The extent of center-surround inhibition for colored items in working memory

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Abstract

Remembering a color suppresses the representations of similar colors, but not of distinct colors, producing a center-surround inhibition (CSI) to resolve the competition between similar colors. In this study, three probe experiments were conducted to investigate the extent of CSI for colored items in working memory (WM). In Experiments 1 and 2, two WM items (distance 0°, 20°, 40°, or 60° in color space) were presented sequentially, one of which was cued to compare with the probe (matched or non-matched). The probe distance between the non-matched probe (NP) and cued WM item was 30° in Experiment 1 and 30°, 60°, or 90° in Experiment 2. Results for matched probe (MP) revealed that two WM items might produce a maximal CSI at distance 20°, and fall outside each other's inhibitory surround at distance 40°. However, the CSI was not found in the NP conditions (i.e., distance 30°, 60°, or 90°) in both Experiments 1 and 2, suggesting that the NP might be unsuitable for investigating the CSI in WM. In Experiment 3, participants were asked to discriminate which WM item was matched with the probe (no NP conditions). RTs were slowest at distance 20°, but were almost equal across distance 30°, 40°, 50°, or 60°. These results demonstrated that two WM items might produce a maximal CSI at distance 20°, and begin to fall outside each other's inhibitory surround at distance 30°.

Keywords center-surround inhibition · working memory · inhibitory surround

Attending to a specific feature (e.g., color, orientation, motion direction) inhibits the processing of similar but not distinct features in feature space. This is called the center-surround inhibition (CSI) in feature-based attention (Loach, Frischen, Bruce, & Tsotsos, 2008; Störmer & Alvarez, 2014; Tombu & Tsotsos, 2008). According to the CSI, the discrimination performance between two features exhibits a U-shaped curve with increasing feature distance, with the best performance for two identical or distinct features, and with the worst performance for two similar features.

Extent of CSI in attention

Color has been extensively studied in CSI research for its effective guidance of attention (Bartsch et al., 2017; Fang, Becker, & Liu, 2019; Störmer & Alvarez, 2014; Wang, Miller, & Liu, 2015). Störmer and Alvarez (2014) presented two visual fields with randomly moving dots. In each field, there were two sets of colored dots: One color was indicated as a target and the other served as a distractor. Color distance between two targets was specified by angular distance (i.e., 0°–60°) on a color wheel defined in the CIELAB color space (Commission Internationale de l'Eclairage, 1978). This color wheel was used in several studies (Fang, Becker, et al., 2019; Wang et al., 2015; Zhang & Luck, 2008). Two colors sampled closer in angular distance were more similar than two colors sampled further away. Participants simultaneously attended to the two sets of target colored dots and detected brief intervals of coherent motion in one target color. Detection accuracy was higher for distances 0° and 60° than the other distances (i.e., 10°, 20°, 30°, 40°, and 50°). As the target-to-target distance increased, accuracy first decreased and then increased (i.e., U-

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shaped curve), and the lowest accuracy appeared at distance 30°. These results demonstrated that attending to a color produces a maximal CSI on similar colors at distance 30°, and the distinct colors fall outside the attended color's inhibitory surround at distance 60°.

Extent of CSI in working memory (WM)

WM content could guide visual attention (Downing, 2000; Kiyonaga, Egner, & Soto, 2012; Kiyonaga, Korb, Lucas, Soto, & Egner, 2014; Olivers, Meijer, & Theeuwes, 2006; Saad & Silvanto, 2013; Soto, Hodson, Rotshtein, & Humphreys, 2008). Several researchers have described WM as the selective attention directed toward internal representations (Awh & Jonides, 2001; Chun, 2011; Johnson et al., 2013; Kiyonaga & Egner, 2013, 2014; Oberauer & Hein, 2012; Postle, 2006). The CSI has been found when the attended stimuli were held in WM (Fang, Ravizza, & Liu, 2019; Kiyonaga & Egner, 2016; Yang & Mo, 2017; Yang, Mo, Wang, & Yu, 2017). Kiyonaga and Egner (2016) investigated the extent of CSI in WM. Participants remembered a colored WM item and performed an orientation judgment on the slanted target line in the search test. Search target and vertical distractor line were each surrounded by a colored circle. WM-target color distance ranged from 0° to 180° in the HSV (hue, saturation, value) color space (Smith, 1978). The hue of colors was specified by angles on a color wheel as in the CIELAB color space. Search reaction time (RT) exhibited an inverse U-shaped curve with increasing WM-target distance, with the fastest RT for distances 0° and 30°, and the slowest RT for distance 20°. These results revealed that the CSI is maximal at distance 20°, and targets fall outside the WM item's inhibitory surround at distance 30°. These distances were smaller than those in attention (i.e., distances 30° and 60°).

Kiyonaga and Egner (2016) conducted an EZ-diffusion model on the search performance (Ratcliff & McKoon, 2008; Wagenmakers, van der Maas, Dolan, & Grasman, 2008; Wagenmakers, van der Maas, & Grasman, 2007). This model transforms the RT, variance of RT, and accuracy into drift rate to examine the quality of information at different WM-target distances. Drift rate also exhibited a U-shaped curve with increasing WM-target distance, with the highest drift rate for distances 0° and 30° (i.e., with no difference). These results supported that targets fall outside the WM item's inhibitory surround at distance 30° when attention is guided by the WM content.

Kiyonaga and Egner (2016) then asked participants to simultaneously hold two colored WM items (distance 0°, 20°, 40°, or 60°), and one of which was cued for a probe task. Participants then discriminated whether the probe item was matched [i.e., distance 0°, the matched probe (MP)] or

nonmatched [i.e., distance 30°, the nonmatched probe (NP)] with the cued WM item. Probe RTs exhibited an inverse U-shaped curve with increasing WM item distance, with the faster RTs for distances 0° and 60° than distances 20° and 40°. These results suggested that two similar WM items (i.e., distances 20° and 40°) interfered with each other because they fell within each other's inhibitory surround. However, no inhibition were found between two distinct WM items (i.e., distance 60°). These findings demonstrated that WM representation is characterized by a CSI mechanism, and two WM items fall outside each other's inhibitory surround at distance 60°.

