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Revisiting congruency effects in the working memory Stroop task

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Abstract

The working memory Stroop task is to name the color of a rectangular patch with keypress while holding a color word in working memory. Previous studies using this variant of the Stroop task have shown that congruency between the color patch and the color word significantly affects both color naming and working memory, with the worsening of task performance when the color patch is semantically incongruent rather than congruent with the color word. However, it remains unclear with regard to cognitive mechanisms underlying such congruency effects in the working memory Stroop task. By including a control condition among the congruent and incongruent conditions in a working memory Stroop task, the present study showed that nearly all of the working memory Stroop effect can be facilitation, and that interference, if present, is markedly smaller than facilitation in this form of the Stroop effect. There was also a critical contrast between the working memory and classic Stroop effects in terms of facilitation and interference, with larger facilitation and smaller interference in the working memory Stroop effect than in the classic Stroop effect. Moreover, working memory for a color word can be either facilitated or interfered with by the perceptual judgment (color naming) of an interposed color patch during the retention interval, depending on whether the color patch is semantically congruent or incongruent with the color word. Together, these results suggest that both facilitation and interference mechanisms can contribute to the overall congruency effects in the working memory Stroop task.

Keywords Working memory · Stroop effect · Attention · Facilitation · Interference

Introduction

The Stroop task (Stroop 1935) is considered one of the benchmark measures of attention commonly used in psychological research (for comprehensive reviews, see MacLeod 1991; Parris et al. 2021). In the classic color-word Stroop task, participants are required to name the ink color of a visually presented color word while ignoring the meaning of the word. The ink color and the word meaning could be semantically congruent (e.g., RED written in red) or incongruent (e.g., BLUE written in red). The typical experimental results show that congruency between the ink color and the word meaning significantly affects color-naming performance, in that responses are slower and less accurate in the incongruent condition than in the congruent condition. This congruency effect is referred to as the *classic Stroop effect*, which is a well-known phenomenon and has commonly been interpreted to reflect relatively automatic attentional processing of the task-irrelevant word meaning. When the Stroop task also includes a control condition (e.g., a noncolor word CAT written in red), the results usually further show that while performance is worse in the incongruent condition than in the control condition (i.e., Stroop interference), performance is better in the congruent condition than in the control condition (i.e.,

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Stroop facilitation). The classic Stroop effect therefore usually involves not only interference in the incongruent condition, but also facilitation in the congruent condition (e.g., Hanslmayr et al. 2008; Hasshim & Parris 2021; Kane & Engle 2003; MacLeod 1998). However, evidence suggests that while the Stroop interference effect is usually large and reliable, the Stroop facilitation effect is often weak and fragile and, consequently, sometimes can be absent or even reversed (Hershman & Henik 2019; Kalanthroff et al. 2015; Kalanthroff & Henik 2013; MacLeod 1991).

Recently, Kiyonaga and Egner (2014) developed a so-called working memory Stroop task in which participants were asked to name the color of a rectangular patch with keypress while holding a color word in working memory. The color patch could be semantically congruent or incongruent with the color word being held in working memory. The results showed that color-naming performance was markedly slower in the incongruent condition than in the congruent condition. Kiyonaga and Egner referred to this congruency effect as the working memory Stroop effect. Importantly, they found that the working memory Stroop effect mimics the classic Stroop effect, with both forms of the Stroop effect being comparable in magnitude and exhibiting similar key properties. The findings were interpreted by Kiyonaga and Egner as evidence that an incongruent color word internally maintained in working memory can interfere with color-naming performance in the same manner as a color word that is currently attended and perceived in the external environment. The working memory Stroop effect is therefore considered evidence supporting the notion that active maintenance of information in working memory is akin to internally directed attention to the information representation within the mind (Chun 2011; Kiyonaga & Egner 2013, 2014).

The working memory Stroop effect is a robust and reliable congruency effect on color-naming performance, which has been well established by previous studies using the working memory Stroop task (Chen et al. 2017; Kiyonaga & Egner 2014; Pan et al. 2019; Wang et al. 2021). However, it remains unclear what exact cognitive mechanisms drive the working memory Stroop effect. Although the working memory Stroop effect has previously been considered to be that holding an incongruent color word in working memory produces an interference effect on the naming of an intervening color patch, no direct evidence for this idea has so far been established. To the best of our knowledge, there have been only three published studies on the color-word version of the working memory Stroop effect. Two of these studies did not include a control condition in the working memory Stroop task (Kiyonaga & Egner 2014; Pan et al. 2019), rendering it impossible for them to assess whether the working memory Stroop effect is indeed composed of interference and/or facilitation effects. The other one included a control condition in the working memory Stroop task, but it failed to obtain an interference effect, with only a facilitation effect being observed (Wang et al. 2021). The lack of interference in the working memory Stroop effect reported by Wang et al. (2021) suggests that active maintenance of a conflicting color word in working memory may not interfere with the intervening color-naming task as strongly as has previously been suggested (Kiyonaga & Egner 2014; Pan et al. 2019). It is therefore possible that interference from an incongruent color word in working memory is weak and not stable, and that facilitation from a congruent color word in working memory instead plays a more crucial role in producing the working memory Stroop effect.

This possibility seems highly likely if one considers evidence showing that compared with the effects in a standard Stroop task in which a color word and a color patch are presented simultaneously, interference decreases and facilitation increases when the color word, which is merely passively viewed, is presented before the color patch with a relatively long stimulus-onset asynchrony (SOA; Coderre et al. 2011; Glaser & Glaser 1982). Thus, it appears that participants can efficiently resolve conflict from the incongruent color word presented prior to the color-naming task, reducing or even eliminating its interference with color-naming performance in the incongruent condition. The increased facilitation effect occurs probably because the prior presentation of a color word creates a semantic priming effect so that the semantic representation of a congruent color patch has already been activated before the color patch is presented, markedly facilitating the color-naming performance in the congruent condition (Coderre et al. 2011). These mechanisms may be particularly prone to occurring if the prior color word is actively maintained in working memory when performing the subsequent color-naming task, considering that the content of working memory can be utilized in a flexible manner for facilitation or inhibition of processing (Woodman & Luck 2007). It therefore follows that interference might be smaller than facilitation in the working memory Stroop effect.

In addition to the congruency effect on color-naming performance (i.e., the working memory Stroop effect), previous studies using the working memory Stroop task also found that memory performance was both slower and less accurate when the color word being held in working memory was incongruent rather than congruent with the interposed color patch (Kiyonaga & Egner 2014; Pan et al. 2019; but see Wang et al. 2021). It has previously been suggested that this congruency effect on working memory performance arises because an attention-demanding filtering process is needed in the incongruent condition, to resolve conflict from the word information being maintained in working memory (Kiyonaga & Egner 2014; Pan et al. 2019). The attentional filtering process could have diverted limited attentional resources away from active maintenance of verbal information in working memory, thereby leading to worse memory performance on incongruent trials. Thus, according to this account, the congruency effect on working memory performance should be driven solely by interference with memory maintenance in the incongruent condition. However, it is possible that the congruency effect on working memory performance may also be driven by facilitation of memory maintenance in the congruent condition. That is, working memory maintenance of a color word may benefit from the perceptual judgment of a semantically congruent color patch during the retention interval. Given that attending a visual stimulus that matches the current content of working memory could improve memory performance by refreshing working memory representations through perceptual resampling of the memory-matching visual stimulus (Woodman & Luck 2007), it is possible that a facilitation mechanism may contribute to the congruency effect on working memory performance through enhancement of memory representations in the congruent condition.

Therefore, it has remained unclear so far with regard to cognitive mechanisms underlying congruency effects on performance in the working memory Stroop task. The first goal of the present study was to clarify the nature of the working memory Stroop effect (i.e., the congruence effect on color-naming performance) in terms of facilitation and interference. In Experiments 1–3, we created a control condition among the congruent and incongruent conditions in the working memory Stroop task. This allowed us to directly assess whether the working memory Stroop effect is composed of facilitation and/or interference by separately comparing color-naming performance in the control condition with that in the congruent and incongruent conditions. Note that although Wang et al. (2021) have already examined the working memory Stroop effect in terms of facilitation and interference by including a control condition in the task, their results are isolated evidence and hence remain to be replicated with a different choice of control condition. For example, it is possible that Wang et al.'s failure to observe an interference effect may simply be due to the lack of power caused by the particular stimuli they used in the control condition, as the choice of control stimuli is crucial to obtain facilitation and interference in a Stroop task (MacLeod 1991). It should also be noted that Wang et al. (2021) have not investigated whether a Stroop interference effect can emerge when there are more frequent occurrences of congruent trials among the control and incongruent trials. Given that the extent of interference with color-naming performance in a working memory Stroop task is modulated by the percentage of congruent trials in the task (Kiyonaga & Egner 2014), it is possible that the interference effect could be observed only when congruent trials are more frequent. These issues are addressed in our current experiments. Moreover, here we extended previous work by directly contrasting the individual effects of facilitation and interference between the working memory and classic Stroop effects, to highlight the differences between these two forms of the Stroop effect in terms of facilitation and interference.

