1-1-2009

What's On Your Mind: The Influence of the Contents of Working Memory on Choice

Starla Weaver

Running Head: WORKING MEMORY’S CONTENTS

What’s on Your Mind: The Influence of the Contents of Working Memory on Choice

Starla M. Weaver

Lehigh University

It is often the case that information must be maintained until it can be applied. The active storage and manipulation of information over short periods of time takes place within working memory (WM). Holding information in WM can allow for successful functioning. However, keeping information active in WM can affect other cognitive processes. For instance, information in WM can influence processes of selective attention. Maintaining specific information in WM can bias selective attention toward items related to that information (Huang & Pashler, 2007). Information in WM can also influence processes of executive attention. Maintaining high WM loads can limit executive attention and lead to increases in stereotypic responding (Towse & Cheshire, 2007). The current study examined the influence of information in WM on behavioral selection. In particular we examined whether the specific tasks one chooses to perform within a multitasking environment would be influenced by information being maintained in WM. We hypothesize that information in WM will influence choice through a combination of biases to selective and executive attention.

Selective Attention

At any given time the amount of information available to the senses will exceed that which can be processed perceptually. Selective attention specifies which of the available inputs will be processed. Selection can be driven by stimulus dependent, bottom-up processes (Treisman & Gormican, 1988) or top-down goals (Wolfe, 1998). Furthermore top-down attentional goals can bias selective attention and allow specific features relating to one's current target to draw attention in an automatic fashion (Serences et al., 2005; Yantis, 2000). In their biased competition model, Desimone and Duncan (1995) propose that selective attention can be biased toward a specific set of stimuli via attentional templates that can specify the features, location, or identity of to-be-attended targets. A representation of the target held active in WM is used to bias processing when competition between multiple perceptual inputs is encountered (Chelazzi, Miller, Duncan & Desimone, 1993; Moran and Desimone, 1985).

Selective attention utilizes WM as a means of actively maintaining representations of features to which attention should be biased. One consequence is that items being maintained in WM appear to bias attention even in situations in which selection bias is not strictly relevant to one's current goals (Downing, 2000; Huang & Pashler, 2007; Moores & Maxwell, 2008; Olivers, Meijer & Theeuwes, 2006; Soto & Humphreys 2007). Huang and Pashler (2007) labeled the automatic draw of attention toward items in WM as consonance-driven orienting. For example, in Moore and Maxwell (2008) participants presented with a picture to remember were asked to make an identification judgment concerning a letter that appeared in the center of either the memory picture or a neutral picture. Although the picture being maintained was paired with the target letter on only 20% of trials, participants were faster and more accurate at identifying the target when it was presented on the to-be-remembered picture, suggesting that attention was biased toward that picture. Consonance-driven orienting has been distinguished from simple perceptual priming (Moores & Maxwell, 2008; Olivers et al., 2006; Soto & Humphreys, 2007); has been found for both stimuli that matched or are related to targets held in WM (Huang & Pashler, 2007; Olivers et al., 2006); and has even been found in situations where such orienting always impaired primary task performance (Soto & Humphreys, 2007).

Nevertheless, consonance-driven orienting may not be strictly automatic (Downing & Dodds, 2004; Woodman & Luck, 2007). For example Woodman and Luck (2007) found that participants were able to inhibit items that matched the contents of WM within visual search tasks where attentional capture would have always impaired performance. In this case it appeared that selective attention could be biased either toward or against items in WM depending on the functionality of such a bias. The authors concluded that attentional capture by items in WM is not strictly automatic. However, they noted that such capture was likely to occur in situations where it would be beneficial to or have a neutral effect on primary task performance, as well as in situations where an emphasis was placed on WM accuracy. In these situations consonance-driven orienting was highly likely because attending to stimuli that match those one is attempting to maintain in WM allows the representation of the item to be refreshed, causing an increase in successful storage.

If consonance-driven orienting acts as a mechanism by which selective attention aids in WM maintenance, then situations that allow shifts in selective attention toward representations in WM ought to result in more effective storage than situations where such shifts are prevented. Research on the storage of locations in WM suggests that this is indeed the case (Awh, Jonides, & Reuter-Lorenz, 1998; Lawrence, Myerson & Abrams, 2004). It seems that locations are maintained in WM through shifts in selective attention toward those locations (see Awh & Jonides, 2001 for review). As a result selective attention during the retention interval appears biased toward locations in WM, such that stimuli appearing in those locations receive preferential processing (Awh et al., 1998).

Selective attention and WM share a symbiotic relationship in which WM can aid selective attention by keeping active a representation of to-be-attended targets; and selective attention can aid WM by refreshing to-be-remembered representations. Thus, research on selective attention and WM maintenance converge on the idea that selective attention will be biased toward features that match those being maintained in WM. As a result it may be expected that if information one is maintaining in WM were to become available within a multitasking environment, selective attention is likely to be drawn to that information.

