Working memory has been implicated as a core cognitive construct that predicts how well people perform on many tasks that require higher-order cognition. For example, measures of working memory predict performance on tests of real-world abilities such as reading comprehension (Daneman & Carpenter, 1980; McVay & Kane, 2012), following classroom directions (Engle, Carullo, & Collins, 1991), learning a computer language (Kyllonen & Stephens, 1990; Shute, 1991), multitasking (e.g., performing four tasks simultaneously; Bühner, König, Pick, & Krumm, 2006; Hambrick, Oswald, Darowski, Rench, & Brou, 2010), and solving novel problems (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Martinez & Colom, 2009). People with a greater working memory capacity (WMC) exhibit an advantage over people with lesser WMC in many aspects of cognition.

Individual differences research has and continues to serve an important role in building and testing the connections of the nomological net (the network of interrelationships among constructs; Cronbach & Meehl, 1955) around the construct of WMC. Instead of viewing individual variation as noise, as is done in traditional experimental work, individual difference researchers harness the information provided by this variation to reveal critical associations and boundaries of how constructs relate to one another (Cronbach, 1957). Underwood (1975) has proposed that individual differences can be used as a “crucible” for theory construction whereby predictions of nomothetic theories that are confirmed by individual difference studies are allowed to exist, but failed predictions condemn the theory.

Researchers interested in individual differences typically use complex span tasks to measure WMC. Daneman and Carpenter (1980) developed the first complex span tasks in their pioneering work on the relationship between WMC and reading comprehension. Daneman and Carpenter’s tasks (two visual, one auditory) interleaved a simple span task (i.e., recall of a list of items) with a processing task. Subjects read aloud (or listened to) sentences presented in sets of two to six. After each set of sentences, subjects recalled the last word from all the sentences. These tasks required subjects to maintain or recover the last word of each sentence while (or in between) reading sentences. In two experiments, subjects’ performance on Daneman and Carpenter’s (1980) complex span tasks correlated strongly with the ability to recall facts from a story (*r*s = .67 - .81), with verbal SAT scores (*r*s = .49 – .59), and with questions about which noun a passage-ending pronoun referred to (*r*s = .72 – .90).

Turner and Engle (1989) used math equations instead of sentences for the processing task to test whether the relation between the processing portion of the complex span task and the criterion measure was important for complex spans predictive ability. This Operation Span Task (Ospan) presents subjects with a compound equation and solution [e.g., *(3 \* 2) - 1 = 5*)] and asks them to verify whether the solution is correct. The task interleaves words to be remembered with these equations. With the Ospan task, Turner and Engle found that a relation with reading comprehension still existed (*r* = .40). To examine if it was a general proficiency on the processing task that led to the relationship with reading comprehension, Turner and Engle partialed out their subject’s quantitative ability (using their quantitative SAT scores) from the relationship between Ospan and reading comprehension. The relationship was still statistically significant (*r* = .25). Turner and Engle (1989) provided evidence that what is measured by complex span tasks, presumably WMC, represents a domain-general construct that differs among people.

Complex span tasks have moderate to high internal consistency ranging from 0.7 -0.9 (Conway et al., 2002; Engle, Tulhoski et al., 1999; Kane et al., 2004; Unsworth, Heitz, Schrock, & Engle, 2005) and test-retest reliability usually ranging between 0.8 - 0.9 (Klein & Fiss, 1999; Turley-Ames & Whitfield, 2003; Unsworth et al., 2005).Complex span tasks are reliable, but are they valid measures of WMC? Because of the correlational nature of individual differences work, it is important to rule out third variables. Two confounding variables that have been investigated are strategy-use and effort. Using different tactics, Dunlosky and Kane (2007) and Turley-Ames and Whitfield (2003) have tested the hypothesis that the relation between complex span tasks and higher-order cognition is strategy driven. Both studies support the conclusion that effective strategy use did not mediate the relation between complex span tasks and higher-order cognition. In fact, Turley-Ames and Whitfield provided evidence that differential strategy usage masks the strength of the complex span and higher-order cognition relation.

Complex span tasks also do not predict higher-order cognition because the people who perform well on them are simply exerting more effort. In other words, the relation is not the result of people who just try harder in general on both the predictor and criterion measures. Heitz, Schrock, Payne, and Engle (2008) found that when given monetary incentives, low and high-WMC subject groups (upper and lower quartiles of the WMC distribution determined during a prior testing session) both improved performance. Most importantly, the effects of the incentives were additive with WMC.

**Evidence for relation between WMC and attention**

Ample evidence suggests that complex span tasks index the ability to control attention.Two dichotic listening experiments are illustrative. Conway, Cowan, and Bunting (2001) instructed subjects to verbally shadow the stimuli in one ear and to ignore stimuli in the other. Each subject’s name was presented once in the unattended ear. Sixty-five percent of low Ospan scorers heard their name while only 20% of high Ospan scorers heard theirs. Higher-WMC subjects were either more capable of inhibiting distracting stimuli or better at boosting the gain on the relevant stimulus (see Egner & Hirsch, 2005). Using the same task as Conway et al. (2001), Colflesh and Conway (2007) changed the instructions. Now, subjects were told to monitor both ears. Higher-WMC subjects (67%) were more likely to report hearing their name than lower-WMC subjects (35%). These two results provide evidence that WMC relates to the ability to control attention to auditory stimuli in accord with task goals for either superior monitoring of one channel or multiple channels.

**Functional importance of attentional control to WMC**

Why does complex span performance predict performance on higher-order cognitive tasks. No single factor has been shown to fully account for the WMC-fluid intelligence relationship.

Engle, Tuholski, Laughlin, and Conway (1999) and Conway et al. (2002) conducted similar latent-variable studies to parse out the contributions of short-term memory (STM) and WMC to fluid intelligence (a notable difference between the two was the inclusion of a latent variable for processing speed in Conway et al.). Both sets of authors conceptualized STM and WMC tasks to require the temporary storage of memorial information. But in addition to this storage, the complex span tasks measure an attentional control component that comes into play to maintain (or recover) the memory items when the interleaved processing portion of the complex span task is performed. In Engle, Tuholski et al. (1999), they used the equation: (WMC = STM + controlled attention + measurement error) to summarize this conceptualization. Indeed, consistent with this conceptualization when the common variance in STM and WMC was accounted for, the residual WMC variance was strongly related to fluid intelligence (in Engle, Tuholski et al. *r* = .49, in Conway et al. *r* = .60), while the common variance for WMC and STM, and the unique contributions of STM, were not.

