

How Working Memory Capacity Relates to Top-Down and Bottom-Up Components of the Trial-by-trial Modulation of the Simon Effect*

Rebecca B. Weldon¹, Eva Zita Patai², Myeong-Ho Sohn³, Jini Tae^{4†}

¹SUNY Polytechnic Institute, ²King's College London, ³The George Washington University,
⁴Gwangju Institute of Science and Technology

The conflict effect is typically smaller following incongruent than congruent trials, and this trial-by-trial modulation has been interpreted as evidence for increased top-down control for efficient selection of task-relevant information. An alternative explanation suggests that this modulation is due to bottom-up feature integration, the notion that stimulus and response features from one trial are automatically bound in an event file. Therefore, complete repetition or alternation of stimulus and response features across trials results in better performance than partial repetition of features, since the latter requires unbinding of the event file from the previous trial. In the present study, using the Simon task, we examined how working memory capacity (WMC) is related to the top-down and bottom-up components of the modulation of the conflict effect. We found that: 1) WMC was negatively correlated with the trial-by-trial Simon effect on partial repetition trials, the portion that reflects top-down control processing. 2) WMC was not associated with the Simon effect of complete repetitions and alternations, the portion that reflects bottom-up processing. 3) Medium and high WMC individuals may be using a different strategy than low WMC individuals. In combination, our findings lend insight into factors that may relate to the trial-by-trial modulation of the Simon effect. Implications for these findings are discussed.

Keywords: conflict adaptation, Simon task, cognitive control, working memory, individual difference

1차원고접수 21.02.05; 수정본접수: 21.04.05; 최종게재결정 21.04.08

Cognitive control is essential for making a well-reasoned decision in accordance with task-relevant goals in the face of distracting task-irrelevant stimuli. Cognitive control is often investigated using interference paradigms such as the Stroop task (Stroop, 1935), Simon task (Simon & Small, 1969), and flanker task (Eriksen & Eriksen, 1974).

These interference paradigms typically consist of

congruent and incongruent trials. For example, congruent trials in the Simon task require a spatial response to the target dimension (e.g., color) that matches the irrelevant spatial location of the stimulus (e.g., pressing a left key to respond to a green-colored stimulus that appears on the left side of the screen). Incongruent trials require a spatial response that does not match the spatial location of the stimulus (e.g., pressing a left key to respond to a

* This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2020S1A3A2A02103899).

† Corresponding author: Jini Tae, 123 Cheomdangwagi-ro, Buk-gu, Gwangju, E-mail: jini0930@gist.ac.kr

green-colored stimulus that appears on the right side of the screen). The presence of an incongruent stimulus induces conflict in information processing, resulting in increased reaction times and error rates, which presumably reflect the extra demand of cognitive control. Researchers often compute the "conflict effect" as the difference in performance on incongruent versus congruent trials.

While the conflict effect can be interpreted as evidence of top-down intervention to overcome the distractor-induced conflict and therefore increase the selective processing of the target, it has also prompted questions regarding the implementation of cognitive control. For example, how does one know when to exert a greater amount of cognitive control? In their conflict-monitoring model, Botvinick, Braver, Barch, Carter, and Cohen (2001) proposed a monitoring mechanism that is devoted to detecting the necessity to increase the level of top-down control. According to the conflict-monitoring model, cognitive control is recruited when there are environmental demands to deal with the costly effects of distractors.

The conflict-monitoring model gathers supporting evidence from the result that the conflict effect can be contextually modulated. For example, the conflict effect is smaller in a block of predominantly incongruent trials than in a predominantly congruent block (Logan & Zbrodoff, 1979), presumably because participants have increased the level of top-down control in the former (Botvinick et al., 2001). Also, the conflict effect is sequentially modulated by the congruency of the previous trial (Gratton, Coles, & Donchin, 1992). Specifically, an interference task involves four possible trial-to-trial congruency sequences: congruent-congruent (CC), congruent-incongruent (CI), incongruent-congruent (IC), and incongruent-incongruent (II). The conflict effect following an incongruent trial, the difference between II and IC, is smaller than the same effect following a congruent trial, the difference between CI and CC. This trial-by-trial modulation takes place presumably because the conflict signal detected in the previous trial has increased the level of top-down control (Botvinick et al.,

2001). The trial-by-trial modulation, therefore, has been interpreted as the detection of a conflict signal that heightens the level of top-down control, resulting in increased selectivity of the task-relevant information (or increased suppression of task-irrelevant information; Kerns et al., 2004; Stürmer, Leuthold, Soetens, Schrter, & Sommer, 2002; for a review, see Braem et al., 2019).