The extent of CSI in WM is 30° in the search test and 60° in the probe test (Kiyonaga & Egner, 2016). These results have been explained by the different task demands in the two tests. Specifically, the extent of CSI is 30° when one item is remembered, but it extends to 60° when two items are simultaneously held in WM. However, there might be a defect concerning the NP. It has been found that attending to a color produces a maximal CSI on similar colors at distance 30° (Störmer & Alvarez, 2014). Attending to a NP (i.e., distance 30°) might produce a CSI on the cued WM item. This raised the possibility that two kinds of CSI were involved in the NP condition. Specifically, the CSI between two WM items that we aimed to explore, and the CSI between the NP and cued WM item that should be excluded. In contrast, there were no CSI between the MP and cued WM item because they were the same colors (See Fig. S1 in the Supplemental materials). However, the results for the two probe types were not analyzed separately, and the extent of CSI in WM was unclear.

This study aimed to investigate the extent of CSI in WM. In Experiment 1, the probe test of Kiyonaga and Egner (2016) was modified to examine whether there was an inhibition between the NP and cued WM item. Probe distance between the NP and cued WM item was 30°. If the worse performance was found for NP than MP, the inhibition might be involved. Experiment 2 further explored the inhibition between the NP and cued WM item by manipulating the probe distance. Probe distance between the NP and cued WM item was 30°, 60°, or 90°. If there was a CSI between the NP (i.e., distance 30°) and cued WM item, performance should be worse for NP at distance 30° than NP at distance 60° or 90°. If there was no CSI between the NP and cued WM item, performance should be equal across probe distances 30°, 60°, or 90°. In Experiment 3, participants were asked to discriminate which WM item was matched with the probe, only MP condition was involved (no NP conditions). The results were expected to be identical to the results for MP in both Experiments 1 and 2. We hypothesized that two WM items might produce a maximal CSI at distance 20°, and fall outside each other's inhibitory surround at distance 30°.

Experiment 1

Methods

Participants

Seventy-one healthy participants took part in this experiment (21 males, 50 females, $M_{\text{age}} = 23.3$ years, $SD = 2.7$). All participants had normal or corrected-to-normal eyesight, and none were color blind. Approval for this study was granted from the Research Ethics Committee of Liaoning Normal University of China, and this study complied with the ethical guidelines of the Declaration of Helsinki. All participants gave informed consent and were paid on completion of the experiment (likewise for Experiments 2 & 3).

Design and materials

A 2 (probe type: MP, NP) $\times$ 4 (WM item distance: 0°, 20°, 40°, 60°) within-subjects design was adopted. Probe distance was defined as the distance between the probe and cued WM item. Two types of probe [the MP (i.e., distance 0°) and NP (i.e., distance 30°)] were included. WM item distance was defined as the color distance between two WM items. The direction of probe distance and WM item distance was randomly selected to be clockwise or anticlockwise. WM item distance (0°, 20°, 40°, 60°), cue (“1,” “2”), and probe type (MP, NP) were presented equally often and in a random order. The hue of WM items and probe (each 2.8° diameter, stroke width = .3°) were randomly selected in 10° steps around an HSV (hue, saturation, value) color wheel, the saturation and value (corresponding to lightness) both were .85 (see Fig. 1a).

All the stimuli were sequentially displayed on a white background on a 19-inch computer screen with a resolution of 1,024 $\times$ 768 pixels. Participants sat approximately 60 cm away from the screen (likewise for Experiments 2 & 3).

Procedure

Each trial began with a 1,000-ms fixation cross in the center of screen, followed by two sequentially presented colored circle WM items. Two WM items were each displayed for 750 ms and separated by a 500 ms blank. After a 2,000-ms delay, a cue (“1” or “2”) appeared for 750 ms to indicate which WM item would be probed. A probe item with a question mark above it was then displayed for 2,000 ms (see Fig. 1b). Participants were asked to remember two WM items, then discriminated whether the probe was matched or nonmatched with the cued WM item by pressing the “f” or “j” key as quickly and accurately as possible. The assignment of MP/NP to response keys was counterbalanced across participants. When a key press was submitted, a mask image appeared for 1,500 ms to diminish a backward mask effect. Each participant completed 20 practice trials and 192 experimental trials (48 trials per WM item distance).

Data analysis

Probe accuracy (ACC) was defined as the percentage of correct responses in each condition. Probe reaction time (RT) was defined as the time between probe item onset and the key press. Drift rate was transformed from RT, variance of RT, and accuracy to reflect the quality of memory information by an EZ-diffusion model. The inverse efficiency score (IES;

Fig. 1 a A color wheel in the HSV color space that varied only in hue. b Examples for the materials and procedure used in Experiment 1 (i.e., WM item distance was 60°). In the MP condition (50% of trials), the probe was

matched with the cued WM item. Whereas in the NP condition (50% of trials), they were at a distance of 30°. (Color figure online)

Townsend & Ashby, 1978, 1983) is equal to the RTs divided by accuracy, thus, a higher IES indicates worse performance (longer RTs or lower accuracy). IES was calculated to avoid the speed–accuracy trade-off (likewise for Experiments 2 & 3).

Overall results included the probe accuracy, probe RTs, drift rate, and IES for the overall trials. Based on the probe type, overall results were sorted into two categorized results for MP and NP. Differences between the results for MP and NP were calculated.

Incorrect responses were excluded from the probe RT analyses (19.2%), as were latencies that were three standard deviations either above or below the mean probe RTs per experimental condition per participant (0.7%).

First, a repeated-measures analysis of variance (ANOVA) with the within-subjects factor WM item distance (0°, 20°, 40°, 60°) was conducted on the overall results. Second, the repeated-measures ANOVAs with probe type (MP, NP) and WM item distance (0°, 20°, 40°, 60°) as within-subjects factors were performed on the categorized results. Third, a repeated-measures ANOVA with the within-subject factor WM item distance (0°, 20°, 40°, 60°) was conducted on the differences between the results for MP and NP.