Motivated by this, two recent latent-variable studies examined similar multi-faceted accounts of how WMC, as primarily measured by complex span tasks, relates to fluid intelligence (Shipstead. Lindsay, Marshall, & Engle, 2014; Unsworth, Fukuda, Awh, & Vogel, 2014).nEach study examined the contributions of attention control, retrieval from secondary memory, and primary memory abilities. In both studies, the best fitting model suggested that the relationship is fully mediated by these 3 factors.

**Characterizing the features of attentional control in WMC**

In both Engle, Tuholski et al. (1999) and Conway et al. (2002), WMC measures composed of verbal tasks correlated strongly with non-verbal (figural/spatial) measures of fluid intelligence. This result led both research teams to conclude that WMC is domain-general (in accord with Turner & Engle, 1989). Kane et al. (2004) explicitly examined the domain-generality of WMC. In agreement with the domain-general proposition for WMC, a confirmatory factor analysis (CFA) model of WMC with separate verbal and spatial WMC factors did not reflect the observed data any better than a single WMC factor solution. In a CFA model with all WMC and STM tasks included, a four-factor solution with separate verbal and spatial WMC and STM factors performed the best. At first blush, this looks like contradictory evidence for the domain-general view of WMC, but the WMC tasks were statistically determined to be more strongly correlated with each other than the STM tasks. Verbal and spatial WMC factors shared 70%-85% of their variance while the spatial and verbal STM factors shared only 40% of their variance. This stronger association between verbal and spatial complex span tasks represents the domain-general contribution of controlled attention to WMC. Together with the evidence previously provided by Engle, Tuholski et al. (1999) and Conway et al. (2002), the proposition that WMC is more of a domain-general construct than STM seems to be supported. Additionally, the finding of stronger correlations between spatial and verbal WMC measures than those from spatial and verbal STM measures is not unique (Babcock & Salthouse, 1990; Henry, 2001; Park et al., 2002; Swanson & Howell, 2001).

**SEM Studies of the Relation Between WMC and Higher-order Cognition**

In a SEM, Kane et al. (2004) loaded all STM and WMC span tasks onto a controlled attention factor, all of the verbal tasks on a verbal storage factor, and all spatial tasks on a spatial storage factor. That is, all of tasks loaded on two factors, one for the type of storage and one for attentional control. The attentional control factor had a loading of .52 on the fluid intelligence factor. In Engle, Tuholski et al. (1999), the controlled attention factor (the unique residual variance in the WMC factor after being residualized for common storage factors) loaded .49 on fluid intelligence, and in Conway et al. (2002), the controlled attention factor (constructed with another method of removing the common variance attributed to storage) loaded .60 on fluid intelligence. The similarity and consistency of the magnitude of the controlled attention factors (all derived differently, but all conceptually and theoretically consistent) and fluid intelligence relations across studies is strong evidence that controlled attention is a critical source of variation in higher-order cognition.

McVay and Kane (2012a) further examined the relationship between WMC and higher order cognition by having subjects report their thought content (in response to experimenter-administered probes) during reading tasks and attentional tasks. To index attention, McVay and Kane used a Sustained Attention to Response Task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), an antisaccade task (Hallett, 1978), and a numerical Stroop task. It has been previously established that WMC is related to mind wandering (e.g., thoughts unrelated to the task being performed; Kane et al., 2007; McVay & Kane, 2009; 2012b). If attentional control is important for the relationship between WMC and reading comprehension, reported lapses in attention while performing reading tasks should, at least partially, mediate the relation. Moreover, if controlled attention is responsible for the relation between WMC and reading comprehension, the variance common to measures of WMC and controlled attention should predict comprehension and reports of mind wandering should mediate this relation. Indeed, this is what McVay and Kane found. Reports of mind wandering partially mediated a relationship between measures of WMC and reading comprehension, variance common to the attentional tasks and WMC predicted reading comprehension and this relation was partially mediated by mind wandering, providing more evidence that attentional abilities are part of WMC’s predictive power.

**WMC and Visual Attention Relations.**

*Attentional blink*. In the attentional blink paradigm, subjects attempt to identify two visual targets (defined by the experimenters) that are presented serially in rapid succession in the same spatial location amid distractors. For example, subjects may be required to report letter targets presented amid number distractors where each stimulus is presented for 100ms. Regardless of intervening distractors, subjects have difficulty reporting the second target when it appears within 200-500 ms of the first target (e.g. Broadbent & Broadbent, 1987; Chun & Potter, 1995; Duncan, Ward, & Shapiro, 1994; Reeves & Sperling, 1986). This period of time is referred to as the attentional blink (AB). The AB is thought to result from a bottleneck in a secondary stage of stimulus processing (Chun & Potter, 1995). In a first stage, all stimuli are analyzed and then, in a second stage, the stimuli are consciously recognized (similar to late selection theories of attention; Deutsch & Deutsch, 1963). In a review, Dux and Marois (2009) provide evidence that this bottleneck is the product of multiple processes including: attentional selection of the target, encoding of the target into working memory, response selection, and the inhibition of distractors. Colzato, Spape, Pannebakker, and Hommel (2007) found that subjects who had higher Ospan scores had smaller ABs (*r* = -.33). That is, subjects with higher Ospan scores were better able to identify the second target presented closer to the first target than subjects with lower Ospan scores. Because of the multiple determinants of AB, this results does not provide much clarity on what higher-WMC subjects are doing to achieve this smaller AB. Fortunately, Arnell and Stubitz (2010) further specified the relationship between AB and WMC by having subjects complete a visual WMC task (change detection task; Luck & Vogel, 1997) and a task designed to assess how effective subjects are at filtering information out of working memory (adapted from Vogel, McCollough, & Machizawa, 2005). Visual WMC was positively related to filtering efficiency, but only filtering efficiency was related to AB. Better filterers had smaller ABs. Visual WMC showed no relation to the AB. Arnell and Stubitz’s results suggest that WMC is related to the AB because of selective attention processes. That is, lower-WMC subjects permit at least some distractors (on some occasions) to progress through the first stage of processing into the more intensive second stage, thereby interfering with the identification and reporting of the second target.

