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Is Working Memory Load Irrelevant to Inhibitory Cognitive Control in Negative Priming?

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Abstract

Two issues were addressed in this study. First, it addresses the viability of the assertion that working memory is crucial for reducing distraction by maintaining the prioritization of relevant over irrelevant information in visual selective attention tasks. The authors tested this hypothesis in an experiment involving a modified n-back task with attentional displays consisting of a distractor word superimposed on a target picture. Working memory load is deemed to be low in a 1-back task and relatively higher in a 2-back task. Here we report surprising results from 1- and 2-back versions of an n-back task with negative priming measures to assess the extent of distractor word processing. The second issue addressed a controversy in the negative priming literature involving whether it is possible to obtain negative priming effects with a large pool of stimuli, since it is generally thought that obtaining negative priming with words requires that words are encountered repeatedly as targets before becoming ignored distractors in the prime display of a prime-probe couplet. Thus, negative priming is ostensibly only produced when a relatively small pool of words is used, and these words exchange roles, acting as targets on some trials and distractors on others in the course of the task. Here, significant negative priming effects were observed despite using a large pool of stimuli and without ever having the distractor word appear as a target stimulus prior to the target probe on an ignored repetition trial. Possible resolutions to the opposing findings are provided.

Keywords: Selective attention; Cognitive load; N-back task; Negative priming; Inhibition

Introduction

Despite extensive research on working memory and on visual selective attention, the interaction between the two has rarely been investigated. One exception is the highly influential work of de Fockert JW et al. [1] reported in Science. They reported that working memory is crucial for reducing distraction by maintaining the prioritization of relevant over irrelevant information. Their findings were derived from a task combining two unrelated tasks – one requiring visual selective attention and the other working memory – to see if increasing load in the working memory task would increase the processing of visual distractors in the selective attention task. Participants in their study were asked to remember the order of four digits presented either in a random order (high working memory load) or in a fixed order (low load), while categorizing famous names superimposed on irrelevant distractor faces. They found significantly more interference from an irrelevant famous face in the name classification ("politician" vs. "pop-star") task in the high memory load condition, compared to the low memory load condition. As such, high load seemed to reduce the efficiency of selection and thereby increased the interfering effects of irrelevant stimuli. Accordingly, de Fockert JW et al. [1] concluded that participants were better able to block out the interfering effects of an incongruent face when concurrent memory load obligations are low, whereas when memory load is high, there is more extensive processing of the distractor face resulting in more interference.

However, there are critical reasons for questioning the notion that low cognitive load enhances peoples' ability to prioritize target over non-target information in a selective attention task. These reasons are based on questionable design and analyses in the de Fockert JW et al. [1] study. For example, their experiment was ostensibly designed to investigate the role of working memory on visual selective attention. One problem in their design was that it induced divided attention instead of selective attention by including congruent stimuli in their task (e.g., the target name Mick Jagger on the distractor face of Mick Jagger). It is well known that whenever congruent stimuli are included in Stroop-like conflict resolution tasks it causes people to divide attention between targets and distractors in an experiment-wide manner. This is evidenced by the fact that as more congruent trials are added, Stroop interference effects increase in the incongruent condition [2-4]. Thus, the effects reported were effectively based more on a divided attention task than a selective attention task. This is problematic if the main goal is to investigate the impact of a manipulation on selective attention processes.

The problem with the analyses they conducted involved contrasting the congruent condition with the incongruent condition, and reporting that there was a larger interference effect between the congruent and incongruent conditions under the high load than the low load condition. This is where the idea that there is a failure to prioritize the target from distractor information under high working memory load comes from. When congruent and incongruent conditions are contrasted, however, it is impossible to determine whether the seemingly larger RT difference under high load is due to RT interference cost in the incongruent condition, or RT benefit in the congruent condition. For instance, it may simply be that familiar face stimuli are processed very rapidly. Hence, on a congruent trial under high load, the face may have such a beneficial effect on responding to the matching target name that it actually overrides what normally would be a processing cost due to load. Close scrutiny of their results supports this conjecture, because in both of their experiments the participants responded numerically slightly faster to the congruent condition in the high load than the low load condition. Clearly, the only way to obtain a realistic assessment of incongruent distractor interference costs as a function of memory load is by comparing an incongruent face condition with a neutral face condition and eliminating the congruent face condition from the task.

