotype effects. In S. Chaiken & Y. Trope (Eds.), <u>Dual-process theories in social</u> <u>psychology</u> (pp. 361-382). New York: The Guilford Press.
- Batchelder, W. H. & Riefer, D. M. (1990). Multinomial processing models of source monitoring. <u>Psychological Review</u>, <u>97(4)</u>, 548-564.
- Batchelor, J., Harvey, A. G., & Bryant, R. A. (1995). Stroop Colour Word Test as a measure of attentional deficit following mild head injury. <u>Clinical Neuropsychologist</u>, 9(2), 180-186.
- Bodner, G.E., Masson, M.E.J., & Caldwell, J.I. (2000). Evidence for a Generate-Recognize model of episodic influences on word-stem completion. <u>Journal of Experimental</u> <u>Psychology: Learning, Memory, and Cognition, 26(2), 267-293.</u>
- Braver, T. S. & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation, <u>Neuroscience & Biobehavioral Reviews</u>, <u>26(7)</u>, 809-817.
- Braver, T. S., Barch, D. M., & Cohen, J. D. (1999). Cognition and control in schizophrenia: A computational model of dopamine and prefrontal function. <u>Biological Psychiatry</u>, <u>46(3)</u>, 312-328.
- Brink, J. & McDowd, J. (1999). Aging and selective attention: An issue of complexity or multiple mechanisms? Journal of Gerontology: Psychological Sciences, 54, 30-33.
- Caldwell, J. I. & Masson, M. E. J. (2001). Conscious and unconscious influences of memory for object location. <u>Memory & Cognition</u>, <u>29(2)</u>, 285-295.

- Cermak, L. S., Verfaellie, M., Butler, T., & Jacoby, L. L. (1993). Attributions of familiarity in amnesia: Evidence from a fame judgment task. <u>Neuropsychology</u>, 7(4), 510-518.
- Chalfonte, B. L., & Johnson, M. K. (1996). Feature memory and binding in young and older adults. <u>Memory & Cognition</u>, 24(4), 403-416.
- Cheesman, J. & Merikle, P. M. (1986). Distinguishing conscious from unconscious perceptual processes. <u>Canadian Journal of Psychology</u>, 40(4), 343-367.
- Cohen, J. D., Braver, T. S., & O'Reilly, R. C. (1998). A computational approach to prefrontal cortex, cognitive control, and schizophrenia: Recent developments and current challenges. In A. C. Roberts & T. W. Robbins (Eds.), <u>The prefrontal cortex: Executive</u> <u>and cognitive functions</u> (pp. 195-220). New York: Oxford University Press.
- Cohen, J.D., Dunbar, K., & McClelland, J.L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. <u>Psychological Review</u>, <u>97</u>, 332-361.
- Conway, A. R. A. & Engle, R. W. (1994). Working memory and retrieval: A resourcedependent inhibition model. JEP: General, 123(4), 354-373.
- Conway, A.R.A, Cowan, N., & Bunting, M.F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. <u>Psychonomic Bulletin & Review</u>, <u>8(2)</u>, pg 331-335.
- Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D. J., & Minkoff, S. R. B. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. <u>Intelligence</u>, <u>30</u>, 163-184.
- Conway, A. R. A., Tuholski, S. W., Shisler, R. J., & Engle, R. W. (1999). The effect of memory load on negative priming: An individual differences investigation. <u>Memory & Cognition</u>, <u>27(6)</u>, 1042-1050.
- Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. <u>Psychological Bulletin</u>, <u>104(2)</u>, 163-191.
- Cowan, N. (1995). <u>Attention and memory: An integrated framework</u>. New York: Oxford University Press.
- Craft, J.L. & Simon, J.R. (1970). Processing symbolic information from a visual display: Interference from an irrelevant directional cue. Journal of Experimental Psychology, <u>83</u>, 415-420.

