Published in final edited form as:

Psychol Sci. 2014 August ; 25(8): 1619–1629. doi:10.1177/0956797614536739.

The working memory Stroop effect: When internal representations clash with external stimuli

Anastasia Kiyonaga and Tobias Egner

Duke University

Abstract

Working memory (WM) has recently been described as internally directed attention, implying that internally activated WM content should impact behavior exactly like a visually perceived and attended stimulus. We tested whether holding a color-word in WM, rather than attending to it in the external environment, can produce interference in a color-discrimination task, mimicking the classic Stroop effect. Over three experiments, the “WM Stroop effect” recapitulated core properties of the classic “attentional” Stroop effect, displaying equivalent congruency effects, additive contributions from stimulus- and response-level congruency, and susceptibility to modulation by the proportion of congruent and incongruent trials. Moreover, WM maintenance was inversely related to attentional demands during the WM delay, with poorer memory following incongruent than congruent trials. Together, these results suggest that WM and attention rely on the same resources and operate over the same representations.

Working memory (WM) has traditionally been considered a dedicated system for the short-term maintenance and manipulation of internal information (Baddeley & Hitch, 1974), whereas attention has described the selective focusing on a limited amount of information in the environment (e.g., Broadbent, 1958). Recent evidence suggests, however, that these two constructs, formerly deemed distinct, are in fact intimately linked. Spatial attention is recruited to maintain mental representations (e.g., Awh, Jonides, & Reuter-Lorenz, 1998; Nobre et al., 2004), WM capacity predicts visual search performance (Anderson, Vogel, & Awh, 2013; Poole & Kane, 2009), and a high load on either WM maintenance or visual attention can impair performance in the other (e.g., Chen & Cowan, 2009; de Fockert, 2001; Woodman & Luck, 2010). Human neuroimaging studies have, furthermore, shown that WM maintenance activates the same neural representations of sensory stimuli that are modulated by externally directed attention (e.g., Ranganath, Cohen, Dam, & D’Esposito, 2004), and patterns of sensory cortical activity from visually attending a stimulus can be used to decode the identity of that stimulus when it is maintained in WM (e.g., Emrich, Riggall, LaRocque, & Postle, 2013; Serences, Ester, Vogel, & Awh, 2009). Accordingly, some theories now describe WM as attention directed at internal representations (Awh & Jonides, 2001; Chun,

Correspondence concerning this article can be addressed to Anastasia Kiyonaga or Tobias Egner, Department of Psychology and Neuroscience, Duke University, 450 Research Drive, Levine Science Research Center, Room B203, Box 90999, Durham, NC 27708. anastasia.kiyonaga@duke.edu; tobias.egner@duke.edu.

Author Contributions

A. Kiyonaga and T. Egner developed the study concept and design. A. Kiyonaga collected and analyzed the data, under the supervision of T. Egner. Both authors wrote the paper and approved the final version for submission.

2011; Cowan, 1988; Gazzaley & Nobre, 2012; Kiyonaga & Egner, 2013; Oberauer & Hein, 2012; Postle, 2006). Here, “internal attention” refers to attention operating over representations of items that are no longer present in the environment, and therefore must be activated endogenously. “External attention,” on the other hand, refers to attention operating over representations of items that are currently visible in the environment, and therefore activated by an external stimulus.

Several observations of WM and attention processes proceeding unhampered by one another have generated debate about whether the linkage between them is indeed obligatory (e.g., Hollingworth & Maxcey-Richard, 2012; Woodman, Vogel, & Luck, 2001). In the present work, we conducted a strong test of the hypothesis that WM and attention draw on the same (attentional) resources and operate over the same representations. It follows from this view that maintaining an item in WM should impact behavior comparably to visually attending that item, and consequently that classic effects of attention should replicate in the WM domain. Recent support for this hypothesis stems from the finding that directing attention internally to refresh a particular item in WM produces a decrement in responding to a matching probe, akin to well-known “inhibition of return” effects in visual attention (Johnson et al., 2013). Similarly, active maintenance in WM can produce visual after-effects much like adaptation effects from prolonged viewing of a stimulus (Saad & Silvanto, 2013). Here, we extended this line of inquiry by testing the equivalence of WM and attention in what is probably the best-known and most widely-used probe of attentional filtering, namely the color-naming Stroop task (Stroop, 1935). In Experiment 1, we developed a “WM Stroop task” to test whether holding a word internally in WM, rather than attending to it in the external environment, can produce interference effects in a perceptual discrimination task of color patches during the WM delay interval. In Experiments 2 and 3, we submit the “WM Stroop effect” to additional scrutiny, testing whether it mimics a number of core properties of the classic, “attentional” Stroop effect. We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study.