When the above two flaws are rectified, very different outcomes are observed [5-7]. In a version of the task modeled closely after de Fockert et al. [1], which included the congruent condition and compared congruent with incongruent condition results, our pattern of findings perfectly replicated theirs. However, when all congruent face trials were eliminated from the task, and appropriate contrasts were conducted between the neutral face and incongruent face conditions, there was no difference whatsoever in the amount of interference from incongruent faces as a function of high versus low memory load. By eliminating congruent trials and contrasting the incongruent face condition with a neutral face condition, our findings provide a more appropriate vehicle for investigating the role of working memory on visual selective attention, because they are uncontaminated by artefacts. Crucially, those findings question the conclusions by de Fockert and colleagues suggesting that inhibitory cognitive control resources fail to operate under high working memory load conditions.

In subsequent research, de Fockert, Mizon & D'Ubaldo [8] followed-up on their earlier work by again testing the idea that the efficiency of selective attention depends on the availability of cognitive control mechanisms. And more specifically, that distractor processing should increase with high load on working memory [9]. They tested this prediction in the context of a negative priming manipulation where the prediction from their earlier work was that working memory load (i.e., cognitive control load) would also affect the negative priming effect produced when a distractor from 1 trial appears as a target on the next trial. They measured priming on trials that involved either high or low cognitive control load, and found that under high control load, negative priming was completely eliminated, and thus concluded that the negative priming effect depends on the availability of inhibitory cognitive control resources. Similar to their (2001) study, these findings also conflict with our earlier results [5,6] as described above. Because interference effects were the same regardless of memory load, our findings suggest that in a selective attention task inhibitory cognitive control resources remain intact even under high working memory load conditions.

In the present study, we aimed to test the generalizability of the results and conclusions by de Fockert et al. [1,8] using a different task that contains a working memory load manipulation, coupled with a selective attention component. With regard to the working memory load manipulation, 1-back (low memory load) versus 2-back (high memory load) versions of an n-back task were used. While the 1-back task requires only the detection of an immediately repeated targeted stimulus, 2 stimuli must be maintained in memory and continuously checked against each new attention display for repetition in the 2-back task. With regard to the selective attention component, the present study uses attention displays consisting of a distractor stimulus (either a word or consonant string) superimposed on a target picture. Moreover, a negative priming measure is incorporated to assess the degree of processing of ignored words [10,11]. As far as we know, this is the first time a negative priming manipulation was used in an n-back task.

Negative priming occurs when an irrelevant distractor, which is ignored on a prime display, causes a delayed response and/or more incorrect responses when it appears as the target on a following probe display [12]. We incorporated a manipulation where a word that is ignored names the picture on the next display (Figure 1). Negative priming, in this experiment, would be in evidence if responses to probe pictures are slower or more error-prone, relative to an appropriate control condition. If participants in the current experiment showed an unavailability of inhibitory cognitive control under the high working memory load condition, then there should be less evidence for negative priming under the high load (2-back), than low load (1-back) condition. On the other hand, if there is no reduction in magnitude of negative priming under the high load condition, it would cast doubt on the notion that cognitive or working memory load causes failures of inhibitory control in visual selective attention. Obtaining a negative priming effect from an ignored non-target word to its subsequent pictorial representation would imply deep-level processing of the word to at least a semantic conceptual level, regardless of whether this happens under high or low load.