All effects with more than one degree of freedom have been adjusted for sphericity violations using the Greenhouse–Geisser correction. Main effects or interactions were subjected to LSD-corrected pairwise comparisons or simple effects analysis (likewise for Experiments 2 & 3).

Results

The mean accuracy, RTs, drift rate, and IES for all conditions were reported in Table 1.

Overall results

The ANOVA revealed a significant main effect of WM item distance on accuracy, $F(3, 210) = 11.366, p < .001, \eta_p^2 = .140, 1 - \beta = .999$. Pairwise comparisons showed higher accuracy for distance 0° than the other distances, $ps < .001$. No significant differences were found among the other distances, $ps \geq .118$ (see Fig. 2a).

For the probe RTs, a significant main effect of WM item distance was observed, $F(3, 210) = 23.998, p < .001, \eta_p^2 = .255, 1 - \beta = 1.0$, with the faster RTs for distance 0° than the other distances, $ps < .001$, and the slower RTs for distances 20° and 40° than distance 60°, $ps \leq .036$. There were no significant differences between distance 20° and distance 40°, $p = .438$ (see Fig. 2b).

The main effect of WM item distance on drift rate was significant, $F(3, 210) = 29.191, p < .001, \eta_p^2 = .294, 1 - \beta = 1.0$. Drift rate was higher for distance 0° than the other distances, $ps < .001$, and lower for distance 40° than distance 60°, $p = .023$. No significant differences were observed among the other distances, $ps \geq .201$ (see Fig. 4a).

For the IES, a significant main effect of WM item distance was observed, $F(3, 210) = 30.822, p < .001, \eta_p^2 = .306, 1 - \beta = 1.0$, with the lower IES for distance 0° than the other

Table 1 Mean ACC, RTs, drift rate, and IES (and SDs) for all conditions in Experiments 1 and 2

	WM item distance	Probe type in Experiment 1				Probe distance in Experiment 2			
		Overall	MP (0°)	NP (30°)	Differences	0°	30°	60°	90°
ACC (%)	0°	83.7 (7.1)	92.5 (8.1)	74.9 (12.8)	17.6 (16.0)	94.8 (5.5)	74.6 (14.2)	96.9 (4.3)	97.0 (5.8)
	20°	80.1 (7.3)	86.4 (8.0)	73.8 (12.8)	12.6 (15.6)	88.5 (8.3)	59.9 (19.3)	96.0 (6.5)	97.6 (5.4)
	40°	79.0 (8.8)	87.8 (10.8)	70.1 (13.5)	17.7 (17.1)	89.0 (7.8)	65.5 (15.9)	92.7 (6.7)	95.8 (4.9)
	60°	80.3 (6.9)	88.9 (10.5)	69.3 (13.4)	19.6 (19.5)	89.7 (6.7)	54.3 (15.3)	91.5 (8.9)	95.8 (6.3)
RT (ms)	0°	718 (140)	696 (152)	763 (151)	67 (121)	639 (126)	746 (144)	618 (123)	607 (133)
	20°	783 (149)	766 (158)	815 (157)	49 (118)	729 (138)	807 (162)	644 (115)	614 (120)
	40°	777 (141)	728 (138)	847 (177)	119 (138)	708 (136)	843 (170)	693 (141)	640 (135)
	60°	760 (145)	735 (154)	826 (171)	90 (147)	696 (139)	880 (179)	694 (152)	667 (133)
Drift rate	0°	.157 (.049)	.232 (.082)	.115 (.070)	.117 (.111)	.251 (.079)	.112 (.085)	.303 (.1)	.318 (.115)
	20°	.124 (.037)	.163 (.058)	.098 (.058)	.066 (.084)	.171 (.058)	.035 (.106)	.284 (.101)	.324 (.106)
	40°	.118 (.044)	.178 (.069)	.082 (.064)	.096 (.092)	.181 (.064)	.062 (.071)	.228 (.091)	.291 (.099)
	60°	.127 (.038)	.189 (.076)	.086 (.071)	.103 (.12)	.184 (.061)	.015 (.064)	.227 (.1)	.275 (.095)
IES (ms)	0°	864 (188)	763 (198)	1060 (320)	297 (338)	678 (152)	1051 (341)	640 (140)	631 (157)
	20°	986 (221)	898 (222)	1141 (324)	243 (306)	836 (203)	1601 (985)	677 (151)	634 (147)
	40°	994 (212)	845 (209)	1266 (415)	421 (436)	808 (203)	1446 (934)	754 (170)	671 (152)
	60°	954 (206)	844 (230)	1263 (466)	419 (512)	783 (179)	1772 (664)	770 (203)	701 (162)

Fig. 2 Mean accuracy (a) and probe RTs (b) for each WM item distance in Experiment 1. Error bars represent standard errors of the mean. * $p < .05$, *** $p < .001$

distances, $ps < .001$, and the higher IES for distances 20° and 40° than distance 60°, $ps \leq .033$. There were no significant differences between distance 20° and distance 40°, $p = .566$ (see Fig. 4b).

Categorized results

For the accuracy, the ANOVA showed a significant main effect of probe type, $F(1, 70) = 103.886$, $p < .001$, $\eta_p^2 = .597$, $1 - \beta = 1.0$, and a significant main effect of WM item distance, $F(3, 210) = 13.359$, $p < .001$, $\eta_p^2 = .16$, $1 - \beta = 1.0$. Probe Type $\times$ WM Item Distance interaction was significant, $F(3, 210) = 4.82$, $p = .003$, $\eta_p^2 = .064$, $1 - \beta = .862$. Simple effects analysis revealed a lower accuracy for NP than MP in each WM item distance, $ps < .001$. For MP, accuracy was higher for distance 0° than the other distances, $ps \leq .003$. No significant differences were found among the other distances, $ps \geq .05$. For NP, accuracy was higher for distances 0° and 20° than distances 40° and 60°, $ps \leq .013$. No significant differences were found among the other distances, $ps \geq .353$ (see Fig. 3a).