*Inattentional blindness*. When a person fails to consciously detect an unexpected stimulus while they are performing another demanding task, they are said to experience inattentional blindness (IB; Mack & Rock, 1998). IB is considered a consequence of selective attention (Neisser, 1979). That is, the unexpected stimulus is undetected because attention is selectively focused on expected “task-relevant” dimensions. Because of higher-WMC subjects’ seemingly superior selective attention abilities in dichotic listening and attentional blink tasks, we may expect higher-WMC subjects to experience more IB. Seegmiller, Watson, and Strayer (2011) tested this hypothesis by having subjects watch a video (from Simon & Chabris, 1999) where the subjects were instructed to count the number of passes made by basketball players. Unexpectedly, a person in a gorilla suit walked across the screen about halfway through the 24 second video. Here, when subjects were accurate in the monitoring task, higher WMC led to *better* detection of an unexpected stimulus (67% of higher Ospan subjects noticed vs. 36% of lower Ospan subjects). However, when subjects in Seegmiller et al. were not accurate in the monitoring task, no WMC-related differences were found.

Hannon and Richards (2010) found that higher Ospan scorers detect the unexpected stimulus more than lower Ospan scorers. They had subjects complete an Ospan task, a visual WM task (change detection task; Luck & Vogel, 1997), and an IB task. Hannon and Richards’ IB task had subjects monitor white and black letters as they moved around a computer screen. Subjects had to count how many times the white letters touched the edge of the display while ignoring the plight of the black letters. After 5 seconds of this continuous monitoring task, a red plus crossed the center of the display. In a logistic regression model with age, gender, visual WMC and Ospan scores as predictors, only Ospan performance predicted inattentional blindness.

Using the same IB task, Richards, Hannon, and Deraksham (2010) examined measures of inhibition, WMC, and processing style as potential predictors of IB and, again, found that only Ospan predicted IB with higher Ospan scorers experiencing less IB.

Recently, Bredemeier and Simons (2012) failed to replicate the negative association between Ospan and IB. They used a more demanding monitoring task and the unexpected stimuli was less salient then in the previous work. Overall, their subjects only noticed the unexpected stimuli 27% percent of the time —which is lower than in the previous individual differences studies. Bredemeier and Simon’s results combined with the monitoring accuracy dependent results of Seegmiller et al. suggest that WMC and monitoring difficulty (of either primary or secondary task components) interact in the prediction of IB. When the monitoring task is relatively easy, higher-WMC subjects may not need to have their attention locked in on the monitoring task for successful performance. This may permit higher-WMC subjects to be less selective with their attention and thereby leading them to notice the unexpected stimulus more often.

*Visual search.* Because prior work had demonstrated WMC-related individual differences in tasks that require attentional control (Kane, Bleckley, Conway, and Engle, 2001; Kane & Engle, 2003; covered in detail below), and prominent models of visual attention propose a role for endogenously driven attention (Treisman & Gelade, 1980; Wolfe, 1994), Kane et al. (2006) expected that higher-WMC subjects would be faster at locating targets among arrays of perceptually similar distracters, but results from a pilot study showed no such association. Following from this pilot study, Kane et al. rigorously tested for a relation between visual search and WMC in multiple experiments that included feature-absence, conjunction, and spatial-configuration visual searches. Regardless of the difficulty of the search to be executed, they found no reliable WMC-related differences in the efficiency of visual search. Initially, it was believed that WMC would relate to all effortful attention tasks that require top-down control (Engle, 2002). This proposition has not held up. Some effortful controlled attention tasks relate to WMC while others do not. Sobel, Gerrie, Poole, and Kane (2007) manipulated a conjunction search task to examine top-down and bottom-up contributions to visual search. In conditions which permitted bottom-up properties (through perceptual grouping manipulations) to drive efficient search, no WMC-related differences were found. But in conditions that where bottom-up influences had to be overcome by top-down strategies for efficient search, higher-WMC subjects had shallower search slopes indicating that they were better able to effectively override the automatic influence of bottom-up influences than lower-WMC subjects.

In three experiments, Pool and Kane (2009) used a modified visual search paradigm to test whether WMC-related individual differences would be produced in a task that cued subjects to the likely target location. By providing the target location, the cue permitted subjects to block distractor processing from uncued locations. In their first experiment, Poole and Kane found WMC variation only predicted search performance when targets were presented with a large of amount distractor interference. In relatively “clean” trials where subjects only had to search among four positions, no WMC-related differences were found. In Experiments 2 and 3(where all trials contained large amounts of interference), Poole and Kane found that higher-WMC subjects were faster to identify targets when cues were presented 1.5 seconds before but not when cues were presented 300 milliseconds before the search display. Poole and Kane also varied the number of locations to be attended to on a trial-by-trial basis (this information was conveyed to subjects via the cue). There was no relation between WMC and the number of locations to be attended to. Poole and Kane’s results suggest that lower-WMC subjects were initially able to deploy their attention as effectively as higher-WMC subjects, but they couldn’t maintain that focus over longer delays (at least in conditions with a lot of interference).

Taken together, the results from Kane et al. (2006), Sobel et al. (2007), and Poole and Kane (2009) suggest that WMC is not related to prototypical visual search but search task requirements can be manipulated to produce to WMC-related individual differences. When top-down control is needed to override the influence of bottom-up processes or when attentional focus needs to be maintained in face of interference, higher-WMC subjects outperformed lower-WMC subjects. The lack of a relation between WMC and prototypical visual search demonstrates that WMC is not related to all types of endogenous attentional control.

*Visual attention to cued location.* Bleckley, Durso, Crutchfield, Engle, and Khanna (2003) tested if WMC variation (measured by Ospan) predicts differences in how visual attention is allocated. Bleckley et al. had subjects identify a centrally presented target letter and then localize another displaced letter that could appear on one of three concentric rings that appeared around the central letter. The ring that the displaced letter was to appear on was validly cued on 80% of trials with the words *close*, *medium*, or *distant*. The cue was displayed for 2 seconds; then the grid (i.e., the concentric rings) was displayed for 2 seconds before being replaced by the central and displaced letter. The central letter and displaced letters were presented for 150 ms before the entire screen was pattern masked. Bleckley et al. hypothesized that because of previous demonstrations of superior controlled attention capabilities by higher-WMC subjects, higher-WMC subjects would be more precise with their allocation of attention while lower-WMC subjects would deploy their attention in a more diffuse spotlight formation. Following from this, they expected higher-WMC subjects’ performance (i.e., accuracy) to suffer more than lower-WMC subjects on invalidly cued trials where the target was inside —but not outside­— the cued ring.

