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More conservative go/no-go response criterion under high working memory load

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Previous work has shown that the efficiency of selective attention depends on the availability of cognitive control functions, including working memory. Here we examined the role of working memory in another task involving executive control, namely, a go/no-go task. Participants performed the Sustained Attention to Response Task, which requires withholding a prepotent response to an infrequent target, when at the same time placing a low or high load on an unrelated working memory task. Working memory load had the effect of reducing accuracy on the go trials, when at the same time increasing accuracy on the no-go trials. We interpret these findings to suggest that high working memory load led to a shift to a more conservative response criterion.

Keywords: Go/no-go task; Response criterion; SART; Working memory.

There is growing evidence that working memory and attention are intimately linked (e.g. Awh & Jonides, 2001; Awh, Vogel, & Oh, 2006; Chun, 2011; Gazzaley & Nobre, 2012). Many studies have shown that distractibility during a selective attention task is increased when concurrent load on a task of working memory is high (e.g. Lavie & De Fockert, 2005; Lavie, Hirst, De Fockert, & Viding, 2004). Moreover, individuals with low working memory capacity are often more distractible on tasks of selective attention (e.g. Engle & Kane, 2004; Kane, et al., 2007).

Such findings suggest that working memory plays a key role in the control of attention, possibly by prioritising the processing for relevant target information and minimising the processing for concurrent irrelevant information during task performance (Lavie et al., 2004). However, attention does not always involve restricting processing to certain information at the expense of competing inputs, but can also require maintaining sufficient processing of all incoming information over time, in order to act efficiently by responding to certain stimuli, when withholding responses to other stimuli. The main aim of the present research was to investigate the role of working memory in the ability to maintain goal-appropriate performance on a go/no-go task.

We used the Sustained Attention to Response Task (SART, Robertson, Manly, Andrade, Baddeley, & Yiend, 1997)—a go/no-go paradigm in which participants make speeded responses to a majority of non-targets when withholding their response to an infrequent target item. Two types of errors can be made in the SART—errors of omission (inappropriately withholding the response to the go non-targets) and errors of commission (erroneously responding to the no-go target). The latter occur frequently (from 25 to 50% of the time; e.g. Chan, 2001; Helton,

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Head, & Russell, 2011; Helton, Weil, Middlemiss, & Sawers, 2010) and are thought to be indicative of lapses of sustained attention (e.g. Manly, Robertson, Galloway, & Hawkins, 1999; Robertson et al., 1997). Furthermore, the SART is often used as a measure of vigilance and sustained attention in both healthy participants (e.g. a SART-like task used by Redick, Calvo, Gay, & Engle, 2011) and brain-damaged patients (e.g. Johnson et al., 2007; Manly et al., 1999).

The SART requires attention to be maintained on the task over time, which would imply that it relies on the availability of cognitive control functions like working memory. Consequently, participants should do better on the SART when these cognitive control functions are available (e.g. Engle & Kane, 2004; Kane et al., 2007). Indeed, work comparing individuals with varying levels of working memory capacity has demonstrated poorer go/no-go performance on SART-like paradigms for participants with low, compared to those with high capacity (e.g., Redick et al., 2011). Furthermore, Grandjean & Collette (2011) reported that both participants' no-go accuracy and response speed on a go/no-go task were compromised when high working memory demands were also imposed. Moreover, studies using tasks other than the SART have also found that high working memory load was associated with a reduced ability to withhold a prepotent response, such as making an anti-saccade (e.g. Roberts, Hager, & Heron, 1994). Together, these findings suggest that participants are generally more successful at go/no-go tasks when working memory resources are made available.

One explanation of participants' go/no-go performance comes from a considerable body of research conducted by Helton and colleagues (Helton et al., 2010, 2011; Helton & Warm, 2008). Helton et al. (2010, 2011) showed that participants change their response criterion as a function of the perceptual load of the SART. Thus, when the task was perceptually easy (e.g. a spatially certain SART or when the stimuli were preceded by reliable colour cues), participants were more liberal (i.e. they responded to the targets quickly and frequently). In contrast, when the task was perceptually demanding (e.g. a spatially uncertain SART or when the stimuli were preceded by unreliable colour cues), they became more conservative (i.e. they responded more slowly and were more likely to withhold a response). Helton et al. (2010, 2011) interpreted these findings by suggesting that errors of omission were strategic rest-stops ("taking a breather") used by the participants as inhibitory control aids when the cognitive demands of the task were high. On this view, any type of additional load is predicted to disrupt SART performance since it will engage some of participants' attentional resources, leaving only a limited amount to carry out the task. Importantly, according to the latter perspective, as withholding the prepotent responses becomes more difficult, participants are more likely to employ a different response strategy in order to optimise their performance. In other words, when inhibition becomes difficult, they are predicted to stop responding or wait longer before making a response. In sum, participants' go/no-go performance might reflect a response strategy to compensate for the depletion of attentional resources.