Experiment 1

In the classic Stroop effect, participants are slower (and less accurate) to name the ink color of a color-word stimulus when the meaning of the color-word is incongruent with the ink color (e.g., RED written in blue) than when it is congruent (e.g., BLUE written in blue; MacLeod, 1991). This response slowing on incongruent trials is thought to be due to costly, yet still imperfect, attentional filtering of the task-relevant color information (e.g., Cohen, Dunbar, & McClelland, 1990). By contrast, erroneous responses on incongruent trials appear to be attributable to intermittent “goal neglect”—an inadvertent reading response primed by the color-word on a subset of trials (e.g., Kane & Engle, 2003). From this characterization of the Stroop effect, we can derive three key predictions for a WM Stroop task: First, maintaining an incongruent color-word in WM should produce conflict and slow the naming of an external color patch just as if the word were being attended externally. Second, since a color patch cannot prime an alternative word-reading task, the WM Stroop task, unlike the standard Stroop, should not be subject to a Stroop effect in error rates. Third, the attention-demanding filtering process, during incongruent trials, should divert attentional resources from maintaining the WM content, and result in poorer memory following incongruent than

congruent trials (cf. Barrouillet, Bernardin, & Camos, 2004). Experiment 1a tested these predictions by having participants complete a classic color-naming Stroop task, as well as a dual-task WM/color-discrimination paradigm, in counterbalanced order.

Methods

Participants—Participants were recruited via Amazon Mechanical Turk (MTurk; <https://www.mturk.com>) and provided informed consent in accordance with the Duke University Institutional Review Board. Participants could sign up for all experiments regardless of age, native language, or country of residence, but were required to have previously completed at least 500 tests via MTurk, and hold a record of supplying acceptable data to the experimenter at least 95% of the time. We could thus be assured that participants were competent in English and able to successfully follow task instructions. Participants were prevented from completing more than one experiment in this series.

To ensure that data collected via MTurk would be comparable to those collected in the laboratory, and would replicate established effects, we first administered a pilot version of the classic color-naming Stroop task to 20 MTurk participants. We did indeed observe the expected Stroop congruency effect, with a fairly large effect size (Cohen's $d = .7$). With the goal of achieving a power of .8 at $\alpha = .01$, and the expectation of a medium-large effect size, Experiment 1a was administered to 40 participants (Cohen, 1992). After excluding data from those with chance-level accuracy or responses on fewer than 2/3 trials, 35 participants (17 female; mean age: 34; range: 22–65) were included in the analysis.

Stimuli and procedure

Classic color-word Stroop task: The standard Stroop task comprised a series of color-words, which were written in colored ink. A word—either “red”, “blue”, “green” or “yellow”—was centrally displayed on each trial for 500msec, on a neutral grey background, in one of four ink colors (RGB values: red=255,0,0; blue=0,0,255; green=25,200,25; yellow=225,215,40), separated by a 1000msec intertrial interval (ITI). Participants were required to report the color of the ink, regardless of the meaning of the word, using one of four designated response buttons for each of the possible colors. Congruent (ink color and word meaning agree) and incongruent (ink color and word meaning differ) trials occurred equally often and in randomized order. Participants completed 20 practice trials, during which they received feedback on every trial, followed by 96 experimental trials without feedback. This Stroop task is used here to assess the degree of conflict in a perceptual task (color-naming) from irrelevant *externally attended* visual stimuli.

WM Stroop task: As illustrated in Figure 1, our dual-task WM/color-discrimination paradigm entailed a delayed match-to-sample WM test, interleaved with a color-judgment task during the delay. The WM sample—which participants were instructed to remember for a test at the end of the trial—was a word written in black ink (either “red”, “blue”, “green” or “yellow”) displayed centrally for 1000msec. After a 2000msec inter-stimulus interval (ISI), a rectangular patch was centrally presented for 500msec in one of four colors (RGB values: red=255,0,0; blue=0,0,255; green=25,200,25; yellow=225,215,40). Before the end of a 1000msec ISI, participants were required to report the color of the patch using one of four

designated response buttons for each of the possible colors (Figure 1b; colors mapped on to the letters ‘A’, ‘S’, ‘J’, and ‘K’). A WM probe word (either “red”, “blue”, “green” or “yellow”) then appeared for 3000msec, accompanied by instructions (which remained consistent from trial to trial) denoting with which buttons to respond whether the probe was a match (press “1”) or non-match (press “0”) to the WM sample word. An asterisk then appeared for 1500msec to signal the start of a new trial. Congruent (color patch and meaning of WM sample agree) and incongruent (color patch and meaning of WM sample differ) trials, as well as match and non-match WM probes, occurred equally often and in randomized order. Participants completed 20 practice trials, during which they received feedback on every color judgment and WM probe, followed by 120 experimental trials, without feedback. This novel dual-task WM paradigm is used here to assess the degree of conflict in a perceptual task (color-naming) from irrelevant *internally attended* representations.

Results

We conducted 2 (Counterbalance order: Stroop first vs. WM first) $\times$ 2 (Task: Stroop vs. WM) $\times$ 2 (Congruency: Congruent vs. Incongruent) mixed ANOVAs to examine the impact of conflicting information on color-naming performance, and whether the extent of that impact varied when the information was internally or externally activated. Performance measures for all experiments included mean correct response time (RT) and accuracy (% correct) for trials with a response. For the WM task, color patch judgments were included only when the WM probe was also correctly recognized. Mean RT and accuracy for all conditions in all experiments are reported in Table 1.