While the contextual modulation of the conflict effect has been interpreted as the result of dynamic regulation of top-down control processes, an alternative account argues that such modulation, especially the trial-by-trial modulation, reflects bottom-up feature integration. Mayr, Awh, and Laurey (2003), for example, used the classic flanker task to examine the effect of stimulus repetition on the trial-by-trial modulation. The authors demonstrated that the sequential modulation was only observed under conditions of complete target and distractor repetitions, and could not be observed when such repetitions were eliminated altogether. Hommel, Proctor, and Vu (2004) proposed a "feature integration" account, suggesting that the cognitive system creates an "event file" that binds stimulus and response features, be it relevant or irrelevant to the current task. As a result of feature binding on one trial, three kinds of transitions can occur in the next: complete repetition of every stimulus and response feature; complete alternation of stimulus and response features—therefore, no "carryover" from the previous trial; or partial repetition of some stimulus and response features. Hommel et al. (2004) argue that complete repetition trials can benefit from feature priming and complete alternation trials simply require the binding of new features. In contrast, partial repetition trials require un-binding of the previous event file and re-binding the partially repeated features with new features. Hommel et al. (2004) demonstrated that participants were significantly slower at performing the partial repetition trials, and that the trial-by-trial modulation disappeared when complete repetition and alternation trials were removed. This finding has since been replicated and extended; there are many who argue that the trial-by-trial modulation observed in interference paradigms like the Simon task cannot be attributed to

a top-down control mechanism triggered by conflict monitoring (Hommel et al., 2004; Mayr et al., 2003; Schmidt, 2013; Schmidt & De Houwer, 2011).

According to the feature integration account, the trial-by-trial modulation is achieved by the binding cost. The feature integration account notes that, for example, with a two-choice Simon task, which has been adopted by a majority of the studies using the task (however, see Akçay & Hazeltine, 2011 for exceptions), the CC and II sequences involve only complete repetition and alternation of features, while the CI and IC sequences involve only partial repetition. Therefore, the feature integration account suggests that CI and IC trials are subjected to un-binding and re-binding processes, resulting in slower reaction times. In examining the effect of feature integration in the trial-by-trial modulation, Wendt, Kluwe, and Peters (2006) predicted that, if the trial-by-trial modulation of the Simon effect is due to active modulation of top-down control, then an experimental manipulation that further increases the control level should reduce the Simon effect to the extent of complete elimination. In their experiments, they increased the number of colors associated with a particular spatial response as a manipulation that should reduce the Simon effect. Instead of eliminating the Simon effect, however, this manipulation resulted in a reverse Simon effect, a result that cannot be explained by the conflict-induced increment of a control level. Rather, their results showed a consistent cost of partial repetition of irrelevant stimulus location and the response location in comparison with the complete repetition and the complete alternation of these features. For example, both congruent and incongruent trials showed similar amounts of partial repetition cost. Together with other studies (Hommel et al., 2004; Mayr et al., 2003), Wendt et al.'s results are in line with the theory that bottom-up processes contribute to the trial-by-trial modulation.

There has been some work devoted to feature binding and working memory (Ecker, Maybery, & Zimmer, 2013; Zokaei, Heider, & Husain, 2014), and there has been some research examining the individual differences in conflict adaptation effects (Keye, Wilhelm, Oberauer, &

Sturmer, 2014). However, to our knowledge, no one has examined how individual differences in working memory capacity (WMC) relate to bottom-up and top-down contributions to the trial-by-trial modulation. The purpose of the current paper is to examine the relationship between the different components of the trial-by-trial modulation in the Simon task and WMC. We use WMC as an individual difference measure of top-down control capacity, because it has been repeatedly demonstrated that high WMC individuals show better task performance in laboratory tasks that require inhibiting the automatic response. For example, in a dichotic listening task, in which participants are instructed to pay attention to information presented to one ear (the attended channel) while ignoring information presented to the other ear (the unattended channel), high WMC individuals were less likely to hear their name presented to the unattended channel, suggesting that WMC is associated with the ability to filter out distractors (Colflesh & Conway, 2007). Using a modified Stroop task, Kane and Engle (2003) showed that, relative to low WMC individuals, high WMC made fewer errors on incongruent trials in blocks that consisted of mostly congruent trials. Kane, Bleckley, Conway, and Engle (2001) used an antisaccade task, in which participants had to either make an eye movement towards a cue (prosaccade task) or make an eye movement in the opposite direction of a cue (antisaccade task). There was no difference in performance on the prosaccade trials as a function of WMC, but on antisaccade trials, high WMC individuals were faster and made fewer errors and than low WMC individuals.

Our approach is guided by the notion that the part of the trial-by-trial modulation that can be attributed to top-down cognitive control should reflect a factor that is related to top-down control, namely WMC. However, the part of the trial-by-trial modulation that can be attributed to bottom-up processes will not be related to WMC. Our rationale is consistent with findings that top-down control processes help to resolve memory-retrieval conflict (binding and unbinding processes that lengthen response time). Other researchers

have dissociated the importance of top-down versus bottom-up control in memory retrieval. Neuroimaging studies have identified relevant neural mechanisms of this process. Tomita, Ohbayashi, Nakahara, Hasegawa, and Miyashita (1999) found that a top-down signal from the prefrontal cortex is sent to the inferior temporal cortex prior to memory retrieval in monkeys. More recent research has identified the neural substrates of inhibiting competing memories during memory retrieval. The lateral prefrontal cortex sends a top-down signal to suppress competing memories in posterior areas, which facilitates adaptive forgetting (Wimber, Alink, Charest, Kriegeskorte, & Anderson, 2015).