Executive Attention

Once selective attention has guided the perceptual processing of stimuli in an environment, responses to those stimuli can be made. One role of executive attention is to choose, enable, and coordinate response performance (Logan, 1985). While habitual responses to frequently encountered stimuli can be made without the aid of executive attention (Norman & Shallice, 1986), executive attention ensures that actions appropriate for the current situation are able to be performed, particularly in situations where multiple response options are available.

A number of approaches have been used to study executive attention. One particularly fruitful approach has been the task-switching paradigm (see Monsell, 2003 for review). During task switching the to-be-performed task alternates periodically between trials, such that the response appropriate for a single stimulus may vary depending on the task required on that trial. Many accounts of task switching assume that executive attention is needed in order to ensure that the appropriate response is executed on each trial in accordance with changing task demands (see for example Monsell, 2005).

Nevertheless, passive processes also contribute to task switching performance (Allport, Styles & Hsieh, 1994). For example the speed with which a participant can respond to a stimulus is influenced by automatic retrieval of stimulus-response bindings (Kiesel, Wendt, & Peters, 2007; Koch & Allport, 2006; Waszak & Hommel, 2007; Waszak, Hommel, & Allport, 2003, 2005; Wylie & Allport, 2000). Responding to a stimulus appears to create a stimulus-response episode that is automatically retrieved when the stimulus is presented again within the same context (Logan, 1988). Automatic retrieval of past episodes prime previously performed responses (Waszak & Hommel, 2007). As a result the task that has most recently or frequently been paired with a stimulus is able to be performed more quickly than the alternative task (Koch & Allport, 2006). Further when a task-switching paradigm employs two sets of univalent stimuli, the presentation of a single stimulus type can automatically activate the associated task, making it available for performance.

The contribution of passive factors, like stimulus-response binding, in task switching has led to debate concerning the role that executive processes play in switching between tasks (see for example Logan, 2003). The degree of executive attention required may depend on the specific paradigm in which the task switch takes place (Monsell, 2005). In particular, the more environmental support offered by a task-switching paradigm the less executive attention is likely to be required (Arrington & Logan, 2005). For example the voluntary task-switching paradigm provides a participant with very little environmental support (Arrington & Logan, 2005). In this paradigm participants are instructed on the performance of two tasks and are asked to perform each task equally often and in a random order. Participants are then free to select the specific task to perform on each trial. Due to the minimal amount of environmental support provided on a trial by trial basis in this paradigm, voluntary task switching is particularly well suited for studying executive attention.

Voluntary task switching performance must be driven by top-down executive processes in the absence of explicit task instructions (Arrington & Logan, 2005; Liefooghe, Demanet, & Vandierendonck, In Press). Nevertheless, passive processes can also influence task choice (Arrington, 2008; Mayr & Bell, 2006). Stimulus-response bindings are one such process. Arrington, Weaver, & Pauker (2009) found that participants showed a preference for performing the task that had initially been paired with a stimulus. This effect was found even when the initial stimulus-task pairing was randomly determined by the experimenters. In addition when the onset of two univalent stimuli was varied, participants more often performed the task afforded by the stimulus that became available first (Arrington, 2008). The stimulus presented first triggered the associated task before the alternative task could be activated. The order of stimulus presentation influenced the order of task activation leading to a bias in responding.

In the previous section we noted that the order in which multiple stimuli within an environment are processed can be influenced by the contents of WM. Objects being stored in WM are likely to receive preferential processing due to consonance-driven orienting. Stimulus-response bindings provide a mechanism by which this preferential processing may lead to an influence on task choice. In particular, processing of a univalent stimulus can activate the task afforded by that stimulus and, within the voluntary task-switching paradigm, bias performance toward that task. If items in WM can bias selective attention toward the processing of specific stimuli in a multitasking environment and the processing of specific stimuli can bias responding then the contents of WM may be capable of influencing task choice within situations where that content is not strictly relevant.

The Current Study

The purpose of the present study was to determine the influence of the contents of WM on task choice within multitasking environments. The extent to which information in WM is able to influence task choice may depend on the type of information being maintained. Baddeley's influential model of WM (i.e. 1992) distinguishes between the storage of verbal information such as identities, and visual information such as locations. These domains appear functionally and neurologically distinct (Baddeley, 1996b; Kane et al., 2004; Sakai & Passingham, 2003). In the current study we assessed the separate influence of information from each type of domain on choice.

Participants were presented with a memory array displaying three characters in three locations and were asked to maintain either the identities (identity-domain condition) or locations (location-domain condition) of the characters in that array. Participants then performed a series of voluntary task-switching trials on a digit affording even/odd classification and a letter affording consonant/vowel classification. On half of the trials one of the stimuli's identities matched the identity of a character from the memory array. On the other half of the trials one of the stimuli's locations matched a location from the memory array. We hypothesized that participants would show a bias for performing tasks afforded by stimuli that matched the memory array on the dimension they were maintaining in WM. Specifically, participants in the identity-domain condition were expected to be more likely to perform tasks afforded by stimuli that matched identities held in WM, while participants in the location-domain condition were expected to be more likely to perform tasks afforded by stimuli that appeared in locations held in WM.

