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# High working memory load leads to more Ebbinghaus illusion

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Running head: Ebbinghaus illusion and memory load

# Abstract

The evidence that distractor processing increases with greater load on working memory has come mainly from Stroop-type interference tasks, making it difficult to establish whether cognitive load affects distractor processing at the perceptual level or during response selection. We measured the Ebbinghaus illusion under varying levels of working memory load to test whether cognitive control is also relevant for preventing processing of distractors that do not produce any response conflict, and instead affect target processing at the perceptual level. The Ebbinghaus illusion was greater under high working memory load, suggesting that availability of cognitive control functions is critical to reduce distractor processing even for distractors that are not associated with a response. We conclude that the effect of loading working memory during selective attention leads to greater distractor perception.

The question of the extent to which irrelevant distractors are processed is fundamental to the study of selective attention. Load theory of selective attention (Lavie, Hirst, De Fockert & Viding, 2004) proposes that two contrasting types of load can affect the efficiency of selective attention. Firstly, an increase in the perceptual load of the relevant task in displays that also contain to-be-ignored distractors leads to a reduction in distractor processing (e.g., Lavie, 1995; Lavie & Cox, 1997). Secondly, in situations where the distractor is likely to undergo processing, such as under low perceptual load or for very salient distractors that easily interfere with target processing (e.g. distractor faces), cognitive control is necessary to maintain current processing priorities by keeping a clear distinction between target-related and distractor-related information. Consequently, a reduction in the availability of cognitive control mechanisms, due to ongoing or recent engagement of these mechanisms in other tasks or processes (i.e. high cognitive control load), is predicted to lead to an increase in distractor processing.

Evidence indeed supports the notion that the level of distractor processing in situations where selective attention to a target is required depends critically on the availability of cognitive control mechanisms, which serve to minimize the processing of distractor information. When interference effects from irrelevant flanker letters were measured under conditions of high working memory load (imposed via a separate task), this interference was significantly greater than that found under low working memory load conditions (e.g., Lavie et al., 2004; see Lavie, 2005, for review, but see Kim, Kim, & Chun, 2005; Park, Kim, & Chun, 2007, for evidence that increased load on working memory can also lead to reduced distractor processing under certain circumstances). Findings from neuroimaging have also shown modulations of distractor-related processing as a function of working memory load

(De Fockert, Rees, Frith & Lavie, 2001). Cognitive control functions for which this effect on distractor processing has been demonstrated include working memory (De Fockert et al., 2001; Lavie & De Fockert, 2005, 2006) and dual task coordination (Lavie et al., 2004).

To date, much of the evidence for the importance of cognitive control functions in minimizing distraction has come from Stroop-type tasks, in which greater distractor processing is inferred when there is a greater difference in responses to targets accompanied by compatible (or neutral) versus incompatible distractors. For example, in De Fockert et al. (2001) target names were classified more slowly when accompanied with a face from another response category, and this difference was significantly modulated by working memory load. Although these findings clearly demonstrate that distractors are processed to a greater extent under high working memory load, the question remains unanswered as to whether the unavailability of working memory for selective attention leads primarily to increased perceptual processing of irrelevant information, or primarily to increased response conflict because the distractors are associated with a different response to that associated with the current target. In other words, are the increased distractor effects observed under high working memory load the result of greater distractor perception per se, or does loading working memory lead to greater difficulty resolving the response conflict that occurs when a response to the irrelevant distractors has to be prevented?

The neuroimaging evidence that face-specific activity in fusiform gyrus was greater under high working memory (De Fockert et al., 2001) load suggests that distractors were indeed perceived to a greater extent, however the poor temporal resolution of the BOLD signal precludes the exact timing of the effect to be identified with confidence. Moreover, since activity in frontal cortex has been associated with increased response conflict in Stroop tasks (e.g., Van Veen, Cohen, Botvinick, Stenger, & Carter, 2001; Mitchell, 2006), it may be that working memory and response conflict resolution have shared frontal resources, and that loading working memory leads to sub-optimal resolution of the response conflict created by an incompatible distractor. Previous behavioural evidence also hints at the possibility that increased memory load leads to greater distractor perception. Effects of attentional capture by irrelevant singletons tend to be greater under higher memory load, even when the distractor is not associated with any response (Lavie & De Fockert, 2005; Olivers, Meijer, & Theeuwes, 2006). However, attentional capture likely also involves cognitive control, especially since the distractors that produce attentional capture tend to be highly salient stimuli, so that active control is needed to prevent responses to the distractors (Müller, Krummenacher, Geyer & Zehetleitner, 2008).