For both tasks, participants were much slower to make the ink color response in the incongruent condition (vs. congruent), $F(1, 33) = 74.14$, $p < .001$, $\eta^2_p = .69$. This sizeable effect of congruency was, moreover, of equivalent magnitude for both the classic color-word Stroop task (Figure 2a; 84msec), and the WM task (Figure 2b; 83msec). There were no other main effects or interactions (all $p > .1$, all $\eta^2_p < .05$). Regardless of whether the conflicting information was an internally maintained WM sample or an externally attended word, participants were dramatically slowed by its presence, and to a nearly identical degree.

Participants were significantly more accurate overall for congruent trials, $F(1, 33) = 10.99$, $p < .005$, $\eta^2_p = .25$, but there was also an interaction between task and congruency, $F(1, 33) = 9.76$, $p < .005$, $\eta^2_p = .23$. The main effect of congruency was only evident during the classic color-word Stroop, $t(34) = 3.6$, $p < .001$, but *not* the WM task, $p > .1$, for which performance was more accurate overall, $F(1, 33) = 15.66$, $p < .001$, $\eta^2_p = .32$. There were no other main effects or interactions (all $p > .1$, all $\eta^2_p < .05$). The conflicting information that slowed response times, thus, only produced more errors when it was simultaneously presented and visible with the relevant stimulus for the perceptual task.

WM probe performance was evaluated with two-tailed t-tests comparing trials when the color patch had been congruent or incongruent with the meaning of the WM sample. Participants were both slower, $t(34) = 5.9$, $p < .001$, and less accurate, $t(34) = 2.9$, $p < .01$, on the WM test when the delay-period color patch had been incongruent with the meaning of the memory sample. The conflict between the internal content and external stimulus that

slowed color-responding, thus, seemed to have a reciprocal impact on maintenance of the WM representation.

Experiment 1 established a “WM Stroop effect” representations in WM can interfere with task performance just like stimuli that are currently attended in the external environment. Specifically, as predicted, internally maintaining an incongruent color-word drastically slowed the naming of an external color patch, analogous to when the word was simultaneously attended externally. Only when the incongruent stimulus was concurrently externally presented (i.e., classic Stroop), and could therefore trigger an alternative task, however, did it produce more errors. Finally, WM content was remembered more poorly during incongruent trials, when the attentional filtering process presumably diverted attentional resources from WM maintenance. We also conducted additional experiments to ensure that this effect would be observed in-person in the laboratory (see Supplemental Experiment 1), and to rule out a priming-based explanation for these findings (Supplemental Experiment 2; cf. Warren, 1972). These data therefore support the proposal of equivalence and reciprocity between internally vs. externally activated mental representations. In Experiment 2, we provide a more profound test of this proposal by assessing whether the WM Stroop effect is susceptible to the same manipulations as the classic Stroop effect.

Experiment 2

A typical Stroop interference effect can be decomposed into conflict contributions from both the semantic overlap between the ink color and word meaning stimulus dimensions (i.e., stimulus-level conflict), as well as the fact that the two dimensions typically cue two different manual responses (i.e., response-level conflict; e.g., De Houwer, 2003). According to our equivalency argument, the same should be true of the WM Stroop effect. Here we test this hypothesis by varying the degree of conflict at the stimulus and response levels, in both classic color-word and WM Stroop tasks, which were completed in counterbalanced order.

Methods

Participants—As with Experiment 1, we aimed to collect 40 usable datasets. With the expectation that about 10–20% of respondents would fail to meet performance criteria, we recruited 50 participants via MTurk. Eight participants were excluded for chance level accuracy and responses on fewer than 2/3 trials, thus 42 participants (23 female; mean age: 34.2; range: 18–60) are included in the analysis.

Stimuli and procedure—All stimulus values and timing parameters for both the standard and WM Stroop tasks were identical to Experiment 1 (Figure 1a). Whereas, in Experiment 1, each ink color mapped onto a unique response button, however, the critical manipulation in Experiment 2 was the mapping of two ink colors onto a single manual response (Figure 1c; cf. De Houwer, 2003). So, for both the Stroop color-word and the WM delay color-patch, the same button would be used to respond to an ink color of either red or blue, for instance. Accordingly, in both tasks there were three trial types: (1) Congruent (e.g., the ink color is red and the irrelevant word is “red”), (2) Stimulus Incongruent (e.g., the ink color is red and the irrelevant word is “blue”, which maps onto the same manual response), and (3) Stimulus + Response Incongruent (e.g., the ink color is red and the irrelevant word is “green”, which

maps on to a different manual response). These trial types occurred equally often and in randomized order. For both tasks, participants completed 20 practice trials with feedback, then 144 experimental trials without feedback. If maintaining an item in WM impacts behavior just like visually attending that item, then both stimulus and response conflict should make a contribution to the WM Stroop effect. Consequently, color judgments should be slower when both the WM word meaning and associated response are incongruent, as opposed to just the word meaning.

Results

We conducted 2 (Counterbalance order: Stroop first vs. WM first) $\times$ 2 (Task: Stroop vs. WM) $\times$ 3 (Congruency: Congruent, Stimulus Incongruent, Stimulus + Response Incongruent) mixed ANOVAs to examine the impact of conflicting information at the stimulus and response levels on color-naming performance, and whether the extent of that impact varied when the information was internally or externally attended.