In this study, we investigate WMC effects on trial-to-trial modulation on a Simon task. We hypothesized that, for low WMC capacity individuals, the trial-by-trial modulation reflects more of a bottom-up factor, which will be reflected in the similar amount of partial repetition cost regardless of the congruency. In contrast, for high WMC individuals, the trial-by-trial modulation should reflect more of a top-down factor, which will be reflected in the reduced Simon effect for the partial binding trials. That is, all individuals will be equally susceptible to the effects of stimulus-response binding, since feature integration is largely an automatic process. However, we hypothesized that WMC differences would emerge in the sequential Simon effect if this effect at least partly reflects top-down regulation of cognitive control.

We adopted a four-color version of the Simon task (two colors assigned to each response key) to allow for the investigation of the Simon effect for partial repetition trials separately from the same effect for complete repetitions or alternations. We used the full range of WMC in regression and ANOVA analyses to examine whether there is a relationship between the bottom-up component of the Simon effect (i.e., the effect for only complete repetitions and alternations) and WMC, as well as the top-down component of the Simon effect (i.e., the effect for only partial repetition trials) and WMC. We predict that WMC will have no effect on the bottom-up component of the Simon effect, but that WMC will be

substantially related to the top-down component.

Method

Participants

We recruited 136 undergraduate students from the George Washington university for research participation credit. This study was approved by the George Washington University Institutional Research Board.

Procedure

Participants completed two complex working memory span tasks and the Simon task, and the order of administration was counterbalanced across participants. The automated span tasks consisted of Operation span (Ospan) and Reading span (Rspan) (Redick et al., 2012; Unsworth, Heitz, Schrock, & Engle, 2005). Participants were required to verify math problems (for Ospan) or sentences (Rspan) while maintaining to-be-remembered (TBR) letters in WM. For example, each trial began with the presentation of a TBR letter, followed by either a math problem or a sentence to verify, depending on the span task at hand. This sequence was repeated for a certain number of times depending on the set size. There were five set sizes (3, 4, 5, 6, 7), each of which was presented three times at random order. The participant received an instruction on the screen that encouraged maintenance of math or reading accuracy at or above 85% for all trials. In order to prevent rehearsal of letters, if the participant did not verify the math problem or sentence in the allotted amount of time, it was counted as an error. Participants received constant feedback based on performance (see Unsworth et al., 2005, for procedural details). Both span tasks are comprised of a total of 75 letters and 75 math problems or sentences. The individual WMC score was calculated only from those sequences from which the participant accurately recalled all of the TBR letters in the exact order of presentation while correctly verifying the problems. WMC is the sum of all perfectly recalled sets of letters. For example, if correctly recalled items were 4 letters in a set size of 4, and 3 letters in a set size of 5, the span score

would be 4 (4+0) (Unsworth et al., 2005). Therefore, the WMC score can range from 0 to 75.

Participants also performed the Simon task prior to or following completion of the span tasks. In this version of the Simon task, participants were instructed to respond to the color of a small circle (Verdana font, size 36, bold) that appeared either to the left or right of the center of the screen (25% or 75% in reference to the left-hand side of the screen). Participants responded by pressing the left key ('S') if the stimulus was green or yellow and the right key ('L') if the stimulus was red or blue. Each trial began with a 500 ms warning signal, followed by the Simon task stimulus, presented for a maximum duration of 1000 ms or until the participant responded. Feedback was provided for both speed and accuracy for 1000 ms. Participants completed a total of two blocks (180 trials/block). In each block, 50% of the trials were congruent (stimulus response matched the irrelevant stimulus location) and 50% were incongruent (stimulus response did not match the stimulus location). Stimulus color, location, and congruency were randomized across trials. Stimuli were delivered in E-Prime on Dell computers with 17" monitors.

Results

We used the following exclusion criteria: overall reaction time, Simon effect for complete repetitions or alternations, and Simon effect for partial repetition trials. Five outliers were excluded from all analyses: two based on a mean reaction time falling outside of 2.5 standard deviations

from the mean and three based on a Simon effect on the partial repetition trials falling outside of 2.5 standard deviations from the mean. Including these outliers in the analyses does not change the results.

The WMC score was calculated by computing the mean of the Ospan and Rspan scores. The correlation between Rspan scores and Ospan scores was $r = .589$, $p < .001$. As a general description, overall mean accuracy on the Simon task was 93%, with a range from 78 – 99%. The higher the WMC, the greater the mean accuracy, $r = 0.18$, $p < .05$. Overall mean reaction time on accurate trials was 511 ms, ranging from 368 to 661 ms. There was no correlation between WMC and mean reaction time, $r = -0.03$, $p = .78$. For the principal analyses, we conducted linear regression and ANOVA analyses with the full range of WMC scores to examine the WMC effect on both the Simon effect for complete repetitions and alternations and the Simon effect for partial repetitions.