Consider a trial where the subject receives a distant cue (i.e., the cue for the farthest ring from the center). The subject should configure his or her attention to center of the screen and the distant ring. When the target then appears inside the distant ring, subjects who were more tightly focused on just the distant ring and the center position should perform worse than the subject who is unable to deploy their attention as precisely and instead ends up covering the whole area from the outer ring to the center with their attention. For all subjects, invalidly cued letters occurring outside the cued ring were poorly localized (67% correct), but lower-WMC subjects localized invalidly cued letters inside the cued ring better than did higher-WMC subjects (72% vs. 64%); the authors interpreted this finding as providing evidence that higher-WMC subjects are able to configure their attention discontiguously while lower-WMC subjects deploy their visual attention more diffusely in a spotlight formation. But in light of the Poole and Kane (2009) results where WMC did not relate to the number of discontiguous locations to be attended to and only predicted performance when attentional focus had to be maintained (for 1.5 seconds), it’s possible that Bleckley et al. would have produced null results if they used a shorter period of time shorter than the 2 seconds they used between the cue and the target display.

**WMC and Habit Restraint Relations**

*Antisaccade task*. Kane, Bleckley, Conway, and Engle (2001) directly tested the assertion that complex span tasks measure an attentional ability. They had subjects, classified as either low or high WMC depending on an Ospan score, complete an antisaccade task (Hallett, 1978). Kane et al.’s antisaccade task required subjects to detect an abrupt visual-onset cue (a flashing equal sign; =) and to use this cue to direct attention to a target. Once the target appeared (it was masked after 50ms), subjects reported the target identity by pressing a designated key. Kane et al. (2001) had subjects complete two blocked within-subject conditions: a prosaccade condition where the target appeared at the location of the equal sign and an antisaccade condition where the target appeared opposite of the side of the screen from where the cue appears. For successful performance in the prosaccade condition, subjects could let the habitual, exogenously-driven response of orienting towards the cue guide them. But in the antisaccade condition, subjects had to use endogenous control to either initially prevent their eyes from orienting to the cue, or, if they didn’t prevent this orienting, to disengage from the cue and quickly move their focus to the target side of the screen. This task made very limited demands on memory storage or retrieval; therefore, if higher-WMC subjects performed better than lower-WMC subjects in the antisaccade condition, there is arguably an element of attention control measured by the Ospan task. As predicted by the controlled attention view of working memory (Engle, Kane et al., 1999), variation in WMC did not predict the reporting of targets (in RTs and errors) in the more automatic prosaccade condition —where successful performance was guided by environmentally provided cues. But in the antisaccade condition, where endogenous control was necessary to counter the strong signals from the environment, lower-WMC subjects made more initial saccades towards the cue and were slower to move their eyes to the target after these erroneous saccades than were higher-WMC subjects (measured with eye-tracking in Experiment 2). Here, then, we see a relation between performance on a complex span task and an attention task that bear little methodological similarity to one another. Moreover, with no WMC-related differences found in the prosaccade blocks, it is again shown that subjects who differ in WMC do not differ in *all* types of tasks.

Unsworth, Schrock, and Engle (2004) also examined how WMC variation relates to antisaccade task performance. Unsworth et al. measured subjects’ eye movements and did not require subjects to identify a target at the saccade destination. That is, subjects just had to move their eyes to the target. In their Experiment 1, they replicated Kane et al.’s findings with antisaccade and prosaccade trials blocked (WMC-related differences in anti- but not prosaccade trials). Unlike previous experiments that used blocked designs, in Experiment 2, Unsworth et al. mixed prosaccade and antisaccade trials. On a trial-by-trial basis, a task cue (presented 200 ms before the location cue) signaled what type of saccade should be made. The authors predicted that this manipulation would make the control of attention necessary even on prosaccade trials and, therefore, WMC-related performance differences would now be found on these trials. Indeed, lower-WMC subjects were slower and more erroneous on both anti- and prosaccade trials. Unsworth et al. used a third experiment to suggest a causal mechanism. To this end, they had subjects complete four saccade tasks: endogenous prosaccade and antisaccade tasks, and exogenous prosaccade and antisaccade tasks. In the endogenous tasks, the cue was a centrally presented arrow that pointed towards the eventual target location. Whereas in the exogenous tasks, the target location cues were flashing squares either at the location of, or opposite to the target. Unsworth et al. reasoned if the suppression of reflexive saccades is primarily responsible for the WMC-related performance differences, higher-WMC subjects will outperform lower-WMC subjects only in the antisaccade tasks. But if voluntary generation of saccades is the driver of the relationship between WMC and saccade performance, these relations should be found in all versions of the task except for the exogenous prosaccade. Indeed, this is what they found. Lower-WMC subjects performed worse than higher-WMC subjects on all tasks that required voluntary saccade generation.

*Sustained attention to response task (SART)*. McVay and Kane (2009) used a SART variant of a go/no-go task to examine relations among WMC, mind wandering, and task performance. Here, in this section, I will focus strictly on task performance (mind wandering will be addressed below). In this 45 minute task, subjects responded (by pressing the space bar on a standard computer keyboard) to all stimuli except for infrequent targets (11% of trials). McVay and Kane used three versions of the SART task: one where targets were distinguished from non-targets on a semantic basis (food vs. animal words), one where these task elements were distinguished on a perceptual basis (lowercase vs. uppercase words), and another perceptual-semantic where case was perfectly predictive of semantic category. Because accuracy did not differ across the SART versions, McVay and Kane collapsed across the different versions and found that WMC was positively related to target accuracy, and negatively related to RT variability. McVay and Kane (2012b) investigated whether WMC’s relation to SART task performance differed depending on task demands. They contrasted WMC relations on a traditional SART task which requires frequent responding to non-targets and rare withholding of responses to targets to performance on a vigilance version of the SART task which requires withholding responses to frequent non-targets and responding to rare targets. In the traditional SART, WMC variation related positively to accuracy, negatively to RT variability and to extremely slow responses. In the vigilance version, WMC was not related to performance. In the traditional SART task, control over habitual responding (pressing the space bar over and over again) is at a premium whereas in the vigilance SART the level of interference in the way of habitual responding is nonexistent. Here, it seems that there needs to be a sufficient level of interference or conflict in the task for WMC-related individual differences to be revealed.