- Curran, T. & Hintzman, D.L. (1995). Violations of the independence assumption in process dissociation. Journal of Experimental Psychology: Learning, Memory, and Cognition, 21, 531-547.
- Daneman, M. & Carpenter, P. A. (1980). Individual differences in working memory and reading. Journal of Verbal Learning and Verbal Behavior, 19, 450-466.
- Daneman, M. & Hannon, B. (2001). Using working memory theory to investigate the construct validity of multiple-choice reading comprehension. Journal of Experimental Psychology: <u>General</u>, 130(2), 208-223.
- Daneman, M. & Tardif, T. (1987). Working memory and reading skill re-examined. Coltheart Max Ed Attention and performance 12: The psychology of reading. Lawrence Erlbaum Associates, Inc, Hillsdale, NJ, US.
- Davidson, P. S. R., & Glisky, E. L. (2002). Neuropsychological correlates of recollection and familiarity in normal aging. <u>Cognitive</u>, <u>Affective</u>, <u>& Behavioral Neuroscience</u>, <u>2(2)</u>, 174-186.
- de Fockert, J. W., Rees, G., Frith, C. D., & Lavie, N. (2001). The role of working memory in visual selective attention. <u>Science</u>, <u>291</u>, 1803-1806.
- Dempster, F. N. (1991). Inhibitory processes: A neglected dimension of intelligence. Intelligence, 15(2), 157-173.
- Dennett, D.C. (1984). <u>Elbow Room: The Varieties of Free Will Worth Wanting</u>. Cambridge, MA: The MIT Press.
- D'Esposito, M., Detre, J.A., Alsop, D.C., & Shin, R.K. (1995). The neural basis of the central executive system of working memory. <u>Nature</u>, <u>378(6554)</u>, 279-281.
- Devine, P. G. & Monteith, M. J. (1999). Automaticity and control in stereotyping. In S. Chaiken & Y. Trope (Eds.), <u>Dual-process theories in social psychology</u> (pp. 339-360). New York, NY: Guilford Press.
- Duncan, J. (1990). Goal weighting and the choice of behavior in a complex world. <u>Ergonomics</u>, <u>33</u>, 1265-1279.
- Duzel, E., Picton, T. W., Cabeza, R., Yonelinas, A. P., Scheich, H., Heinze, H., & Tulving, E. (2001). Comparative electrophysiological and hemodynamic measures of neural activation during memory-retrieval. <u>Human Brain Mapping</u>, <u>13(2)</u>, 104-123.
- Engle, R. W. (2002). Working memory capacity as executive attention. <u>Current Directions in</u> <u>Psychological Science</u>, <u>11(1)</u>, 19-23.

- Engle, R.W., Cantor, J., & Carullo, J.J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. <u>Journal of Experimental Psychology:</u> <u>Learning, Memory, & Cognition, 18</u>, 972-992.
- Engle, R. W., Conway, A. R. A., Tuholski, S. W., & Shisler, R. J. (1995). A resource account of inhibition. <u>Psychological Science</u>, 6(2), p. 122-125.
- Engle, R. W., Nations, J. K., & Cantor, J. (1990). Is "working memory capacity" just another name for word knowledge? Journal of Educational Psychology, 82(4), 799-804.
- Engle, R.W., Tuholski, S.W., Laughlin, J.E., & Conway, A.R.A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. Journal of Experimental Psychology: General, 128(3), 309-331.
- Gathercole, S.E. & Baddeley, A.D. (1993). <u>Working memory and language</u>. Hillsdale, NJ: Erlbaum.
- Gernsbacher, M. A. & Faust, M. E. (1991). The mechanism of suppression: A component of general comprehension skill. Journal of Experimental Psychology: Learning, Memory, & Cognition, 17(2), 245-262.
- Gernsbacher, M. A., Varner, K. R, & Faust, M.E. (1990). Investigating differences in general comprehension skill. Journal of Experimental Psychology: Learning, Memory, & Cognition, 16(3), 430-445.
- Goldman-Rakic, P.S. (1987). Circuitry of primate prefrontal cortex and regulation of behavior by representational memory. In F. Plum (Ed.), <u>Handbook of Physiology – The Nervous</u> <u>System, Vol. 5</u> (pp. 373-417). Bethesda, MD: American Physiological Society.
- Gruppuso, V., Lindsay, D. S., & Kelley, C. M. (1997). The process dissociation procedure and similarity: Defining and estimating recollection and familiarity in recognition memory. Journal of Experimental Psychology: Learning, Memory, and Cognition, 23, 259-278
- Hasher, L. & Zacks, R. T. (1979). Automatic and effortful processes in memory. Journal of Experimental Psychology: General, 108(3), 356-388.
- Hasher, L. & Zacks, R.T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), <u>The Psychology of Learning and Motivation</u>, Vol. 22 (pp. 193-225). San Diego: Academic Press.
- Hasher, L., Quig, M., & May, C.P. (1997). Inhibitory control over no-longer-relevant information: Adult age differences. <u>Memory & Cognition</u>, <u>25(3)</u>, 286-295.
- Hay, J.F. & Jacoby, L.L. (1996). Separating habit and recollection: Memory slips, process dissociations, and probability matching. <u>Journal of Experimental Psychology: Learning</u>, <u>Memory, & Cognition</u>, 22(6), 1323-1335.