Performance of the standard Stroop task was overall faster than the WM task, $F(1, 40) = 42.83$, $p < .001$, $\eta^2_p = .52$, and there was a main effect of congruency, $F(2, 80) = 36.74$, $p < .001$, $\eta^2_p = .48$ (Figure 3). The congruency effect followed a strong linear trend, $F(1, 40) = 62.32$, $p < .001$, $\eta^2_p = .61$, in that participants were fastest when both stimulus and response dimensions were congruent, slower when only the stimulus dimension conflicted with the meaning of the visually presented or internally maintained word, and slowest when both stimulus and response dimensions were incongruent. There were no other main effects or interactions (all $p > .1$, all $\eta^2_p < .05$). To directly contrast the individual contributions of stimulus and response-level processing between tasks, however, we also calculated effect scores for stimulus conflict (Stimulus Incongruent – Congruent) and response conflict (Stimulus + Response Incongruent – Stimulus Incongruent) and compared each of these between the standard and WM Stroop tasks with two-tailed t-tests. While stimulus conflict contributions were comparable for both tasks, $t(41) = 1.2$, $p > .2$, the contribution from response-level conflict was slightly greater in the standard Stroop task, $t(41) = 2.2$, $p < .05$, when the irrelevant distractor word was presented simultaneously with the color-naming task. As demonstrated by the strong linear effect of congruency, and absence of an interaction between task and congruency, nonetheless, both the standard Stroop effect and the conflict effect from WM content comprise unique contributions from stimulus-level and response-level processing.

Participants were overall more accurate in the WM task, $F(1, 40) = 47.94$, $p < .001$, $\eta^2_p = .55$, and more accurate for congruent trials, $F(2, 80) = 8.4$, $p < .001$, $\eta^2_p = .17$, but there was an interaction between task and congruency, $F(2, 80) = 4.42$, $p < .05$, $\eta^2_p = .1$, in that this accuracy difference was only evident in the color-word Stroop task. There were no other main effects or interactions (all $p > .1$, all $\eta^2_p < .05$). While RTs were slowed by the presence of discordant information in both tasks, in a manner that scaled with the number of levels on which there was conflict (i.e., some interference from stimulus conflict alone, but more interference when there was additional conflict in the response dimension), accuracy was worsened by conflict only in the color-word Stroop task.

WM recognition performance was evaluated using one-way ANOVAs with the 3-level factor of congruency (Congruent, Stimulus Incongruent, Stimulus + Response Incongruent). Congruency between the WM sample and color patch impacted both the speed, $F(2, 82) = 12.81, p < .001, \eta^2_p = .24$, and accuracy, $F(2, 82) = 3.65, p < .05, \eta^2_p = .08$, of WM probe responses. Mirroring the RT pattern for the color judgment portion of the task, probe responses were slower (and less accurate) when the WM sample was semantically incongruent with the color patch stimulus, and *slowest* (and least accurate) when both the stimulus and corresponding response were incongruent. The extent to which the color patch judgment interferes with WM maintenance seems to scale with the degree of conflict the internal content produces—and thus the amount of attentional filtering it requires—in the perceptual task.

Experiment 2 demonstrated that the WM Stroop effect is susceptible to conflict at both the stimulus and response levels—also a quintessential property of the classic Stroop effect. Moreover, WM probes were recognized most poorly following color judgments with the greatest amount of conflict, again supporting the idea of a mutual correspondence between internally and externally attended information. In Experiment 3, we tested whether yet another key property of the classic Stroop effect would be reproduced in the WM Stroop effect.

Experiment 3

The extent of interference in the color-word Stroop task is strongly modulated by the proportion of congruent trials in the task (e.g., Logan & Zbrodoff, 1979)—a finding typically attributed to adjustments in attentional strategy to best suit the processing of the most frequently occurring trial type (e.g., Gratton & Donchin, 1992). Thus, when incongruent trials are more frequent, the size of the Stroop effect is minimized. If the interference we have observed from internal WM content does indeed operate like the standard Stroop effect, then it should be equally amenable to strategic attentional control processes, and the magnitude of the congruency effect should therefore scale parametrically with the proportion of congruent trials in a block of the experiment. Experiment 3, accordingly, comprised a block-level manipulation of the proportions of congruent and incongruent trials, in both the classic and WM Stroop tasks.

Methods

Participants—Because it required a greater number of trials to produce sufficient cases of congruent and incongruent items in every block condition, we administered the color-word Stroop and WM tasks to separate groups of participants. We used three different block proportion congruency conditions (75% congruent, 50% congruent, 25% congruent), thereby producing six possible sequences in which the conditions could occur. We conducted a complete counterbalance in that each of the six possible combinations were administered to an equal number of participants. In order to ensure ample participants in each counterbalance condition, 54 total participants were recruited via MTurk for each the color-word and WM Stroop tasks. After excluding those with chance-level accuracy and responses on fewer than 2/3 trials, 42 classic Stroop participants (18 female; mean age: 33.3;

range: 23–52) and 48 WM participants (18 female; mean age: 32.7; range: 23–61) were included in the analysis.