Redick, Calvo, Gay, and Engle (2011) used a shorter version of the traditional SART task, but unlike McVay and Kane (2009, 2012b), they found no WMC-related differences. In their Experiment 1, Redick et al. had all subjects complete two blocks of trials. In the first block, subjects were instructed to not press a button whenever a letter X appeared on the screen, but to press the button whenever one of 15 other consonants appeared. In the second block, these instructions were reversed (do not press a button for non-X trials and press the button for X trials). Twenty percent of the trials in each block were no-go trials. Although Redick et al. found no differences in a traditional SART task in Experiment 1, they did find WMC-related performance differences in additional experiments with versions of the SART where responding to the target was contingent upon what occurred on previous trials. For example, in their Experiment 2, subjects were to press a button whenever they saw an M or a W, but only if the identity of the target had alternated from the last target. Redick et al. reported a reanalysis of McVay and Kane’s (2009) data and found WMC predicted SART accuracy in the conceptual and conceptual-perceptual SART tasks but not in the strictly perceptual SART. Redick et al.’s findings provide support for a relation between WMC and memory retrieval (or maintenance) but can not account for the findings of McVay and Kane (2009, 2012b). Perhaps the longer duration of McVay and Kane’s tasks and the lower proportion of no-go targets compared to Redick et al. allowed for failures of goal maintenance by lower-WMC subjects while Redick et al.’s task preparations did not. Currently, I can offer no compelling explanation of why WMC is related to semantic but not perceptual SART tasks.

**WMC and Mind Wandering**

*WMC and mind wandering in daily life.* Kane, Brown, et al. (2007) had one hundred and twenty six subjects, who had previously had their WMC measured, carry Palm Pilot Personal Digital Assistants (PDAs) for one week. The PDAs beeped randomly over the course of the seven days. The beep signaled the subjects to complete a questionnaire (on the PDA). The questionnaire asked subjects if they were thinking about something other than what they were doing and various other questions to provide context for the activity being performed. Kane, Brown, et al. (2007) found an interaction between task demand and WMC in the production of off-task thoughts. When subjects reported high concentration, effort, or challenge on the task being performed, higher-WMC subjects reported having significantly fewer off-task thoughts than lower-WMC subjects.

*WMC and mind wandering in SART tasks.* In the laboratory, McVay and Kane (2009) examined how WMC and mind wandering influence performance on a SART task. As reported above, higher-WMC subjects exhibited more accurate and stable (less RT variability) performance on a SART task (no-go task with infrequent targets to withhold responses to). Mind wandering, assessed with thought probes during the SART task, accounted for approximately 50% of the variation between WMC and both SART accuracy and RT variability. McVay and Kane’s follow-up study (2012b) also found that mind wandering partially mediated the relationship between WMC and accuracy, RT variability, and extreme slow responses.

**Synthesis of WMC relations to Visual Attention, Habit Restraint, and Mind Wandering**

Whether, or how much, controlled attention is responsible for complex span tasks’ prediction of higher-order cognition may be debatable (Chuderski et al, 2012; Colom et al. 2008; Conway et al. 2002; Engle, Tuholski et al., 1999; Mogle et al. 2008; Shelton et al, 2010; Unsworth & Spillers, 2010), but several studies above indicate that complex span tasks index specific attentional abilities. Work with dichotic listening (Conway et al, 2001; Colflesh & Conway, 2007) and saccade tasks (Kane et al., 2001; Unsworth et al., 2004) highlights that WMC relates to performance in tasks which make minimal memorial demands. WMC seems to be important in maintaining attention to the task at hand (Kane et al., 2007; McVay & Kane, 2009, 2012b) and to locations in visual attention tasks (Bleckley et al., 2003; Poole & Kane 2009). WMC related to performance in saccade tasks that require voluntary saccades (Unsworth et al. 2004), but results from prototypical visual search tasks (Kane et al., 2006; Poole & Kane, 2009) indicate that WMC is not related to all forms of endogenous attentional control. Mind wandering accounted for a sizable proportion of WMC-related variance in SART tasks (McVay & Kane, 2009, 2011). It’s possible that attentional lapses (at least some times in the form of mind wandering) partially account for the relations between WMC variation and all of the tasks covered above. But this clearly isn’t the whole story (mind wandering only partially mediated WMC-performance relations). Sobel et al.’s (2007) manipulation of a search task (from a prototypical task with no relations to WMC into a task where higher WMC related to better performance) reveals that the strength of bottom-up task influences can be crucial for the detection of WMC-related individual differences. That is, by making the characteristics of the search display a somewhat reliable indicator of what should be searched, on trials where these characteristics *did not* indicate the target location higher-WMC subjects outperformed lower-WMC subjects. By introducing cognitive conflict that required control to resolve, WMC’s influence was revealed. Below, I will examine the relation between WMC variation and attention in tasks known to present this type of conflict.

**WMC-related individual differences in cognitive conflict tasks**

The tasks discussed below are similar to the habit restraint tasks covered above in that for successful performance they require top-down control to override more automatic responses that are triggered by contextual task elements. They differ from SART and Antisaccade tasks because both the response relevant and irrelevant task dimensions are presented simultaneously. Because of this, on incongruent trials the influence of these dimensions is opposed to one another. How variation in WMC relates to the resolution of the conflict created by this opposition holds promise to further illuminate the relations among WMC, attention, and performance.

**Stroop**

Kane and Engle (2003) used the Stroop (1935) task to further specify the relation between WMC (operationalized as Ospan score) and performance on attentional tasks. The Stroop task requires both the ability to maintain the task goal and efficiently process the imperative stimulus features. In the task, subjects are presented with a color word (in the tasks described here words are presented one at a time) that is either displayed in the color that matches (is congruent with) or mismatches (is incongruent with) the word’s identity. The task goal —to name the color the word is displayed in— must be maintained (or otherwise kept easily accessible). If goal access is not maintained, the subject will default to the more habitual action of reading the word. When this happens an error will be made on incongruent trials or responding will be facilitated on congruent trials (word reading is faster than color naming). Moreover, even if the task goal is successfully maintained, WMC-related differences still may be found in RTs on incongruent trials, which would reflect differential abilities to resolve response competition presented on trials with conflicting colors and color-words.