In order to further address the question whether the observed increase in distractor processing results from greater distractor perception or greater response conflict, we tested the effect of imposing load on working memory on apparent size judgments in Ebbinghaus displays. The Ebbinghaus (or Titchener) illusion is a perceptual phenomenon where the apparent size of a central target object is affected by the size of surrounding inducers (see Figure 1), so that targets with small inducers are perceived as larger than targets with large inducers. We predicted that the unavailability of working memory to prevent processing of the inducers would lead to an increase in the experience of the illusion. Importantly, any such evidence of greater distractor processing cannot be explained in terms of greater response conflict, since the Ebbinghaus illusion does not depend on conflict between responses associated with the target and the distractor, but rather on the contrast between target and distractor sizes. Therefore, an increase in the amount of illusion under high working memory load cannot be due to less successful resolution of any conflict between responses associated with the target and with distractors. In fact, if imposing working memory load during processing of Ebbinghaus displays leads to greater likelihood of responding to the size of the distractors, rather than the target circle, then high working memory load will result in an apparent reduction in the amount of illusion experienced. Thus, greater response conflict will lead to more responses being made to the target with the large inducers (i.e., less illusion), whereas greater perception of the distractors will lead to more responses to the target with small inducers (i.e., more illusion).

## Method

### Participants

Ten students from Goldsmiths were tested individually in exchange for course credit. All participants had normal or corrected-to-normal vision.

### Apparatus and stimuli

The experiment was conducted on a PC running e-prime software (Schneider, Eschman & Zuccolotto, 2002). Ebbinghaus stimulus configurations were presented in black on a white background and consisted of two target circles in horizontal orientation, one surrounded by large inducing stimuli and one surrounded by small inducing stimuli (see Figure 1). The centre-to-centre distance between the target and each inducer subtended 4.2° of visual angle for the large inducers and 2.1° for the small inducers. The centre-to-centre distance between the inducers subtended 4.8° for the large inducers and 1.6° for the small inducers. In the small inducers configuration, inducers were presented with a diameter subtending 0.5°, and the size of the central target circle remained constant at 2.4° diameter. In the large inducers configuration, inducers were presented with 4.2° diameter, and the target diameter ranged from 2.2° to 2.9°, with 0.1° steps. Thus, relative to the target in the small inducers condition of 2.4°, the size of the target circle in the large inducers condition was 92%, 96%, 100%, 104%, 108%, 112%, 116%, and 120%, respectively. The asymmetry in the stimulus set makes use of the fact that a reverse illusion does not occur (large inducers will never produce the illusion of a larger target). It also has the advantage that the middle stimulus is not the veridical. Thus, neither random performance nor any strategy based on the range of target sizes in the large inducers condition will lead to veridical performance.

For the working memory task, memory sets contained either one (low working memory load) or six digits (high load) between 1 and 9. The order of the six digits in the high load memory set was random, with the constraint that no more than two digits were presented in sequential order. For the memory probe, one digit was presented in the centre followed by a question mark. Probe digits were equally likely to be present or absent in the trial set and equally likely to probe any of the six possible memory set positions in the trials of high working memory. In addition, probe condition (present or absent) was counterbalanced across trials so that it was equally likely to follow each of the 16 (eight target size differences, with large inducers either on the left or on the right) possible Ebbinghaus displays. Eighty trials were created for each condition of working memory load according to these specifications, with five repetitions of each Ebbinghaus display.

## Procedure

Each participant first completed four blocks of 12 practice trials each, two blocks with low memory load and two with high memory load. The first two blocks (one low and one high memory load) were without inducer circles, and participants were instructed to indicate which circle was greater (the one on the left or the right) by making a key press with either the left or right index finger. The last two practice blocks (again one low and one high memory load) were with inducer circles. After training, participants were presented with four experimental blocks of 40 test trials each, two blocks for each working memory load condition (order counterbalanced across participants). Each trial started with a blank screen for 1000ms, followed by the memory set of one (low load) or six (high load) digits presented for 1500 ms. Participants were instructed to try and remember all the digits in the set until the end of the trial. After a 1000ms retention interval, the Ebbinghaus display was presented until a response was recorded. On each presentation of the two stimulus configurations, participants were asked to choose the target circle they thought was the larger by making a key press with either the left or right index finger. Participants received no feedback on the accuracy of this response. Both within each block and within each target size in the large inducers configuration, the small inducers target was equally likely to occur on the left or on the right of the display. Following the response to the Ebbinghaus display, there was a 1000ms blank interval, after which the memory probe was presented until a response was recorded. Participants were instructed to make a left index key press when they thought the memory probe was part of the set for that trial, and a right key press when they thought it was not. Accuracy feedback to the memory probe response was given in the form of tone following incorrect responses. Viewing distance was approximately 60 cm.