Regressions

We used separate components of the Simon effect as measures of top-down control and binding, and examined these measures as a function of WMC. We examined the effect of WMC score on the overall Simon effect, which decreased as WMC increased, $\beta = -.20$, $t(130) = -2.29$, $p < .05$. We assessed two different components of the Simon effect. WMC was not associated with the Simon effect for only complete repetition and alternation trials, $\beta = -.13$, $t(130) = -1.51$, $p = .13$ (see Figure 1a). We then examined the

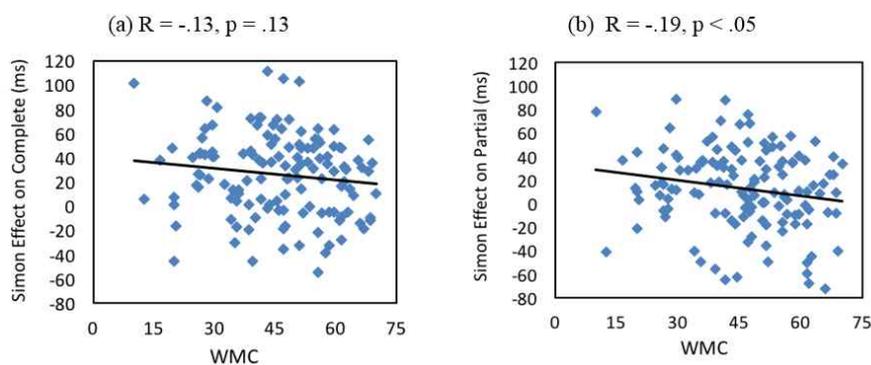


Figure 1. (a) The Simon effect for complete repetitions and alternations as a function of WMC ($n=131$).

(b) The Simon effect for partial repetitions as a function of WMC ($n=131$).

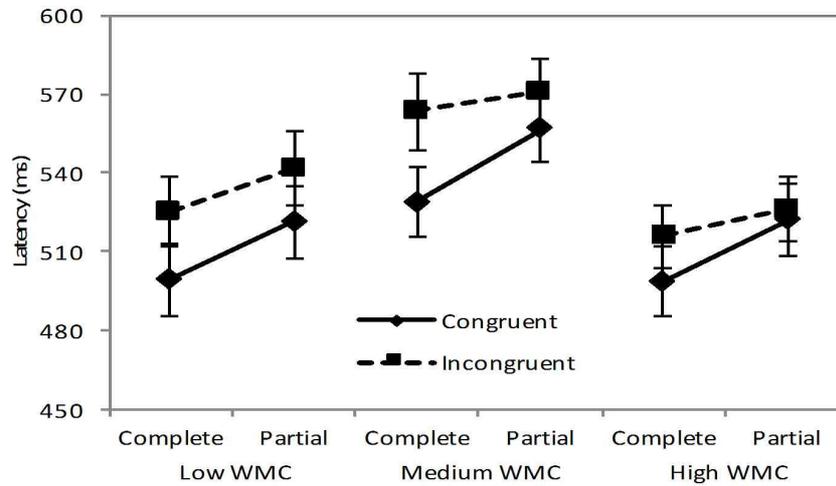


Figure 2. Mean latency as a function of binding type (Complete = complete repetitions and alternations; Partial = partial repetitions), current congruency, and WMC group.

effect of WMC on the Simon effect for partial repetition trials (trials in which either response or location repeats and the other switches). The partial repetition Simon effect decreased as WMC increased, $\beta = -.19$, $t(130) = -2.13$, $p < .05$ (see Figure 1b). These regressions (from Figure 1a and Figure 1b) trend in the direction consistent with our hypotheses, but are not significantly different from one another, z -score = .57, $p = .57$. Therefore, we ran ANOVA analyses to further our understanding of WMC group differences in the sequential Simon effect.

ANOVA: feature integration effect

To further examine the WMC group difference, we ran ANOVA analyses on latency and accuracy. We grouped participants into thirds based on average span scores, and contrasted the lowest third ($n = 44$, WMC range 10–40.5, mean WMC = 29.78) with the middle third ($n = 44$, WMC range 41–53, mean WMC = 47) and the highest third ($n = 43$, WMC range 53.5–70, mean WMC = 60.83).