In the present research, we measured SART performance when manipulating working memory load to examine the role of working memory in two aspects of SART performance. First, we hypothesised that the effect of working memory on the ability to follow task instructions (to respond to certain stimuli but not to others) can be measured in terms of participants' response accuracy. Based on previous findings, suggesting that successfully withholding a prepotent response requires working memory (e.g. McVay & Kane, 2009; Redick et al., 2011; Roberts et al., 1994), we predicted that SART performance would suffer when working memory was loaded: participants should find it harder to avoid responding to the no-go stimuli. Second, we examined whether working memory load produced a shift in participants' response criterion. Thus, when participants were more likely to execute a response on both types of trials (i.e. adopted a liberal criterion), a better performance on go trials and worse performance on no-go trials was expected. The latter is in line with the reported reduction in no-go accuracy when working memory resources are unavailable (e.g. McVay & Kane, 2009; Redick et al., 2011; Roberts et al., 1994). Alternatively, consistent with work suggesting that perceptual task difficulty results in a reduced tendency to respond (i.e. a more conservative response criterion; Helton et al., 2010, 2011), participants may be expected to be more successful on the no-go trials and less successful on the go trials in the high working memory condition.

METHOD

Participants

A volunteer sample of 35 (7 male and 28 female) participants aged between 18 and 36 (M = 20.6 years, SD = 3.4 years) took part in the study. All participants were first-year psychology undergraduates from Goldsmiths, University of London and the University of Essex. They took part in the experiment in exchange for course credits. All had normal or corrected-to-normal vision.

Stimuli and procedure

The experiment was designed and run using E-prime software (Schneider, Eschman, & Zuccolotto, 2002). Stimuli were presented in black on a white background on a computer monitor at a viewing distance of approximately 40 cm (see Figure 1).

Each trial started with a memory set, presented centred at fixation in 30pt Arial font for 500 ms under low working memory load or 2000 ms under high load. The memory set consisted of a single digit between 1 and 9 in the low-load condition, or a randomly selected (without replacement) set of six digits in the high-load condition. Participants were instructed to try and keep the digits in memory until the end of the working memory trial. The memory set was followed by a blank screen for 500 ms in the low-load condition and 2000 ms in the high-load condition. Next, the SART was presented, consisting of 10 sequential SART displays. On each SART display, one of the following symbols was shown in 48pt Arial font:} @ # % > = ¶ $ ¤. Symbols were presented for 250 ms at one of three possible locations with equal probability, either at fixation, or 40 mm to the left or right of fixation (based on Helton et al., 2010, 2011). Each symbol display was preceded by a 200 ms fixation display containing place holders (+ + +) on the three possible stimulus locations and followed by the same display (+ + +) for 1000 ms.

Since each SART block consisted of 220 trials and there were nine symbols, it was not possible to present each symbol on an equal number of trials, thus each stimulus appeared on at least 24 trials, however, two or three stimuli appeared on 25 trials. Therefore, the target symbol was presented on roughly 11% of the trials, whereas the non-targets occurred 89% of the time. Participants were instructed to make a speeded response to each symbol by using the index finger of their preferred hand to press the SPACEBAR on the computer keyboard, but to withhold their response when the target symbol was displayed. The identity of the target symbol was counterbalanced between participants.

Following the sequence of 10 SART trials, the memory probe was displayed at fixation, until response. The probe consisted of a single digit, and participants used their left index and middle fingers to indicate whether the probe digit had been present (by pressing "1" on the computer keyboard) or absent (by pressing "2" on the computer keyboard) in the memory set for that trial. Visual accuracy feedback was given after each working memory response. For both load conditions, the probe digits were equally likely to have been present or absent in the set. In the high working memory load condition, the first and last digits in the memory set could not appear as probes. Participants completed two practice blocks of 30 SART trials each (three working memory trials at each level of load), followed by two experimental blocks of 220 SART trials (one block for each level of working memory load). The order of presentation of low and high working memory load blocks was counterbalanced across participants.