- Hedden, T. & Park, D. A. (2003) Contributions of source and inhibitory mechanisms to agerelated retroactive interference in verbal working memory. <u>Journal of Experimental</u> <u>Psychology: General</u>, <u>132(1)</u>, 93-112.
- Henson, R. N. A., Rugg, M. D., Shallice, T., Josephs, O., & Dolan, R. J. (1999). Recollection and familiarity in recognition memory: An event-related functional magnetic resonance imaging study. Journal of Neuroscience, 19(10), 3962-3972.
- Hitch, G. J., Towse, J. N., & Hutton, U. (2001). What limits children's working memory span? Theoretical accounts and applications for scholastic development. <u>Journal of</u> <u>Experimental Psychology: General</u>, <u>130(2)</u>, 184-198.
- Jacoby, L.L. (1991). A process dissociation framework: Separating automatic from intentional uses of memory. Journal of Memory & Language, 30(5), 513-541.
- Jacoby, L.L. (1998). Invariance in automatic influences of memory: Toward a user's guide for the process-dissociation procedure. <u>Journal of Experimental Psychology: Learning</u>, <u>Memory, & Cognition</u>, 24(1), 3-26.
- Jacoby, L.L. (1999). Ironic effects of repetition: Measuring age-related differences in memory. Journal of Experimental Psychology: Learning, Memory, & Cognition, 25(1), 3-22.
- Jacoby, L. L., Debner, J. A., & Hay, J. F. (2001). Proactive interference, accessibility bias, and process dissociations: Valid subject reports of memory. <u>Journal of Experimental</u> <u>Psychology: Learning, Memory, & Cognition, 27(3)</u>, 686-700.
- Jacoby, J. J. & Kelley, C. M. (1992). A process-dissociation framework for investigating unconscious influences: Freudian slips, projective tests, subliminal perception, and signal detection theory. <u>Current Directions in Psychological Science</u>, <u>1(6)</u>, 174-179.
- Jacoby, L. L., Kelley, C. M., & McElree, B. D. (1999). The role of cognitive control: Early selection versus late correction. In S. Chaiken & Y. Trope (Eds.), <u>Dual-Process Theories</u> <u>in Social Psychology</u> (pp. 383-400). New York: Guilford Press.
- Jacoby, L.L., McElree, B., & Trainham, T.N. (1999). Automatic influences as accessibility bias in memory and Stroop tasks: Toward a formal model. In D. Gopher & A. Koriat (Eds.), <u>Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application</u> (pp. 461-486). Cambridge, MA: The MIT Press.
- Jacoby, J. J., Toth, J. P., & Yonelinas, A. P. (1993). Separating conscious and unconscious influences of memory: Measuring recollection. <u>Journal of Experimental Psychology:</u> <u>General</u>, <u>122(2)</u>, 139-154.

James, W. (1890). The principles of psychology (Vol 1). New York: Dover Publications, Inc.

- Jennings, J.M., & Jacoby, L.L. (1993). Automatic versus intentional uses of memory: Aging, attention, and control. <u>Psychology and Aging</u>, <u>8(2)</u>, 283-293.
- Jiang, J., Haxby, J.V., Martin, A., Ungerleider, L.G., & Parasuraman, R. (2000). Complementary neural mechanisms for tracking items in human working memory. <u>Science</u>, <u>287</u>, 643-646.
- Jonides, J. & Mack, R. (1984). On the cost and benefit of cost and benefit. <u>Psychological</u> <u>Bulletin, 96</u>, 29-44.
- Joordens, S. & Merikle, P.M. (1993). Independence or redundancy? Two models of conscious and unconscious influences. Journal of Experimental Psychology: General, 122(4), 462-467.
- Kahneman, D. (1973). Attention and effort. Englewood Cliffs, NJ: Prentice-Hall.
- Kane, M.J., Bleckley, M.K., Conway, A.R.A., & Engle, R.W. (2001). A controlled-attention view of working-memory capacity. <u>Journal of Experimental Psychology: General</u>, <u>130(2)</u>, 169-183.
- Kane, M.J. & Engle, R.W. (2000). Working memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. <u>JEP: LMC</u>, <u>26(2)</u>, 336-358.
- Kane, M.J. & Engle, R.W. (2003). The contributions of working memory capacity, goal neglect, and task set to Stroop interference: Data and a new theory. <u>Journal of Experimental</u> <u>Psychology: General.</u>
- Kane, M. J. & Engle, R.W. (2002). The role of prefrontal cortex in *working-memory* capacity, executive attention, and general fluid intelligence: An individual-differences perspective. <u>Psychonomic Bulletin & Review</u>, 9(4) 637-671
- Kane, M.J., Hambrick, Z. D., Wilhelm, O., Tuholski, S.W., Payne, T., & Engle, R.W. (unpublished manuscript). Working memory is domain-free.
- Kazes, M., Laurence B., Danion, J., Amado, I., Dominique, W., Philippe, R., & Poirer, M. (1999). Impairment of consciously controlled use of memory in schizophrenia. <u>Neuropsychology</u>, <u>13(1)</u>, 54-61.
- Koriat, A. & Goldsmith, M. (1996). Monitoring and control processes in the strategic regulation of memory accuracy. <u>Psychological Review</u>, <u>103(3)</u>, 490-517.
- Kramer, A.F., Hahn, S., Irwin, D.E., & Theeuwes, J. (2000). Age differences in the control of looking behavior: Do you know where your eyes have been? <u>Psychological Science</u>, <u>11</u>, 210-217.