While we expect participants to show a bias toward performing tasks associated with stimuli that matched the contents of WM, an alternative possibility should be considered. Participants may intentionally choose not to perform the task associated with items in WM. The voluntary task-switching paradigm instructs participants to perform two tasks in a random order. Repeatedly performing tasks associated with information in WM may not appear random to participants. As a result participants may choose to override the bias associated with the contents of WM on some trials in order to perform more randomly. In other words selective attention may be biased toward the information in WM, but participants may choose to redirect their attention after the initial bias in order to perform the task afforded by the alternative stimulus. This process should take more time than simply performing the task afforded by the stimulus to which attention had been initially drawn. Thus in this situation increased response times (RT) would be expected on trials where participants do not perform the task afforded by the stimulus that matches the information they are holding in WM.

Methods

Participants. Thirty-two Lehigh University undergraduates participated in exchange for partial course credit. Participants reported having normal or corrected-to-normal vision.

Apparatus and stimuli. The experiment was administered on a Dell Dimension computer with a 17 inch CRT monitor running the E-prime 1.1 software package. Stimuli were sampled randomly from the letter set A, C, E, I, R, P, M, and U and the numbers 2-9. Stimuli were presented in 18 point courier new font on a light gray background. Characters in the memory array were blue. All other stimuli were black. Stimuli appeared within a 5 x 5 array of locations centered on the screen. A plus sign was always located at the center of the array. The remaining locations within the central row and central column of the array remained blank. Thus the stimuli appeared within the 16 remaining locations with four possible target locations in each quadrant (see Figure 1). The array extended approximately 6.4 cm above and below fixation and 7 cm to the left and right of fixation. Viewing distance was not constrained.

Design. The study featured a 2x2 mixed-factor design. The first variable was WM domain or type of information designated for retention in WM, which varied between-subjects. The two domains were identity-domain and location-domain. The second variable was trial type, which varied within-subjects. Trial type was based on the relationship between the stimuli appearing in that trial and the characters presented in that block's memory array. The two trial types were identity-match trials, which featured one stimulus whose identity matched one of the characters in the memory array, and location-match trials, which featured one stimulus whose location matched one of the characters in the memory array. The alternative stimulus was always neutral with regard to its identity and location. The primary dependant variable of interest was the proportion of matches performed, or the proportion of trials in which participants performed the task associated with the stimulus that matched a character presented in the memory array.

Procedure. Experimental sessions began with a series of practice blocks each containing eight trials intended to familiarize participants with the stimulus-response mapping for each task and the process of selecting between tasks at random. Participants performed one practice block in which they made even/odd judgments and one block in which they made consonant/vowel judgments. Next participants performed one practice block of voluntary task-switching trials. They then performed two practice blocks that included the entire experimental procedure (see Figure 1). Each experimental block began with the presentation of a memory array that remained on the screen for 3000 ms. All participants saw a memory array consisting of three alphanumeric characters. Participants in the identity-domain condition were instructed to remember only the identity of the characters, while participants in the location-domain condition were asked to remember only the locations marked by the characters. Then, following a 500-ms blank screen, two voluntary task-switching trials were completed. Each trial consisted of a letter and number presented simultaneously. Participants had the choice of making either an even/odd judgment concerning the number or a consonant/vowel judgment concerning the letter. As in previous voluntary task-switching studies, participants were instructed to attempt to perform each task equally often and in a random order, but were given no instruction concerning the specific task to perform on each trial (Arrington & Logan, 2004a). Responses were made using the index and middle finger of separate hands for each task. Responses were mapped to the "d" "f" "j" and "k" keys and were counterbalanced across participants. Voluntary task-switching trials were separated by a 500-ms response-stimulus interval. Each block concluded with a memory test. In the identity-domain condition, a stimulus accompanied by a question mark was presented in the center of the screen. In the location-domain condition, a location was marked by a question mark. Participants pressed the "y" key for yes if the test item or location was one that they were attempting to remember or the "n" key for no if it was not. The correct answer for the memory test had a 50% chance of being yes. The word *correct* or *incorrect* then appeared on the screen indicating the accuracy of the participant's performance on the memory test. One hundred experimental blocks were performed resulting in 200 voluntary task-switching trials.

Results

Voluntary task-switching trials were sorted into tasks based on the hand used to respond to each trial and into task transitions based on the tasks performed on trial n-1 and trial n. Two participants whose voluntary task switching accuracy fell below 90% were replaced. Data from one participant who failed to switch tasks throughout the experiment was excluded. Blocks in which the memory test was incorrect and trials in which task performance was incorrect were not included in task choice or RT analyses. Trials with RTs two standard deviations away from that participant's mean RT were excluded from analysis, resulting in a loss of 4.7% of trials.