For the RTs, there was a significant main effect of probe type, $F(1, 70) = 43.044$, $p < .001$, $\eta_p^2 = .381$, $1 - \beta = 1.0$, and a significant main effect of WM item distance, $F(3, 210) = 22.432$, $p < .001$, $\eta_p^2 = .243$, $1 - \beta = 1.0$. Probe Type $\times$ WM Item Distance interaction was significant, $F(3, 210) = 8.159$, $p < .001$, $\eta_p^2 = .104$, $1 - \beta = .99$, with the slower RTs for NP than MP in each WM item distance, $ps < .001$. RTs were faster for distance 0° than the other distances for the two probe types, $ps \leq .011$. For MP, RTs were slower for distance 20° than distances 40° and 60°, $ps \leq .005$. No significant differences were found between distance 40° and distance 60°, $p = .496$. For NP, RTs were slower for distance 40° than distance 20°, $p = .003$. There were no significant differences between distance 60° and distance 20° or 40°, $ps \geq .066$ (see Fig. 3b).

For the drift rate, there was a significant main effect of probe type, $F(1, 70) = 99.331$, $p < .001$, $\eta_p^2 = .587$, $1 - \beta = 1.0$. The main effect of WM item distance was significant, $F(3, 210) = 26.56$, $p < .001$, $\eta_p^2 = .275$, $1 - \beta = 1.0$, as was the Probe Type $\times$ WM Item Distance interaction, $F(3, 210) = 6.127$, $p \leq .001$, $\eta_p^2 = .08$, $1 - \beta = 0.93$. Drift rate was lower for NP than MP over all WM item distances, $ps < .001$. Drift rate was higher for distance 0° than the other distances for the

Fig. 3 Mean accuracy (a) and probe RTs (b) for all conditions in Experiment 1. Error bars represent standard errors of the mean. ** $p < .01$, *** $p < .001$

two probe types, $ps \leq .007$. For MP, drift rate was lower for distance 20° than distance 60° , $p = .008$. No significant differences were found among the other distances, $ps \geq .097$. For NP, drift rate was higher for distance 20° than distance 40° , $p = .029$. No significant differences were found among the other distances, $ps \geq .101$ (see Fig. 4a).

A significant main effect of probe type was observed on IES data, $F(1, 70) = 71.977$, $p < .001$, $\eta_p^2 = .507$, $1 - \beta = 1.0$, and a significant main effect of WM item distance, $F(3, 210) = 22.541$, $p < .001$, $\eta_p^2 = .244$, $1 - \beta = 1.0$. The Probe Type $\times$ WM Item Distance interaction was also significant, $F(3, 210) = 8.934$, $p < .001$, $\eta_p^2 = .113$, $1 - \beta = .98$, with the higher IES for NP than MP in each WM item distance, $ps < .001$. IES was lower for distance 0° than the other distances for two probe types, $ps < .001$. For MP, IES was higher for distance 20° than the other distances, $ps \leq .014$. No significant differences were found between distance 40° and distance 60° , $p = .922$. For NP, IES was lower for distance 20° than distances 40° and 60° , $p \leq .005$. There were no significant differences between distance 40° and distance 60° , $p = .92$ (see Fig. 4b).

A significant main effect of WM item distance was observed on accuracy differences between MP and NP, $F(3, 210) = 4.82$, $p = .003$, $\eta_p^2 = .064$, $1 - \beta = .862$, on RT differences, $F(3, 210) = 8.159$, $p < .001$, $\eta_p^2 = .104$, $1 - \beta = .99$, on drift rate differences, $F(3, 210) = 6.198$, $p \leq .001$, $\eta_p^2 = .08$, $1 - \beta = .93$, and on IES differences, $F(3, 210) = 8.934$, $p < .001$, $\eta_p^2 = .113$, $1 - \beta = .98$. The accuracy differences, drift rate differences, and IES differences were smaller for distance 20° than the other distances, $ps \leq .048$. RT differences were smaller for distance 20° than the distance 40° and 60° conditions, $ps \leq .006$. No significant differences were observed among the other distances, $ps \geq .61$ (see Table 1).

Discussion

Overall accuracy was highest for distance 0° , but was almost equal across the other distances, indicating a low load to remember two identical WM items (i.e., distance 0°). Overall RTs and

IES both exhibited an inverse U-shaped curve with increasing WM item distance, with the slower RTs and higher IES for distances 20° and 40° than distances 0° and 60° . Overall drift rate exhibited a U-shaped curve with increasing WM item distance, with the highest drift rate for distances 0° and 60° , and the lowest drift rate for distance 40° , indicating a maximal CSI at distance 40° . These results were in line with Kiyonaga and Egner (2016), suggesting that two WM items might fall outside each other's inhibitory surround at distance 60° .

Performance for the two probe types was analyzed separately. Lower accuracy and drift rate were observed for NP (i.e., distance 30°) than MP (i.e., distance 0°), revealing a greater inhibition in the NP than MP condition. Consistent with the overall results, accuracy for MP was equal for each distance except for distance 0° , and drift rate for MP showed a CSI in WM. The difference was that the lowest drift rate and highest IES were at distance 20° , indicating that the maximal CSI might appear at distance 20° . This distance was smaller than that for the overall results (i.e., distance 40°). Results for NP revealed that accuracy and drift rate for distance 20° or 40° were no different from that for distance 0° or 60° , suggesting that the CSI was not found in this condition.