The second goal of the present study was to understand the sources of the congruency effect on memory performance in the working memory Stroop task. In Experiment 4, we directly tested the idea that the congruency effect on working memory performance reflects the impact of the intervening perceptual task (color naming) on working memory processing. We asked whether passively viewing an intervening color patch without any perceptual demands would generate a similar congruency effect to when actually performing an attention-demanding perceptual task on the color patch. If a perceptual demand on the color patch indeed plays a crucial role in determining the congruency effect on memory performance, then we should expect that the congruency effect would be reduced when the color patch was merely passively viewed compared to when it was perceptually identified. In Experiment 5, we sought to test the possibility that both facilitation and interference mechanisms could underlie the overall congruency effect on working memory performance. To this end, Experiment 5 included a control condition in which no color patch was interposed during working memory maintenance of a color word. By separately comparing memory performance in the control condition with that in the incongruent and congruent conditions, we assessed whether the overall congruency effect on working memory performance is due to facilitation on congruent trials, to interference on incongruent trials, or to both.

Experiment 1

The aim of this experiment was to clarify the nature of the working memory Stroop effect by including a control condition in which the to-be-remembered word was semantically irrelevant (i.e., neither congruent nor incongruent) to the intervening color patch. Participants were shown a word written in Chinese (the sample) at the beginning of each trial and were required to hold it in working memory throughout the trial. After a delay, a memory-test item, which was a word written in English, was displayed in order to probe memory performance. This manipulation would force observers to complete the memory task on the basis of congruency between semantic meanings rather than physical forms of the memory sample and the memory-test item. During the retention interval of working memory, participants had to name the color of a rectangular patch presented at the center of the screen by pressing an explicitly designated key. Critically, the color patch could be semantically congruent, incongruent, or irrelevant with the word meaning of the memory sample. We assessed whether color-naming performance would significantly vary as a function of congruency between the sample word and the color patch.

Method

Participants

A group of 21 adult students (five males; 19–25 years of age) from Hangzhou Normal University participated in this experiment for monetary compensation. The data from one participant were excluded from the analysis because he did not complete the memory test on any of the trials, leaving the final sample of 20 participants. In this and the following experiments, all participants were right-handed and reported having normal or corrected-to-normal vision. They were native Chinese speakers and also skilled readers of English. Informed consent was obtained from each participant prior to the experiment, which was conducted in accordance with the tenets of the Declaration of Helsinki and local ethics regulations.

Apparatus and stimuli

The experiment was controlled by E-prime software. Responses were made on a standard keyboard. The stimuli were presented on a 17-in. CRT monitor with a resolution of 1,024 × 768 pixels and a 100-Hz refresh rate. The memory samples were eight Chinese characters, which indicated "red," "blue," "green," "yellow," "horse," "cat," "dog," and "sheep," respectively. The animal words were used as control stimuli, as evidence suggests that the working memory maintenance demand for an animal word is comparable to that for a color word (Pan et al. 2019). Note that we did not choose nonword letter strings (e.g., jkm; xtqz) as control stimuli because they had no specific meanings to be committed for the working memory task. The memory-test items were eight English words that semantically matched the Chinese words. All of the word stimuli were printed in black and in Courier New font 35 pt. The stimuli for the color-naming task were colored rectangular patches (13.5 × 4.5 cm). The color of a patch was selected from a pool of four colors (in RGB coordinates: red: [255, 0, 0], blue: [0, 0, 255], green: [25, 200, 25], and yellow: [255, 215, 40]). All stimuli were presented on a gray background at a viewing distance of approximately 57 cm.

Procedure and design

Participants initiated each trial by pressing the space bar. Each trial began with the display of a black central fixation cross for 500 ms. Then, a Chinese word was presented at the center of the screen for 500 ms (memory sample). Here, participants were instructed to memorize the meaning of the word and to keep it in mind throughout the entire trial. After a delay of 1,000 ms, a colored rectangular patch was centrally presented for 500 ms, followed by the fixation display for 1,000 ms. Within a 1,500-ms period after the patch onset, participants were required to name the color of the patch by pressing one of four designated response keys for each of the possible colors. Then, a memory test was presented. Here, an English word appeared at the center of the screen, and participants were required to indicate by keypress whether the English word and the memory sample were the same or different in terms of their meanings. The memory-test word remained in view until the participant had responded or until 3,000 ms had passed (see Fig. 1).

There were three types of trials, each defined by the congruency between the memory sample and the color patch. On congruent trials, the memory sample was a color word and its meaning agreed with the color of the patch. On incongruent trials, the memory sample was also a color word, but its meaning differed from the color of the patch. Note that the memory-test word was always semantically incongruent with the color patch on incongruent trials. On control trials, the memory sample was an animal word, and therefore it was semantically irrelevant to the color patch. The three types of trials occurred with the same probability and in randomized order. The memory-test word always belonged to the semantic category of the memory sample word, and they were the same with respect to the semantic meaning on half of the trials ("same" trials) and different on the other half ("different" trials). Participants completed 24 practice trials on which feedback was provided for every keypress response to the color patch and the memory test, followed by a total of 192 experimental trials without feedback. They were encouraged to perform both working memory and color-naming tasks as accurately and quickly as possible.

Data analysis

In all of the experiments reported here, performance measures were mean response time (RT) from trials on which responses were correct and mean accuracy (% correct) on trials with a response. To determine the effect of working memory on color-naming performance, analyses of the color-naming data were limited to trials on which memory-test responses were correct. However, we note that the pattern of the color-naming results did not change when also including trials on which memory-test responses were not correct.

Results and discussion

Table 1 shows the mean RTs and accuracies for all conditions of Experiment 1. An analysis of color-naming RTs showed that there was a significant main effect of congruency, $F(2, 38) = 18.529$, $p < .001$, $\eta_p^2 = .494$ (Fig. 2). Critically, post hoc comparisons with Bonferroni correction revealed that color-naming RTs were significantly faster on congruent trials than on both control, $t(19) = 4.815$, $p < .001$, Cohen's $d = 1.077$, and incongruent trials, $t(19) = 3.995$, $p = .002$, Cohen's $d =$

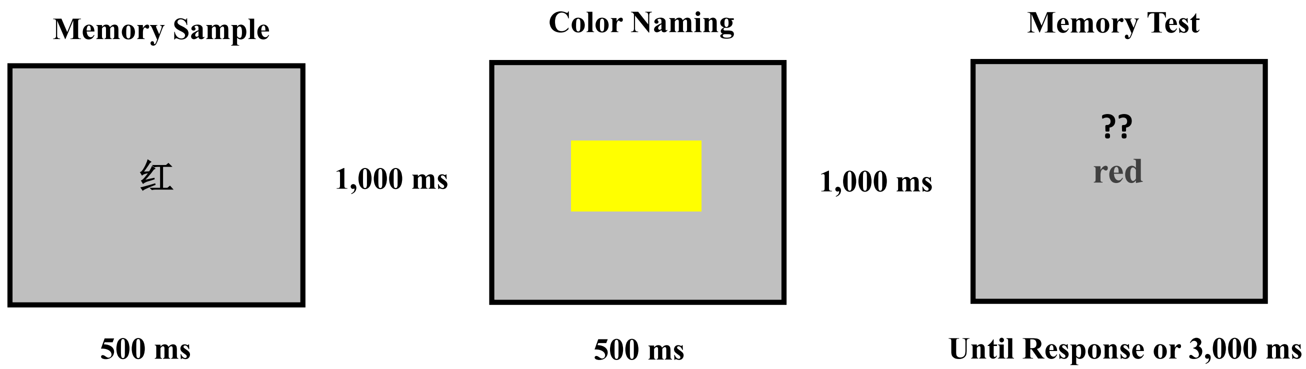

Fig. 1 Schematic illustration of the trial sequence and example stimuli in Experiment 1