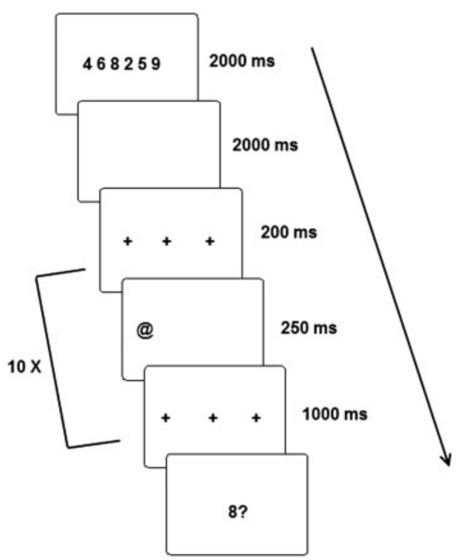

Figure 1. An example of a trial sequence in the high working memory load. Note that the same procedure was followed in the low working memory load with the difference that 1 digit (instead of 6) was presented for 500 ms in the beginning of each SART sequence.

Statement of transparency

To ensure research transparency, we report how we determined our sample size, all data exclusions, manipulations and measures in the study (Simmons, Nelson, & Simonsohn, 2012). We initially reported results for 13 participants, and after review, increased our sample size to 30 to increase power. Importantly, the results were the same for the smaller and the larger samples, and the key effects would survive a correction for multiple tests. Finally, we did not exclude any measures or conditions from the analyses.

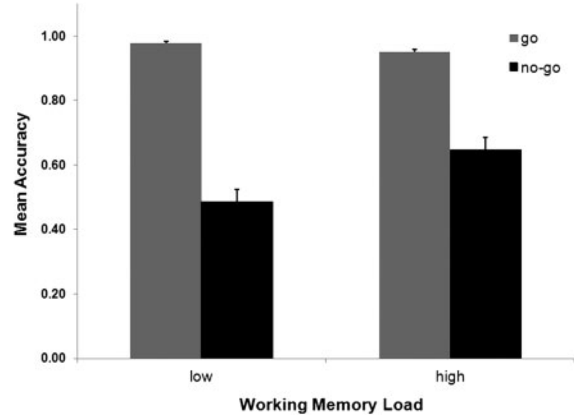

Figure 2. Mean accuracy rates in the low and the high working memory load as a function of the required stimulus response (“go” or “no-go”).

RESULTS

First, we established that the working memory manipulation was effective, by computing mean correct reaction times and accuracy rates to the memory probe, as a function of working memory load. Participants took significantly longer to respond to the probe digit in the high working memory load condition (M = 1725 ms), than in the low-load condition (M = 1391 ms; $t(29)$ = 7.50, SEM = 44.60, p < .001, Cohen’s d = 0.97). Although participants’ performance on the working memory task did not differ significantly in terms of accuracy (high load, M = 0.837; low load, M = 0.842, p > .8), inverse efficiency scores (mean correct RTs divided by accuracy rates) showed that performance was significantly worse under high (M = 2135) than low working memory load (M = 1679; $t(29)$ = 4.08, SEM = 111.54, p < .001, Cohen’s d = 0.75).

For the SART analysis, only trials on which participants responded correctly to the memory probe were included. Mean accuracy scores were computed as a function of working memory load (low and high) and response type (go and no-go), and entered into a two-way Analysis of Variance (ANOVA) (see Figure 2). The main effect of working memory load was significant, $F(1, 29)$ = 27.87, MSE = 0.135, p < .001, partial eta sq. = 0.490. Overall, accuracy was higher under high (M = 0.798) than low (M = 0.731) working memory load. The main effect of response type was significant, $F(1,29)$ = 122.64, MSE = 4.752, p < .001, partial eta sq. = 0.809. Thus, accuracy was considerably higher for go trials (M = 0.964) than for no-go trials (M = 0.566), showing that participants were more likely to make errors of commission than errors of omission. Importantly, there was a significant interaction between working memory load and response type, $F(1, 29)$ = 36.28, MSE = 0.265, p < .001, partial eta sq. = 0.556. Follow-up tests showed a significant reduction in accuracy with increasing load for go trials (low load, M = 0.977; high load, M = 0.950; $t(29)$ = 3.39, SEM = 0.008, p = .002, Cohen’s d = 0.83), whereas accuracy rates on the no-go trials showed the opposite pattern as a function of load, with higher accuracy under high load (M = 0.646) compared to low load (M = 0.485; $t(29)$ = 5.90, SEM = 0.027, p < .001, Cohen’s d = 0.76).