Stimuli and procedure—All stimulus values, timing parameters, and response mappings for both the standard and WM Stroop tasks were identical to Experiment 1 (Figure 1a). Whereas Experiments 1 and 2 comprised equal proportions of each trial type, Experiment 3 incorporated three blocked conditions with varying proportions of congruent and incongruent trials: 75% congruent/25% incongruent, 50% congruent/50% incongruent, and 25% congruent/75% incongruent. Each block condition occurred once, in counterbalanced order. Participants in both tasks completed 20 practice trials with feedback, followed by blocks of 96 trials of each proportion congruency condition, totaling 288 experimental trials.

Results

Mean correct RT and accuracy were entered into a 2 (Task: Stroop vs. WM; between-subjects) $\times$ 2 (Congruency: Congruent vs. Incongruent) $\times$ 3 (Proportion Congruent: 75%, 50%, 25%) mixed ANOVAs. As in the earlier Experiments, participants were markedly slower on incongruent trials, $F(1, 88) = 165.28, p < .001, \eta^2_p = .65$, but the extent of this interference was also modulated by the proportion of congruent trials in the block, $F(2, 176) = 26.6, p < .001, \eta^2_p = .23$. As shown in Figure 4, the speed difference between congruent and incongruent trials was greatest when there was a larger percentage of congruent trials, and smallest when there was a larger percentage of incongruent trials. There were no other main effects or interactions (all $p > .1$, all $\eta^2_p < .05$). Thus, just as the size of the classic color-word Stroop effect is modulated by the proportion of congruent trials (e.g., Figure 4a), so is the effect of conflict from internal WM content, and to a comparable degree (Figure 4b).

Participants were also more accurate overall on the WM task, $F(1, 88) = 12.3, p < .001, \eta^2_p = .12$, and like Experiments 1 and 2, were more accurate for congruent trials (vs. incongruent), $F(1, 88) = 26.65, p < .001, \eta^2_p = .23$. Also like the earlier experiments, trial congruency had a greater impact on the color-word Stroop task than the WM task, $F(1, 88) = 6.9, p < .01, \eta^2_p = .07$. The proportion congruency manipulation, however, did not impact task accuracy, nor did it modulate the effect of congruency on accuracy (all other $p > .1$, all $\eta^2_p < .05$). While the conflict processes that slowed RTs in the Stroop and WM tasks were susceptible to the ratio of congruent to incongruent trials, accuracy was neither impacted by interfering WM content nor the relative occurrence of this interference.

Again, participants were slower, $F(1, 47) = 70.65, p < .001, \eta^2_p = .60$, and less accurate, $F(1, 47) = 18.12, p < .001, \eta^2_p = .28$, at memory probe recognition judgments when the color patch was incongruent with the WM sample. Probe accuracy was also better during blocks with greater numbers of incongruent trials, $F(2, 94) = 3.97, p < .05, \eta^2_p = .08$, and the effect of congruency on probe accuracy decreased with an increasing proportion of incongruent trials, $F(2, 94) = 7.76, p < .005, \eta^2_p = .14$. Hence, the control processes that minimized the effect of congruency on color discrimination—when incongruent trials were more frequent—also manifested in better memory recognition.

Experiment 3 established that yet another fundamental property of the classic Stroop effect—modulation by the proportion of congruent trials—is replicable in the WM domain. Whether conflicting information was maintained in WM or a concurrent visible distractor, its impact was attenuated when conflict trials occurred more often, further demonstrating that internally and externally activated representations can impact behavior comparably.

Discussion

The nature of the linkage between WM and attention has been keenly studied of late, generating evidence for the unification of the two concepts, but also some cause for their continued demarcation. We examined the hypothesis that WM can be considered internally oriented attention, a powerful test of which is that WM content should influence behavior precisely like an attended external stimulus. We have found that responding to a perceptual judgment is dramatically slowed when an incongruent stimulus is internally maintained in WM, and this “WM Stroop effect” exhibits several archetypal properties of the classic color-naming Stroop effect. Representations in WM can therefore impact performance of an attention task as robustly as though they were being visually perceived.

These data suggest that WM shares representations with visual attention, consistent with conceptualizations of WM as internally directed or “reflective” attention (cf. Chun & Johnson, 2011), and observations that the two rely on shared neural mechanisms (Awh, Anillo-Vento, & Hillyard, 2000; Ikkai & Curtis, 2011; Lepsien, Griffin, Devlin, & Nobre, 2005). It follows, from this description of WM, that there should be a trade-off between demands from internally and externally activated representations (cf. Barrouillet et al., 2004; Kiyonaga & Egner, 2013), and that costly attentional filtering of incongruent trials should detract attention from maintaining the WM content. Accordingly, in our three experiments, not only was color-naming slowed, but WM content was maintained more poorly when it conflicted with the external stimulus. Although one can imagine that a WM representation that is robust enough to conflict with color-naming should also be easily accessible when probed, we instead found WM recognition to be reliably slower and less accurate on incongruent trials, suggesting that the interference resolution processes on those trials did indeed draw from the same pool of attentional resources as WM maintenance. This WM decrement, furthermore, scaled with the extent of interference between the WM sample and the perceptual stimulus, which varied with the degree of conflict on a given trial, as well as the proportion of congruent trials in a block of the experiment. The latter observation—that both color-naming and WM performance were less impaired when incongruent trials were more frequent—further suggests that control processes dampened interference not by suppressing the irrelevant stimulus dimension (which should result in worse WM) but by more efficient attentional filtering of the relevant stimulus (resulting in faster color-naming and thereby more opportunity to direct attention toward maintaining WM content; cf. Egner & Hirsch, 2005). These data thus substantiate claims that WM and visual attention share cognitive resources, and moreover illuminate the mechanisms of control over conflict from WM representations.