0.893, while the latter two did not differ significantly from each other, $t(19) = 2.032$, $p = .169$, Cohen's $d = 0.454$. To further explore the null effect of interference, we conducted the one-sided Bayesian paired-samples *t*-test for the color-naming RT difference between incongruent and control trials, using the default settings of JASP (JASP Team, 2020). This test was one-sided, because the alternative hypothesis is that color naming should be slower on incongruent trials than on control trials. The Bayes Factor analysis indicated that the data were 11 times more likely to have been generated by the null model than by the alternative model ($BF_{01} = 11.356$). The main effect of congruency on color-naming accuracy, however, did not approach significance, $F < 1$, suggesting that there was no sign of speed-accuracy trade-off in performing the color-naming task. The results showed that holding a congruent color word in working memory facilitated the perceptual judgment of an intervening color patch, while no evidence was found that the maintenance of an incongruent color word in working memory interfered with the intervening color-naming task. Thus, at least under the present experimental settings, the effect of congruency on color-naming performance in a working memory Stroop task was driven by a memory-based facilitation rather than an interference mechanism. This finding is in agreement with the behavioral results of Wang et al. (2021) who used a different choice of control condition, suggesting that active maintenance of a conflicting color word in working memory may not interfere with the intervening color-naming task as strongly as has previously been proposed (Kiyonaga & Egner 2014; Pan et al. 2019).

Analyses of working memory performance showed that congruency between the memory sample and the color patch affected both the speed, $F(2, 38) = 14.152$, $p < .001$, $\eta_p^2 = .427$, and the accuracy, $F(2, 38) = 11.788$, $p < .001$, $\eta_p^2 = .383$, of memory-test responses. Pairwise comparisons revealed that memory-test responses were both faster, $t(19) = 4.449$, $p < .001$, Cohen's $d = 0.995$, and more accurate, $t(19) = 4.472$, $p < .001$, Cohen's $d = 1.000$, on congruent trials than on incongruent trials. Consistent with previous findings (Kiyonaga & Egner 2014; Pan et al. 2019), the present results suggest that the intervening color-naming task can conversely influence concurrent processing of color words in working memory. Note that here we did not evaluate working memory performance by comparing control trials with either congruent or incongruent trials, considering that the memory content on control trials (i.e., animal words) was essentially different from that on congruent and incongruent trials (i.e., color words). This also applies to analyses of working memory performance for the following experiments in which word

Table 1 Mean response times and percentages of correct responses for all conditions of Experiment 1

	Color naming		Memory test	
	RT (ms)	Accuracy (%)	RT (ms)	Accuracy (%)
Congruent	770 (140)	92.9 (6.9)	908 (201)	94.3 (5.4)
Control	843 (134)	93.4 (7.6)	953 (211)	93.6 (7.9)
Incongruent	831 (132)	92.1 (8.1)	990 (220)	89.8 (8.0)

Note. Standard deviations are included in parentheses

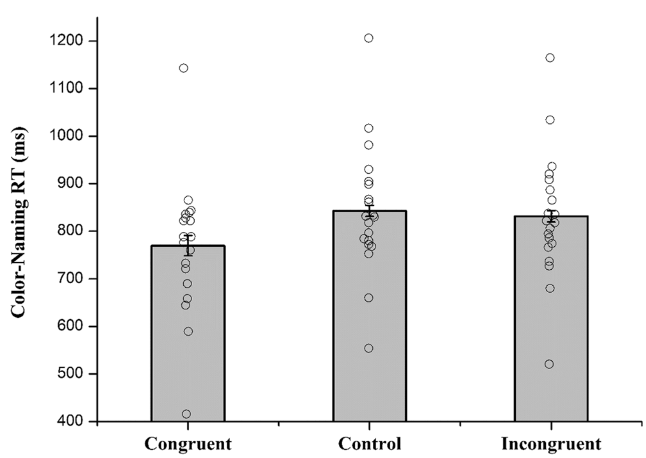

Fig. 2 Mean correct color-naming response times as a function of congruency in Experiment 1. Error bars indicate within-subject 95% confidence intervals (Loftus & Masson 1994). The empty circles represent data of individual participants

stimuli for the memory task involved distinct semantic categories across the congruency conditions.

Experiment 2

The aim of this experiment was to test whether the absence of interference with color naming from a to-be-remembered incongruent color word was due to a lack of power induced by the word stimuli used here. It is possible that, for some unknown reason, the interference effect could not be obtained with the current animal words as control stimuli, even if a classic Stroop task was used (e.g., indicating the ink color of a visually presented word while ignoring the meaning of the word). To address this concern, in Experiment 2 we examined the congruency effect on color-naming performance with the same words we had used in Experiment 1, but now, apart from the working memory Stroop task, a classic, perceptual version of the Stroop task was also included, as was in Kiyonaga and Egner's (2014) study. Substantial evidence has shown that the interference effect is very robust in a classic color-word Stroop task (MacLeod 1991; Parris et al. 2021), so that if an interference effect was absent for both the working memory and classic Stroop tasks in Experiment 2, this would favor a lack-of-power account; otherwise, we could not account for the absence of an interference effect of a to-be-remembered incongruent color word on color-naming performance by a lack of power caused by the use of animal words as control stimuli. Moreover, this experiment would shed further light on the differences between the working memory and classic Stroop effects by directly contrasting their individual effects of facilitation and interference.

Method

A new group of 20 students (four males; 19–26 years of age) were recruited to participate in this experiment. Each participant was required to perform a working memory Stroop task and a classic Stroop task separately. The stimuli and timing parameters for the working memory Stroop task were identical to those used in Experiment 1. For the classic Stroop task, the stimuli consisted of eight Chinese words (four color words and four animal words), which were the same as those used in Experiment 1, but here they were printed in colored ink rather than in black. A word was centrally presented on the gray background on each trial for 500 ms in one of four ink colors (i.e., red, blue, green, and yellow), which were exactly identical to those of color patches used in the working memory Stroop task. Each word was separated by a 1,000-ms intertrial interval. Participants were required to report the color of the ink, regardless of the meaning of the word, by pressing one of four designated response keys for each of the possible colors. In both the working memory and classic Stroop tasks, there were 50%, 25%, and 25% of the trials for the congruent, incongruent, and control conditions, respectively. Participants completed a total of 384 experimental trials, half of which were for the working memory Stroop task and the other half for the classic Stroop task. The order of the working memory and classic Stroop tasks was counterbalanced across participants, and both the speed and the accuracy were emphasized for each task.

Results and discussion

Table 2 shows the mean RTs and accuracies for all conditions of Experiment 2. Color-naming data were analyzed with task (working memory Stroop vs. classic Stroop) and congruency (congruent vs. control vs. incongruent) as within-subjects factors. A repeated-measures analysis of variance (ANOVA) on color-naming RTs showed a significant main effect of task, $F(1, 19) = 8.659$, $p = .008$, $\eta_p^2 = .313$, in that color-naming performance was overall slower in the working memory Stroop task than in the classic Stroop task. The main effect of congruency was also significant, $F(2, 38) = 86.967$, $p < .001$, $\eta_p^2 = .821$. Critically, there was a significant interaction between task and congruency, $F(2, 38) = 7.429$, $p = .002$, $\eta_p^2 = .281$. Analysis of simple effects showed that the congruency effect was reliable in both the working memory Stroop task, $F(2, 38) = 63.835$, $p < .001$, $\eta_p^2 = .771$, and the classic Stroop task, $F(2, 38) = 23.552$, $p < .001$, $\eta_p^2 = .553$ (Fig. 3). To obtain further insights into the nature of this interaction, we calculated effect scores for Stroop congruency (incongruent minus congruent), Stroop facilitation (control minus congruent), and Stroop interference (incongruent minus control), and compared each of these between the working memory and classic Stroop tasks using two-sided *t*-tests. Consistent with the results of Kiyonaga and Egner (2014), the overall Stroop congruency effect was evident for both the working memory Stroop task (105 ms) and the classic Stroop task (77 ms), and its magnitude did not differ significantly between the two tasks, $t(19) = 1.442$, $p = .165$, Cohen's $d = 0.323$. However, although the Stroop facilitation effect was present for both tasks, it was significantly greater in the working memory Stroop task (106 ms) than in the classic Stroop task (43 ms), $t(19) = 4.565$, $p < .001$, Cohen's $d = 1.021$. More importantly, while the Stroop interference effect was present in the classic Stroop task (34 ms), it was absent in the working memory Stroop task (-1 ms), which differed significantly from each other, $t(19) = 2.266$, $p = .035$, Cohen's $d = 0.507$. The outcome of a repeated-measures ANOVA over color-naming accuracy yielded only a significant main effect of congruency, $F(2, 38) = 15.033$, $p < .001$, $\eta_p^2 = .442$, indicating that more errors in color naming were produced by conflict from an incongruent color word. There were no other main effects or interactions (all *p*s > .327, all η_p^2s < .057).