- Kyllonen, P.C. & Christal, R.E. (1990). Reasoning ability is (little more than) working memory capacity?! <u>Intelligence</u>, <u>14</u>, 389-433.
- Lindsay, D.S.& Jacoby, L.L. (1994). Stroop process dissociations: The relationship between facilitation and interference. Journal of Experimental Psychology: Human Perception and Performance, 20(2), 219-234.
- Linscott, R. J. & Knight, R. G. (2001). Automatic hypermnesia and impaired recollection in schizophrenia. <u>Neuropsychology</u>, <u>15(4)</u>, 576-585.
- Lowe, D. G. & Mitterer, J. O. (1982). Selective and divided attention in a Stroop task. Canadian Journal of Psychology, <u>36</u>, 684-700.
- Lu, C.H. &. Proctor, R.W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. <u>Psychonomic Bulletin</u> <u>and Review</u>, <u>2</u>, 174-207.
- Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. JEP:G, 130(2), 199-207.
- MacLeod, C.M. (1991). Half a century of research on the Stroop effect: An integrative review. <u>Psychological Bulletin</u>, 109, 163-203.
- Masson, M. & Miller, J. A. (1983). Working memory and individual differences in comprehension and memory of text. Journal of Educational Psychology, 75, 314-318.
- McBride, D. M., Dosher, B. A., & Gage, N. M. (2001). A comparison of forgetting for conscious and automatic memory processes in word fragment completion tasks. Journal of Memory and Language, 45, 585-615.
- Merikle, P. M., Joordens, S., & Stolz, J. A. (1995). Measuring the relative magnitude of unconscious influences. <u>Consciousness & Cognition</u>, <u>4(4)</u>, 422-439.
- Mitchell, K. J., Johnson, M. K., & Raye, C. L. (2000). Aging and reflective processes of working memory: Binding and test load deficits. <u>Psychology & Aging</u>, <u>15(3)</u>, 527-541.
- Monsell, S. (1996). Control of mental processes. In V. Bruce (Ed.), <u>Unsolved mysteries of the</u> <u>mind: Tutorial essays in cognition</u> (pp. 93-148). Hove, England: Erlbaum.
- Norman, D. A. & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), <u>Consciousness and</u> <u>self-regulation</u> (pp. 1-18). New York: Plenum Press.
- Numan, B., Sweet, J. J., & Ranganath, C. (2000). Use of the California Verbal Learning Test to detect proactive interference in the traumatically brain injured. <u>Journal of Clinical</u> <u>Psychology</u>, <u>56(4)</u>, 553-562.

- Oberauer, K. (2001). Removing irrelevant information from working memory: A cognitive aging study with the modified Sternberg task. Journal of Experimental Psychology: Learning, <u>Memory, and Cognition, 27(4)</u>, 143-156.
- Posner, M. I. & Snyder, C.R.R. (1975). Attention and cognitive control. In R. L. Solso (Ed.), <u>Information Processing and Cognition: The Loyola Symposium</u> (pp. 55-85). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Raven, J. C., Court, J. H.,& Raven, J. (1977). <u>Raven's Progressive Matrices and Vocabulary</u> <u>Scales</u>. (New York: Psychological Corporation.)
- Rosen, V. M. & Engle, R. W. (1997). The role of working memory capacity in retrieval. Journal of Experimental Psychology: General, 126(3), 211-227.
- Rosen, V. M. & Engle, R. W. (1998). Working memory capacity and suppression. Journal of Memory and Language, 39, 418-436.
- Salthouse, T. A., Toth, J. P., Hancock, H. E., & Woodard, J. L. (1997). Controlled and automatic forms of memory and attention: Process purity and the uniqueness of agerelated influences. Journals of Gerontology Series B: Psychological Sciences & Social Sciences, 52B(5), 216-228.
- Schacter, D. L., Verfaellie, M., & Anes, M. D. (1997). Illusory memories in amnesic patients: Conceptual and perceptual false recognition. <u>Neuropsychology</u>, <u>11(3)</u> 331-342.
- Schmitter-Edgecombe, M. (1999). Effects of divided attention and time course on automatic and controlled components of memory in older adults. <u>Psychology and Aging</u>, <u>14(2)</u>, 331-345.
- Schmitter-Edgecombe, M., & Nissley, H. M. (2000). Effects of divided attention on automatic and controlled components of memory after severe closed-head injury. <u>Neuropsychology</u>, <u>14(4)</u>, 559-569.
- Schneider, W. & Detweiler, M. (1987). Working memory architecture. In G. H. Bower (Ed.), <u>The Psychology of Learning and Motivation. Vol 21</u> (pp. 53-119). San Diego, CA: Academic Press.
- Shallice, T. (1994). Multiple levels of control processes. In C. Umilta & M. Moscovitch (Eds.), <u>Attention and Performance XV</u> (pp.395-420). Cambridge, MA: MIT Press.
- Shiffrin, R. M. & Schneider, W. (1977). Controlled and automatic human information processing. II. Perceptual learning, automatic attending, and a general theory. <u>Psychological Review</u>, 84, 127-90.

