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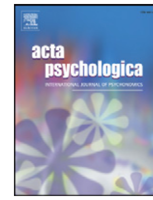

The effect of working memory capacity on conflict monitoring☆

Rebecca B. Weldon [a,*], Harry Mushlin [b], Bia Kim [c], Myeong-Ho Sohn [a]

[a] Department of Psychology, The George Washington University, 2125 G. St., N.W. Washington, DC 20052, USA
[b] NYU School of Medicine, 550 1st Avenue, New York, NY 10016, USA
[c] Department of Psychology, Pusan National University, Busan 609-735, Republic of Korea

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ABSTRACT

The conflict adaptation effect, a reduced interference effect upon the detection of a conflict signal (e.g., following an incongruent trial), has been interpreted as evidence for active regulation of top-down cognitive control. We hypothesized that the extent of conflict adaptation should be related to individuals' working memory capacity (WMC), which has been repeatedly demonstrated to reflect the level of cognitive control. Using the Simon task, in Experiment 1, we quantified the conflict adaptation ratio (CAR) transiently as the ratio of the conflict effect following an incongruent trial to the conflict effect following a congruent trial, controlling for the reaction time that often correlates with WMC. We observed that the CAR varied from highly negative with low WMC scores to near-zero with high WMC scores. This result suggests that high WMC individuals, when detecting conflict, adjust the level of cognitive control optimally so that their performance is less susceptible to the presence of a distractor. In Experiment 2, we quantified the CAR in a sustained manner as the ratio of the conflict effect from predominantly incongruent blocks to the conflict effect from predominantly congruent blocks. Again, the CAR varied from negative to zero as WMC increased. These results suggest that WMC may reflect, in addition to the ability to maintain a level of control, the ability to adjust the level of control appropriately to the contextual demands.

1. Introduction

Individuals differ in terms of working memory capacity (WMC), the amount of information that one can maintain and update while simultaneously engaging in a secondary task. Individual differences in WMC have been consistently correlated with performance in a variety of cognitive tasks (Colflesh & Conway, 2007; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2003). For example, higher WMC reflects better ability to focus attention (Colflesh & Conway, 2007; Kane & Engle, 2003), better ability to filter out distractors (Vogel, McCullough, & Machizawa, 2005), and better ability to maintain task goals (McVay & Kane, 2009). The implication of these results is that WMC may directly reflect the ability to exert cognitive control. Alternatively, the present study explores the possibility that WMC may also contribute to cognitive control via conflict monitoring, which collectively refers to cognitive processes devoted to the detection of the environmental demands to increase the level of cognitive control. In other words, we propose that WMC differences may be related to the ability to adjust the level of top-down control adaptively to the conflict signal.

Interestingly, the effect of WMC emerges only when the task at hand requires top-down intervention, but not when the task only taxes bottom-up processes. For example, WMC is correlated with antisaccadic eye-movement in which the prepotent response towards the cued location must be inhibited, but not with prosaccadic eye-movement (Kane et al., 2001). WMC is also correlated with performance on a visual search task for a conjunctive target (e.g., when two features need to be combined in a conscious, effortful manner) but not for a feature target (e.g., when the automatic encoding of a feature is sufficient) (Vogel, Woodman, & Luck, 2001). Furthermore, individual differences in performance on the Stroop task arise when the trials are predominantly congruent, therefore requiring active maintenance of a task goal to respond to occasional incongruent trials (Kane & Engle, 2003; Redick & Engle, 2006). When trials are predominantly incongruent, even low WMC individuals can maintain the appropriate level of control throughout the trials. Therefore, these results suggest that the WMC difference may lie in the ability to flexibly adjust the level of control in response to task demands, in addition to the ability to maintain the level of control in a stable manner.

The question of when to exert top-down control has prompted yet another field of research, conflict monitoring, which in the current paper refers to a collection of processes devoted to detecting a need for greater cognitive control. The idea of conflict monitoring was proposed based on the assumption that one should flexibly adjust the level of top-down control in response to the environmental demands that vary from one moment to another. The conflict monitoring

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* Corresponding author. Tel.: +1 202 994 7846(Work).
E-mail address: rweldon@gwmail.gwu.edu (R.B. Weldon).

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process is the mechanism that evaluates the environmental demand for cognitive control and produces a signal to increase the level of control when the demand is substantially high (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Gratton, Coles, & Donchin, 1992).

Most of the evidence for the conflict monitoring process comes from research that utilizes an interference paradigm. For example, in a Stroop paradigm, a stimulus consists of a target (e.g., color of ink) and a distractor (e.g., printed word). The distractor may designate either a congruent response (e.g., word "green" printed in green ink) or an incongruent, conflicting response (e.g., word "red" printed in green ink) in relation to the response associated with the target. The typical result is that the latency associated with incongruent stimuli (RT_{inc}) is longer than the latency associated with congruent stimuli (RT_{con}), which is referred to as the *conflict effect* (CE), expressed as below.

$$CE = RT_{inc} - RT_{con} \tag{1}$$

Therefore, the conflict effect reflects the extra cognitive resources required to deal with the interference caused by distractors. The critical evidence for the conflict monitoring process is that the conflict effect can be contextually modulated, conflict adaptation effect. For example, the conflict effect is smaller when the majority of trials are incongruent than when the majority of trials are congruent (Gratton et al., 1992; Kane & Engle, 2003). Presumably, the predominantly incongruent trials make the conflict information salient so that a high level of control can be maintained throughout trials (Logan & Zbrodoff, 1979). Also, the conflict effect following incongruent previous trials is smaller than the conflict effect following congruent previous trials. That is, following incongruent trials, participants detect the need to increase the level of control, which in turn reduces the susceptibility to the presence of a distractor.