Across five experiments, Kane and Engle (2003) manipulated the congruent trial proportion between and within subjects.(For example, in Experiment 1 subjects either completed a task with 0% or 75% congruent trials and in Experiment 2 all subjects first completed a block of trials with 0% congruent trials and then completed a block of trials with 75% congruent trials.) In a Stroop task with a high proportion of congruent trials there is little environmental support for the goal of color naming, because on most trials subjects can produce correct responses by reading the word. Support for this goal must be maintained endogenously, so high congruency conditions should reveal individual differences in goal-maintenance ability. In low congruency conditions, much of the endogenous burden of goal maintenance is removed because the frequent incongruent trials serve as reminders of the task goal, but even when this task goal is maintained it still needs to be executed properly. Efficient execution of the goal requires the cognitive system to bias attentions towards (or boost the gain from) the imperative stimulus feature or to inhibit the influence of the task-goal irrelevant stimulus features. Therefore, individual differences in low congruency conditions reflect the efficiency with which conflict between stimulus features is resolved. Critically, in high congruency (low goal support) conditions, high and low WMC subjects differed in both the amount of error interference (incongruent error rate minus congruent error rate) and RT facilitation (neutral RT minus congruent RT), with low WMC subjects making more errors and experiencing more facilitation that did high WMC subjects. But in conditions that were supportive of the task goal (low proportion congruency), high and low WMC subjects differed, not in errors, but in RT interference (either the difference between incongruent and neutral or congruent trials) with lower-WMC subjects experiencing more interference than did higher-WMC subjects. The WMC-related differences in error interference and facilitation in the high congruency condition demonstrate goal neglect on the part of lower-WMC subjects. That is, without the support from frequent goal reminders (incongruent trials), the task goal was lost and lower-WMC subjects resorted to the more habitual word reading. In low congruency conditions, WMC-related individual differences in the amount of RT interference seem to reflect the ability to resolve response competition. Taken together, these results provide evidence for the two factor theory of WMC’s influence on cognitive control (Engle & Kane, 2004; Kane et al. 2007), with high WMC being associated with a superior ability to maintain the task goal and also to resolve response competition.

WMC-related differences in the size of Stroop effects have been found multiple times in high congruency Stroop tasks with both verbal and manual responses (Hutchison, 2010; Long & Prat, 2002; Unsworth and Spillers, 2010; Unsworth, Redick, Spillers, & Brewer 2012), but recent work by Meier and Kane (2012a) suggests that more than a high proportion of congruent trials is necessary to differentiate high and low WMC subjects’ performance. In our Experiment 1, in a high congruency condition, we limited the amount of congruent trials that could occur consecutively and did not permit colors or words to repeat on consecutive trials. We observed no WMC-related performance differences. In Experiment 2, repetitions of color and words were permitted from trial-to-trial and the constraint on the number of consecutive congruent trials was lifted (as in prior studies). Here, we observed WMC-related performance differences in a Stroop task —less Stroop interference in both RT and errors for higher-WMC subjects.

**Flanker**

In a flanker task, subjects must identify a target stimulus among other stimuli that can be the same as the target or different from the target. In a congruent flanker trial, the target and flanking stimuli match (e.g., SSSSS). In an incongruent trial, the target and flanking stimuli do not match (e.g., HHSHH). In both congruent and incongruent trials, the non-target stimuli are all the same —with letters most often being used as stimuli. Responding is slowed on incongruent trials compared to congruent trials. Flanker interference is commonly measured as the RT difference between these two types of trials. In a prototypical flanker task the target is always in the center of a horizontal array, so uncertainty of target stimulus location, or visual search, cannot explain this slowing.

Using the flanker task (with the letters H and S as stimuli), Heitz and Engle (2007) tested the hypothesis that WMC predicts the speed with which people can constrain their visual focus to the central, target location. Previous work using behavioral, ERP, and neuroimaging indicators has found that when attention is tightly constrained to a target, less information from distractors is processed (e.g., Eriksen & St. James, 1986; Handy, Soltani, & Magnum, 2001; LaBerge et al., 1991; Lavie, 1995; Rees et al., 2007). Heitz and Engle’s design was based on previous work by Gratton et al. (1988), who examined the time-course of information processing in a flanker task. Their results were consistent with a dynamic spotlight (or zoom lens) view of attention, where attention starts out in a diffuse state that permits information from both the target and distractors to enter the system; when the distractors are incongruent, performance is impaired. As time elapses, the focus of attention closes in on the target. The tighter the focus of attention, the more diminished the impact of response-incongruent distractors are on performance

On congruent trials the information from the distractors leads to the same response as the target while on incongruent trials the information from the target and distractors lead to different responses, resulting in conflict. Gratton et al.’s findings (see Figure 2) for the time course were as follows: 1) For both congruent and incongruent trials, the trials with the fastest RTs were performed around chance accuracy because responding is based on no information from the stimulus. 2) On incongruent trials only, fast —but not the fastest— RTs were performed at *below chance* accuracy. This dip below chance was interpreted as occurring because visual focus was not yet constrained to the target so responses were based on the identity of the flanking stimuli. 3) After the fastest congruent trials, and the subsequent dip in accuracy for the incongruent trials, performance gradually increased (with congruent trial performance superior to incongruent trial performance at multiple intermediate time points) and at the slowest RTs the flanker effect (the difference in accuracy between congruent and incongruent trials) disappeared.

In three experiments, Heitz and Engle (2007) found experimental patterns similar to those found by Gratton et al. (1988). Most importantly, high and low WMC groups (WMC group was determined by Ospan quartiles [1st quartile = low WMC, 4th quartile = high WMC] in Experiments 1 and 2 and by a composite of three complex span tasks in Experiment 3) differed in performance at the intermediate time points on incongruent trials while performing similarly on congruent trials. Because of the equivalence at the fastest and slowest RTs but WMC-related differences at the intermediate time points, it appears that higher-WMC subjects were able to constrain their focus to the target more quickly than lower-WMC subjects. This allowed higher-WMC subjects to avoid accumulating deleterious distractor information as quickly as lower-WMC subjects (see Figure 3). Heitz and Engle did not find overall (irrespective of time course) WMC-related differences in flanker interference (in RTs or errors). The differences reported were on accuracy, conditional on RT when responding to a deadline. If no effort was made to examine the time-course, the conclusion that flanker task performance is not related to WMC would have been supported by the data. However, WMC-related overall differences have been found in the flanker task interference using other variants of the task (Redick & Engle, 2006; Shipstead, Harrison, & Engle, 2012; Unsworth & Spillers, 2010).

**Simon**

Simon and Small (1969) produced the Simon effect by presenting subjects with tones to either the left or right ear. The tones varied in pitch. Specific tones required a response key to be pressed by either the right or left hand (e.g., a high tone required a key to be pressed with the left hand vs. a low tone required a key to be pressed with the right hand). Simon and Small found that subjects were slower to respond when the tone was presented in the ear on the opposite side of the body from the hand needed for the response (compared to when the tone was presented in the ear on the same side as the response hand). The congruency between the task-irrelevant stimulus location (i.e., the left or right ear) and the response location (i.e., left or right key press) impacted performance. That is, subjects were faster when the stimulus location was congruent with the response location than when the stimulus location was incongruent with the response. Most commonly, the difference in RT between incongruent and congruent trials is labeled the Simon effect. Older adults, a population with lower WMC (Bopp & Verhaeghen, 2005), show a greater Simon effect than younger adults (for a review see Proctor, Vu, & Pick, 2005), and bilinguals, a population who are proficient in tasks that present conflicting stimulus dimensions (Bialystok & Craik, 2009), show smaller Simon effects than do monolinguals (Bialystok & Craik, 2004; Bialystok, 2006). From this, we may expect WMC to be related to the resolution or avoidance of this type of conflict, I am aware of no findings of WMC-related individual differences in Simon effects.