While the observation of a WM Stroop effect supports the notion of a compulsory linkage between internally and externally activated representations (cf. Hollingworth, Matsukura, &

Luck, 2013; Soto, Hodson, Rotshtein, & Humphreys, 2008), the modulation of the effect by the proportion of congruent trials nonetheless underscores that the impact of WM content on perceptual judgments is to some degree pliable. Much like attentional capture by WM contents (Kiyonaga, Egner, & Soto, 2012), and standard Stroop interference (Logan & Zbrodoff, 1979), the WM Stroop effect can be by modulated by cognitive control.

Although the WM Stroop effect replicated several key characteristics of the classic Stroop effect, however, it also differed in a notable way: incongruent WM samples failed to produce more errors in the color-naming test. Likely because the WM delay-period color patches presented no external cues to a habitual alternate task (like word-reading in the standard Stroop), accuracy on the WM Stroop task was higher overall, and was insensitive to congruency. The WM Stroop effect thus emulated the response slowing patterns of the standard Stroop effect, while the accuracy pattern fit with dual-mechanism accounts of Stroop interference (e.g., Kane & Engle, 2003). Furthermore, when the response mapping scheme was simplified to explore the individual contributions of stimulus- and response-level conflict (Experiment 2), standard Stroop performance was faster than the WM task, and displayed a relatively greater contribution from conflict at the response level. Perhaps because of the temporal overlap between target and distractor presentation in the standard Stroop, or the dual-task demands of the WM task (which employed separate response schemes for color judgments and memory probes), the externally-attended distractors of the standard Stroop task produced somewhat more response interference.

Several studies have demonstrated a tradeoff between attention and WM, using unrelated internal and external stimuli and varying load in either domain (Barrouillet et al., 2004; Chen & Cowan, 2009; de Fockert, 2001). While these implicate a shared executive resource, but would still allow a differentiation between the content of WM and attention, the WM Stroop task entails no such manipulation of load: there is always a single word to remember, and a uniformly discriminable color patch to judge, but it is only the conflict between them that varies. Consistent with notions that WM constitutes sustained recruitment of stimulus representations in early sensory cortical areas (e.g. Awh & Jonides, 2001; Serences et al., 2009), the WM Stroop effect provides a behavioral indication that WM and attention operate over the same representations as well. A consequence of this representation-sharing would be that dissimilar items trigger less mutual interference, which could give the appearance of dedicated stores for certain types of content, as well as the separability of WM and attention if the executive attention resource is not fully taxed. We therefore espouse a shared selection mechanism for internally and externally directed attention, whereby one domain will suffer only when that resource is fully occupied in the other, but also shared representations between internally and externally activated content, whereby the influence between them will be greatest when that content overlaps (cf. Kim, Kim, & Chun, 2005). The classic color-naming Stroop task is a stronghold of selective attention research, and here we have replicated several well-established properties of the Stroop effect in the WM domain. WM content can conflict with a perceptual task, and appears to be subject to the same attentional filtering processes as sensory stimuli.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This research was funded in part by National Institute of Mental Health Award R01MH087610 to T.E.. We thank Stephen Mitroff for helpful comments on a draft of the manuscript, and Jiefeng Jiang and John Lucas for help with experimental programming.