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Insert Figure 1 around here

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## Results

Data from one participant, who misunderstood the instructions and responded to the size of the inducers rather than the target circle, was excluded. For the remaining nine participants, responses to the memory probe digit were less accurate under high memory load compared to low load (mean accuracy .89 vs .94, $t(8) = 2.36$, $SEM = .023$, $p < .05$), as well as slower (mean latency 1287 ms vs 1032 ms, $t(8) = 2.12$, $SEM = 119.8$, $p < .05$), confirming that our memory manipulation was successful in increasing load on working memory. Trials with an incorrect response to the memory probe were excluded from further analyses.

To measure the Ebbinghaus illusion, we computed the probability of choosing the target with small inducers, so that a higher score indicates more illusion (apart for the first two displays, in which the target with small inducers was indeed larger; see Figure 2). These probabilities were entered into a 2 (working memory load: high, low) x 8 (large inducers target size: 92%, 96%, 100%, 104%, 108%, 112%, 116%, and 120%) repeated measures ANOVA, with participants as the random factor. Not surprisingly, there was a main effect for large inducers target size ($F(2,16) = 55.45$, $MSe = .089$, $p < .001$ (Greenhouse-Geisser corrected); $\eta_p^2 = .874$): the larger the target with small inducers was, the more frequently is was chosen. Most important for our investigation was a significant main effect for working memory load ($F(1,8) = 6.18$, $MSe = .019$, $p < .05$; $\eta_p^2 = .436$). There was more illusion under high working memory load (mean probability of choosing the target with small inducers = .826), compared to low working memory load (mean probability of choosing the target with small inducers =.769). The interaction between working memory load and large inducers target size was also significant (F(4,28) = 3.06, MSe = .018, $p < .05$ (Greenhouse-Geisser corrected); $\eta_p^2 = .277$). This was likely due to a ceiling effect when the large inducers had a smaller target circle than the small inducers (see Figure 2).

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Insert Figure 2 around here

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We also computed the point of subjective equality (PSE) for each participant by linear interpolation, which was the size difference between the two targets at which a participant chose each target (i.e., with large inducers and with small inducers) in 50% of the trials. Analysis of the differences of PSEs from veridicality (large inducers target size 100%) revealed that both load conditions produced a highly significant illusion (under high load t(8) = 19.45, $p < .001$; under low load t(8) = 12.61, $p < .001$). Importantly, PSEs were greater under high working memory load compared to low load (t(8) = 2.35, SEM = .259, $p < .05$, Cohen's *d* = .78). On average, the 2.4° target with small inducers was seen the same size as a 2.8° target with large inducers under high load, and as a 2.7° target with large inducers under low load.

Finally, we had to establish that the increased effect under high memory load was not due simply to reduced accuracy in size contrast judgments under high load, in which case the variance in the size contrast judgments would also be greater under high compared to low load. Instead, when the between-subjects variance was compared between high and low load for each display, with target size as the random factor, there was a trend for less between-subjects variance under high load (t(7) = 2.02, SEM = .013, p = .083). Similarly for the within-subject variance, a 2 (load) x 8 (large inducers target size) ANOVA on subjects' standard deviations in each condition showed a marginally significant main effect of load, with less variance in high versus low load, F(1,8) = 4.81, MSe = .003, p = .06.

## Discussion

Observers experienced a stronger Ebbinghaus illusion when they were holding a set of six digits in working memory than when a single digit was held in working memory. This effect is unlikely due to a general reduction in accuracy in target size judgments under high memory load, since this may have led to the same drop in accuracy at all target size differences. Instead, whereas for target size differences of 92%, 96% and 100%, there was no difference whatsoever in size judgments between low and high memory load, the amount of illusion was consistently greater for the remaining target size differences under high working memory load. More importantly, the conclusion that this difference indeed reflects more illusion rather than overall poorer performance under high load is supported by the observation that neither between-subjects nor within-subjects variance in size contrast judgments were greater in high than in low load.