The other main issue addressed here is the claim that negative priming does not occur unless a small set of stimuli are recycled in target and distractor roles. This view is motivated by Strayer & Grison [13] who found that negative priming is absent unless unattended distractors on prime trials have previously appeared as attended targets in the experience of the participant within the context of the experiment. In the present study, however, unattended distractor words were used only once, and never served as a prior target stimulus. Therefore, if negative priming were to be obtained in either the 1-back or 2-back version of this task, it would challenge the view that a distractor must first have been presented as a target for negative priming to occur. Obtaining negative priming in either version of the present n-back task would, on the other hand, corroborate earlier results showing that negative priming may nevertheless emerge even when a large pool of stimuli is used, wherein ignored distractors never served as previous targets and have the role of distractor only once in the context of the experiment [14-18].

Material and Methods

Participants

Two-hundred and sixty-four students enrolled in an undergraduate cognitive psychology course at the University of Canterbury participated as part of course requirements. All were naïve to the purpose of the experiment and none had any prior experience with the task or the priming manipulations involved. They were assigned randomly by designated lab stream into 1-back (N = 124) and 2-back (N = 142) conditions.

Stimuli and design

The experiment included negative priming trials in both 1-back and 2-back versions of the task. With respect to the memory load manipulation, participants were presented with a sequence of pictures (each with an overlaid word) and were required to respond same when the current picture had been presented on the previous display (in the 1-back condition) or on the display 2-back in the sequence (in the 2-back condition), and to respond different unless the picture had been repeated within the relevant n-back condition, respectively. The 1-back stream contained no 2-back repetitions and the 2-back stream contained no immediate repetitions. With respect to the negative priming manipulation, trial couplets were created by arranging pairs of contiguous displays where either the word ignored on the first picture named the picture to appear on the second display (ignored repetition condition) or the ignored word on the first picture bore no relation to the second picture (control condition). Sample n-back and priming trials are depicted in Figure 1.