Table 2 Mean response times and percentages of correct responses for all conditions of Experiment 2

	Classic Stroop task		Working memory Stroop task			
			Color naming		Memory test	
	RT (ms)	Accuracy (%)	RT (ms)	Accuracy (%)	RT (ms)	Accuracy (%)
Congruent	612 (99)	93.4 (9.3)	658 (116)	93.4 (7.2)	871 (165)	95.2 (4.8)
Control	655 (117)	91.5 (10.5)	764 (109)	93.7 (6.1)	910 (181)	94.3 (6.9)
Incongruent	689 (112)	88.8 (9.8)	763 (125)	90.0 (7.8)	989 (194)	87.1 (9.5)

Note. Standard deviations are included in parentheses

Analyses of working memory performance showed that congruency between the memory sample and the color patch in the working memory Stroop task affected both the speed, $F(2, 38) = 30.444$, $p < .001$, $\eta_p^2 = .616$, and the accuracy, $F(2, 38) = 22.909$, $p < .001$, $\eta_p^2 = .547$, of memory-test responses. Pairwise comparisons revealed that memory-test responses were both faster, $t(19) = 7.991$, $p < .001$, Cohen's $d = 1.787$, and more accurate, $t(19) = 5.189$, $p < .001$, Cohen's $d = 1.160$, on congruent trials than on incongruent trials. This pattern of results is the same as that of Experiment 1, suggesting that the intervening color-naming task conversely induces a powerful impact on concurrent processing of color words in working memory.

As in Experiment 1, we failed to observe an interference effect in color-naming RT for the working memory Stroop task. However, the absence of Stroop interference is unlikely due to a lack of power induced by the word stimuli used in the working memory Stroop task, since we indeed obtained a significant interference effect in color-naming RT for the classic Stroop task with the same words. In addition to the difference in Stroop interference between the two tasks, there were also distinct facilitation effects between them, with markedly greater facilitation in the working memory Stroop task than in the classic Stroop task. Thus, although the overall magnitude was comparable between the working memory and classic Stroop effects, their individual components (i.e., interference and facilitation effects) were very different.

Experiment 3

In the prior two experiments, we found no evidence for any interference effects in color-naming RTs for the working memory Stroop task. We only observed interference with color-naming accuracy from an incongruent color word being held in working memory in Experiment 2. Such an interference effect in accuracy suggests a greater extent of Stroop interference from the conflicting information maintained in working memory in Experiment 2 than in Experiment 1. Given that congruent trials in the working memory Stroop task occurred more frequently in Experiment 2 (50% of all trials) than in Experiment 1 (33.3% of all trials), the greater interference may have resulted from the more frequent occurrence of congruent trials among the control and incongruent

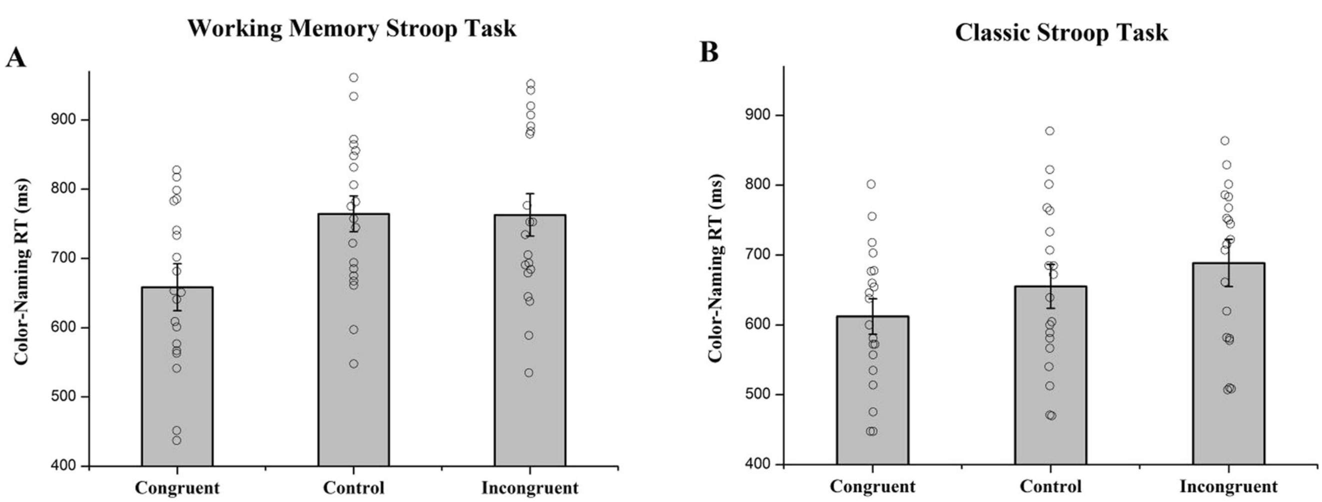

Fig. 3 Mean correct color-naming response times as a function of congruency for the (**A**) working memory and (**B**) classic Stroop tasks in Experiment 2. Error bars indicate within-subject 95% confidence intervals (Loftus & Masson 1994). The empty circles represent data of individual participants

trials. Indeed, evidence has shown that the working memory Stroop effect increases with the percentage of congruent trials in the task, just like the standard Stroop effect (Kiyonaga & Egner 2014). Accordingly, if the percentage of congruent trials further increases, one might expect Stroop interference to be more clearly manifested in both measurements of RT and accuracy. We tested this possibility in Experiment 3 where congruent trials occurred on 76% of all trials in the working memory Stroop task.

Method

This was similar to that used in Experiment 1 with the following exceptions. A new group of 20 students (two males; 18–25 years of age) participated in this experiment. Each participant completed a total of 350 experimental trials for the working memory Stroop task in which there were 76%, 12%, and 12% of the trials for the congruent, control, and incongruent conditions, respectively.

Results and discussion

Table 3 shows the mean RTs and accuracies for all conditions of Experiment 3. The analysis of color-naming RTs showed that there was a significant main effect of congruency, $F(2, 38) = 29.448$, $p < .001$, $\eta_p^2 = .608$ (Fig. 4). Bonferroni-corrected post hoc comparisons revealed that color-naming RTs were markedly faster on congruent trials than on both control, $t(19) = 5.605$, $p < .001$, Cohen's $d = 1.253$, and incongruent trials, $t(19) = 5.881$, $p < .001$, Cohen's $d = 1.315$. Critically, color-naming RTs were significantly slower on incongruent trials than on control trials, $t(19) = 3.245$, $p = .013$, Cohen's $d = 0.726$, and this interference effect (62 ms) was markedly smaller than the facilitation effect (134 ms), $t(19) = 2.635$, $p = .016$, Cohen's $d = 0.589$. The main effect of congruency in color-naming accuracy was also significant, $F(2, 38) = 7.237$, $p = .002$, $\eta_p^2 = .276$. Bonferroni-corrected post hoc contrasts showed that color-naming performance was significantly less accurate on incongruent trials than on both control, $t(19) = 2.682$, $p = .044$, Cohen's $d = 0.600$, and congruent trials, $t(19) = 2.797$, $p = .034$, Cohen's $d = 0.625$, while the latter two did not differ from each other, $t < 1$. As expected, when the percentage of congruent trials was sufficiently high in the working memory Stroop task, there was Stroop interference with color-naming performance in both measurements of RT and accuracy.