Overall, the amount of illusion experienced in this study was very large. This may in part be because we used relatively large size differences between the target and the inducer circles. Previous work has shown that the illusion increases with an increase in the size difference between test and inducer circles (Massaro & Anderson, 1971). However, this is unlikely to fully explain the strength of the illusion observed here: in a previous Ebbinghaus study, we used configurations in which the size of the small inducers was 21% of that of the accompanying target, and the size of the large inducers 160% of the average size of the accompanying target (De Fockert, Davidoff, Fagot, et al., 2007). In that study, the overall amount of illusion produced by circle inducers in an English sample was .13°. In the present study, the size of the small inducers was 20% of that of the accompanying target, and the size of the large inducers 172% of the average size of the accompanying target, yet we found a level of overall illusion of 0.4°. Instead, the strong overall illusion may be due to the dual task nature of the experiment, which will have imposed an increased cognitive load in both low and high load, leading to greater illusion. Previous work (Lavie et al., 2004) has shown that the requirement to switch between tasks also leads to increased distractor interference, and the dual task employed here may have produced strong baseline levels of Ebbinghaus illusion in both low and high memory load, which were further increased when working memory was loaded.

These findings are in line with evidence that the amount of Ebbinghaus illusion can be modulated by manipulating whether or not inducers are attended (Shulman, 1992). When both small and large inducers accompanied a target circle, and attention was directed to the large inducers, the target had a smaller apparent size than when attention was directed to the small inducers. This suggests that the amount of illusion depends on whether or not the inducers receive attention, and we have shown that a reduced ability to direct attention away from the inducers under high working memory load leads to an increase in the amount of illusion.

These results strongly suggest that increased working memory load during selective attention leads to greater perception of irrelevant distractors, rather than more response conflict. If high working memory would have made observers more confused about responding to a large distractor circle rather than the larger target circle, this would have resulted in the opposite effect: seemingly less illusion (because the target with the large inducers would be chosen more often) under high working memory load. Instead, we found that the Ebbinghaus was greater under high working memory load, suggesting that the inducers were perceived better under high working memory load, and that perception of the inducers was prevented more successfully under low working memory load. Importantly, this increased perception of the inducers affected processing of the target circle, and led to more Ebbinghaus illusion.

In conclusion, we have provided new evidence for the prediction from load theory of selective attention that variations in the availability of working memory lead to differences in the extent of distractor processing. We have shown this using a perceptual size illusion that depends on bottom-up inputs such as the size of the inducers (e.g., Rose & Bressan, 2002). Our data does not speak to the precise nature of the Ebbinghaus illusion, and there is evidence that the illusion can also depend on cognitive factors, such as conceptual similarity between the target and the inducers (e.g., Coren & Miller, 1974; Coren & Enns, 1993), and visual marking of the inducers (Müller & Busch, 2006). Moreover, the increase in illusion under high memory load could reflect, amongst other possibilities, greater inducer processing per se or less efficient disengagement from the inducers. From the present data, we cannot distinguish between these possibilities, and further work is needed to provide a more detailed explanation of how load leads to greater inducer processing in Ebbinghaus displays. The findings do, however, support the prediction from load theory that the efficiency of selective attention in separating processing for task-relevant information from processing for task-irrelevant information depends critically on the availability of working memory.