Task Choice: Proportion of matches. The proportions of matches performed by participants in each WM domain condition separated by trial type and trial number are displayed in Figure 2. Notably participants tended to perform a greater number of matches when the stimulus matched the memory array on the dimension they were maintaining in WM than when it matched the memory array on the undesignated domain. Participants maintaining locations (*M*=.538) performed more matches than participants maintaining identities (*M*=.502). In addition the proportion of matches performed was greater on trial one (*M*=.554) than on trial two (*M*=.486). A 2 (WM domain: identity-domain, location-domain) x 2 (trial type: identity-match, location-match) x 2 (trial number: one, two) mixed factor analysis of variance (ANOVA) with WM domain as a between-subject factor found a main effect of WM domain, $F(1,29)=11.23$, $p<.01$, $?_p^2=.28$ and a main effect of trial number $F(1,29)=22.16$, $p<.001$, $?_p^2=43$. Critically for the current hypothesis, there was also a significant WM domain x trial type interaction, $F(1,29)=4.41$, $p<.05$, $?_p^2=.13$. No other effects reached significance. The results suggest that choice was biased toward tasks associated with information in WM.

Task choice: Task transitions. The task transitions between trial one and trial two were analyzed to consider whether participants complied with the voluntary task-switching instructions to perform the tasks in a random order. Following these instructions would have required performing an equal number of switches and repetitions. One-sample t-tests were used to compare the proportion of switches performed in each WM domain condition to .5. The proportion of switches performed did not vary from .5 for participants in either the identity-domain ($M=.548$) or location-domain ($M=.475$) conditions, *t*s < 1[1].

Task Performance. Memory test accuracy and voluntary task-switching accuracy were assessed across WM domain condition using independent sample t-tests. Memory test accuracy was higher for participants in the identity-domain condition ($M=.976$) than for participants in the location-domain condition ($M=.700$), $t(29)=20.35$, $p<.001$. This finding is consistent with previous work indicating that maintaining locations is more difficult than maintaining identities (Brisson & Jolicoeur, 2007). Mean voluntary task-switching accuracy was high and did not vary by WM domain condition (identity-domain: $M=.974$, location-domain: $M=.981$), $t(29)=.94$, p=.36.

[1] Analysis of RTs for the second trial of each block found that task repetitions (1114 ms) were performed significantly more quickly than task switches (1252 ms), $F(1,29)=8.12$, $p<.01$, $?_p^2=.22$.

The speed of match and non-match trials were compared in order to determine if participants were actively avoiding matches on a subset of trials in order to better comply with the instructions to perform tasks randomly. RTs are displayed in Figure 3. The pattern of results was contrary to what would be expected if participants were actively moving their attention on non-match trials. Match trials that involved performing the task associated with the specific information held in WM were performed more slowly than non-match trials. Matches and non-matches for the alternative WM domain had similar RTs. RT was assessed with a 2(WM domain: identity-domain, location-domain) x 2(trial type: identity-match, location-match) x 2(task match: WM-match, non-match) mixed factor ANOVA with WM domain as a between-subjects factor. A significant main effect of task match was found, $F(1,29)= 8.00$, $p<.01$, $?_p^2=.22$; however, this effect was qualified by a significant 3-way interaction, $F(1,29)=4.47$, $p<.05$, $?_p^2=.13$.

Discussion

The current study examined the influence of the contents of WM on choice of tasks within a multitasking environment. Previous research has noted that selective attention tends to be captured by items being maintained in WM via consonance-driven orienting (Downing, 2000; Huang & Pashler, 2007; Moores & Maxwell, 2008; Soto & Humphreys, 2007). As a result these items receive preferential processing. In addition research on executive attention has found that responses can become activated merely by the processing of a stimulus that uniquely affords a particular response due to stimulus-response binding (Kiesel et al., 2007; Koch & Allport, 2006; Waszak & Hommel, 2007; Waszak, et al., 2003; 2005; Wylie & Allport, 2000). Within the voluntary task-switching paradigm, where participants must exert executive control in the absence of external cues indicating which task to perform, stimulus-response bindings appear capable of influencing task choice (Arrington, 2008; Arrington et al., 2009). It was therefore hypothesized that within a multitasking environment the processes of consonance-driven orienting and stimulus-response binding would lead in increased availability of tasks associated with information in WM such that task choice would be biased toward those tasks. The found pattern of results supports this hypothesis. Participants in the identity-domain condition performed a greater proportion of matches on trials that matched the memory array on the identity dimension while participants in the location-domain condition performed a greater proportion of matches on trials that matched the memory array on the location dimension. The results suggest that the processes of selective and executive attention work together to influence the tasks one chooses to perform within environments that afford multiple tasks.

In addition to the hypothesized bias toward performing tasks associated with the contents of WM, the current study found a greater proportion of matches on trial one than trial two. Task availability appears to play a large role in influencing task choice (Arrington & Logan, 2005). The availability of a given task on any specific trial is likely to be influenced by multiple factors. In particular, priming from performance on the previous task appears to make the most recently performed task especially available. This increased availability has been proposed to contribute to switch costs within measures of task switching performance (Allport, et al., 1994) and repetition biases in measures of voluntary task choice (Arrington & Logan, 2005). However, the first trial of a block lacks this source of availability, as availability of each task appears to be essentially reset at the beginning of each new series of task-switching trials (Schneider & Logan, 2006). Within the current study previous task priming is likely to have contributed to the decreased influence of the memory array on trial two.