References

- Anderson DE, Vogel EK, Awh E. A Common Discrete Resource for Visual Working Memory and Visual Search. *Psychological Science*. 2013; 24(6):929–938. [PubMed: 23572280]
- Awh E, Anllo-Vento L, Hillyard SA. The Role of Spatial Selective Attention in Working Memory for Locations: Evidence from Event-Related Potentials. *Journal of Cognitive Neuroscience*. 2000; 12(5):840–847. [PubMed: 11054925]
- Awh E, Jonides J. Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences*. 2001; 5(3):119–126. [PubMed: 11239812]
- Awh E, Jonides J, Reuter-Lorenz PA. Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance*. 1998; 24(3):780–790. [PubMed: 9627416]
- Baddeley, AD.; Hitch, G. *Psychology of Learning and Motivation*. Vol. Vol. Volume 8. Academic Press; 1974. Working Memory; p. 47-89. Retrieved from <http://www.sciencedirect.com/science/article/pii/S0079742108604521>
- Barrouillet P, Bernardin S, Camos V. Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*; *Journal of Experimental Psychology: General*. 2004; 133(1):83.
- Broadbent, DE. *Perception and communication*. Elmsford, NY, US: Pergamon Press; 1958. The general nature of vigilance. In; p. 108-139.
- Chen Z, Cowan N. How verbal memory loads consume attention. *Memory & Cognition*. 2009; 37(6): 829–836. [PubMed: 19679862]
- Chun MM. Visual working memory as visual attention sustained internally over time. *Neuropsychologia*. 2011; 49(6):1407–1409. [PubMed: 21295047]
- Chun MM, Johnson MK. Memory: Enduring Traces of Perceptual and Reflective Attention. *Neuron*. 2011; 72(4):520–535. [PubMed: 22099456]
- Cohen J. A power primer. *Psychological Bulletin*. 1992; 112(1):155–159. [PubMed: 19565683]
- Cohen JD, Dunbar K, McClelland JL. On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*. 1990; 97(3):332–361. [PubMed: 2200075]
- Cowan N. Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin*. 1988; 104(2):163–191. [PubMed: 3054993]
- De Fockert JW. The Role of Working Memory in Visual Selective Attention. *Science*. 2001; 291(5509):1803–1806. [PubMed: 11230699]
- De Houwer J. On the role of stimulus-response and stimulus-stimulus compatibility in the Stroop effect. *Memory & Cognition*. 2003; 31(3):353–359. [PubMed: 12795477]
- Egner T, Hirsch J. Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience*. 2005; 8(12):1784–1790.
- Emrich SM, Riggall AC, LaRocque JJ, Postle BR. Distributed Patterns of Activity in Sensory Cortex Reflect the Precision of Multiple Items Maintained in Visual Short-Term Memory. *The Journal of Neuroscience*. 2013; 33(15):6516–6523. [PubMed: 23575849]
- Gazzaley A, Nobre AC. Top-down modulation: bridging selective attention and working memory. *Trends in Cognitive Sciences*. 2012; 16(2):129–135. [PubMed: 22209601]

- Gratton G, H G, Donchin E. Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General*. 1992; 121(4):480–506. [PubMed: 1431740]
- Hollingworth A, Matsukura M, Luck SJ. Visual Working Memory Modulates Rapid Eye Movements to Simple Onset Targets. *Psychological Science*. 2013; 24(5):790–796. [PubMed: 23508739]
- Hollingworth A, Maxcey-Richard AM. Selective Maintenance in Visual Working Memory Does Not Require Sustained Visual Attention. *Journal of Experimental Psychology. Human Perception and Performance*. 2012
- Ikkai A, Curtis CE. Common neural mechanisms supporting spatial working memory, attention and motor intention. *Neuropsychologia*. 2011; 49(6):1428–1434. [PubMed: 21182852]
- Johnson MR, Higgins JA, Norman KA, Sederberg PB, Smith TA, Johnson MK. Foraging for Thought An Inhibition-of-Return-Like Effect Resulting From Directing Attention Within Working Memory. *Psychological Science*. 2013
- Kane MJ, Engle RW. Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*. 2003; 132(1):47–70. [PubMed: 12656297]
- Kim SY, Kim MS, Chun MM. Concurrent working memory load can reduce distraction. *Proceedings of the National Academy of Sciences of the United States of America*. 2005; 102(45):16524. [PubMed: 16258067]
- Kiyonaga A, Egner T. Working memory as internal attention: Toward an integrative account of internal and external selection processes. *Psychonomic Bulletin & Review*. 2013; 20(2):228–242. [PubMed: 23233157]
- Kiyonaga A, Egner T, Soto D. Cognitive control over working memory biases of selection. *Psychonomic Bulletin & Review*. 2012; 19(4):639–646. [PubMed: 22528872]
- Lepsien J, Griffin IC, Devlin JT, Nobre AC. Directing spatial attention in mental representations: Interactions between attentional orienting and working-memory load. *NeuroImage*. 2005; 26(3):733–743. [PubMed: 15955482]
- Logan GD, Zbrodoff NJ. When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory & Cognition*. 1979; 7(3):166–174.
- MacLeod CM. Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*. 1991; 109(2):163–203. [PubMed: 2034749]
- Masson M, Loftus G. Using confidence intervals for graphically based data interpretation. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*. 2003; 57(3):203–220.
- Nobre AC, Coull JT, Maquet P, Frith CD, Vandenberghe R, Mesulam MM. Orienting Attention to Locations in Perceptual Versus Mental Representations. *Journal of Cognitive Neuroscience*. 2004; 16(3):363–373. [PubMed: 15072672]
- Oberauer K, Hein L. Attention to Information in Working Memory. *Current Directions in Psychological Science*. 2012; 21(3):164–169.
- Poole BJ, Kane MJ. Working-memory capacity predicts the executive control of visual search among distractors: the influences of sustained and selective attention. *Quarterly Journal of Experimental Psychology (2006)*. 2009; 62(7):1430–1454. [PubMed: 19123118]
- Postle BR. Working memory as an emergent property of the mind and brain. *Neuroscience*. 2006; 139(1):23–38. [PubMed: 16324795]
- Ranganath C, Cohen MX, Dam C, D'Esposito M. Inferior Temporal, Prefrontal, and Hippocampal Contributions to Visual Working Memory Maintenance and Associative Memory Retrieval. *The Journal of Neuroscience*. 2004; 24(16):3917–3925. [PubMed: 15102907]
- Saad E, Silvanto J. How Visual Short-Term Memory Maintenance Modulates Subsequent Visual Aftereffects. *Psychological Science*. 2013; 24(5):803–808. [PubMed: 23558546]
- Serences JT, Ester EF, Vogel EK, Awh E. Stimulus-Specific Delay Activity in Human Primary Visual Cortex. *Psychological Science*. 2009; 20(2):207–214. [PubMed: 19170936]
- Soto D, Hodsoll J, Rotshtein P, Humphreys GW. Automatic guidance of attention from working memory. *Trends in Cognitive Sciences*. 2008; 12(9):342–348. [PubMed: 18693131]