Accuracy and latency for all conditions is presented in Table 1. We ran a latency ANOVA to examine the effects of binding on the conflict effect. Following the analysis of Wendt et al. (2006), we defined the binding transition in terms of the repetition of the irrelevant stimulus feature (location) and the response feature (see Figure 2). We ran a 3 (WMC group: low, medium, high) \times 2 (binding type: complete repetition or switch,

partial repetition) \times 2 (current congruency: congruent, incongruent) ANOVA. There was a marginal main effect of WMC group, $F(2, 128) = 2.63$, $p = .08$, $\eta^2 = .04$. All participants were significantly faster at congruent trials versus incongruent trials, $F(1, 128) = 69.89$, $p < .001$, $\eta^2 = .35$. Partial repetitions took longer than complete repetitions or alternations, $F(1, 128) = 69.33$, $p < .001$, $\eta^2 = .35$. Furthermore, binding type interacted with current congruency, $F(1, 128) = 13.43$, $p < .001$, $\eta^2 = .10$. WMC group interacted with current congruency, $F(2, 128) = 3.59$, $p < .05$, $\eta^2 = .05$. The Simon effects for the low WMC (23 ms) and medium WMC (25 ms) groups did not differ, $t(86) = -.26$, $p = .80$. However, the Simon effect for the high WMC group (10 ms) was significantly smaller than low and medium groups, $t(85) = 2.27$, $p < .05$ and $t(85) = 2.50$, $p < .05$, respectively. The congruency effect for complete repetitions and alternations (26 ms) was significantly greater than the congruency effect for partial repetitions (13 ms), $t(130) = 3.65$, $p < .001$, but this interaction was not modulated by WMC, $F(2, 128) = 1.56$, $p = .21$, $\eta^2 = .02$.

We initially predicted that lower WMC individuals should show an equal amount of partial binding cost regardless of the binding type, while higher WMC individuals should show a reduced Simon effect for partial repetition trials, the type of trial that requires top-down controlled processing. Although the three-way interaction was not significant, we further examined

WMC groups in separate latency ANOVAs to investigate whether the Simon effect was different depending on the trial-by-trial feature binding. First in the low WMC group, the interaction between binding type and current congruency was not significant, $F(1, 43) = .73, p = .40, \eta^2 = .02$. In the low WMC group, the Simon effects for both the complete repetition or alternation trials (25 ms) and the partial repetition trials (20 ms) were significant, $t(43) = 5.00, p < .001$, and $t(43) = 4.22, p < .001$, respectively, and they were not significantly different from each other, $p > .40$. In the medium WMC group, however, the interaction between binding type and current congruency was significant, $F(1, 43) = 9.96, p < .005, \eta^2 = .19$. In the medium group, the Simon effects for both the complete repetition or alternation trials (34 ms) and the partial repetition trials (14 ms) were significant, $t(43) = 6.61, p < .001$, and $t(43) = 2.60, p < .05$, respectively, and they were significantly different from each other, $t(43) = 3.14, p < .005$. Also, in the high WMC group, the interaction between binding type and current congruency was significant, $F(1, 42) = 5.48, p < .05, \eta^2 = .12$. In the high WMC group, the Simon effect for the complete repetition or alternation trials (17 ms) was significant, $t(42) = 3.68, p < .005$, and this effect was greater than the Simon effect for the partial repetition trials (4 ms), $t(42) = 2.36, p < .05$.

Next, for accuracy result, there was no main effect of WMC group, $F(2, 128) = 1.74, p = .18, \eta^2 = .03$. All

participants were significantly more accurate for congruent trials versus incongruent trials, $F(1, 128) = 17.36, p < .001, \eta^2 = .12$. Participants were not as accurate for partial repetitions as for complete repetitions or alternations, $F(1, 128) = 54.91, p < .001, \eta^2 = .30$. Binding type did not interact with current congruency, $F(1, 128) = .09, p = .76, \eta^2 = .001$. There were no other main effects or interactions.

General discussion

The present experiment investigated two main questions: (1) We aimed to elucidate whether the trial-by-trial modulation in the Simon task reflects bottom-up feature integration processes or top-down control processes. (2) We set out to examine how WMC differentially relates to these two components of the trial-by-trial modulation. We predicted that WMC would not be associated with the bottom-up effects of feature integration, while WMC would be related to the part of the Simon effect that reflects top-down control processing.

First, we analyzed the trial-by-trial Simon effect as a function of WMC (see Figure 1a and Figure 1b). We utilized all participants and examined measures of top-down and bottom-up processing with WMC as the independent variable. Most importantly, as WMC increased, the partial repetition Simon effect (the

Table 1. Mean Accuracy and Latency With Standard Deviation in Parentheses for Each Working Memory Capacity Group by Binding Type and Current Congruency

	Latency (ms)				Accuracy			
	Complete rep or sw		Partial rep		Complete rep or sw		Partial rep	
	Con	Inc	Con	Inc	Con	Inc	Con	Inc
Low WMC (N=44)	449 (92)	525 (88)	521 (92)	542 (93)	0.93 (0.07)	0.96 (0.05)	0.90 (0.06)	0.92 (0.05)
Medium WMC (N=44)	529 (90)	563 (95)	557 (85)	570 (87)	0.95 (0.05)	0.95 (0.04)	0.92 (0.06)	0.93 (0.04)
High WMC (N=43)	499 (87)	516 (80)	522 (89)	526 (81)	0.95 (0.05)	0.96 (0.04)	0.93 (0.06)	0.93 (0.05)

Note. WMC = working memory capacity, rep = repetition, sw = switch, Con = congruent, Inc = incongruent.

component of the Simon effect that cannot be attributed to bottom-up feature integration) decreased. This may be evidence for different control adjustment strategies utilized in individuals of varying WMC. Perhaps partial repetition trials increased arousal and cognitive control adjustments in higher WMC individuals, resulting in reduced conflict effects, supporting claims that both feature binding and conflict-triggered adjustments in control likely play a role in sequential modulation of the Simon effect (Verguts & Notebaert, 2009). This signifies that WMC is important for exerting top-down control in a more difficult type of trial, when stimulus and response links from the previous trial need to be unbound. We found that the Simon effect for the complete repetition and alternation trials, the portion of the Simon effect that can be attributed to bottom-up feature integration, was not related to WMC. However, it should be noted that some authors suggest that feature integration and binding are capacity-limited and controlled processes (e.g., Treisman, 1988).