An additional finding of the current study was that participants in the location-domain condition performed a greater proportion of matches than those in the identity-domain condition. The location-domain condition was also associated with a greater number of memory errors suggesting that maintaining locations may have placed a greater load on WM. This finding is consistent with previous work noting the increased load generated by maintaining spatial information in WM (Brisson & Jolicoeur, 2007). Large WM loads appear to limit executive processes (Baddeley, 1996a). The result is reduced ability to prioritize selective attention (de Fockert, Rees, Firth & Lavie, 2001) and inhibit proponent responses (Hester & Garavan, 2005). Within the current study a reduction in executive processes, created by the load of maintaining locations, may have lead to the increased influence of the memory array in that condition. A similar result was found by Oberauer & Goth (2006) who noted that the spatial but not verbal WM loads influenced primary task performance even when that information was not needed for the primary task. Future research is needed to determine whether the increased influence of the memory array found in the location-domain condition is, as we have suggested, a result of the increased load created by maintaining locations or if there is something specific about the way in which spatial information is maintained that makes it more likely to interfere with primary task performance.

With regard to RT data, it had been proposed that participant's attention may be initially biased toward stimuli that matched the information they were holding in WM but that on a subset of trials participants may choose to move their attention to the alternative stimulus in order to perform tasks more randomly. This movement of attention would have increased the RT of non-match trials compared to trials where the task afforded by the stimulus that matched the contents of WM was performed. Unexpectedly, the opposite RT pattern was found. Match trials associated with the contents of WM were performed more slowly than non-match trials. The result suggests that participants were not actively moving their attention on non-match trials. Indeed the pattern of task choice found in this study suggests that such a strategy was hardly necessary. While a significant influence of the contents of WM was found, the size of this influence was not large (M=.038). Additionally, the proportion of switches performed indicated that participants were complying with instructions to perform tasks randomly, suggesting that executive attention was actively engaged during task choice. The RT data suggest that this pattern was able to be obtained without sacrificing RT on non-match trials. Instead we posit that RT was increased on WM-match trials in the service of WM maintenance. Participants may have used WM-match trials as an opportunity to refresh WM representations (Woodman & Luck, 2007). Indeed memory accuracy did increase slightly as the number of match trials performed during that block increased (zero WM-matches: M=.833, one WM-match: M=.844, two WM-matches: M=.852) suggesting that performing the task associated with the stimulus that matched the contents of WM allowed the representation to be refreshed and WM storage to be enhanced. The benefit to WM maintenance afforded by the opportunity to refresh representations in WM may have been worth a small sacrifice of RT on those trials.

Conclusion

The connection between WM and attention has been repeatedly proposed. Models of WM frequently cite the importance of executive attention for the manipulation of information within WM (Baddeley, 1996a; Kane, Bleckley, Conway & Engle, 2001; Norman & Shallice, 1986). As a result, a great deal of literature has focused on the influence that WM loads that limit executive attention can have on performance in various situations, including task switching (Baddeley, Chincotta & Adlam, 2001; Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008; Logan, 2004). However, how the specific content of such loads may influence attention has been considered far less often. This lack of consideration is somewhat surprising given the potential for information in WM to guide selective attention (Downing, 2000; Huang & Pashler, 2007; Moores & Maxwell, 2008). As demonstrated by the current study, the contents of WM may have the potential to exert an influence on both selective and executive attention processes. Studies of WM are likely to benefit from an integrated research approach that considers how these processes may work together to influence the selection and performance of behavior.

Reference

Allport, A., Styles, E.A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta, & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 421-452). Cambridge, MA: Mit Press.

Arrington, C.M. (2008). The effect of stimulus availability on task choice in voluntary task switching. *Memory & Cognition, 36*, 991-997.

Arrington, C. M., & Logan, G. D. (2004a). The cost of a voluntary task switch. *Psychological Science*, *15*, 610-615.

Arrington, C.M. & Logan, G.D. (2004b). Episodic and semantic components of the compound-stimulus strategy in the explicit task-cuing procedure. *Memory & Cognition*, *32*, 965-978.

Arrington, C. M., & Logan, G. D. (2005). Voluntary task switching: Chasing the elusive homunculus. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*, 683-702.

Arrington, C. M., Weaver, S. M., & Pauker, R. L. (2009). *Stimulus priming in task choice during voluntary task switching.* Manuscript in preparation.

Awh, E. et al. (1999). Rehearsal in spatial working memory: Evidence from neuroimaging. *Psychological Science, 10,* 433-437.

Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences*, *5,* 119-126.

Awh, E., Jonides, J., & Reuter-Lorenz, P.A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 780-790.

Baddeley, A. (1992). Working Memory. *Science, 255*, 556-559.

Baddeley, A. (1996a). Exploring the Central Executive. *The Quarterly Journal of Experimental Psychology, 49A,* 5-28.

Baddeley, A.U. (1996b). The fractation of working memory. *Proceedings of the National Academy of Sciences, 93,* 13468-13472.