Keye, Wilhelm, Oberauer, & van Ravenzwaaij (2009) measured the WMC of 150 subjects (with two complex span tasks and a memory updating task) and had these subjects complete a Simon task. Keye et al. used a vertical Simon task with diamond and squares as stimuli. Subjects were to press a key on the top of a custom keyboard for diamonds and lower key for squares. Diamonds appearing on the top of the screen and squares appearing on the bottom of the screen were congruent trials with squares on the top and diamonds on the bottom being incongruent trials. Half of the trials were congruent. Keye et al. only found a small, non-significant association (*r* = -.16) between WMC and the Simon effect. .

Recently, Meier and Kane (2012b) measured WMC with three complex span tasks and then had subjects complete a task where they had to indicate if an arrow was pointing up or down. One arrow was shown at a time. On a given trial the arrow appeared to the right or left of the screen’s center and at other times the arrow was above or below the screen’s center. The arrow location was always irrelevant. Subjects pressed one key to indicate an up arrow and another key for a down arrow. These keys were on the same horizontal plane as each other with one located on the left side of the keyboard while the other was on the right (mapping was counterbalanced across subjects). On trials where the location of the stimulus arrow was either to the left or right of center of the screen a Simon effect was found (~40 ms). Interestingly, in a condition with 50% congruent trials, there were no WMC-related individual differences found in the size of Simon effects.

**WMC and Conflict Task Summary**

In Stroop tasks, higher WMC relates to better task goal maintenance and the ability to better resolve conflict generated between stimulus elements that lead to conflicting responses (Hutchison, 2010; Kane and Engle, 2003; Long & Prat, 2002, Meier & Kane, 2012a; Unsworth et al, 2012; Unsworth & Spillers, 2010). Flanker task data suggests that higher-WMC subjects are able to more quickly focus their attention on the task critical stimuli to limit the influence of potentially performance hindering distracters (Heitz & Engle, 2007; Redick & Engle, 2006, Shipstead et al., 2012). No reliable relations between WMC variation and Simon effects have been reported (Keye et al, 2009; Meier & Kane, 2012b). In light of the work of McVay and Kane (2009, 2012a, 2012b), mind wandering probably accounts for some of WMC’s predictive ability in Stroop and flanker tasks by disrupting goal maintenance (particularly in high congruency contexts), but there is still predictive variance that needs to be explained. In the two-factor theory of WMC and cognitive control (Engle & Kane, 2004; Kane et al. 2007), goal maintenance and response competition are posited to account for WMC’s influence. As previously stated, mind wandering is at least a partial explanation of WMC’s relation to goal maintenance. Results from flanker tasks suggest that rather than resolving competition, higher-WMC subjects may be able to avoid the competition by preemptively cutting of input from potential sources of interference. Parallel distributed processing models of Stroop performance (Cohen, Dunbar, & McClleland, 1990) also suggest that attention can be biased towards only task-relevant stimulus elements in a top-down manner. All three of the tasks above present conflict, but WMC only reliably relates to two of these tasks. Perhaps, we can leverage these findings into a more specific account of WMC and attention relations.

The conflict tasks covered above (i.e., Stroop, flanker, and Simon) can be classified as stimulus-response compatibility (SRC) tasks (Hommel & Prinz, 1997; Proctor & Reeve, 1990). These tasks are distinguished by their proclivity to produce conflicts that interfere with some stage or component of information processing. The defining observation of SRC tasks is that when the relation between and within stimulus and response sets are natural and intuitive, performance is relatively fast and accurate. But, when there is a mismatch between and/or within stimulus and response sets, performance is impaired. For example, a person more easily responds to the display of a number by naming that number, than if she were instructed to respond with another number’s name or the name of an arbitrary color. Or a person is faster to press a button on his left side when the button controls something such as a light that also occurs on his left side than when the light is on his right side. In the first example, correspondence between the stimulus (number) and response sets (number’s name, alternate number’s name, color) determines performance and in the second example performance is impacted by the location of the switch and the light. Most simply put, performance on a task is determined by the fit between and within the set of stimuli and the set of responses. Most of the work regarding SRC tasks has focused on determining what causes these stimulus-response compatibility effects (for reviews, see Hommel & Prinz, 1997; Proctor & Reeve, 1990; Proctor & Vu, 2007). However, relatively little attention has been given to what people do to *combat* this interference (but see Ridderinkhoff [2002] for an example with the Simon task). What people do to cope with interference, in particular, what higher-WMC subjects do, is really the key question in regards to advancing WMC theory.

WMC predicts performance on some Stroop and flanker tasks (Heitz & Engle, 2007; Kane & Engle, 2003; Meier & Kane, 2012a; Redick & Engle, 2006; Shipstead et al, 2012), but there is no evidence that WMC predicts Simon performance (and evidence that it does not; Keye et al., 2009; Meier & Kane 2012b). Using crude subtractive logic (Donders, 1869), the most salient difference among flanker, Stroop, and Simon tasks is that flanker and Stroop tasks contain overlap between relevant and irrelevant *stimulus* dimensions while the Simon task does not. This suggests that WMC helps resolve stimulus-stimulus but not stimulus-response conflicts.

**An example of how Dimensional Overlap can be used to specify the WMC attention relationship**

Meier and Kane (2012b) tested whether WMC relates to the resolution of stimulus-stimulus conflict, stimulus-response conflict, or both. Subjects completed a task where some trials presented just stimulus-stimulus conflict and other trials presented stimulus-response conflict (adapted from Liu, Banich, Jacobsen, & Tanabe, 2004). As described in the Simon effect section of the conflict task review, subjects were presented with an up or a down arrow that was either below or above, or to the left or right, of fixation (all equidistant from central fixation). The irrelevant stimulus dimension of arrow location to the left or right of fixation overlapped with the horizontally oriented key-press responses. Thus, subjects were presented with stimulus-response conflict (Simon) trials when the arrow location was on the opposite side of the screen from the key to be pressed. On trials where the arrow was above or below the screen’s midpoint, however, the irrelevant (vertical location) and relevant (arrow direction) stimulus dimensions overlapped, producing stimulus-stimulus conflict on trials where the arrow direction conflicted with the arrow location (e.g., an up arrow presented below fixation; a down arrow presented above fixation). For both of these trial types, stimulus location is irrelevant, and the task goal is the same. So here, if we see any WMC-related performance differences, (following the logic of the two factor theory of WMC and cognitive control) we can assume the difference is in how response competition is resolved.