It is important to note that we did not find a three-way interaction between binding type (complete or partial), current congruency (congruent, incongruent), and WMC group (low, medium, high). Arguably, a limitation of the current study may be that the Simon task was not sensitive enough to observe differences in performance on complete versus partial binding trials as a function of WMC. Nonetheless, assigning participants to low, medium, and high WMC groups allowed us to examine group differences in complete and partial binding Simon effects (see Figure 2). Two important findings stand out from binding type \times current congruency analyses conducted separately for each WMC group. First, the interaction between binding type and current congruency was significant for the medium and high WMC groups, but not for the low WMC group. Second, when we examined this result in more detail, we found that in the medium WMC group, the Simon effects for both the complete repetition or alternation trials (34 ms) and the partial repetition trials (14 ms) were significant, and were significantly different from each other. However, in the high WMC group, the Simon effect for the complete repetition or alternation trials (17 ms) was significant, but

the Simon effect for the partial repetition trials was not significant (4 ms). Therefore, given the observed differences in the binding by Simon effect interaction across the three different WMC groups, there is some evidence to suggest that with an increase in WMC, different strategies emerge (see Figure 2).

We used two WMC groups to examine WMC differences in strategies. When comparing low and medium WMC groups, we found that there was a marginal three-way interaction between WMC group, binding type, and current congruency, suggesting that low and medium WMC groups may be using different strategies. The low WMC group was also faster than the medium WMC group. One explanation for these findings is that there may be a shift from bottom-up to top-down control strategies from low to medium WMC. When medium and high WMC groups were included in the analysis, the three-way interaction was not significant. Further, high WMC were significantly faster than medium WMC. The lack of a three-way interaction suggests that high WMC and medium WMC individuals may use the same top-down control strategy, but perhaps high WMC are doing so more efficiently.

Our results fit well within the context of the current literature. We found that there are not WMC differences in the congruency-sequence effect for trials that involve mostly bottom-up processing, which aligns with results reported by Keye et al. (2014) and Meier and Kane (2013), who found that WMC did not relate to trial-to-trial adjustments on interference tasks. However, our analyses allowed us to observe that the partial repetition Simon effect was modulated by WMC. That is, participants with higher WMC scores had reduced Simon effects for partial repetition trials. The various permutations of stimulus and response repetitions in the present study may have increased the difficulty of the Simon task, and thus, WMC differences in trial-by-trial modulations were more likely to emerge for the trials that required more top-down control.

Furthermore, it is important to note that these results cannot be attributed to the scaling effect of reaction time (i.e., the faster the reaction time is, the smaller the

observed effects). If reaction time was in fact driving the relationship between the partial repetition Simon effect and WMC, then reaction time should have also resulted in similar effects in the other regressions in which WMC was included as the independent variable. It is also the case that overall mean reaction time was not correlated with WMC. Therefore, we can conclude that reaction time did not scale down the size of the conflict effects in higher WMC individuals. Our results are consistent with findings from previous studies that suggest that performance on the Simon task reflects bottom-up feature binding effects (e.g., Wendt et al., 2006). However, we do find evidence of top-down control processing, suggesting that both repetition priming and top-down control processes contribute to interference effects, as has been previously suggested (e.g., Akçay & Hazeltine, 2007; Davelaar & Stevens, 2009; Kim & Cho, 2014; Verguts & Notebaert, 2009).

The current study focused on individual differences in WMC, but there are other individual difference variables that would potentially relate to the trial-by-trial modulation of the Simon effect. Previous research has shown that self-reported impulsivity predicts performance on several executive control tasks (Enticott, O'Gloff, & Bradshaw, 2006). Enticott et al. (2006) found that participants higher in motor impulsiveness, non-planning impulsiveness, attentional impulsiveness, and overall impulsiveness took longer to resolve Stroop conflict. Participants higher in non-planning impulsiveness showed more response inhibition errors on an Inhibitory Reach Task, in which participants had to withhold an automatic reaching response to a distractor (Enticott et al., 2006). In a study conducted by Lieberman (2000), the researcher found a relationship between extraversion and working memory, in that extraverts performed better on a working memory task than introverts. Other research studies have examined the effects of reward and punishment on cognitive control adjustments (e.g., Braem, Duthoo, & Notebaert, 2013), often using self-reported BAS/BIS (behavioral approach system, behavioral inhibition system) scores as measures of sensitivity to reward and sensitivity to punishment, respectively (Carver

& White, 1994). In the context of the current research study, further research is needed to investigate how other individual differences (e.g., impulsivity, extraversion, sensitivity to reward, and sensitivity to punishment) relate to repetition priming versus top-down control processes on the Simon task.