Table 3 Mean response times and percentages of correct responses for all conditions of Experiment 3

	Color naming		Memory test	
	RT (ms)	Accuracy (%)	RT (ms)	Accuracy (%)
Congruent	683 (147)	91.3 (8.6)	896 (175)	95.0 (5.4)
Control	818 (149)	90.8 (8.6)	971 (210)	95.2 (5.7)
Incongruent	879 (173)	83.7 (17.9)	1160 (264)	77.1 (16.7)

Note. Standard deviations are included in parentheses

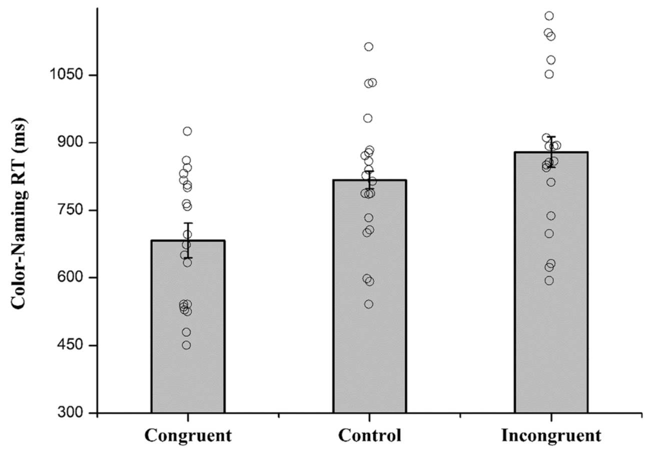

Fig. 4 Mean correct color-naming response times as a function of congruency in Experiment 3. Error bars indicate within-subject 95% confidence intervals (Loftus & Masson 1994). The empty circles represent data of individual participants

Analyses of working memory performance showed that congruency between the memory sample and the color patch affected both the speed, $F(2, 38) = 34.946$, $p < .001$, $\eta_p^2 = .648$, and the accuracy, $F(2, 38) = 28.830$, $p < .001$, $\eta_p^2 = .603$, of memory-test responses. Pairwise comparisons revealed that memory-test responses were both faster, $t(19) = 7.912$, $p < .001$, Cohen's $d = 1.769$, and more accurate, $t(19) = 5.265$, $p < .001$, Cohen's $d = 1.177$, on congruent trials than on incongruent trials. These results are consistent with the pattern of memory performance observed in Experiments 1 and 2, confirming the belief that the intervening color-naming task can conversely influence concurrent processing of color words in working memory.

Experiment 4

The preceding experiments consistently showed worse memory performance on incongruent trials than on congruent trials. Such a congruency effect on working memory performance was considered to reflect the impact of the intervening perceptual task (color naming) on working memory processing. In Experiment 4, we sought to provide a direct test of this idea by asking if passively viewing an intervening color patch without any perceptual demands would generate a similar congruency effect to when actually performing an attention-demanding perceptual task on the color patch. Participants were asked to perceptually identify the intervening color patch in the *Attend-Color-Patch* condition and to merely passively view the color patch in the *Ignore-Color-Patch* condition. We examined whether the congruency effect on working memory performance would differ between the two conditions. If a perceptual demand on the color patch indeed plays a crucial role in determining the congruency effect on memory performance, then we should expect that the congruency effect would be reduced when the color patch was merely passively viewed compared to when it was perceptually identified.

Method

This was similar to that used in Experiment 1 except as follows. The stimuli used in the working memory task were always color words, and there were no animal words involved. Accordingly, the intervening color patch could be semantically congruent or incongruent with the color word being maintained in working memory, with no possibility that the color patch could be semantically irrelevant to the memorized word. In the *Attend-Color-Patch* condition, participants were asked to immediately identify the intervening color patch by keypress during working memory maintenance. In the *Ignore-Color-Patch* condition, the intervening color patch was task-irrelevant so that participants had to merely passively view the color patch without an explicit perceptual requirement. The two conditions were blocked and their presentation order was counterbalanced across participants. Participants completed one *Attend-Color-Patch* block and one *Ignore-Color-Patch* block. Each block contained 208 experimental trials in which congruent and incongruent trials occurred equally often and in randomized order. A new group of 20 students (one male; 18–25 years of age) participated in this experiment.

Results and discussion

Table 4 shows the mean RTs and accuracies for all conditions of Experiment 4. The color-naming data in the *Attend-Color-Patch* condition were analyzed with two-sided *t*-tests contrasting congruent with incongruent trials. Performance on the color-naming task was both faster, $t(19) = 5.945$, $p < .001$, Cohen's $d = 1.329$, and more accurate, $t(19) = 2.213$, $p = .039$, Cohen's $d = 0.495$, on congruent trials than on incongruent trials, indicating the presence of the working memory Stroop effect.

Table 4 Mean response times and percentages of correct responses for all conditions of Experiment 4

	Color naming		Memory test	
	RT (ms)	Accuracy (%)	RT (ms)	Accuracy (%)
Attend-Color-Patch				
Congruent	727 (182)	93.3 (5.8)	838 (178)	96.6 (2.9)
Incongruent	808 (146)	91.1 (7.6)	941 (199)	92.4 (4.8)
Ignore-Color-Patch				
Congruent	--	--	604 (133)	96.0 (2.9)
Incongruent	--	--	624 (126)	94.8 (4.0)

Note. Standard deviations are included in parentheses

Working memory performance was analyzed with attentional condition (Attend-Color-Patch, Ignore-Color-Patch) and congruency (congruent vs. incongruent) as within-subject factors. The outcome of a two-way repeated-measures ANOVA over memory-test RTs showed that the main effect of attentional condition was significant, $F(1, 19) = 85.795$, $p < .001$, $\eta_p^2 = .819$, with slower memory performance in the *Attend-Color-Patch* condition than in the *Ignore-Color-Patch* condition. The main effect of congruency was also significant, $F(1, 19) = 37.268$, $p < .001$, $\eta_p^2 = .662$, with faster memory performance on congruent trials than on incongruent trials. Critically, there was a significant interaction between congruency and attentional condition, $F(1, 19) = 24.098$, $p < .001$, $\eta_p^2 = .559$, indicating that the congruency effect in memory-test RT was markedly larger in the *Attend-Color-Patch* condition than in the *Ignore-Color-Patch* condition (Fig. 5a). Analysis of simple effects further showed that the congruency effect in memory-test RT was reliable in the *Attend-Color-Patch* condition, $F(1, 19) = 49.452$, $p < .001$, $\eta_p^2 = .722$, whereas it was not statistically reliable in the *Ignore-Color-Patch* condition, $F(1, 19) = 2.819$, $p = .110$, $\eta_p^2 = .129$.

Mirroring the pattern of RT results, an analysis of memory-test accuracy showed a significant main effect of congruency, $F(1, 19) = 14.647$, $p = .001$, $\eta_p^2 = .435$, with memory performance being more accurate on congruent trials than on incongruent trials. Critically, there was a significant interaction between congruency and attentional condition, $F(1, 19) = 8.324$, $p = .009$, $\eta_p^2 = .305$, suggesting that the congruency effect in memory-test accuracy was larger in the *Attend-Color-Patch* condition than in the *Ignore-Color-Patch* condition (Fig. 5b). Analysis of simple effects further showed that the congruency effect in memory-test accuracy was reliable in the *Attend-Color-Patch* condition, $F(1, 19) = 16.784$, $p < .001$, $\eta_p^2 = .469$, whereas it was not statistically reliable in the *Ignore-Color-Patch* condition, $F(1, 19) = 2.761$, $p = .113$, $\eta_p^2 = .127$. The main effect of attentional condition did not approach significance, $F(1, 19) = 1.102$, $p = .307$, $\eta_p^2 = .055$. Together, the memory-test RT and accuracy results indicated that mere exposure to an intervening color patch, without an explicit perceptual requirement, did not produce a similar congruent effect on working memory performance to when the color patch was perceptually identified. Thus, it is conceivable that perceptual processing of the color patch is crucial to determine the congruency effect on memory performance in the working memory Stroop task.