In two experiments with 50% incongruent trials (half the horizontally oriented trials and half the vertically oriented trials), we found that WMC related to RT conflict resolution on stimulus-stimulus overlap (“Stroop-like”) trials but not on stimulus-response overlap (“Simon”) trials. That is, higher-WMC subjects were better able than lower-WMC subjects to combat the interference created from the semantic conflict of identifying an up arrow located on the down side of the screen and down arrows located on the up side of the screen. However, higher-WMC subjects were no better than lower-WMC subjects at resolving stimulus-response conflict created from the arrows appearing contralateral to the response key. Moreover, in our Experiment 1, we also created trials that were combinations of stimulus-stimulus and stimulus-response conflict. These trials presented an arrow that was above or below the screen’s midpoint as well as either to the left or the right of center (e.g., between 10 and 11 o’clock on a clock face; see Figure 6). For example, when a left response is assigned to an up arrow, and the up arrow appears below and to the right of the screen’s midpoint, conflict is created between both stimulus-stimulus (down location vs. up arrow) and stimulus-response (right location vs. left response) dimensions. Or, (still with the same instructions) an up arrow appears above and to the right of the midpoint, conflict only exists between the arrow location (right) and response location (left). The up arrow appears above the screen’s midpoint so no conflict exists between the location (up) and the identity of the arrow (up arrow). Again, we found that WMC is only related to the resolution of stimulus-stimulus conflict on these trials and not stimulus-response conflict. In these studies, we see a dissociation between WMC’s relation to the resolution of response competition depending on the specific characteristic of the competition.

**Conclusions**

The ability to control attention appears to play some role in WMC’s relation to higher-order cognition. Defining when and how this control contributes to performance will provide specificity to theoretical accounts of WMC. Some boundary conditions for controlled attention have been identified, but currently there is no theoretical framework for these boundaries. Here, Dimensional Overlap is proposed as such a theory. Using Dimensional Overlap Theory, Meier and Kane’s (2012b) results suggest that WMC affects information processing at the stimulus identification phase. If we can limit WMC-related differences to the stimulus identification phase of tasks that link action and perception, we could then focus on what is exactly happening here. An intuitive explanation would be that higher-WMC subjects are able to preemptively bias the processing of stimulus features in accordance with task goals (cf. Cohen et al., 1990).

More work needs to be done to solidify, and test for the generalization of, the localization of WMC effects to stimulus identification processes

Figure 1



Figure 2



Figure 3



Figure 4



Figure 5

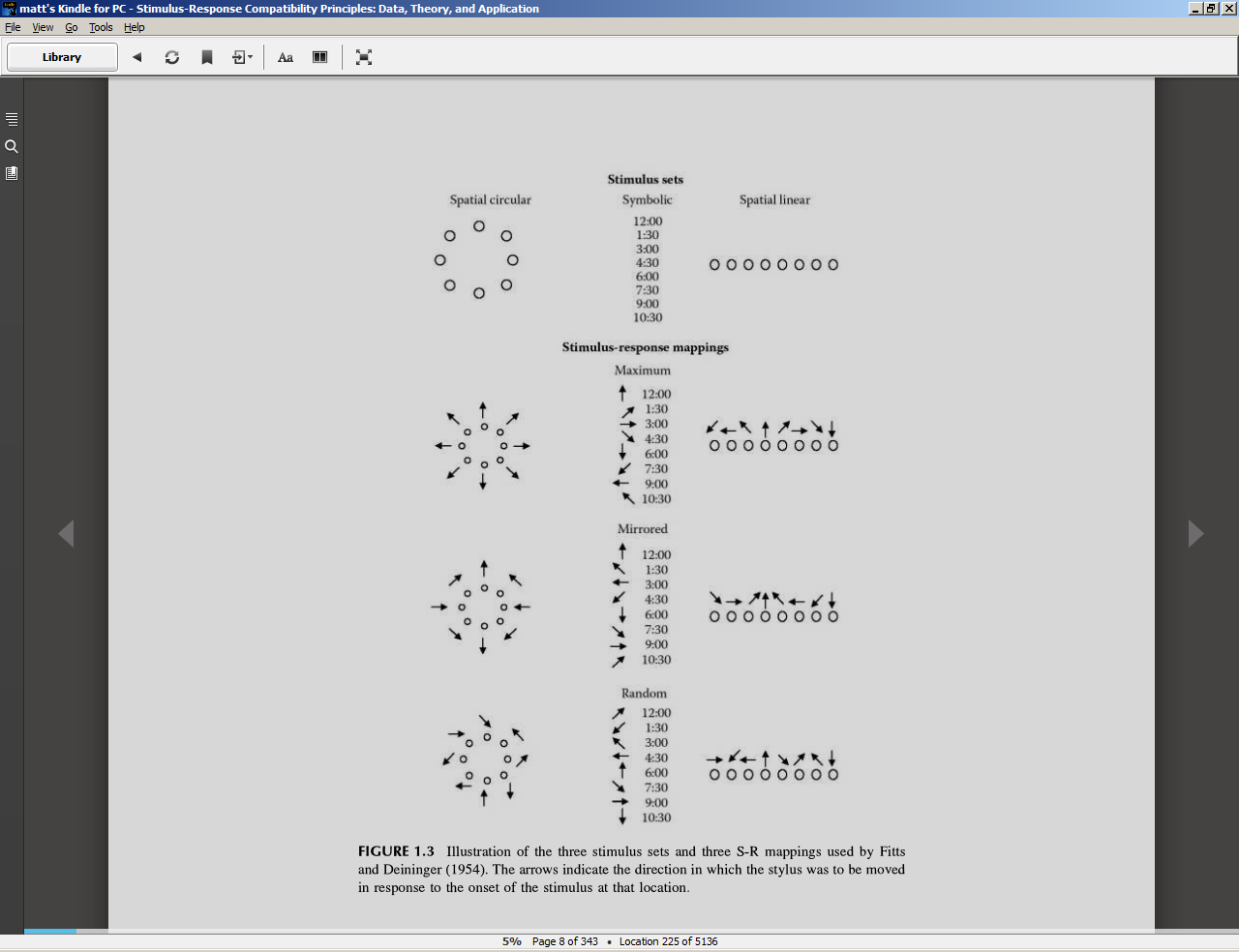


Figure 6.