- Stroop JR. Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*. 1935; 18(6):643–662.
- Warren RE. Stimulus encoding and memory. *Journal of Experimental Psychology*. 1972; 94(1):90–100.
- Woodman GF, Luck SJ. Why is information displaced from visual working memory during visual search? *Visual Cognition*. 2010; 18(2):275–295.
- Woodman GF, Vogel EK, Luck SJ. Visual Search Remains Efficient When Visual Working Memory Is Full. *Psychological Science*. 2001; 12(3):219–224. [PubMed: 11437304]

a Working memory task sequence

b Experiment 1

Unique responses for each ink color

Equal proportions of each trial type

50% congruent	50% incongruent
---------------	-----------------

c Experiment 2

Two stimulus colors map onto one response

Equal proportions of each trial type

33.3% stim + resp congruent	33.3% stim congruent resp incongruent	33.3% stim + resp incongruent
-----------------------------	---------------------------------------	-------------------------------

d Experiment 3

Same response mappings as Experiment 1

Proportion of congruent trials varies by block

75% congruent	25% incongruent
50% congruent	50% incongruent
25% congruent	75% incongruent

Fig. 1.
a) Trial Sequence and timing for the WM Stroop task. Participants were asked to remember a word, then indicate the color of a rectangular patch, and finally report whether a probe word matched the WM sample. b) Experiment 1 comprised the basic test for a WM Stroop effect. c) Experiment 2 decomposed the WM Stroop effect into contributions from both stimulus- and response-level conflict. d) Experiment 3 tested whether the WM Stroop effect would be modulated by the proportion of congruent trials.

Experiment 1 Effects of external & internal conflict

a Color-word Stroop

Ink color judgment

b Working Memory

Color patch judgment

Fig. 2.

Response times (in msec) for the classic color-naming and working memory Stroop tasks.

Error bars represent confidence intervals as recommended by Masson and Loftus (2003).

Experiment 2 Contributions of stimulus & response conflict

a Color-word Stroop

Ink color judgment

b Working Memory

Color patch judgment

Fig. 3.

Response times (in msec) for the classic color-naming and working memory Stroop tasks. Error bars represent confidence intervals as recommended by Masson and Loftus (2003).

Experiment 3 Modulation by proportion congruency

a Color-word Stroop

Congruency effect

b Working Memory

Congruency effect

Fig. 4.

Congruency effect scores (response time difference between congruent and incongruent trials) for each block condition of the classic color-naming and working memory Stroop tasks. Error bars represent confidence intervals as recommended by Masson and Loftus (2003).

Table 1

Mean (and standard deviation) response times and accuracy for all conditions.

		Color-word Stroop		WM color patch		WM Probe	
		RT	Acc	RT	Acc	RT	Acc
Experiment 1	Congruent	677 (227)	94.6 (22.5)	682 (247)	96.5 (18.5)	1164 (406)	98.3 (12.8)
	Incongruent	761 (271)	90.2 (29.7)	765 (306)	96.8 (17.5)	1227 (428)	96.5 (18.2)
Experiment 2	Congruent	533 (150)	94.4 (23.1)	621 (209)	97.0 (17.0)	945 (379)	98.4 (12.4)
	Stimulus Incongruent	543 (161)	95.2 (21.3)	645 (182)	97.6 (15.3)	986 (404)	97.3 (16.1)
	Stimulus + Response Incongruent	563 (174)	91.8 (27.4)	651 (198)	97.1 (16.7)	995 (406)	96.9 (17.4)
Experiment 3	75% Congruent	Congruent	697 (228)	94.3 (23.1)	683 (246)	96.8 (17.7)	1101 (364)
		Incongruent	824 (302)	89.5 (30.7)	821 (221)	95.4 (21.1)	1176 (387)
	50% Congruent	Congruent	710 (233)	94.4 (23.0)	695 (242)	97.3 (16.2)	1090 (383)
		Incongruent	796 (271)	90.8 (28.9)	802 (222)	96.6 (18.1)	1141 (388)
	25% Congruent	Congruent	722 (231)	93.5 (24.6)	730 (251)	97.3 (16.0)	1079 (346)
		Incongruent	790 (269)	90.9 28.7)	812 (223)	96.1 (19.4)	1139 (372)