Experiment 5

Although the experiments described above well established the congruency effect on working memory performance (i.e.,

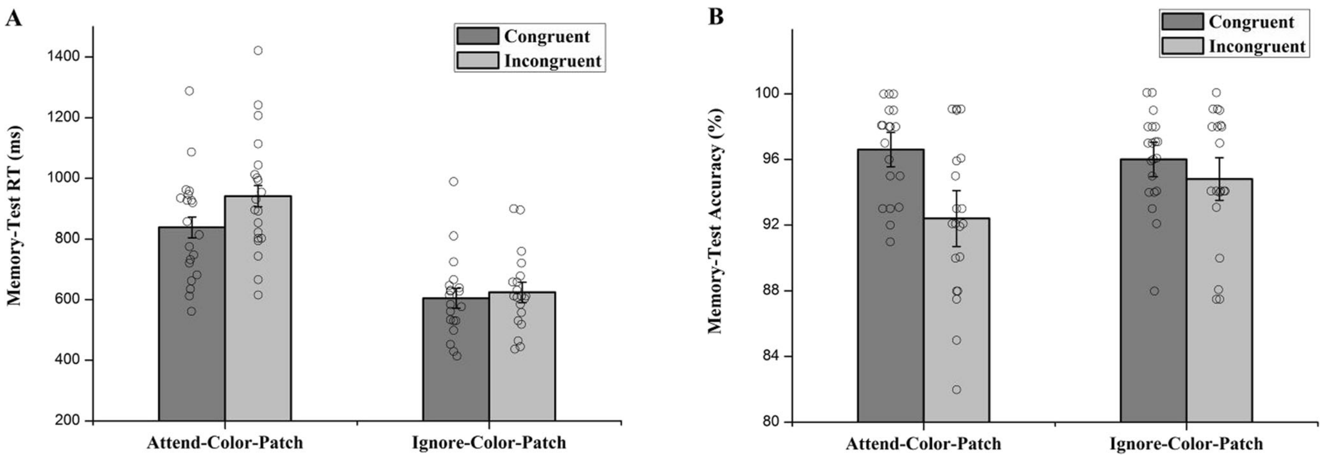

Fig. 5 Means of correct response times (**panel A**) and mean percentages of correct responses (**panel B**) for the memory test in Experiment 4, as a function of attentional condition and congruency. Error bars indicate within-subject 95% confidence intervals (Loftus & Masson 1994). The empty circles represent data of individual participants

faster and more accurate memory-test responses to congruent trials compared to incongruent trials; see alsoKiyonaga & Egner 2014 ; Pan et al. 2019), it still remains unclear what the underlying mechanisms for such an effect are. It has previously been proposed that the attentional filtering process in the incongruent condition could have diverted attentional resources away from active maintenance of information in working memory, thereby producing worse memory performance on incongruent trials (Kiyonaga & Egner 2014; Pan et al. 2019). Under this view, the congruency effect on working memory performance should be driven solely by interference in the incongruent condition. However, it is possible that the congruency effect on working memory performance might also be driven by facilitation in the congruent condition. We propose that both facilitation and interference mechanisms could be the underlying causes of the overall congruency effect on working memory performance. To directly test this idea, Experiment 5 included a control condition in which no color patch was interposed during working memory maintenance of a color word. The control condition was randomly intermixed with the congruent and incongruent conditions, so that the participants could not anticipate whether there would be an intervening color-naming task during the retention interval of working memory on a given trial and hence task preparation for performing on an interposed color patch should be comparable across the three conditions. By controlling for the demand of task preparation, this experiment sought to clarify the mechanisms underlying the overall congruency effect on working memory performance by comparing the control condition with the congruent and incongruent conditions separately. We predict that memory performance would be better in the congruent condition and worse in the incongruent condition, as compared with the control condition.

Method

This was similar to that used in Experiment 1 except that animal words were replaced by color words on control trials. Here, the control trials were instead defined as trials on which there was no color patch interposed during working memory maintenance. That is, there was no color-naming task and only a central fixation cross was presented during the retention interval of working memory on these control trials. Note that the retention interval of the working memory task remained constant (i.e., 2,500 ms) across congruent, control, and incongruent trials. A new group of 20 students (two males; 18–25 years of age) participated in this experiment. Each participant completed 384 experimental trials on which the three types of trials occurred with the same probability and in randomized order.

Results and discussion

The data from one participant were excluded from analyses because he failed to complete the tasks as instructed and performed at chance level in the memory test. Thus, the data analyses were confined to the remaining 19 participants.

Table 5 Mean response times and percentages of correct responses for all conditions of Experiment 5

	Color naming		Memory test	
	RT (ms)	Accuracy (%)	RT (ms)	Accuracy (%)
Congruent	758 (167)	95.2 (4.1)	806 (139)	98.0 (2.0)
Control	--	--	757 (148)	96.6 (2.1)
Incongruent	850 (152)	91.1 (7.2)	887 (149)	96.0 (2.9)

Note. Standard deviations are included in parentheses

Table 5 shows the mean RTs and accuracies for different congruency conditions of Experiment 5. The color-naming performance was compared between congruent and incongruent trials using two-sided *t*-tests. Performance on the color-naming task was both faster, $t(18) = 7.524$, $p < .001$, Cohen's $d = 1.726$, and more accurate, $t(18) = 3.620$, $p = .002$, Cohen's $d = 0.830$, on congruent trials than on incongruent trials, indicating the presence of the working memory Stroop effect.

Working memory performance was evaluated using one-way repeated-measures ANOVAs with the three-level factor of congruency (congruent vs. control vs. incongruent). The results showed that congruency between the memory sample and the color patch affected both the speed, $F(2, 36) = 10.597$, $p < .001$, $\eta_p^2 = .371$, and the accuracy, $F(2, 36) = 6.538$, $p = .004$, $\eta_p^2 = .266$, of memory-test responses (Fig. 6). Bonferroni-corrected post hoc comparisons further indicated that memory performance was significantly slower on incongruent trials than on both control trials, $t(18) = 3.363$, $p = .010$, Cohen's $d = 0.772$, and congruent trials, $t(18) = 3.887$, $p = .003$, Cohen's $d = 0.892$, while the latter two did not significantly differ from each other, $t(18) = 2.162$, $p = .133$, Cohen's $d = 0.496$. The one-sided Bayesian paired-samples *t*-test was conducted to further examine the memory-test RT difference between control and congruent trials, with the alternative hypothesis being that memory performance should be faster on congruent trials than on control trials. The Bayes Factor analysis indicated that the data were 11 times more likely to have been generated by the null model than by the alternative model ($BF_{01} = 11.432$). Memory performance was significantly more accurate on congruent trials than on both control trials, $t(18) = 3.199$, $p = .015$, Cohen's $d = 0.734$, and incongruent trials, $t(18) = 2.939$, $p = .026$, Cohen's $d = 0.674$. However, accuracy of memory-test responses did not differ significantly between control and incongruent trials, $t(18) = 1.064$, $p = .905$, Cohen's $d = 0.244$, though evidence of the one-sided Bayes Factor for this null effect was anecdotal ($BF_{01} = 1.533$; with the alternative hypothesis being that memory-test responses should be less accurate on incongruent trials than on control trials).

It should be noted that although we have controlled for the demand of task preparation for performing on an interposed color patch across the three congruency conditions, task demands in the control condition may still not be entirely comparable to those in the congruent and incongruent conditions. For example, participants should switch between the intervening perceptual task and the memory test in the congruent and incongruent conditions, but not in the control condition where there was actually no intervening task to be performed during the retention interval. As can be seen in Fig. 6a, there was a considerable cost in memory-test RT for both the congruent and incongruent conditions versus the control condition, though the cost effect was not statistically reliable in the congruent condition. Given that switching between two different tasks is associated with a cost in behavioral performance (Monsell 2003), it is plausible that the memory-test RT costs in both the congruent and incongruent conditions were at least partially caused by task switching. Consequently, the observed effect in memory-test RT may not be considered an entire reflection of the congruency effect, but rather a combination of congruency and task-switching effects. With this in mind, we do not wish to make any strong claims based on the memory-test RT data in this experiment. We then primarily discuss the implications of the memory-test accuracy results, which do not show an evident cost in either the congruent condition or the incongruent condition, and hence cannot be accounted for by task switching or any other costly task demands.