- Shiffrin, R. M. (1988). Attention. In R. C. Atkinson & R. J. Herrnstein (Eds.), <u>Stevens'</u> <u>Handbook of Experimental Psychology</u>. New York: John Wiley & Sons.
- Shimamura, A. P. (1995). Memory and the prefrontal cortex. In J. Grafman & K. Holyoak (Eds.), <u>Structure and functions of the human prefrontal cortex</u> (pp. 151-159). New York, NY: Academy of Sciences.
- Shute, V. J. (1991). Who is likely to acquire programming skills? <u>Journal of Educational</u> <u>Computing Research</u>, 7, 1-24.
- Smith, E. E. & Jonides, J. (1999). Storage and executive processes in the frontal lobes. <u>Science</u>, <u>283(5408)</u>, 1657-1661.
- Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer's type. <u>Journal of</u> <u>Experimental Psychology: Human Perception and Performance</u>, <u>22</u>, 461-479.
- Ste-Marie, D. M., Jennings, J. M., & Finlayson, A. J. (1996). Process dissociation procedure: Memory testing in populations with brain damage. <u>Clinical Neuropsychologist</u>, <u>10(1)</u>, 25-36.
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. Journal of Experimental Psychology, 18, 643-662.
- Stuss, D. T. & Alexander, M. (2000). Executive functions and the frontal lobes: A conceptual view. <u>Psychological Research</u>, Special Issue: Executive Control, 63(3-4), 289-298.
- Toth, J. P. (1996a). Conceptual automaticity in recognition memory: Levels-of-processing effects on familiarity. <u>Canadian Journal of Experimental Psychology Special Issue:</u> <u>Implicit Memory Research in 1996, 50(1),</u> 123-138.
- Toth, J. P. (1996b). Memory and attention following traumatic brain injury: Process dissociations. <u>Clinical Neuropsychologist</u>, 10(3), 350-351.
- Toth, J.P. (1997). Implicit habit learning in the elderly: Separating intact from dis-inhibited processes. Presentation at the 38th annual meeting of The Psychonomic Society, Philadelphia, PA.
- Toth, J.P., Levine, B., Stuss, D.T., Oh, A., Winocur, G., & Meiran, N., (1995). Dissociation of processes underlying spatial S-R compatibility: Evidence for the independent influence of what and where. <u>Consciousness and Cognition</u>, 4, 483-501.
- Turner, M. L. & Engle, R. W. (1989). Is working memory capacity task dependent? Journal of Memory and Language, 28, 127-154.

- Vakil, E., Weisz, H., Jedwab, L., & Groswasser, Z. (1995). Stroop Color-Word task as a measure of selective attention: Efficiency in closed-head injured patients. <u>Journal of</u> <u>Clinical & Experimental Neuropsychology</u>, <u>17(3)</u>, 335-342.
- Velanova, K., Jacoby, L. L., Wheeler, M. E., McAvoy, M. P., Petersen, S. E., & Buckner, R. L. (2003). Functional-anatomic correlates of sustained and transient components of controlled processing engaged during episodic retrieval. <u>Journal of Neuroscience</u>, submitted.
- Verghaeghen, P. & De Meersman, L. (1998). Aging and the Stroop effect: A meta-analysis. Psychology and Aging, 13(1), 120-126.
- Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. Journal of Experimental Psychology: General, 131(1), 48-64.
- Yonelinas, A. P., & Jacoby, L. L. (1995). Dissociating automatic and controlled processes in a memory-search task: Beyond implicit memory. <u>Psychological Research</u>, <u>57(3-4)</u>, 156-165.

# Footnotes

1. Two different versions of Reading Span were used. The versions differed primarily in the set sizes they utilized, with Version 1 including set sizes 2-6 and Version 2 including set sizes 2-7. For Version 1, high spans achieved at least a score of 20 (mean = 25.35; SD= 3.13) and low spans scored below 20 (mean = 13.35; SD = 7.00). For Version 2, high spans scored above 35 (mean = 59.56; SD = 29.70) and low spans scored below 35 (mean = 18.91; SD = 14.34).]