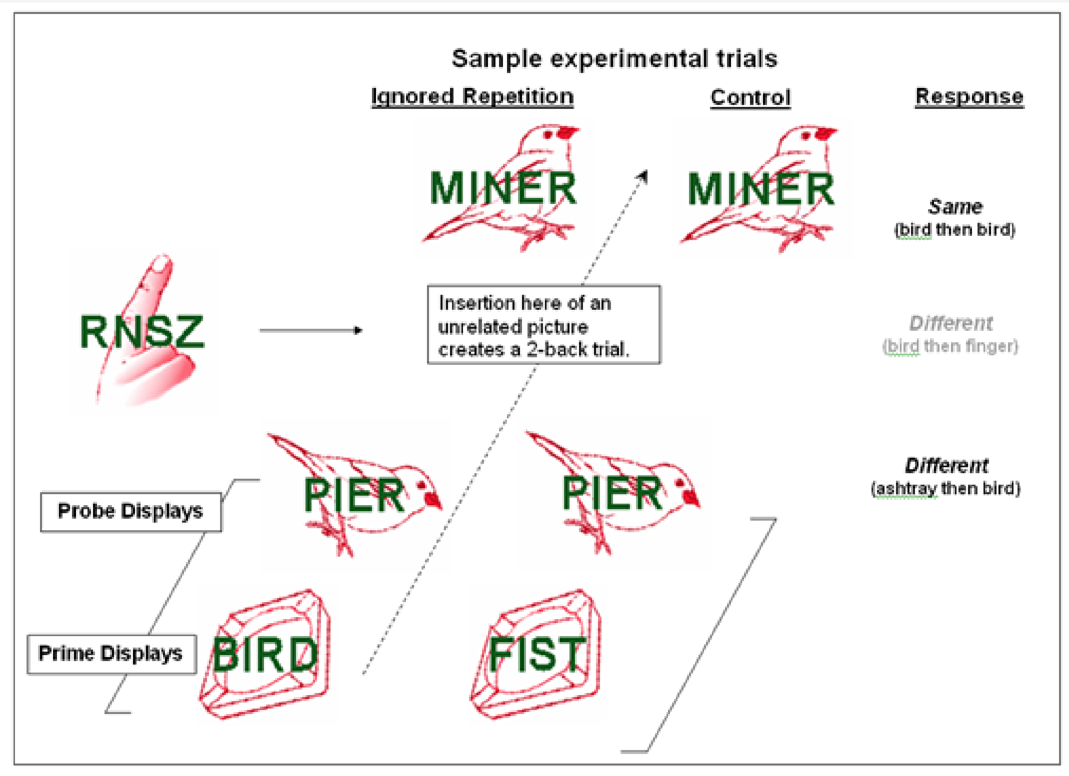

Figure 1: Sample display sequences in which the prime-probe couplet on the left depicts an ignored repetition (negative priming) trial sequence, whereas the one on the right depicts a control sequence of trials.

Participants responded to every display indicating Same when the picture (e.g. bird) appeared on the previous display (1-back condition) or on the display two back in the sequence (2-back condition) and Different for all other displays. The coupled negative priming trials are bracketed. In ignored repetition trials the word on the prime display is the name of the picture on the immediately following probe display. The same critical probe picture appears in both ignored repetition and control sequences but in control trials it is preceded by an unrelated word on the prime display. Pictures were coloured red, words were printed in green.

Negative priming prime and probe displays never involved a repeated picture, so the correct response to all probe targets was different for the ignored repetition condition (as well as the control condition). A tightly counterbalanced design was used in which the set of pictures that served as probe targets in the ignored repetition condition for one group of participants became probe targets in the control condition for a second group and vice versa. Additionally, each picture occupied the same position in the stimulus stream regardless of whether it appeared in an ignored repetition trial or a control trial, as illustrated in Figure 1. Negative priming pairs were created from displays that did not involve picture repetitions. The ignored prime distractor word and following probe picture in negative priming trials always occurred on immediately following displays in both the 1-back and 2-back versions of the task. Seventy-two negative priming coupled displays were inserted at random within a sequence of 303 trials in both the 1-back and 2-back conditions.

All stimuli were scaled to display sizes approximating 5° and positioned centrally on the screen. In addition, all pictures were rotated 30° clockwise or counter clockwise from their canonical orientation so that repeated pictures always were rotated 60° apart. Pictures were drawn from the set of 260 revised gray level Snodgrass and Vanderwart diagrams described in Rossion & Pourtois [19]. Repeated pictures occurred on 1/6th of trials randomly located throughout the trial sequence in both 1-back and 2-back conditions. Accurate performance in both 1-back and 2-back conditions required participants to make a Same response to 1/6th of the displays and a Different response to the remaining displays. Nouns were superimposed on 60% of pictures and consonant strings were overlaid on the remaining 40% of pictures. Four and 5-letter nouns and 4- and 5-letter consonant strings were used, and no word or consonant string was presented more than once to any participant.

Prior to the experimental trials participants completed 42 practice trials in which there were six picture repetitions. Only consonant strings were overlaid on practice pictures. Because the number of pictures available was less than the number of trials minus the number of repetitions, 30 pictures were presented twice at least 123 trials apart (typically more than 260 trials apart). None of these repetitions included trials involved in the negative priming or control conditions. To ascertain whether attention had been withdrawn from the words in the repetition monitoring task, an unexpected catch-trial was presented immediately following the last experimental display. This display comprised a normally appearing picture (that had not been previously presented) overlaid with a 4- or 5-letter noun, and it was immediately followed by a 5-alternative forced-choice recognition test of equal-length words.

The manipulations of interest relate to negative priming and task differences. The experiment employed a mixed between-groups (1- vs. 2-back tasks) x within-subjects (ignored repetition vs. control) design.