Slower RTs and higher IES were found for NP than MP, supporting a greater inhibition in the NP than MP condition. In line with the overall results, RTs and IES for MP exhibited an inverse U-shaped curve with increasing WM item distance, with the slowest RTs and highest IES for distance 20° , suggesting that the maximal CSI might be at distance 20° . No significant differences were found between distance 40° and distance 60° , suggesting that two WM items might fall outside each other's inhibitory surround at distance 40° . This distance was smaller than that for the overall results (i.e., distance 60°), supporting that a greater inhibition might be involved in the NP than MP condition. RTs and IES for NP gradually increased with increasing WM item distance, revealing that the CSI was not found in the NP condition.

Fig. 4 Mean drift rate (a) and IES (b) for all conditions in Experiment 1. Error bars represent standard errors of the mean. * $p < .05$, ** $p < .01$, *** $p < .001$

As WM maintenance was the same in the two probe trials, a greater inhibition for NP than MP might result from an inhibition between the NP and cued WM item. If the worse performance for NP than MP was almost equal for each WM item distance, this might indicate a general inhibition, reflecting a bias to the “yes” response (or MP). However, performance differences between two probe types were smaller for distance 20° than distances 40° and 60°, suggesting that the inhibition between the NP and cued WM item might not be a general inhibition.

The CSI with a maximum at distance 20° was found in the MP condition, but not in the NP condition. This might be because of an inhibition between the NP (i.e., distance 30°) and cued WM item in this condition. If the NP fell outside the cued WM item’s inhibitory surround, no CSI would be found (See Fig. S2 in the Supplemental materials). As it was too easy to discriminate between two extremely distinct colors, resulting in a ceiling effect, two moderate probe distances (i.e., 60°, 90°) were added in Experiment 2.

Experiment 2

Methods

Participants

Sixty-three healthy participants took part in this experiment (25 males, 38 females, $M_{\text{age}} = 21.3$ years, $SD = 3.8$).

Design and materials

A 4 (probe distance: 0°, 30°, 60°, 90°) × 4 (WM item distance: 0°, 20°, 40°, 60°) within-subjects design was adopted in Experiment 2. All materials were the same as those in Experiment 1.

Procedure

The procedure was identical to that in Experiment 1 (see Fig. 5). Each participant completed 32 practice trials and 384 experimental trials (192 MP trials, 48 trials per WM item distance; 192 NP trials, 16 trials per probe distance per WM item distance).

Data analysis

Incorrect responses were excluded from the probe RT analyses (12.3%), as were latencies that were three standard deviations either above or below the mean probe RTs per experimental condition per participant (1.0%).

Repeated-measures ANOVAs with the probe distance (0°, 30°, 60°, 90°) and WM item distance (0°, 20°, 40°, 60°) as within-subjects factors were conducted on the accuracy, probe RTs, drift rate, and IES.

Results

For the accuracy, the ANOVA revealed a significant main effect of probe distance, $F(3, 186) = 331.014$, $p < .001$, η_p^2

Fig. 5 Examples for the materials and procedure used in Experiment 2 (i.e., WM item distance was 60°). In the MP condition, the probe was matched with the cued WM item. Whereas in the NP condition, they were at distances of 30°, 60°, or 90°. (Color figure online)

$= .842$, $1 - \beta = 1.0$, and a significant main effect of WM item distance, $F(3, 186) = 63.878$, $p < .001$, $\eta_p^2 = .507$, $1 - \beta = 1.0$. The interaction of Probe Distance $\times$ WM Item Distance was significant, $F(9, 558) = 19.303$, $p < .001$, $\eta_p^2 = .237$, $1 - \beta = 1.0$. Simple effects analysis revealed a lower accuracy for probe distance 30° than probe distance 0° , 60° , and 90° conditions in each WM item distance, $ps < .001$. Accuracy was higher for probe distance 60° than probe distance 0° in each WM item distance, $ps \leq .008$, except for WM item distance 60° , $p = .151$. Accuracy was higher for probe distance 90° than probe distance 0° in each WM item distance, $ps \leq .033$. Accuracy was higher for probe distance 90° than probe distance 60° in WM item distances 40° and 60° , $ps \leq .001$, but not in WM item distance 0° or 20° , $ps \geq .103$ (see Fig. 6a).

When the probe distance was 0° or 30° , accuracy was higher for WM item distance 0° than the other WM item distances, $ps < .001$. For probe distance 0° , no significant differences were found among the other WM item distances, $ps \geq .187$. For probe distance 30° , accuracy was lower for WM item distance 20° than WM item distance 40° , but higher for WM item distances 20° and 40° than WM item distance 60° , $ps \leq .013$. For probe distance 60° , accuracy was higher for WM item distances 0° and 20° than WM item distances 40° and 60° , $ps \leq .002$. No significant differences were found among the other WM item distances, $ps \geq .244$. For probe distance 90° , accuracy was higher for WM item distance 20° than WM item distances 40° and 60° , $ps \leq .049$. There were no significant differences among the other WM item distances, $ps \geq .153$.

There was a significant main effect of probe distance on RT data, $F(3, 186) = 186.429$, $p < .001$, $\eta_p^2 = .75$, $1 - \beta = 1.0$, and a significant main effect of WM item distance, $F(3, 186) = 64.193$, $p < .001$, $\eta_p^2 = .509$, $1 - \beta = 1.0$. The interaction of Probe Distance $\times$ WM Item Distance was significant, $F(9, 558) = 9.578$, $p < .001$, $\eta_p^2 = .134$, $1 - \beta = 1.0$. RTs were slower for probe distance 30° than probe distances 0° , 60° , and 90° in each WM item distance, $ps < .001$. RTs were faster

for probe distance 60° than probe distance 0° in WM item distances 0° and 20° , $ps \leq .026$, but not in WM item distance 40° or 60° , $ps \geq .21$. RTs were faster for probe distance 90° than probe distance 0° over all WM item distances, $ps \leq .018$. RTs were faster for probe distance 90° than probe distance 60° in each WM item distance ($ps \leq .033$), except for WM item distance 0° , $p = .236$ (see Fig. 6b).