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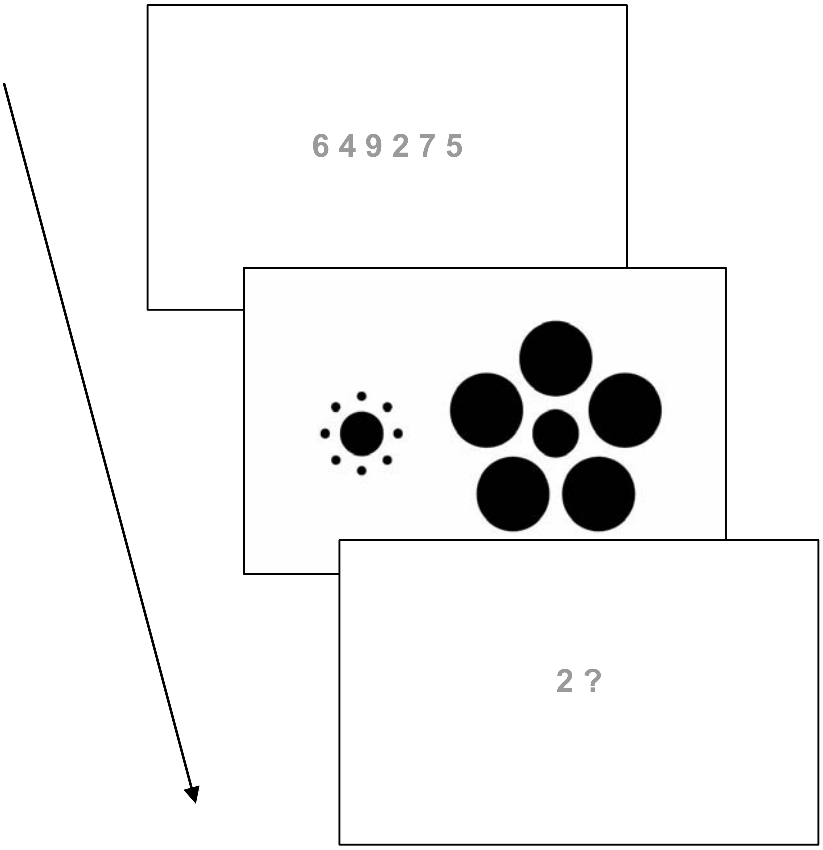
Figure captions:

Figure 1: Example of a high working memory load trial. See text for further details.

Figure 2: Mean frequency of choosing the target with small inducers, as a function of working memory load and large inducers target size. Higher scores indicate greater illusion (for large inducer target sizes of 100% and above). Veridical equality was at large inducers target size 100%. Error bars represent standard error of the mean.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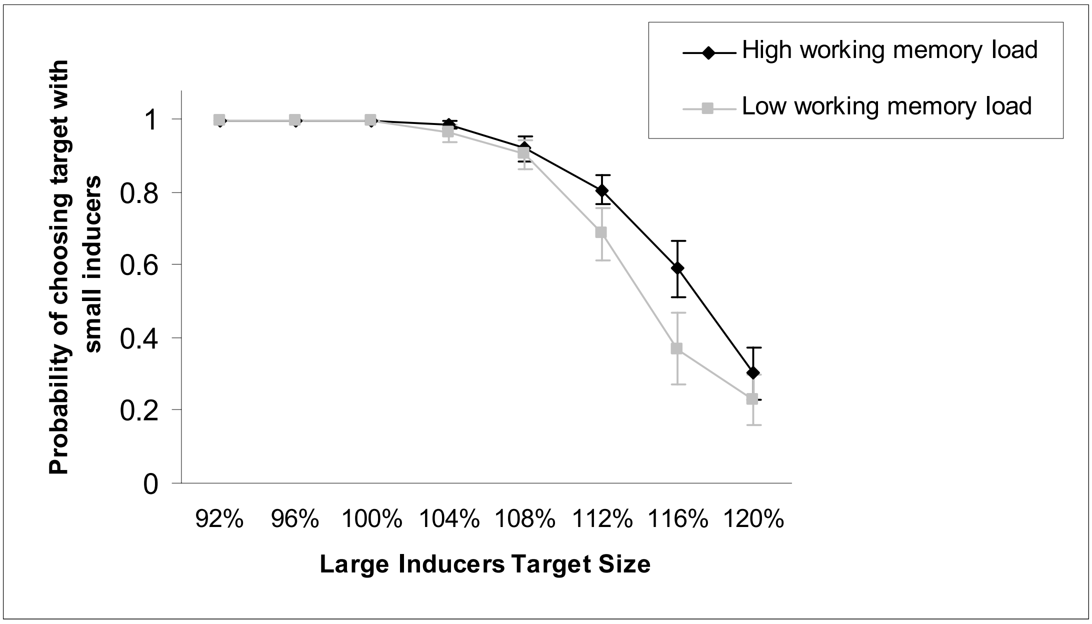
High working memory load
Low working memory load
Probability of choosing target with small inducers
1
0.8
0.6
0.4
0.2
0
92%
96%
100%
104%
108%
112%
116%
120%
Large Inducers Target Size