Baddeley, A.U., Chincotta, D., & Adlam, A. (2001). Working memory and the control of action: Evidence from task switching. *Journal of Experimental Psychology: General, 13,* 641-657.

Brisson, B., & Jolicoeur, P. (2007) Electrophysiological evidence of central interference in the control of visuospatial attention. *Psychonomic Bulletin & Review, 14,* 126-132.

Chelazzi, L., Miller, E.K. Duncan, J., & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature, 363*, 345-347.

de Fockert, J.W., Rees, G., Firth, C.D., & Lavie, N. (2001). The role of working memory in visual selective attention. *Science, 291,* 1803-1806.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18,* 193-222.

Downing, P.E. (2000). Interactions between visual working memory and selective attention. *Psychological Science, 11,* 467-473.

Downing, P.E., & Dodds, C.M. (2004). Competition in visual working memory for control of search. *Visual Cognition, 11,* 689-703.

Hester, R., & Garavan, H. (2005). Working memory and executive function: The influence of content and load on the control of attention. *Memory and Cognition, 33,* 221-233.

Huang, L. & Pashler, H. (2007). Working memory and the guidance of visual attention: Consonance-driven orienting. *Psychonomic Bulletin & Review, 14,* 148-153.

Kane, M.J., Bleckley, M.K., Conway, A.R., & Engle, R.W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General, 130,* 169-183.

Kane, M.J., Hambrick, D.Z., Tuholski, S.W., Wilhelm, O., Payne, T.W., & Engle, R.W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General, 133,* 189-217.

Kiesel, A., Wendt, M., & Peters, A. (2007). Task switching: On the origin of response congruency effects. *Psycholgical Research, 71,* 117-125.

Koch, I., & Allport, A. (2006). Cue-based preparation and stimulus-based priming of tasks in task switching. *Memory & Cognition, 34,* 433-444.

Lavie, N., & de Fockert, J. (2005). The role of working memory in attentional capture. *Psychonomic Bulletin and Review, 12,* 669-674.

Lawrence, B.M., Myerson, J., & Abrams, R.A. (2004). Interference with spatial working memory: An eye movement is more than a shift of attention. *Psychonomic Bulletin & Review, 11,* 488-494.

Liefooghe, B., Barrouillet, P., Vandierendonck, A., & Camos, V. (2008). Working memory costs of task switching. *Journal of Experimental Psychology: Learning, Memory & Cognition, 34,* 478-494.

Liefooghe, B., Demanet, J., & Vandierendonck, A. (In Press). Is advanced reconfiguration in voluntary task switching affected by the design employed? *The Quarterly Journal of Experimental Psychology.*

Lien, M.C., Ruthruff, E. (2008). Inhibition of task set: Converging evidence from task choice in voluntary task switching paradigm. *Psychonomic Bulletin & Review, 15,* 1111-1116.

Logan, G.D. (1985). Executive control of thought and action. *Acta Psychologica, 60,* 193-210.

Logan, G.D. (1988). Toward an instance theory of automatization. *Psychological Reivew, 95,* 492-527.

Logan, G.D. (2003). Executive control of thought and action: In search of the wild homunculus. *Current Directions in Psychological Science, 12,* 45-48.

Logan, G.D. (2004). Working memory, task switching, and executive control in the task span procedure. *Journal of Experimental Psychology: General, 133,* 218-236.

Logan, G.D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance, 29,* 575-599.

Masson, M.E.J., & Loftus, G.R. (2003). Using confidence intervals for graphically based data interpretation. *Canadian Journal of Experimental Psychology, 57,* 203-220.

Mayr, U., & Bell, T. (2006). On how to be unpredictable: Evidence from the voluntary task-switching paradigm. *Psychological Science*, *17*, 774–780.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*, 134-140.

Monsell S. (2005).The chronometrics of task set control. In J. Duncan, L. Phillips, & P. McLeod (Eds.), *Modelling the mind: Speed, control and age*. (pp. 161-190). Oxford, England: Oxford University Press.

Moores, E., & Maxwell, J.P. (2008). The role of prior exposure in the capture of attention by items in working memory. *Visual Cognition, 16,* 675-695.

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science, 229,* 782-784.

Norman, D. A., & Shallice, T. (1986). Attention to action: willed and automatic control of behaviour. in R.J. Davidson, G.E. Schwartz, & D. Shapiro (Eds.), *Consciousness and Self Regulation, Vol. 4* (pp. 1-18). New York: Plenum Press.

Oberauer, K. (2002). Access to information in working memory: exploring the focus of attention. *Journal of Experimental Psychology: Learning Memory & Cognition, 28,* 411-421.

Oberauer, K. (2005). Control of the contents of working memory - A comparison of two paradigms and two age groups. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 31*, 714-728.

Oberauer, K., & Gothe, K. (2006). Dual-task effects in working memory: Interference between two processing tasks, between two memory demands, and between storage and processing. *European Journal of Cognitive Psychology, 18,* 493-519.

Olivers, C.N.L., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *Journal of Experimental Psychology: Human Perception and Performance, 32,*1243-1265.