2. In addition to the correlations discussed in the text, the following are the only other crossdomain correlations to achieve significance at the .05 level: STR75Co and VPI50A = .240, STR50Co and SPI75A = -.357, SST75F and VPI50A = .349, SST50F and SPI75C = -.236, SST25F and VPI50C = -.267. I offer no explanation for these correlations.

# Author's notes

I thank Jeff Toth for his assistance on all aspects of the research reported here. I also thank Randy Engle, the chair of my dissertation committee, and the other committee members, Chris Hertzog, Steve Lindsay, Wendy Rogers, and Andy Smith, for their suggestions and guidance. <u>Table 1</u>. Proportion of correct responses on congruent, incongruent, and guessing trials (standard deviations in parentheses), and process estimates as a function of span and proportion congruency (PC) in Verbal PI.

	<b>Proportion Correct*</b>			<b>Process Estimates</b>	
PC condition	Cong	<u>Incong</u>	Guess	<u>Control</u> <u>A</u>	utomaticity
High Spans					
PC50	.79 (.10)	.74 (.11)	.48 (.12)	.53 (.15)	.55 (.15)
PC75	.85 (.06)	.71 (.13)	.70 (.14)	.56 (.15)	.65 (.16)
Low Spans					
PC50	.69 (.09)	.64 (.12)	.48 (.12)	.33 (.16)	.53 (.11)
PC75	.80 (.10)	.54 (.15)	.69 (.12)	.34 (.18)	.70 (.12)

\* for guess trials, values represent the proportion of high-probability responses.

<u>Table 2</u>. Proportion of correct responses on congruent, incongruent, and guessing trials (standard deviations in parentheses), and process estimates as a function of span and proportion congruency (PC) in Spatial PI.

	<b>Proportion Correct*</b>			<b>Process Estimates</b>	
PC condition	Cong	Incong	Guess	<u>Control</u> <u>A</u>	utomaticity_
High Spans					
PC50	.79 (.09)	.77 (.13)	.49 (.12)	.56 (.20)	.51 (.14)
PC75	.84 (.10)	.73 (.15)	.60 (.14)	.57 (.21)	.62 (.16)
Low Spans					
PC50	.59 (.13)	.59 (.12)	.52 (.12)	.18 (.22)	.50 (.08)
PC75	.64 (.13)	.57 (.12)	.54 (.12)	.21 (.19)	.55 (.12)

\* for guess trials, values represent the proportion of high-probability responses.

<u>Table 3</u>. Mean reaction time (RT; in milliseconds) for correct responses and proportion of correct responses for congruent, incongruent, and neutral trials (standard deviations in parentheses) as a function of span and proportion congruency in Color-Word Stroop.

	<u>RT</u>			<u>Accuracy</u>		
PC condition	<u>Cong.</u>	Incong.	<u>Neut.</u>	<u>Cong.</u>	Incong.	<u>Neut.</u>
High Spans						
PC25	499	534	491	.99	.97	.99
	(31)	(137)	(34)	(.02)	(.03)	(.02)
PC50	484	549	494	.99	.95	.99
	(89)	(106)	(73)	(.01)	(.05)	(.02)
PC75	494	591	513	.99	.92	.99
	(105)	(103)	(91)	(.01)	(.08)	(.02)
Low Spans						
PC25	587	662	601	.98	.93	.99
	(121)	(135)	(108)	(.04)	(.05)	(.02)
PC50	556	661	585	.99	.89	.99
	(103)	(135)	(97)	(.02)	(.09)	(.02)
PC75	543	690	576	.99	.82	.98
	(99)	(169)	(100)	(.02)	(.15)	(.02)

<u>Note</u>: Cong. = congruent, Incong. = incongruent, and Neut. = neutral. "PC" refers to the proportion of congruent trials. See text for details.

<u>Table 4</u>. Difference, interference, and facilitation measures in Reaction Time (RT; in milliseconds) and Accuracy as a function of span and proportion congruency in Color-Word Stroop.