In the current paper, we have provided further evidence for feature binding in response to conflict, yet also some support for top-down control contributions to the sequential Simon effect. We found that WMC was related to the appropriate adjustment of the level of control, as evidenced by the reduced partial repetition Simon effect observed in high WMC individuals. This study also conveys information about the nature of working memory capacity as it relates to top-down control, supporting findings that suggest that WMC relates to the maintenance and adjustment of top-down control (Colflesh & Conway, 2007; Kane et al., 2001; Kane & Engle, 2003; Meier & Kane, 2013; Weldon, Mushlin, Kim, & Sohn, 2013). Furthermore, these findings relate to a growing body of literature on working memory updating (Ecker, Oberauer, & Lewandowsky, 2014).

In the context of the ongoing debate in cognitive psychology regarding the nature of interference effects, it is both interesting and fundamental that we understand which processes are automatic and which processes are controlled. Therefore, it is crucial that we examine findings from commonly used interference paradigms (e.g., Simon) to gain insight into human information processing. The present study suggests that both bottom-up and top-down control processes contribute to the Simon effect, and that the proportion of the Simon effect that cannot be attributed to stimulus-response binding may be related to working memory capacity.

References

- Akçay, Ç., & Hazeltine, E. (2007). Conflict monitoring and feature overlap: Two sources of sequential modulations. *Psychonomic Bulletin & Review*, *14*(4), 742-748.
- Akçay, Ç., & Hazeltine, E. (2011). Domain-specific conflict

- adaptation without feature repetitions. *Psychonomic Bulletin & Review*, 18(3), 505-511.
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, 108, 624-652.
- Braem, S., Bugg, J. M., Schmidt, J. R., Crump, M. J., Weissman, D. H., Notebaert, W., & Egner, T. (2019). Measuring adaptive control in conflict tasks. *Trends in Cognitive Sciences*, 23(9), 769-783.
- Braem, S., Duthoo, W., & Notebaert, W. (2013). Punishment sensitivity predicts the impact of punishment on cognitive control. *PLoS One*, 8(9), e74106.
- Carver, C. S., & White, T. L. (1994). Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: the BIS/BAS scales. *Journal of personality and social psychology*, 67(2), 319-333.
- Colflesh, G. J. H., & Conway, A. R. A. (2007). Individual differences in working memory capacity and divided attention in dichotic listening. *Psychonomic Bulletin & Review*, 14, 699-703.
- Davelaar, E. J. & Stevens, J. (2009). Sequential dependencies in the Eriksen flanker task: A direct comparison of two competing accounts. *Psychonomic Bulletin & Review*, 16(1), 121-126.
- Ecker, U. K., Lewandowsky, S., & Oberauer, K. (2014). Removal of information from working memory: A specific updating process. *Journal of Memory and Language*, 74, 77-90.
- Ecker, U. K., Maybery, M., & Zimmer, H. D. (2013). Binding of intrinsic and extrinsic features in working memory. *Journal of Experimental Psychology: General*, 142(1), 218-234.
- Enticott, P. G., O'Gloff, J. R., & Bradshaw, J. L. (2006). Associations between laboratory measures of executive inhibitory control and self-reported impulsivity. *Personality and Individual Differences*, 41(2), 285-294.
- Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perceptual Psychophysics*, 16, 143-149.
- Gratton, G., Coles, M. G. H., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General*, 121, 480-506.
- Hommel, B., Proctor, R. W., & Vu, K.-P. L. (2004). A feature-integration account of sequential effects in the Simon task. *Psychological Research*, 68, 1-17.
- Kane, M. J., Bleckley, M. K., Conway, A. R., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, 130(2), 169-183.
- Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, 132(1), 47-70.
- Kerns, J. G., Cohen, J. D., MacDonald, III, A. W., Cho, R. Y., Stenger, V. A., & Carter, C. C. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science*, 303, 1023-1026.
- Keye, D., Wilhelm, O., Oberauer, K., & Stürmer, B. (2013). Individual differences in response conflict adaptations. *Frontiers in Psychology*, 4, 947.
- Kim, S., & Cho, Y. S. (2014). Congruency sequence effect without feature integration and contingency learning. *Acta Psychologica*, 149, 60-68.
- Lieberman, M. D. (2000). Introversion and working memory: Central executive differences. *Personality and Individual Differences*, 28(3), 479-486.
- Logan, G.D. & Zbrodoff, N. J. (1979). When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory and Cognition*, 7, 166-174.
- Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience*, 6, 450-452.
- Meier, M. E., & Kane, M. J. (2013). Working memory capacity and Stroop interference: global versus local indices of executive control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39(3), 748-759.
- Redick, T. S., Broadway, J. M., Meier, M. E., Kuriakose, P. S., Unsworth, N., Kane, M. J., & Engle, R. W. (2012). Measuring working memory capacity with automated complex span tasks. *European Journal of Psychological Assessment*, 28(3), 164-171.
- Schmidt, J. R. (2013). Questioning conflict adaptation: proportion congruent and Gratton effects reconsidered. *Psychonomic Bulletin & Review*, 20(4), 615-630.
- Schmidt, J. R., & De Houwer, J. (2011). Now you see it, now