Procedure. Stimulus displays and their timing, and response timing and accuracy were recorded using computers running Superlab Pro for Windows 2.0 (Cedrus Corporation). Same and Different responses were recorded using the buttons on a mouse connected to a serial port to ensure accuracy of response times to within one millisecond. Participants were assigned to 1-back and 2-back tasks randomly, and within each resulting cohort, half were assigned at random to one of the two stimulus sets used for counterbalancing and half to the other stimulus set. Instructions were displayed via computer screen with verbal explanation given by the experimenter who was careful to ensure that the task and procedures were understood, including the need for both speed and accuracy of response. Participants then began the practice trials. During practice displays were presented for 500 ms on early trials reducing in steps to 250ms on the 25th practice display and remaining at 250 ms thereafter. Following the offset of a display the screen remained blank until a response was made. Production of a response initiated the next screen without delay except during practice displays where feedback was visible for 1500 ms on trials where an incorrect response occurred. Experimental trials followed practice trials unobtrusively without any break and the entire sequence of 346 trials, including the catch-trial, was completed in around 10 to 12 minutes. Immediately following the last display (the catch-trial) a screen message instructed participants to note and then write down which of the five displayed words they thought had appeared in the last display.

Result

To confirm that attention was indeed withdrawn from the words in the 1- and 2-back tasks, we used an unexpected, forced-choice, immediate recognition test of the word displayed on the catch trial at the end of the tasks. Overall, 26% of participants chose the correct alternative. This was significantly greater than chance (20%), χ^2 (1, 264) = 6.21, p = .013. In an attempt to eliminate data from participants who may have adopted strategies where attention was divided between words and the monitoring task, all those responding correctly to the catch trial were excluded from further analyses. Consequently, 91 of the 124 participants remained in the 1-back condition and 104 of the 142 participants in the 2-back condition were retained. Including all of the participants in the analyses revealed an identical pattern of results. Probe response times were included in analyses only when responses to both the probe and the preceding prime display were correct and fell within the range of 250 to 1500 ms (1.8% were excluded). Median response times and the error rates were calculated for each participant. Mean response times, standard errors, and mean error percentages are presented in Table 1.

Table 1: Mean Response Times and their Standard Errors (in ms) and Percent Errors.

Task		Ignored Repetition	Control
1-Back	Mean	710	702
	Standard Error	14.6	14.1
	Percent Error	0.8	0.5
2-Back	Mean	840	826
	Standard Error	13.7	13.2
	Percent Error	3.2	1.7

These data were analyzed by mixed ANOVAs, with n-back (1 vs. 2) as the between-subjects variable and priming (control vs. ignored repetition) as the within-subjects variable, performed separately on response times and error rates. Response times were significantly longer on ignored repetition than control trials, F(1,193) = 8.57 p = .004, and errors also occurred significantly more often on ignored repetition than control trials, F(1,193) = 17.79 p<.001. Overall the significantly greater response times (11 ms) and higher error rates in the ignored repetition condition indicate that ignoring a picture's name can impede response to the picture on the following trial among participants who display no immediate explicit knowledge of ignored words on the catch trial.

Response times were significantly longer and errors more common in the 2-back, than the 1-back condition, F(1,193) =

43.21, p<.001, and F(1,193) = 13.42, p =.001, respectively. More importantly, however, for reaction times there was no interaction between the n-back and priming conditions, F(1, 815) = 0.64, p = .43. If anything, the ignored repetition condition took numerically longer than the control condition in the 2-back task (14ms), compared to the 1-back task (8ms). Thus, despite the greater working memory demands of the 2-back task, there is no suggestion in the RT data that the negative priming effect is significantly reduced in this condition. In addition, the error rate analysis of the interaction was significant, F(1,193) = 7.88, p <.005, indicating that more errors were observed in the ignored repetition than the control conditions under the greater working memory demands of the 2-back task, compared to the 1-back task. Furthermore, the general suppressive attentional effect on ignored distractors appears to function quite autonomously because negative priming was observed in the RT data for both the 1- and 2-back tasks, (F(1,90) = 5.30, p < .023, F(1,103) = 4.88, p < .03, respectively. The results also provide clear evidence that the 2-back task was more memory demanding, because overall response times were markedly longer and error rates more than doubled, compared to the 1-back task.