The lack of memory accuracy impairment on incongruent versus control trials suggests that the quality (i.e., precision) of working memory representations might not be significantly

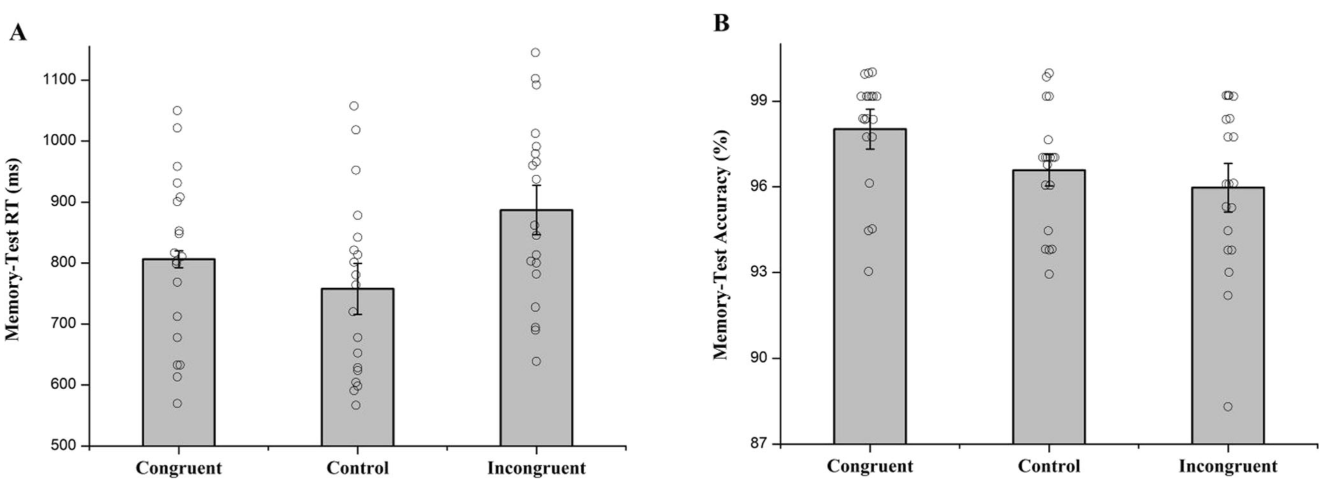

Fig. 6 Means of correct response times (**panel A**) and mean percentages of correct responses (**panel B**) for the memory test as a function of congruency in Experiment 5. Error bars indicate within-subject 95% confidence intervals (Loftus & Masson 1994). The empty circles represent data of individual participants

lowered on incongruent trials, at least under the current experimental settings. This indicates that the attention-demanding filtering process needed to resolve conflicts on incongruent trials may not impair concurrent working memory maintenance as strongly as has previously been suggested (Kiyonaga & Egner 2014; Pan et al. 2019). However, this does not necessarily exclude the possibility that the color-naming task interferes with memory performance on incongruent trials. Given that performing a simple visual identification task requires storing the to-be-identified information into working memory (Bae & Luck 2019), it is possible that the color representation of a rectangular patch was briefly stored in working memory when performing the color-naming task. Consequently, there could be two different color representations being maintained simultaneously in working memory on a given incongruent trial. Because the source formats of these two color representations (i.e., color word and color patch) are often not automatically stored in working memory (Chen et al. 2018; Xu et al. 2020), participants may more likely hesitate to respond to the memory test on incongruent trials due to the possible source confusion between the two color representations during memory retrieval. We suggest that this source confusion may partially account for the observed slowing of memory performance on incongruent trials.

Furthermore, this source confusion may also make participants more likely suffer source misattribution for memory tests (i.e., retrieve the semantic representation of a color patch and compare it with the meaning of the memory-test word) on incongruent versus congruent trials. This is because the memory-test word was always semantically incongruent with the color patch in the incongruent condition and hence source misattribution could lead to incorrect responses to memory tests on "same" rather than "different" trials in that condition. If this was indeed the case, then we should expect more memory errors on "same" trials (with the memory-test word and the memory sample word being the same with respect to semantic meaning) than on "different" trials (with the memory-test word and the memory sample word differing in semantic meaning) in the incongruent rather than the congruent condition. To directly test this idea, we evaluated the accuracy of working memory performance with a one-sided *t*-test by comparing "same" and "different" trials separately for the congruent and incongruent conditions. The test was one-sided, because the alternative hypothesis is that memory-test responses should be less accurate on "same" trials than on "different" trials. As can be seen in Fig. 7, memory performance was significantly less accurate on "same" trials (94.3%) than on "different" trials (97.6%) in the incongruent condition, $t(18) = -3.393$, $p = .002$, Cohen's $d = -0.779$, whereas this was apparently not the case in the congruent condition (98.6% vs. 97.5%), $t(18) = 1.797$, $p = .955$, Cohen's $d = 0.412$. The one-sided Bayes Factor analysis indicated that the accuracy data in the congruent condition were ten times more likely to

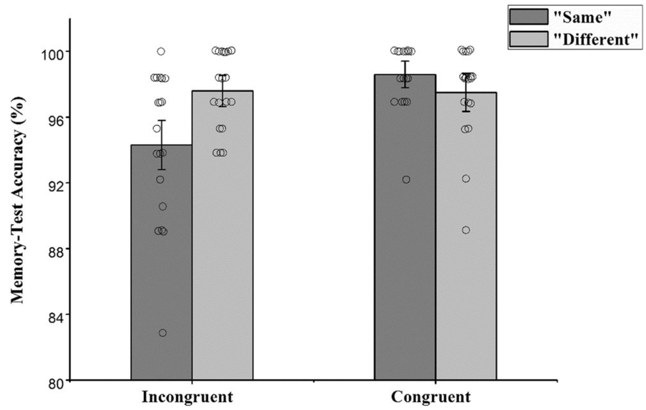

Fig. 7 Mean percentages of correct responses to the memory test on "same" and "different" trials in each of the congruent and incongruent conditions of Experiment 5. Error bars indicate within-subject 95% confidence intervals (Loftus & Masson 1994). The empty circles represent data of individual participants

have been generated by the null model than by the alternative model ($BF_{01} = 10.314$). We note that similar results were also obtained when comparing memory accuracy between "same" and "different" trials in each of the congruent and incongruent conditions for the preceding experiments. These results are consistent with the idea that working memory maintenance might not be impaired to the extent that has previously been suggested when the to-be-remembered color word is semantically incongruent with the interposed color patch. We suggest that the worse memory performance in the incongruent condition than in the congruent condition may be caused at least in part by an interference mechanism due to source confusion between memory representations of both the color word and color patch at retrieval.

In addition to this interference mechanism, we also observed strong evidence for a facilitation mechanism underlying the congruency effect on working memory performance, in that memory-test responses were more accurate on congruent trials than on control trials. This facilitation effect certainly cannot be attributed to switching between two different tasks on congruent trials, because task switching would induce a cost rather than a benefit on congruent trials compared with control trials. Taken together, the present results suggest that the overall congruency effect on working memory performance can be caused not only by the interference mechanism, but also by the facilitation mechanism.

General discussion

The working memory Stroop effect (Kiyonaga & Egner 2014) shows that naming a color patch is affected by congruency between the color patch and a color word being maintained in working memory, with color-naming performance being significantly slower when the color patch and the color word are semantically incongruent rather than congruent. The working memory Stroop effect has previously been considered to show that active maintenance of an incongruent color word in working memory interferes with concurrent naming of an interposed color patch (Kiyonaga & Egner 2014; Pan et al. 2019). However, by including a control condition in the working memory Stroop task, recent research by Wang et al. (2021) failed to obtain a Stroop interference effect when the color patch and the to-be-remembered color word were incongruent, but instead observed a Stroop facilitation effect when they were congruent. This suggests that active maintenance of a conflicting color word in working memory may not interfere with the intervening color-naming task as strongly as has previously been thought (Kiyonaga & Egner 2014; Pan et al. 2019). It is therefore possible that interference from an incongruent color word in working memory, if any, is weak and not stable and that facilitation from a congruent color word in working memory instead plays a more crucial role in producing the working memory Stroop effect. The present study extends previous work by directly testing this possibility across Experiments 1–3, in which a control condition was included in the working memory Stroop task. The results showed that the Stroop interference effect can be obtained only when the occurrence of congruent trials among the control and incongruent trials in the working memory Stroop task was sufficiently frequent (Experiments 2 and 3). The interference effect was absent when the proportion of congruent trials was relatively low (Experiment 1). By contrast, we consistently found a relatively large Stroop facilitation effect across the three experiments, suggesting that facilitation in the working memory Stroop effect is strong and reliable. Thus, it is conceivable that while facilitation in the working memory Stroop effect is large and stable, interference in the working memory Stroop effect is weak and fragile and, consequently, sometimes cannot be observed. Note that as illustrated in the *Introduction* section, the exact reverse is usually the case for the classic Stroop effect (Kalanthroff & Henik 2013; MacLeod 1991). The present results therefore contribute to our understanding of the nature of the working memory Stroop effect in terms of facilitation and interference.