The reduction in accuracy on go trials and the increase in accuracy on no-go trials under high load occurred in the context of equal sensitivity between load conditions: mean d-prime scores were 2.29 under high load and 2.43 under low load (t < 1). Response bias, however, was significantly modulated by working memory load: response bias measure C (e.g. Stanislaw & Todorov, 1999) was lower under high (M = 0.67) compared to low working memory load (M = 1.25; $t(29)$ = 5.35, SEM = 0.109, p < .001, Cohen’s d = 1.22.). Thus, participants were more liberal under low working memory load and more conservative under high load.

The analysis on the untransformed accuracy rates was repeated using an arcsine transformation. The absolute skewness values were lower than 0.5 for all four conditions after transformation, confirming that the transformed variables were normally distributed. The analyses of the untransformed and transformed accuracy rates produced identical patterns of results. After arcsine transformation, there were main effects of working memory load, $F(1,29)$ = 4.99, MSE = 0.016, p = .033, partial eta sq. = 0.147, and response type, $F(1,29) = 228.49$, $MSE = 0.064$, $p < .001$, partial eta sq. = 0.887. Importantly, the interaction between load and response type was again significant, $F(1,29) = 36.25$, $MSE = 0.023$, $p < .001$, partial eta sq. = 0.556. On go trials, accuracy was higher under low load ($M = 1.395$), compared with high load ($M = 1.278$; $t(29) = 3.94$, $SEM = 0.030$, $p < .001$, Cohen's $d = 0.96$). By contrast, on no-go trials, accuracy was higher under high load ($M = 0.746$) compared to low load ($M = 0.527$; $t(29) = 5.26$, $SEM = 0.042$, $p < .001$, Cohen's $d = 0.77$).

Finally, SART response latencies were significantly different in the two load conditions ($t(29) = 2.56$, $SEM = 12.35$, $p = .016$, Cohen's $d = 0.52$], so that latencies were longer under high working memory load ($M = 424$ ms) than low load ($M = 392$ ms). We also found greater within-participants' variability in RT when working memory load was high (Mean $SD = 205.86$; $SD = 51.18$), as compared to when it was low (Mean $SD = 177.36$; $SD = 55.45$; $t(29) = 3.56$, $SEM = 7.999$, $p < .001$, Cohen's $d = 0.53$). It was important to establish that the key difference in withholding accuracy could not be explained in terms of a tendency to postpone responding under high load. To do so, we ran an ANCOVA on SART accuracy rates with the same factors of load and response type as the main analysis, and relative SART latency under low versus high working memory load as a covariate. The ANCOVA produced the same results as the main analysis, with main effects of load ($F(1,28) = 19.98$, $MSE = 0.005$, $p < .001$, partial eta sq. = 0.416) and response type ($F(1,28) = 91.91$, $MSE = 0.037$, $p < .001$, partial eta sq. = 0.766), and a significant load by response type interaction ($F(1,28) = 23.71$, $MSE = 0.007$, $p < .001$, partial eta sq. = 0.459). Importantly, none of the effects involving the covariate were significant, confirming that the differences in accuracy rates as a function of load and response type were independent of changes in response time as a function of load.

DISCUSSION

Our key finding was that loading working memory independently of, but concurrently with, a go/no-go task had the effect of improving participants' ability to withhold responses to infrequent targets, whilst at the same time reducing the likelihood to respond correctly to frequent non-targets. Moreover, although d-prime scores were the same under low and high load, showing that sensitivity was unaffected by working memory, response bias was significantly modulated by load. Therefore, participants were more likely to respond under low, compared to high working memory load, implying a shift towards a more conservative response criterion as a function of load. Finally, the improvement in the ability to successfully withhold responses on the SART was independent of participants' SART latencies, indicating that the performance gain was not simply the result of participants delaying their response under high working memory load.

The present findings are consistent with some previous work comparing sustained attention performance of participants who differ in working memory capacity (e.g. Kane et al., 2007; McVay & Kane, 2009; McVay & Kane, 2012). Within-participants variability in RT was greater under high working memory load, a finding consistent with individual-differences research, where it is generally reported that individuals with low working memory capacity demonstrate a greater RT variability (e.g. McVay & Kane, 2009, 2012). However, some other common findings are a positive association between working memory capacity and accuracy (inconsistent with the present findings) and longer RTs (consistent with the present findings) on a sustained attention task. Still, these studies employ a very different methodology in which vigilance performance is examined over long periods of target search.