Discussion

The present study investigated the effect of working memory load on distractor processing, by using negative priming as the measure of distractor processing. Participants made speeded responses to indicate whether or not an image of a common object had been presented on the immediately preceding trial (1-back, low working memory load) or two trials previously (2-back, high working memory load). Each trial also contained an irrelevant word stimulus, and NP was measured by comparing performance on trials on which the target image was the same as (versus different to) the preceding distractor word. There was overall semantic negative priming when the word and subsequent picture were conceptually identical, which was modulated by working memory load (greater negative priming under high versus low working memory load) in the error rates (but not in the RTs).

Overall, responses were slower and less accurate when a word that named the current picture had been ignored on the previous display. This occurred even though the identity of the words was completely irrelevant and potentially intrusive to the focal task of monitoring the picture sequence. Moreover, it is unlikely that the negative priming occurred because attention had been allocated to the words, since participants who guessed the identity of the ignored word in the final immediate recognition test were eliminated from the analyses. Negative priming was nevertheless obtained between ignored words and subsequent pictures corresponding to these words. This suggests that the words in both the high and low memory load conditions were processed to the level of meaning, and this occurred irrespective of memory load. Crucially, although the negative priming was not greater under high versus low working memory load in the RTs, there were more errors under high load. This suggests that, if anything, there was more evidence for negative priming in the 2-back condition than the 1-back condition, which is the opposite of what would be predicted by de Fockert & colleagues [1,8] cognitive control impairment prediction as a consequence of high memory load.

Initially, de Fockert & colleagues [1] provided evidence purportedly indicating that the efficiency of selective attention depended on the availability of an inhibitory cognitive control mechanism. The claim was based on the observation that distractor processing increases with high load on working memory, which manifested in greater interference due to an inability to prioritize target stimuli from incongruent distractor stimuli. On the basis of these findings and conjectures, de Fockert et al. [8] subsequently hypothesized that cognitive control load should also affect the negative priming effect in a particular way. Specifically, when a non-target distractor from a trial appears as the target on the next trial, negative priming should be maintained under low load, but significantly reduced or eliminated under high load conditions, due to unavailability of inhibitory cognitive control resources in the latter case. As discussed in the introduction, there are likely artefacts that caution against the source of these hypotheses. Moreover, the current pattern of findings is the opposite of what is expected by those predictions.

Since the present n-back task has been shown for the first time to be capable of producing negative priming, it becomes another useful tool for exploring selective attention. An advantage of the n-back task is that it genuinely investigates selective attention, rather than more diffuse or divided attention, by excluding any congruent attentional displays in the task. It is therefore never beneficial to devote some attention to the distractor in our n-back task. There are also potentially important ways to expand the present paradigm. One way would be to make it a completely within-subjects experiment, rather than having the 1-back and 2-back conditions as a between-subjects variable. Another useful variation would be to contrast a 1-back with a 3-back condition instead of 2-back. In this way working memory load would be strained to an even greater degree, thus potentially helping to establish whether increasing memory or cognitive load can cause inhibitory cognitive control capacities to be depleted.

Given recent findings from cognitive neuroscience of an automatic feed-forward sweep of activation extending from earlier and more posterior visual regions to frontal executive and parietal regions, the early processing of unattended words is to be expected [15, 20-22]. This, of course, is not to say that they might not also ultimately undergo active suppression, especially if there is only one distractor concurrently in stiff competition with a task-relevant target [23-28]. On the basis of the present findings, it appears that the magnitude of this suppression effect can be modulated by varying concurrent working memory load, because significantly more errors were observed in the ignored repetition condition than the control condition only in the 2-back task. In addition to the current n-back task, semantic negative priming has also recently been observed using rapid serial presentation streams with temporally separated target and distractor words [29]. Taken together, it appears that inhibiting distracting stimuli in selective attention paradigms is a more ubiquitous and potent processing mechanism than previously thought [30,31].