For probe distances 0° , 30° , and 60° , RTs were faster for WM item distance 0° than the other WM item distances, $ps \leq .002$. For probe distance 0° , RTs were slower for WM item distance 20° than WM item distances 40° and 60° , $ps \leq .011$, but no significant differences were found between WM item distance 40° and WM item distance 60° , $p = .119$. For probe distance 30° , RTs for WM item distance 40° were slower than that for WM item distance 20° , but faster than that for WM item distance 60° , $ps \leq .044$. For probe distance 60° , RTs were faster for WM item distance 20° than WM item distances 40° and 60° , $ps < .001$, no significant differences were observed between WM item distance 40° and WM item distance 60° , $p = .933$. For probe distance 90° , RTs were faster for WM item distances 0° and 20° than WM item distances 40° and 60° , and faster for WM item distance 40° than WM item distance 60° , $ps \leq .01$. No significant differences were found between WM item distance 0° and WM item distance 20° , $p = .446$.

For the drift rate, the ANOVA revealed a significant main effect of probe distance, $F(3, 186) = 298.493$, $p < .001$, $\eta_p^2 = .828$, $1 - \beta = 1.0$, and a significant main effect of WM item distance, $F(3, 186) = 70.167$, $p < .001$, $\eta_p^2 = .531$, $1 - \beta = 1.0$. The interaction of Probe Distance $\times$ WM Item Distance was significant, $F(9, 558) = 8.201$, $p < .001$, $\eta_p^2 = .117$, $1 - \beta = 1.0$. Drift rate was lower for probe distance 30° than probe distance 0° , 60° , and 90° conditions in each WM item distance, $ps < .001$. Drift rate was higher for probe distances 60° and 90° than probe distance 0° over all WM item distances, $ps < .001$. Drift rate was higher for probe distance 90° than probe distance 60° in WM item distances 20° , 40° , and 60° , $ps \leq .003$, but not in WM item distance 0° , $p = .20$ (see Fig. 7a).

Fig. 6 Mean accuracy (a) and probe RTs (b) for all conditions in Experiment 2. Error bars represent standard errors of the mean

Fig. 7 Mean drift rate (a) and IES (b) for all conditions in Experiment 2. Error bars represent standard errors of the mean

When the probe distance was 0° or 30°, drift rate was higher for WM item distance 0° than the other WM item distances, $p < .001$. For probe distance 0°, drift rate was lower for WM item distance 20° than WM item distance 60°, $p = .045$. There were no significant differences between WM item distance 40° and WM item distance 20° or 60°, $p \geq .066$. For probe distance 30°, drift rate was lower for WM item distances 20° and 60° than WM item distance 40°, $p \leq .034$. No significant differences were found between WM item distance 20° and WM item distance 60°, $p = .101$. For probe distance 60° or 90°, drift rate was higher for WM item distances 0° and 20° than WM item distances 40° and 60°, $p \leq .039$. There were no significant differences among the other WM item distances, $p \geq .087$.

There was a significant main effect of probe distance on IES data, $F(3, 186) = 122.239$, $p < .001$, $\eta_p^2 = .663$, $1 - \beta = 1.0$, and a significant main effect of WM item distance, $F(3, 186) = 34.228$, $p < .001$, $\eta_p^2 = .356$, $1 - \beta = 1.0$. The interaction of Probe Distance $\times$ WM Item Distance was significant, $F(9, 558) = 13.37$, $p < .001$, $\eta_p^2 = .177$, $1 - \beta = 1.0$. IES was higher for probe distance 30° than probe distances 0°, 60°, and 90° in each WM item distance, $p < .001$. IES was lower for probe distance 60° than probe distance 0° in each WM item distance ($p \leq .007$), except for WM item distance 60°, $p = .537$. IES was lower for probe distance 90° than probe distance 0° over all WM item distances, $p \leq .001$. IES was lower for probe distance 90° than probe distance 60° in WM item distances 20°, 40° and 60°, $p \leq .002$, but not in WM item distance 0°, $p = .427$ (see Fig. 7b).

When the probe distance was 0°, 30°, or 60°, IES was lower for WM item distance 0° than the other WM item distances, $p \leq .001$. For probe distance 0°, IES was lower for WM item distance 20° than WM item distances 40° and 60°, $p \leq .026$, but no significant differences were found between WM item distance 40° and WM item distance 60°, $p = .086$. For probe distance 30°, IES was lower for WM item distance 40° than WM item distance 60°, $p = .007$. No significant differences were found among the other WM item distances, $p \geq .121$. For probe distance 60°, IES

was lower for WM item distance 20° than WM item distances 40° and 60°, $p < .001$, no significant differences were observed between WM item distance 40° and WM item distance 60°, $p = .336$. For probe distance 90°, IES was lower for WM item distances 0° and 20° than WM item distances 40° and 60°, $p < .001$. IES was lower for WM item distance 40° than WM item distance 60°, $p = .015$. No significant differences were found between WM item distance 0° and WM item distance 20°, $p = .769$.

Discussion

The results of accuracy, probe RT, drift rate, and IES for MP (i.e., distance 0°) were similar to those in Experiment 1, suggesting that two WM items might produce a maximal CSI at distance 20°, and fall outside each other's inhibitory surround at distance 40°. Compared with the MP, performance for the NP was worse (i.e., lower accuracy, drift rate, slower RTs, or higher IES) for probe distance 30° but was equally even better for probe distance 60° or 90°, indicating a greater inhibition for NP at distance 30° than NP at distance 60° or 90°. This was consistent with our prediction that NP (i.e., distance 30°) itself and cued WM item might produce a CSI. As the probe distance increased (i.e., 60°, 90°), NP might fall outside the cued WM item's inhibitory surround, producing no CSI.

For the NP at distance 30°, performance was better (i.e., higher accuracy, drift rate, and lower IES) for two similar WM items (i.e., distance 40°) than two distinct WM items (i.e., distance 60°), RTs gradually increased with increasing WM item distance, suggesting that the CSI was not found in this condition. This was in line with the results for NP in Experiment 1. For the NP at distance 60° or 90°, performance became worse with increasing WM item distance, with no differences between distance 0° and distance 20° or between distance 40° and distance 60°, suggesting that the CSI was not found when the NP fell outside the cued WM item's inhibitory surround.