Grandjean and Collette (2011) used a more similar design and procedure to the present study, since in one of their experiments participants carried out a go/no-go task when concurrently performing simple arithmetic additions. Their results indicated that both participants' no-go accuracy and RTs were compromised when working memory demands were imposed. We speculate that differences between Grandjean and Collette (2011) and our study in the way cognitive load was manipulated (performing an arithmetic task versus maintaining a memory set) may have contributed to the seeming lack of correspondence between the findings. It is likely that the level of load imposed on working memory by the arithmetic task, which involved both maintenance and manipulation of material, was higher than that imposed by our working memory task, which involved high maintenance but no manipulation. Together, these findings raise the important possibility that the relation between working memory load and secondary task performance is not monotonic, so that a moderate increase in working memory may be associated with a performance gain (like we found), whereas more extreme increases in load lead to performance costs (Grandjean & Collette, 2011). We have previously found a similar non-monotonic relationship between the availability of working memory resources and selective attention (Ahmed & De Fockert, 2012). At this point, we can only speculate whether differences in the level of imposed working memory load are responsible for the discrepancy between our findings and those of Grandjean and Collette (2011).

At first glance, the present results seem to be in line with research showing that greater working memory capacity is associated with an increased likelihood of mind-wandering (e.g. Levinson, Smallwood, & Davidson, 2012; Teasdale, Proctor, Lloyd, & Baddeley, 1993). Along these lines, errors of commission have been proposed to represent lapses of attention (e.g. Manly et al., 1999; Robertson et al., 1997) since an erroneous response on a no-go trial in a go/no-go task reflects a mistakenly applied action (i.e. one that is required on the majority of trials is applied to the minority of trials). Thus, a reduction in the availability of working memory resources as a result of high load on a concurrent working memory task (the current findings) may leave fewer available resources for such mind-wandering. Our findings might, therefore, indirectly suggest that mind-wandering is inversely related to working memory load, and that being in a state of high working memory demand prevents the execution of actions, inappropriate to the task at hand. We, nonetheless, doubt that our findings are readily explained in terms of reduced mind-wandering. Mind-wandering of the kind experienced when performing a repetitive task for a prolonged duration is unlikely to have occurred in our paradigm in which we interrupted the SART sequence in order to present the working memory task. Others have also questioned whether the SART is a good measure of lapses of attention (e.g. Helton et al., 2010, 2011).

As hypothesised in the introduction, instead of impairing or improving SART performance, working memory load appears to have the effect of changing participants' response criterion. More specifically, as working memory load increased, participants appeared to become more conservative in their decision whether or not to execute a response, leading to better no-go accuracy and worse go accuracy. A similar finding of a shift to a more conservative response criterion on the SART has been reported previously when a different type of load was manipulated (Helton et al., 2010, 2011). As mentioned earlier, Helton et al. (2010, 2011) showed that under relatively easy perceptual task demands, participants were more liberal, responding to the targets more quickly and frequently, whereas they were slower and more likely to withhold their response under more difficult perceptual task demands. The present findings suggest a similar shift to a more conservative criterion when the perceptual load of the SART remains unchanged, but the concurrent load on working memory is increased. We argue that in the present study, high working memory load had a specific effect on response criterion that is different from the effect of more general manipulations of cognitive control, including fatigue, which have been shown to be associated with an increase, rather than a reduction, in the rate of commission errors (e.g. Scullin & Bugg, 2013).

Previous work supports the conclusion that unavailability of cognitive control resources is associated with a shift towards a more conservative response criterion. There is ample evidence that elderly people are less likely than young people to execute a response when they should not (i.e. they are less likely to produce commission errors), but more likely to fail to respond when they should (i.e. they are more likely to produce omission errors) (e.g. Howard, Bessette-Symons, Zhang, & Hoyer, 2006; Rabbitt & Birren, 1967). Indeed, the elderly have been reported to perform similarly on the SART as did our young participants under high working memory load (e.g. McVay, Meier, Touron, & Kane, 2013). Cognitive ageing is associated with a reduction in cognitive control resources, including working memory (e.g. Hedden & Gabrieli, 2004; Salthouse, Kausler, & Saults, 1988). This, together with the current findings, suggests that a relative depletion of working memory resources, either through cognitive ageing or through loading working memory, can have a similar effect on SART performance. Perhaps the change in response criterion observed in cognitive ageing is a direct consequence of an age-related reduction in working memory capacity.

In sum, high working memory load affected go/no-go performance in an unexpected way. When taxing participants' working memory resources made them slower and less accurate on go-trials, it also led to an improvement in accuracy on no-go trials. These results are most readily explained in terms of high working memory load having the effect of changing participants' response criterion from a more liberal to a more conservative one. The present findings indicate that working memory demand does not always have a deleterious effect on performance.

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