	<u>RT</u>			<u>Accuracy</u>		
PC condition	<u>Diff</u>	Int	Fac	<u>Diff</u>	Int	Fac
High Spans						
PC25	35	43	-8	.02	.02	.00
	(37)	(29)	(38)	(.04)	(.03)	(.02)
PC50	65	55	10	.03	.03	.00
	(35)	(43)	(26)	(.06)	(.06)	(.02)
PC75	97	78	19	.07	.07	.00
	(64)	(59)	(20)	(.08)	(.08)	(.02)
Low Spans						
PC25	75	61	14	.05	.06	01
	(57)	(54)	(57)	(.05)	(.05)	(.04)
PC50	105	76	29	.10	.10	.00
	(61)	(62)	(35)	(.08)	(.09)	(.02)
PC75	147	114	33	.17	.17	.00
	(97)	(102)	(33)	(.15)	(.14)	(.03)

<u>Note</u>: Diff = difference scores, Int = interference scores, and Fac = facilitation scores. "PC" refers to the proportion of congruent trials. See text for details.

<u>Table 5</u>. Color-Naming and Word-Reading estimates from the absolute deadline (600 ms interval depicted) and the relative deadline (neutral = .70 depicted) analyses for Color-Word Stroop.

	Absolute Estimates	Deadline 6 (600ms)	Relative Deadline Estimates (neutral = .70)	
PC condition	<u>Color</u>	<u>Word</u>	<u>Color</u>	<u>Word</u>
High Spans				
PC25	.77 (.25)	.09 (.13)	.65 (.12)	.16 (.13)
PC50	.77 (.27)	.19 (.12)	.64 (.15)	.24 (.12)
PC75	.72 (.31)	.29 (.19)	.64 (.16)	.37 (.19)
Low Spans				
PC25	.50 (.30)	.22 (.12)	.67 (.16)	.23 (.13)
PC50	.52 (.32)	.28 (.15)	.68 (.16)	.34 (.14)
PC75	.51 (.34)	.38 (.18)	.60 (.22)	.47 (.15)
<u>Table 6</u>. Mean reaction time (RT; in milliseconds) for correct responses and proportion of correct responses for congruent, incongruent, and neutral trials (standard deviations in parentheses) as a function of span and proportion congruency in Spatial Stroop.

		<u>RT</u>		Accuracy				
PC condition	<u>Cong.</u>	Incong.	<u>Neut.</u>	<u>Cong.</u>	Incong.	<u>Neut.</u>		
High Spans								
PC25	463	445	422	.94	.94	.96		
	(76)	(84)	(76)	(.09)	(.10)	(.10)		
PC50	425	460	416	.97	.91	.97		
	(59)	(67)	(63)	(.09)	(.10)	(.09)		
PC75	394	481	415	.99	.86	.97		
	(55)	(70)	(65)	(.01)	(.11)	(.03)		
Low Spans								
PC25	555	563	517	.94	.93	.95		
	(127)	(151)	(128)	(.09)	(.10)	(.10)		
PC50	512	581	511	.97	.89	.96		
	(107)	(120)	(106)	(.07)	(.12)	(.09)		
PC75	470	589	481	.98	.82	.96		
	(119)	(148)	(99)	(.08)	(.14)	(.05)		

<u>Note</u>: Cong. = congruent, Incong. = incongruent, and Neut. = neutral. "PC" refers to the proportion of congruent trials. See text for details.

<u>Table 7</u>. Difference, interference, and facilitation measures in Reaction Time (RT; in milliseconds) and Accuracy as a function of span and proportion congruency in Spatial Stroop.

		<u>RT</u>		<u>Accuracy</u>				
<u>PC condition</u>	<u>Diff</u>	<u>Int</u>	Fac	Diff	Int	Fac		
High Spans								
PC25	-19	22	-41	.00	.02	02		
	(36)	(25)	(32)	(.06)	(.06)	(.04)		
PC50	34	44	-10	.06	.06	.00		
	(32)	(26)	(22)	(.06)	(.07)	(.03)		
PC75	88	66	21	.14	.12	.02		
	(38)	(22)	(33)	(.11)	(.10)	(.03)		
Low Spans								
PC25	8	46	-38	.02	.02	01		
	(85)	(62)	(42)	(.07)	(.05)	(.07)		
PC50	70	70	-1	.08	.07	.01		
	(68)	(57)	(50)	(.08)	(.06)	(.04)		
PC75	119	108	11	.15	.14	.02		
	(83)	(76)	(73)	(.13)	(.13)	(.06)		

<u>Note</u>: Diff = difference scores, Int = interference scores, and Fac = facilitation scores. "PC" refers to the proportion of congruent trials. See text for details.

	Absolute Estimates	Deadline s (500ms)	Relative Deadline Estimates (neutral = .70		
PC condition	<u>Form</u>	<u>Space</u>	<u>Form</u>	<u>Space</u>	
High Spans					
PC25	.68 (.22)	07 (.14)	.55 (.09)	09 (.16)	
PC50	.72 (.25)	.11 (.13)	.54 (.16)	.20 (.16)	
PC75	.78 (.24)	.30 (.17)	.58 (.15)	.43 (.14)	
Low Spans					
PC25	.45 (.27)	.04 (.17)	.58 (.11)	.00 (.20)	
PC50	.44 (.30)	.24 (.17)	.59 (.15)	.24 (.16)	
PC75	.50 (.34)	.38 (.19)	.54 (.20)	.44 (.19)	

<u>Table 8</u>. Form and Space estimates from the absolute deadline (500 ms interval depicted) and the relative deadline (neutral = .70 depicted) analyses for Spatial Stroop.