Sakai, K., & Passingham, R.E. (2003). Prefrontal interactions reflect future task operations. *Nature Neuroscience, 6,* 75-81.

Sandrini, M., Rossini, P.M., & Miniussi, C. (2008). Lateralized contribution of prefrontal cortex in controlling task-irrelevant information during verbal and spatial working memory tasks: rTMS evidence. *Nueropsychologia, 46,* 2056-2063.

Schneider, D.W., & Logan, G.D. (2006). Hierarchical Control of Cognitive Processes: Switching Tasks in Sequences. *Journal of Experimental Psychology: General, 135,* 623-640.

Serences, J. T., Shomstein, S., Leber, A. B., Golay, X., Egeth, H., & Yantis, S. (2005). Coordination of voluntary and stimulus-driven attentional control in human cortex. *Psychological Science, 16,* 114-122.

Soto, D. & Humphreys, G.W. (2007). Automatic guidance of visual attention from verbal working memory. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 730-757.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643-662.

Sudevan, P., & Taylor, D.A. (1987). The cuing and priming of cognitive operations. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 89-103.

Towse, J.N., & Cheshire, A. (2007). Random number generation and working memory. *European Journal of Cognitive Psychology, 19,* 374-394.

Treisman, A. (1998). Feature binding, attention and object perception. *Philosophical Transactions of the Royal Society of London, B, 353,* 1295-1306.

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries, *Psychological Review, 95,* 15-48.

Waszak, F., & Hommel, B. (2007). The costs and benefits of cross-task priming. *Memory & Cognition, 35,* 1175-1186.

Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: Role of episodic stimulus-task bindings in task-shift costs. *Cognitive Psychology, 46,* 361-413.

Waszak, F., Hommel, B., & Allport, A. (2005). Interaction of task readiness and automatic retrieval in task switching: Negative priming and competitor priming. *Memory & Cognition, 33,* 595-610.

Wolfe, J.M. (1998). Visual Search. In H. Pashler (Ed). *Attention.* (pp. 13-73). Hove, England: Psychology Press.

Woodman, G.F., & Luck, S.J. (2007). Do the contents of visual working memory automatically influence attentional selection during visual search? *Journal of Experimental Psychology: Human Perception & Performance, 33,* 363-377.

Wylie, G., & Allport, A. (2000). Task switching and the measurement of "switch costs". *Psychological Research, 63,* 212-233.

Yantis, S. (2000). Goal-directed and stimulus-driven determinants of attentional control. In S. Monsell and J. Driver (Eds.) Control of Cognitive Processes: Attention and Performance XVIII (pp. 73-103). Cambridge, MA: MIT Press.

Figure Captions

Figure 1. Trial line and examples of the trial types. Gray blocks indicate all possible stimulus locations and did not appear in the actual experiment.

Figure 2. The mean proportion of matches performed in each WM domain as a function of trial type and trial number. Error bars in this and all figures are 95% confidence intervals calculated from the error term for the within-subject variable as suggested by Masson and Loftus (2003).

Figure 3. Mean response times in each WM domain as a function of trial type and task match.

Figure 1.