- you don't: Controlling for contingencies and stimulus repetitions eliminates the Gratton effect. *Acta Psychologica*, *138*(1), 176-186.
- Simon, J. R., & Small, A. M. (1969). Processing auditory information: Interference from an irrelevant cue. *Journal of Applied Psychology*, *53*, 433-435.
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *121*, 15-23.
- Stürmer, B., Leuthold, H., Soetens, E., Schroter, H., & Sommer, W. (2002). Control over location-based response activation in the Simon task: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(6), 1345-1363.
- Tomita, H., Ohbayashi, M., Nakahara, K., Hasegawa, I., & Miyashita, Y. (1999). Top-down signal from prefrontal cortex in executive control of memory retrieval. *Nature*, *401*(6754), 699.
- Treisman, A. (1988). Features and objects: The fourteenth Bartlett memorial lecture. *The Quarterly Journal of Experimental Psychology*, *40*(2), 201-237.
- Unsworth, N., Heitz, R. P., Schrock, J. C., Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods*, *37*, 498-505.
- Verguts, T., & Notebaert, W. (2009). Adaptation by binding: a learning account of cognitive control. *Trends in Cognitive Sciences*, *13*(6), 252-257.
- Weldon, R. B., Mushlin, H., Kim, B., & Sohn, M. H. (2013). The effect of working memory capacity on conflict monitoring. *Acta Psychologica*, *142*(1), 6-14.
- Wendt, M., Kluwe, R. H., & Peters, A. (2006). Sequential modulations of interference evoked by processing task-irrelevant stimulus features. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(3), 644-667.
- Wimber, M., Alink, A., Charest, I., Kriegeskorte, N., & Anderson, M. C. (2015). Retrieval induces adaptive forgetting of competing memories via cortical pattern suppression. *Nature Neuroscience*, *18*(4), 582-589.
- Zokaei, N., Heider, M., & Husain, M. (2014). Attention is required for maintenance of feature binding in visual working memory. *The Quarterly Journal of Experimental Psychology*, *67*(6), 1191-1213.

작업 기억 용량에 따른 사이먼 과제에서 갈등 순응 방식의 차이

Rebecca B. Weldon¹, Eva Zita Patai², 손명호³, 태진이⁴

¹SUNY Polytechnic Institute, ²King's College London, ³조지워싱턴대학교 심리학과, ⁴광주과학기술원

갈등 순응 효과란 이전 시행에서 불일치한 자극을 처리한 후의 간섭 효과(예: 불일치 조건과 일치 조건의 차이)가 일치한 자극을 처리한 조건에 비해 작아지는 것으로, 연구자들은 이러한 현상이 일어난 이유를 과제와 관련 없는 자극은 무시하고 관련 있는 정보만을 선택적으로 처리하는 하향적 통제 방식에 기인한 것이라 설명한다. 일부 연구자들은 갈등 순응 효과가 나타나는 이유가 하향적 통제 방식에 의한 것이 아니라 자극-반응 연합의 반복 점화 효과에 의한 것이라 설명한다. 본 연구에서는 두 개의 상반된 갈등 순응 방식이 개인의 작업 기억 용량에 따라 다르게 작용하는지를 사이먼 과제를 통해 확인하고자 한다. 개인의 작업 기억 용량은 연산폭 과제와 읽기폭 과제를 사용하여 측정했고, 이 과제가 끝나면 참가자들은 화면의 왼쪽 혹은 오른쪽에 제시되는 원의 색깔을 보고 원의 색깔이 초록색이나 노란색이면 왼쪽 버튼을 빨간색이나 파란색이면 오른쪽 버튼을 누르라는 지시를 받았다. 실험 결과, 작업 기억 용량과 자극-반응 연합의 반복 점화 효과 간에는 부적 상관관계가 나타났고, 하향적 통제 방식을 확인할 수 있는 조건에서는 두 변인 간의 유의미한 상관 효과가 관찰되지 않았다. 이와 더불어 분산 분석 결과는 낮은 작업 기억 용량을 가진 참가자들이 중-고용량 집단과는 다른 갈등 순응 전략을 사용하고 있음을 보여주었다. 본 연구는 인지 통제 능력과 작업 기억이 밀접하게 상호 작용하고 있음을 보여주었고, 나아가 작업 기억 용량에 따라 상반된 갈등 순응 전략을 사용하고 있음을 확인했다는 점에서 의미가 있다.

주제어: 갈등 순응, 사이먼 과제, 인지 통제, 작업 기억, 개인차