Performance for NP (i.e., distance 60° or 90°) was equal even better than that for MP (i.e., distance 0°). It might be easier to discriminate between the NP and cued WM item than between the MP and cued WM item. The result of this might be that the maintenance of the details of WM items was not required in the NP condition. Störmer and Alvarez (2014) suggested that attending to a color produces an inhibitory surround; only when another similar color (i.e., distance 30°) must be attended, they fall within each other's inhibitory surround. If the details of WM items were not maintained, no CSI would be found. In addition, the interaction between the probe task and WM maintenance might be weak when the NP was easy to discriminate. Thus, the CSI between two WM items could not be probed by the NP.

The CSI with a maximum at distance 20° was observed in the MP condition, but not in the NP conditions (i.e., distance 30°, 60°, or 90°), suggesting that the NP might be unsuitable for investigating the extent of CSI (See Fig. S3 in the Supplemental materials). In addition, previous studies indicated that the absence of CSI might be due to the coarse sampling of the feature space (Fang, Becker, et al., 2019; Fang & Liu, 2019; Störmer & Alvarez, 2014; Tombu & Tsotsos, 2008). Therefore, NP was removed, and finer WM item distances were used in Experiment 3.

Experiment 3

Methods

Participants

Eighty healthy participants took part in this experiment. The data for one participant were removed from the analysis because of more than 80% error responses. Therefore,

data from 79 participants were included in the analysis (22 males, 57 females, $M_{\text{age}} = 21.4$ years, $SD = 2.0$).

Design and materials

A one factor (WM item distance: 0°, 10°, 20°, 30°, 40°, 50°, 60°) within-subjects design was adopted in Experiment 3. All materials were the same as those employed in Experiment 1, with the exception that WM item distances were finer than those in Experiment 1.

Procedure

The procedure used in Experiment 1 was modified by removing the NP. Probe was always identical to either of the two WM items (see Fig. 8). Participants were instructed to press the “f” or “j” key as quickly and accurately as possible to discriminate which WM item (first or second) was matched with the probe. When two WM items were both matched with the probe (i.e., WM item distance 0°), half of participants pressed the “f” key, and the other half pressed the “j” key. Each participant completed 20 practice trials and 252 experimental trials (36 trials per WM item distance).

Data analysis

Incorrect responses were excluded from the probe RT analyses (14.02%), as were latencies that were three standard deviations either above or below the mean probe RTs per experimental condition per participant (1.29%).

Repeated-measures ANOVAs with the within-subject factor WM item distance (0°, 10°, 20°, 30°, 40°, 50°, 60°) were performed on the accuracy, probe RTs, drift rate, and IES.

Fig. 8 Examples for the procedure in Experiment 3 (i.e., WM item distance was 30°). The probe was matched with the first WM item in 50% of the trials, or matched with the second WM item in the remaining 50% trials. (Color figure online)

Results

The ANOVA revealed a significant main effect of WM item distance on accuracy, $F(6, 468) = 353.506$, $p < .001$, $\eta_p^2 = .819$, $1 - \beta = 1.0$. Accuracy was higher for distance 0° than distances 10° , 20° , and 30° , $ps < .01$, but lower for distance 0° than distance 60° , $p = .012$. Accuracy was lower for distance 10° than the other distances, $ps < .001$, and lower for distance 20° than the other distances, $ps < .001$, except for distance 10° . Then accuracy increased with increasing WM item distance, $ps \leq .03$. Accuracy for distances 40° and 50° was no different from that of distance 0° , $ps \geq .22$ (see Fig. 9a, Table 2).

For the probe RTs, there was a significant main effect of WM item distance, $F(6, 468) = 126.926$, $p < .001$, $\eta_p^2 = .619$, $1 - \beta = 1.0$. Pairwise comparisons revealed that RTs were faster for distance 0° than the other distances, $ps < .001$, and faster for distance 10° than the other distances, $ps < .001$, except for distance 0° . RTs were slower for distance 20° than the other distances, $ps \leq .037$. No significant differences were found among distance 30° , 40° , 50° , or 60° , $ps \geq .07$ (see Fig. 9b, Table 2).

There was a significant main effect of WM item distance on drift rate data, $F(6, 468) = 189.005$, $p < .001$, $\eta_p^2 = .708$, $1 - \beta = 1.0$, with the higher drift rate for distance 0° than the other distances, $ps \leq .005$, except for distance 60° , $p = .235$. Drift rate was lower for distance 10° than the other distances, $ps < .001$, and lower for distance 20° than the other distances, $ps < .001$, except for distance 10° . Then drift rate gradually increased with increasing WM item distance, $ps \leq .002$. No significant differences were found between distance 40° and distance 50° , $p = .435$ (see Fig. 10a, Table 2).

The ANOVA revealed a significant main effect of WM item distance on IES data, $F(6, 468) = 137.667$, $p < .001$, $\eta_p^2 = .638$, $1 - \beta = 1.0$, with the lower IES for distance 0° than the other distances, $ps < .001$, and with the higher IES for distance 10° than the other distances, $ps < .001$. IES was higher for distance 20° than the other distances, $ps < .001$,

except for distance 10° . Then, IES dramatically decreased with increasing WM item distance, $ps \leq .032$ (see Fig. 10b, Table 2).

Discussion

Compared with the equal accuracy across distances 20° , 40° , or 60° in Experiments 1 and 2, accuracy in Experiment 3 exhibited a U-shaped curve with increasing WM item distance. Accuracy and drift rate were both highest for distances 0° and 60° and lowest for distance 10° , revealing that the memory precision and quality of memory information might be modulated by the CSI. Therefore, the CSI in WM could be observed when the NP was removed. In addition, accuracy for distances 40° and 50° was no worse than that for distance 0° , drift rate for distance 40° was almost equal to that for distance 50° , suggesting that two WM items might have fallen outside each other's inhibitory surround when they were greater than distance 30° .