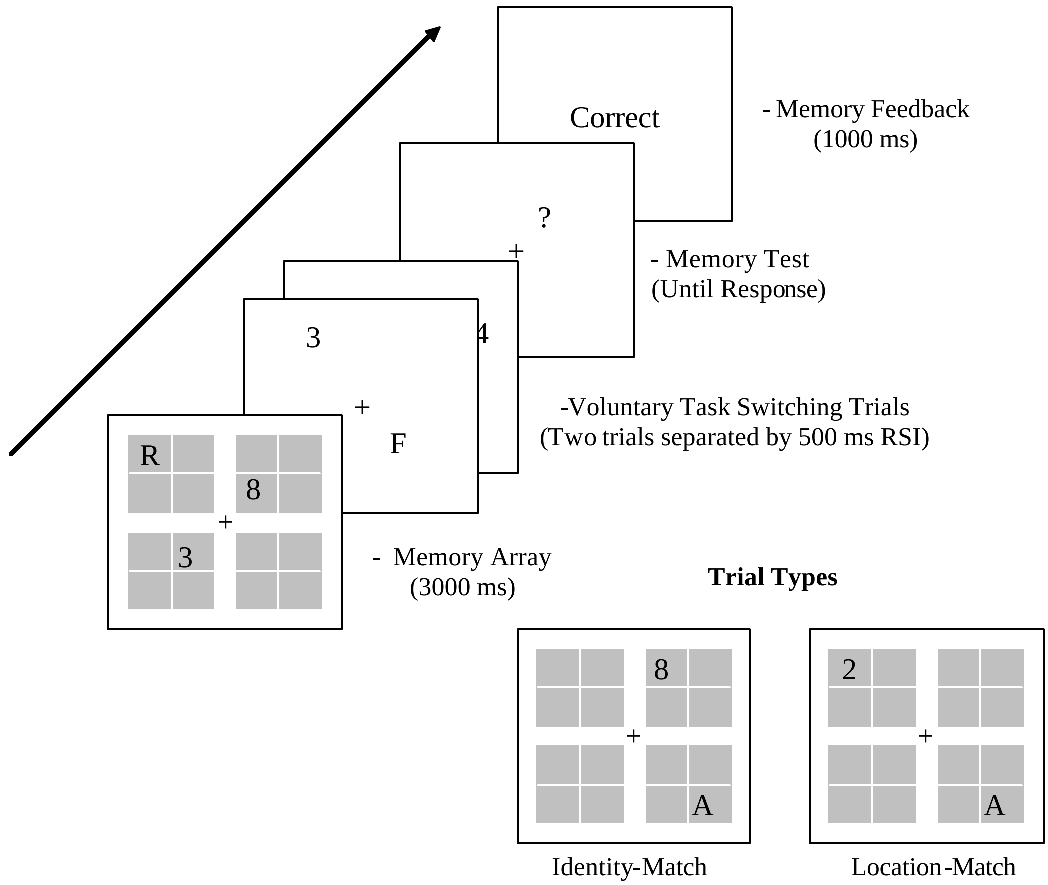

Correct
- Memory Feedback
(1000 ms)
?
+
- Memory Test
(Until Response)
3
4
+
F
-Voluntary Task Switching Trials
(Two trials separated by 500 ms RSI)
R
8
+
3
- Memory Array
(3000 ms)
Trial Types
8
+
A
2
+
A
Identity-Match
Location-Match

Figure 2.

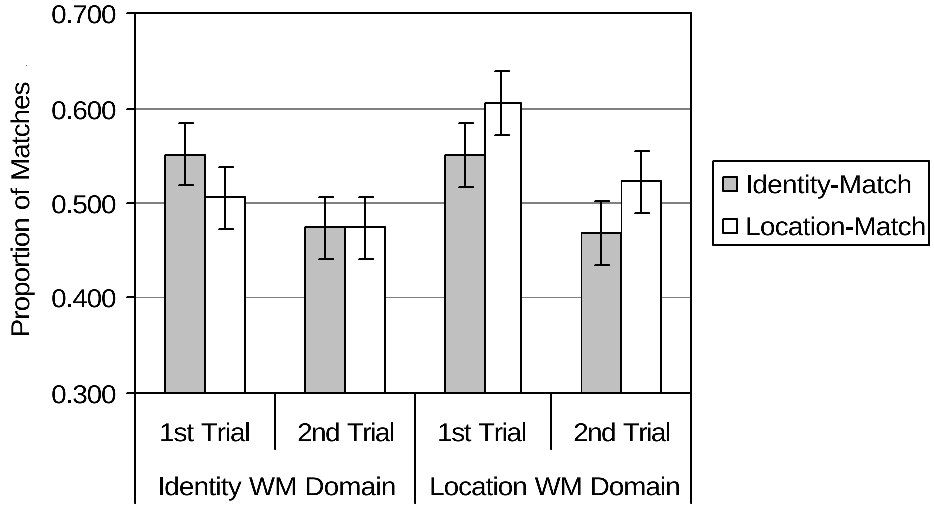
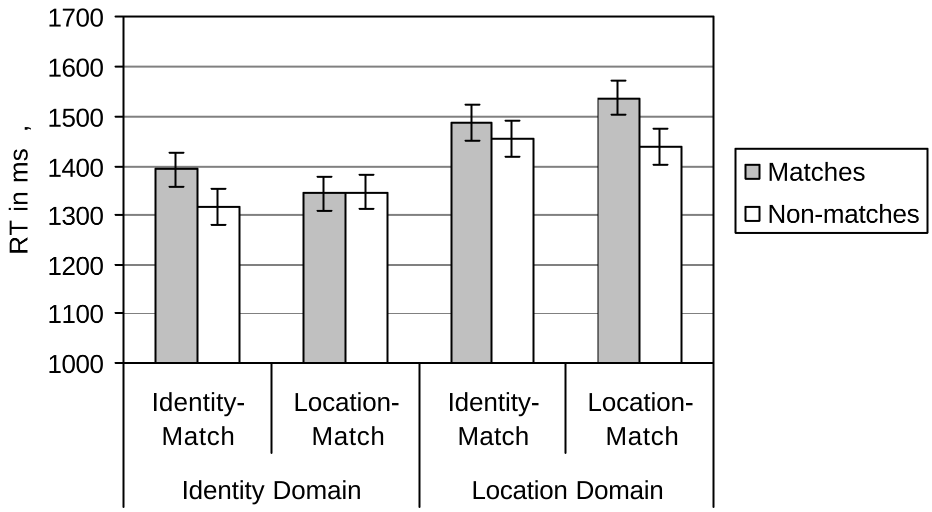

0.700
0.600
0.500
0.400
0.300
Proportion of Matches
Identity-Match
Location-Match
1st Trial
2nd Trial
1st Trial
2nd Trial
Identity WM Domain
Location WM Domain

Figure 3.


1700
1600
1500
1400
1300
1200
1100
1000
RT in ms
Matches
Non-matches
Identity-Match
Location-Match
Identity-Match
Location-Match
Identity Domain
Location Domain