	1	2	3	4	5	6	7	8
1. VPI75C	1.00							
2. VPI50C	<u>.822</u>	1.00						
3. SPI75C	<u>.513</u>	<u>.518</u>	1.00					
4. SPI50C	<u>.560</u>	<u>.569</u>	<u>.908</u>	1.00				
5. VPI75A	296	203	201	195	1.00			
6. VPI50A	.046	062	.194	.160	239	1.00		
7. SPI75A	.284	.333	.187	.369	016	196	1.00	
8. SPI50A	.195	.116	.023	.052	011	.198	.068	1.00

Table 9.	<b>Correlations across th</b>	e Control (C) and	d Automaticity (A) estimates	for Verbal PI (VPI) and	Spatial PI (SPI).
		(-)			······································

<u>Note</u>: VPI = Verbal Proactive Interference task; SPI = Spatial Proactive Interference; 75 = PC75; 50 = PC50; C = controlled processes; A = automatic processes; **bold** = values significant at p < .01 level; *italics* = values significant at p < .05 level. Underlined values are correlations of theoretical interest.

<u>Table 10</u>. Correlations across the Color (C) and Word (W) Estimates for Color-Word Stroop (STR) and the Form (F) and Space (S) Estimates for Spatial Stroop (SST).

	1	2	3	4	5	6	7	8	9	10	11	12	
1. STR75W	1.00												
2. STR50W	<u>.504</u>	1.00											
3. STR25W	<u>.335</u>	<u>.380</u>	1.00										
4. SST75S	135	145	096	1.00									
5. SST50S	007	031	.037	<u>.405</u>	1.00								
6. SST25S	.132	.049	.089	. <u>189</u>	<u>.588</u>	1.00							
7. STR75C	492	131	091	.192	.067	.056	1.00						
8. STR50C	214	146	014	.235	030	020	<u>.273</u>	1.00					
9. STR25C	166	081	.238	.140	014	.195	<u>.445</u>	<u>.605</u>	1.00				
10. SST75F	.168	.004	171	421	.106	075	.192	130	130	1.00			
11. SST50F	.235	.219	006	053	125	.066	066	059	014	<u>.117</u>	1.00		
12. SST25F	.116	.040	.084	009	.022	.198	.069	150	006	. <u>151</u>	. <u>081</u>	1.00	

<u>Note</u>: STR = Color-Word Stroop; SST = Spatial Stroop; 75 = PC75 congruency; 50 = PC50; 25 = PC25; W = word-reading processes; C = color naming; S = spatial processing; F = form-based processing; **bold** = values significant at p < .01 level; *italics* = values significant at p < .05 level. Underlined values are correlations of theoretical interest.

	Ospan	Rspan	Ravens
VPI75C	. <u>517</u>	. <u>581</u>	. <u>579</u>
VPI50C	. <u>450</u>	. <u>548</u>	. <u>515</u>
SPI75C	. <u>627</u>	. <u>603</u>	. <u>648</u>
SPI50C	. <u>598</u>	. <u>618</u>	. <u>674</u>
VPI75A	144	243	105
VPI50A	.061	.001	.035
SPI75A	.234	.330	.274
SPI50A	.032	.136	.094
STR75W	<u>245</u>	<u>266</u>	<u>354</u>
STR50W	<u>293</u>	<u>438</u>	<u>390</u>
STR25W	<u>206</u>	<u>237</u>	<u>391</u>
SST75S	<u>057</u>	. <u>083</u>	. <u>014</u>
SST50S	<u>119</u>	<u>025</u>	<u>076</u>
SST25S	<u>223</u>	<u>208</u>	<u>231</u>
STR75Co	.081	.073	.064
STR50Co	116	189	034
STR25Co	.000	055	143
SST75F	.094	022	.058
SST50F	192	358	178
SST25F	125	074	152

<u>Table 11</u>. Correlations between Estimates, Span Measures, and Ravens.

<u>Note</u>: see Tables 9 and 10 for Memory and Attention abbreviations. **bold** = values significant at p < .01 level; *italics* = values significant at p < .05 level. Underlined values are correlations of theoretical interest.



















## Figure 4. Proportion of Correct Responses in Neutral, Congruent, and Incongruent Conditions in the Spatial Stroop task as a function of PC, Span and Post-Hoc Deadline