In line with Experiments 1 and 2, RTs and IES exhibited an inverse U-shaped curve with increasing WM item distance, providing evidence for a CSI in WM. RTs were slowest at distance 20° , revealing that two WM items might produce a maximal CSI at distance 20° . This was in line with the results for MP in both Experiments 1 and 2. RTs then became faster and were almost equal for two distinct WM items (i.e., distance 30° , 40° , 50° , or 60°), revealing that two WM items might begin to fall outside each other's inhibitory surround at distance 30° . However, IES was highest at distance 10° , which was different from that in Experiments 1 and 2.

The lowest accuracy, drift rate, and highest IES for MP were at distance 20° in Experiments 1 and 2, but at distance 10° in Experiment 3. Finer WM item distances were used in Experiment 3 compared with that in Experiments 1 and 2. It might be difficult to discriminate between two similar WM items (i.e., distance 10°). Additionally, RTs were faster for distance 10° than the other distances, except for distance 0° ,

Fig. 9 Mean accuracy (a) and probe RTs (b) for each WM item distance in Experiment 3. Error bars represent standard errors of the mean. * $p < .05$, *** $p < .001$

Table 2 Mean ACC, RTs, drift rate, and IES (and SDs) for all conditions in Experiment 3

	WM item distance						
	0°	10°	20°	30°	40°	50°	60°
ACC (%)	93.2 (9.3)	59.1 (7.1)	79.1 (8.5)	88.0 (6.6)	93.0 (5.7)	94.7 (4.8)	96.1 (3.9)
RT (ms)	458 (144)	590 (145)	686 (116)	669 (108)	670 (126)	665 (116)	657 (112)
Drift rate	.272 (.107)	.035 (.029)	.123 (.048)	.185 (.051)	.229 (.066)	.235 (.058)	.257 (.062)
IES (ms)	510 (250)	1,006 (241)	877 (173)	765 (137)	724 (152)	705 (129)	686 (130)

suggesting that the CSI at distance 10° might not be maximal. In contrast, RTs were slowest for distance 20°, and performance was worse (i.e., lower accuracy, drift rate, and higher IES) for distance 20° than the other distances, except for distance 10°. Therefore, the maximal CSI might appear at distance 20°.

General discussion

In this study, three probe experiments were conducted to investigate the extent of CSI for colored items in WM. The CSI with a maximum at distance 20° has been found in the MP condition (i.e., distance 0°), but not in the NP conditions (i.e., distance 30°, 60°, or 90°) in both Experiments 1 and 2, suggesting that the NP might be unsuitable for exploring the extent of CSI in WM. Accordingly, the NP was excluded, and finer WM item distances were used in Experiment 3. In line with the results for MP in the first two experiments, two WM items might produce a maximal CSI at distance 20°, and begin to fall outside each other's inhibitory surround at distance 30°.

The probe task that required maintenance of two WM items in Kiyonaga and Egner (2016) was modified, and a smaller extent of CSI was found in this study (i.e., 30°) than in their

study (i.e., 60°). Our analysis of probe types clarified the possible reason: results for the two probe types were not analyzed separately, and their findings were likely biased by the NP. When the NP was excluded, the extent of CSI between two WM items was identical to their search test results for one WM item (i.e., 30°). This was in line with our prediction. Therefore, the extent of CSI in WM might be influenced by the NP rather than the number of WM items.

The CSI has been observed in spatial attention (Boehler, Tsotsos, Schoenfeld, Heinze, & Hopf, 2009; Cutzu & Tsotsos, 2003; Hopf et al., 2006; Müller & Kleinschmidt, 2004; Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005). Fang, Ravizza, et al. (2019) found that the magnitude of performance modulation by CSI is smaller in WM than in spatial attention. They suggested that it is likely because that stimulus encoding could be directly modulated in attention, whereas only previously encoded representations could be operated in WM. Similarly, several notable differences were found between the CSI for colored items in WM and attention. First, the maximal CSI might appear at a smaller color distance in WM (i.e., 20°) than in attention (i.e., 30°). Second, two colored items might begin to fall outside each other's inhibitory surround at distance 30° in WM, but at distance 60° in attention. These findings revealed that the extent of CSI for colored items might be smaller in WM than in attention.

Fig. 10 Mean drift rate (a) and IES (b) for each WM item distance in Experiment 3. Error bars represent standard errors of the mean. * $p < .05$, ** $p < .01$, *** $p < .001$

The CSI was found when two similar colored items were simultaneously held in WM, supporting the view that the CSI emerges in tasks involving high competition between different features (Kiyonaga & Egner, 2016; Loach et al., 2008; Störmer & Alvarez, 2014; Treue, 2014). Our findings demonstrated that the CSI could resolve this competition by suppressing similar WM representations. This was akin to the biased-competition framework of attention, showing that a key function of selective attention is to resolve stimulus competition (Desimone & Duncan, 1995). Therefore, the CSI in WM might be an important selective mechanism.

There were several limitations of this study that should be noted. First, although the CSI has been observed using distinct probe methods, the center-surround profile (i.e., U-shaped curve) of CSI might vary with the task demands (Hopf, Boehler, Schoenfeld, Heinze, & Tsotsos, 2010). Therefore, probe methods should be considered as an influencing factor for the extent of CSI in future studies. Second, finer WM item distances might require more precise memory. The different results in the three experiments might be related to the distance conditions. Future studies are needed to adopt the same distance conditions to explore the extent of CSI. Third, the extent of CSI was indirectly reflected by probe results. Future studies could employ additional techniques (e.g., ERP, fMRI) to directly investigate the neural activities of CSI in WM.

In summary, the NP might be unsuitable for investigating the extent of CSI in WM. Two colored WM items might produce a maximal CSI at distance 20° in color space, and begin to fall outside each other's inhibitory surround at distance 30°.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.3758/s13421-020-01116-3>.

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