The other main issue clarified in the present study involved the assertion that negative priming does not occur unless a small set of words are recycled in target and distractor roles. As discussed earlier, this view is motivated by Strayer and coleagues [13,32,33] who found that negative priming is absent unless unattended distractors on prime trials have previously appeared as attended targets in the experience of the participant within the context of the experiment. In the present context, however, words were used only once, and never served as an attended target (nor as a semantically related picture) prior to their encounter as a distractor stimulus. Therefore, the present results challenge the view that a distractor must first have been presented earlier as a target for negative priming to occur. On the other hand, the present results corroborate others showing evidence of negative priming despite large pools of words wherein ignored distractor words never served as previous targets and have the role of being a distractor only once in the context of the entire experiment [14,16]. We suspect that the contradictory outcomes between these laboratories stem from seemingly minor methodological variations in the tasks and stimuli that are used. For example, Strayer and Grisson used color as the selection cue to differentiate target from distractor words in a negative priming task [34,35]. However, in contrast to the overlapping target and distractor stimuli used in the present study, their words were spatially separated from one another, and thus not highly conflicting. It could be that more highly conflicting stimuli would tend to induce greater attentional suppression of the distracters (and consequently be more likely to produce negative priming), even when a large pool of words constitutes the ignored distractors.

Future Directions

In future investigations of the role of working memory on visual selective attention it will be useful to adhere to the scientific standards introduced here, but also to expand upon the paradigm. One way to extend it would be to make it a completely within-subjects experiment, rather than having the 1-back and 2-back conditions as a between-subjects variable. Another way to extend it would be to modify the present n-back task by incorporating more extreme differences between low and high working memory load conditions. For example, this can be accomplished by making the n-back task differences more extreme (e.g., 1-back vs. 3-back, or 4-back), or by incorporating a dual-task manipulation (e.g., e.g., keeping a non-random vs. random number sequence in mind for short sequences of n-back trials), or both. In this way working memory load would be strained to an even greater degree, thus potentially helping to establish whether increasing memory or cognitive load can cause inhibitory cognitive control capacities to be depleted. If our conjectures are correct, negative priming effects for the ignored repetition condition should emerge completely intact regardless of whether the working memory load conditions were low or high.

Conclusion

In summary, we began by questioning some of the design and analysis features of studies that have attempted to elucidate the role of working memory on visual selective attention. This led to exposing several weaknesses. Particularly problematic features of those studies consisted of including congruent stimuli in a task ostensibly meant to tap selective attention. To investigate selective attention it is important to create a task situation in which there is no inducement to divide attention; a situation where focal concentration is applied only to targeted information. Including congruent trials defeats this purpose by inducing experiment-wide diffuse attention, rather than selective attention. It is worthwhile noting that conscious awareness of congruent trials having this defocusing effect on attention is not necessarily the case for most, or perhaps any, participants. Hence, it is crucial to avoid any subconscious temptation for this to happen. Excluding congruent trials is not only important for inducing selective attention, but also leads to appropriating a suitable neural control condition to be contrasted with the ignored repetition condition under varying working memory loads, as in the current experiment.

When these methodological refinements are incorporated in studies designed to investigate the role of working memory in visual selective attention, there is no evidence for low working memory loads leading to more effective prioritization ability between targets and distractors. Consistent with Neumann (2009) and Neumann and Gaukrodger (2005), increasing working memory load in the context of a visual selective attention task slows down responding in neutral control and incongruent conditions in a uniform fashion. Corroborating those findings, cognitive inhibitory control also appears to be completely undiminished under high compared to low memory load by the current ignored repetition negative priming effects in a novel n-back task. Taken together, the implications from these experiments should help guide selective attention and memory researchers toward a more direct path of understanding the role of working memory on selective attention.

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Conflict of Interest

No conflict of interest.

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