Importantly, our study provides the first demonstration that the working memory Stroop effect does not mimic the classic Stroop effect in terms of facilitation and interference effects. By directly contrasting the working memory and classic Stroop effects in a single task paradigm, the results of Experiment 2 showed that although the overall magnitude of the congruency effect was comparable between these two forms of the Stroop effect, they differed in terms of both facilitation and interference effects. Specifically, we found that while facilitation was larger in the working memory Stroop effect than in the classic Stroop effect, interference was smaller in the working memory Stroop effect than in the classic Stroop effect. This finding is consistent with previous reports (e.g., Coderre et al. 2011; Glaser & Glaser 1982), which have shown that when the passively viewed color word appears before the color patch with a relatively long SOA, the Stroop interference effect becomes smaller and the Stroop facilitation effect becomes larger, as compared with the corresponding effects in a standard Stroop task in which the irrelevant color word and the color patch are presented simultaneously. Importantly, the present results indicate that the working memory and classic Stroop effects may differ from each other in nature, though they have similar properties in some aspects (Kiyonaga & Egner 2014). Accordingly, even if working memory can be considered internally directed attention (Chun 2011; Kiyonaga & Egner 2013), our results suggest that internally attended items maintained in working memory may not always affect behavior exactly like those externally attended stimuli, posing a challenge to the view originally proposed by Kiyonaga and Egner (2014). Indeed, attention is not a unitary construct, but rather refers to different selective processes (Chun et al. 2011). It is conceivable that internal attention operating over working memory representations and external attention operating over perceptual representations may not always influence behavior in a similar manner.

It is noteworthy that, across the set of Experiments 2–5, the present study consistently found that congruency between the color word and the color patch affected perceptual accuracy of the color patch, with performance on the color-naming task being more accurate in the congruent condition than in the incongruent condition. However, this is different from the findings of previous studies (Kiyonaga & Egner 2014; Pan et al. 2019; Wang et al. 2021), which never showed a significant congruency effect on color-naming accuracy in the working memory Stroop task. This is surprising given that the present study is very similar to previous studies with respect to the methods used to investigate the working memory Stroop effect. We speculate that because mean percent correct on color naming in the working memory Stroop task was more than 95% and thus near ceiling in previous studies, the congruency effect on color-naming accuracy in the working memory Stroop task might be obscured due to a ceiling effect in those studies. The near ceiling performance on the color-naming task may be partially caused by the use of a long SOA of 3,000 ms between the memory sample word and the color patch in those previous studies. Indeed, when the level of color-naming performance was reduced in the present study by using a relatively short SOA of 1,500 ms to decrease the time for the preparation to perform the color-naming task after encoding the sample word into working memory, we observed a significant congruency effect on color-naming accuracy in four out of five experiments. That is to say, the color-naming accuracy in the working memory Stroop task may be more susceptible to interference from an incongruent to-be remembered color word when the SOA between the color word and the color patch becomes shorter. Thus, contrary to the prediction of Kiyonaga and Egner (2014) that the Stroop effect on perceptual accuracy should not occur in the working memory Stroop task, our results demonstrate for the first time that the Stroop congruency effect on color-naming accuracy can also occur in the working memory Stroop task, just like in the classic Stroop task. However, cognitive mechanisms underlying the congruency effects on color-naming accuracy may differ between these two versions of the Stroop task. In the classic Stroop task, an externally presented incongruent word could automatically trigger an alternative-word-reading task and therefore produce more errors on color-naming performance in the incongruent condition (Kiyonaga & Egner 2014; MacLeod 1991). By contrast, in the working memory Stroop task, internally maintaining verbal information over a delay may involve the spontaneous use of articulatory rehearsal that consists of sub-vocal speech production over time (Camos et al. 2009, 2011; Oberauer 2019), which could lead to more errors on the naming of a color patch that is semantically incongruent with the verbal memoranda. Thus, we suggest that color-naming performance can suffer interference from articulatory rehearsal of an incongruent color word being held in working memory, thereby generating the Stroop effect on perceptual accuracy in the working memory Stroop task.

The congruency effect on memory performance in the working memory Stroop task has previously been considered to arise because the intervening color-naming task diverts limited attentional resources away from working memory maintenance of color words (Kiyonaga & Egner 2014; Pan et al. 2019). This view relies on the prerequisite that maintenance of verbal information (color words) in working memory must be implemented by a general attention-based mechanism. This appears to be true when one considers that internal maintenance of verbal information in working memory can be accomplished by a domain-general mechanism of attentional refreshing (Camos et al. 2018), through which memory representations are reactivated by internal attentional focusing. However, verbal working memory maintenance can also be implemented by a domain-specific mechanism of articulatory rehearsal that requires no attentional resources after the early setup stage (Naveh-Benjamin & Jonides 1984; Vergauwe et al. 2014). Such an attention-independent mechanism of articulatory rehearsal would be more likely to take place when the verbal memoranda are phonologically dissimilar or when an attention-demanding task is concurrently performed during the retention interval of verbal working memory (Camos et al. 2011). Given that color words typically used in the working memory Stroop task sound very different and that the interposed color-naming task involves a sizable attentional demand, articulatory rehearsal is highly likely the mechanism for maintenance of color words in this variant of the Stroop task. If this was the case, then there would be little reason to expect that the quality of the verbal representation of a color word in working memory is susceptible to substantial interference due to attention being occupied by a concurrent color-naming task. This view appears to be supported by the results of our final experiment showing that memory-test accuracy was actually not impaired on incongruent trials compared with the control trials, suggesting that the precision of working memory representations might not become worse when attention is occupied by the interposed color-naming task. That said, given that we cannot draw a strong conclusion based on a null effect, we do not wish to make a claim that active maintenance of verbal representations of color words cannot be impaired by the concurrent attention-demanding color-naming task.

Thus, we argue that to date there is little evidence that the congruency effect on memory performance in the working memory Stroop task is caused by diverting attentional resources away from working memory maintenance. Given that the color representation of a rectangular patch may be briefly stored in working memory when performing the color-naming task (Bae & Luck 2019), there could be two different color representations being simultaneously maintained in working memory on a given incongruent trial. Because the source formats of these two color representations (i.e., color word and color patch) are often not automatically stored in working memory (Chen et al. 2018; Xu et al. 2020), it is possible that there may be source confusion between the two color representations at retrieval. Accordingly, we suggest that the slowing of memory performance on incongruent trials may be due to the possible source confusion between the two color representations at retrieval on those trials. Moreover, given that this source confusion may make participants more likely suffer source misattribution for memory tests on incongruent trials, more errors on memory performance for incongruent trials compared with congruent trials may reflect a misattribution of information stored in working memory rather than a loss of that information. Thus, the overall congruency effect on memory performance does not necessarily indicate that working memory maintenance is impaired when the to-be-remembered color word is semantically incongruent with the color patch.

The present results provide direct evidence showing that working memory performance on a color word can benefit from identification of the semantically congruent color patch during retention interval, with memory-test responses being more accurate in the congruent condition compared with the control and incongruent conditions. We propose that a perceptual demand on a color patch can strengthen the current memory representation of the semantically matched color word. This is consistent with the view that attending a visual stimulus that matches the current content of working memory could improve memory performance by refreshing working memory representations through perceptual resampling of the memory-matching stimulus (Woodman & Luck 2007). Our results therefore demonstrate that in addition to interference due to source confusion in the incongruent condition, facilitation in the congruent condition can also contribute to the overall congruency effect on working memory performance through enhancement of memory representations of the congruent color words.

Altogether, the present results are of great importance for our understanding of the underlying causes of congruency effects on performance in the working memory Stroop task. In this variant of the Stroop task, not only interference in the incongruent condition, but also facilitation in the congruent condition, can contribute to the overall congruency effects on both the color naming and working memory performance. The critical contrast has also been between the working memory and classic Stroop effects in terms of facilitation and interference, suggesting the difference in nature between these two forms of the Stroop effect. Broadly, this difference between the working memory and classic Stroop effects suggests that working memory as internal attention (Chun 2011; Kiyonaga & Egner 2013) can nevertheless be distinct from external attention with respect to their behavioral impacts.

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Declarations

Conflicts of interest The authors declare that they have no conflicts of interest with respect to the authorship or the publication of this article.

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