The purpose of the current study is to examine the hypothesis that WMC affects cognitive control by way of conflict monitoring. We propose that WMC may reflect the ability to adjust the control level accordingly. As mentioned earlier, individual differences in performance on tasks from the interference paradigm arise only when it is necessary to flexibly respond to conflict information (Kane & Engle, 2003; Redick & Engle, 2006). For example, when the trials are predominantly congruent, high WMC individuals demonstrate a significantly smaller conflict effect, suggesting that they can process unexpected conflict information more efficiently. However, when trials are predominantly incongruent, individual differences in the conflict effect are not evident, presumably because even low WMC individuals can maintain the appropriate level of control throughout the trials. While this evidence strongly implies that WMC may be crucial in accommodating the contextual demands for an appropriate level of control, the direct evidence of individual differences in conflict monitoring has yet to be provided.

There have been a few recent studies examining WMC performance in interference paradigms (Hutchison, 2011; Kane & Engle, 2003), but only two other studies that we are aware of have investigated individual differences in the recruitment of cognitive control using the Simon task (Keye, Wilhelm, Oberauer, & van Ravenzwaaij, 2009; Miller, Watson, & Strayer, 2012). Miller et al. (2012) investigated WMC differences in the error-related negativity (ERN), an event-related potential (ERP) component that is related to the commission of errors, while participants completed a modified Simon task. They found that high WMC individuals have a greater magnitude of the ERN as well as a greater posterror positivity, an ERP component that reflects the updating of information following an error. In combination, these results provide neural evidence for differences in updating information according to task goals as a function of WMC.

Keye et al. examined whether WMC is related to the extent to which individuals flexibly respond to different types of congruence from trial to trial. For example, congruent trials preceded by incongruent trials and incongruent trials preceded by congruent trials may require greater flexibility in adjusting the amount of cognitive control as opposed to when the same type of congruence can be maintained (i.e., congruent trials preceded by congruent trials and incongruent trials preceded by incongruent trials). The results showed that high WMC individuals experienced less reaction time cost associated with the change of congruence type, suggesting that high WMC individuals are more adept at changing levels of conflict from trial to trial. However, because high WMC individuals are generally faster than low WMC individuals, the reduction of the congruence switch effect as measured by Keye et al. may be subject to scaling effects. That is, the effects observed in a group of participants with slower RTs may simply be scaled down in a group of participants with faster RTs (Faust, Balota, Spieler, & Ferraro, 1999).

In the present study, we employ a novel method of quantifying the contextual modulation of the conflict effect. We define the conflict adaptation as the ratio of the conflict effect (CE) in a conflict context (e.g., when following incongruent previous trials) to the CE in a non-conflict context (e.g., when following congruent previous trials, which we refer to as the conflict adaptation ratio (CAR)). When applying to a trial-by-trial adjustment of the CE, the CAR can be expressed as the ratio of the CE following incongruent trials ($CE/n-1^{inc}$) to the CE following congruent trials ($CE/n-1^{con}$) as in the following equation

$$CAR = \frac{CE/n-1^{inc}}{CE/n-1^{con}} \tag{2}$$

in which the numerator is generally smaller than the denominator. Although the above equation represents the trial-by-trial adjustment of conflict effect, which we refer to as the *transient* CAR, the same equation can be extended to calculate the adjustment of the CE in relation to the congruency proportion, referred to in the present paper as the *sustained* CAR. To compute the sustained CAR, we simply replace the numerator with the CE from a predominantly incongruent block of trials and the denominator with the CE from a predominantly congruent block of trials.

Whether transient or sustained, the CAR signifies the extent of adjustment of the level of controlled processing from the non-conflict context in response to a conflict signal. For example, if an individual optimally modulates the level of controlled processing, the CE following an incongruent trial should approach zero, resulting in a near-zero transient CAR. Similarly, if an individual optimally adapts to the predominantly incongruent trials, the CE also approaches zero, resulting in a near-zero sustained CAR. We regard a CAR of zero as "optimal" because the near-zero CE in the conflict context implies that the performance is not affected by the presence of a distractor, a perfect example of top-down control or so-called early selection (Broadbent, 1958).

In contrast, a CAR that is substantially different from zero indicates various types of non-optimal adaptation to a conflict signal. For example, a positive CAR that is significantly different from zero means that the individual has not adjusted the level of control setting from a non-conflict context. That is, upon detecting a conflict signal, the individual undershoots the amount of adjustment of controlled processing. A negative CAR that is significantly different from zero means that the individual has adjusted the level of controlled processing too much in the opposite direction. That is, the cognitive system is overly reacting to the conflict information, resulting in an oppositely signed CE from a non-conflict context to a conflict context. For example, participants often display a reverse Simon effect in response to a conflict signal (Wendt, Kluwe, & Peters, 2006), responding faster to an incongruent trial than to a congruent trial following an incongruent trial. It should be noted that measuring the CAR can be sometimes problematic. For example, if the denominator is zero (e.g., when there is no CE in a non-conflict context), the CAR cannot be calculated. With such exceptional cases excluded, however, the CAR can provide a quantitative characterization of the extent of