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Executive working memory load induces inattentional blindness

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When attention is engaged in a task, unexpected events in the visual scene may go undetected, a phenomenon known as inattentional blindness (IB). At what stage of information processing must attention be engaged for IB to occur? Although manipulations that tax visuospatial attention can induce IB, the evidence is more equivocal for tasks that engage attention at late, central stages of information processing. Here, we tested whether IB can be specifically induced by central executive processes. An unexpected visual stimulus was presented during the retention interval of a working memory task that involved either simply maintaining verbal material or rearranging the material into alphabetical order. The unexpected stimulus was more likely to be missed during manipulation than during simple maintenance of the verbal information. Thus, the engagement of executive processes impairs the ability to detect unexpected, task-irrelevant stimuli, suggesting that IB can result from central, amodal stages of processing.

Attending to an event in the visual world improves its processing (Luck, Hillyard, Mouloua, & Hawkins, 1996; Reynolds, Pasternak, & Desimone, 2000). However, this benefit is likely to come at a cost—namely, the inability to detect other events in that same visual scene (Mack & Rock, 1998; Neisser & Becklen, 1975; Simons & Chabris, 1999; see Chun & Marois, 2002, for a review). This is evidenced by the inattentional blindness (IB) phenomenon, which refers to the inability to consciously perceive an unexpected stimulus, even if it is in plain sight, when attention is diverted away to another stimulus. In a classic example of IB, a substantial proportion of observers failed to detect easily perceivable visual stimuli while engaged in an unrelated line length judgment task (Mack & Rock, 1998).

What causes IB? IB is thought to result from the inability of unexpected, task-irrelevant stimuli to capture attention, thereby preventing them from reaching awareness even though they may still undergo substantial perceptual processing (Moore & Egeth, 1997). Consistent with the attentional hypothesis, IB is influenced by the observer's attentional set (Most, Scholl, Clifford, & Simons, 2005; Most et al., 2001), so that an unexpected stimulus is more likely to be detected if it shares perceptual features with the target of the primary task. Furthermore, increasing the attentional demands of the task can result in increased IB (Simons & Chabris, 1999).

Although attentional engagement in a primary task is crucial to the induction of IB, it is much less clear how such engagement prevents awareness of the unexpected stimulus. Does IB occur solely because the primary task occupies visuospatial attention, or can IB result from the engagement of more central, amodal sources of attention? In support of a primary role for visuospatial attention in IB, unexpected stimuli that share a feature with an attended object (Most et al., 2005; Most et al., 2001) or that are near the focus of visuospatial attention (Most, Simons, Scholl, & Chabris, 2000; Newby & Rock, 1998) are more likely to be detected. However, visuospatial attention likely is not the only process that affects IB, since unexpected stimuli that are near to, or even overlap with, attended objects may also go unnoticed (Koivisto, Hyönä, & Revonsuo, 2004; Moore & Egeth, 1997; Most, Simons, Scholl, & Chabris, 2000; Neisser & Becklen, 1975; Newby & Rock, 1999; Simons & Chabris, 1999). Thus, proximity to the focus of attention is not a sufficient condition for stimulus detection.

The extent to which IB is independent of visuospatial attention can be tested by determining whether tasks that do not engage this form of attention can still induce IB. In one suggestive study, cell phone conversations were found to impair the ability to perceive and remember visual information encountered while driving (Strayer, Drews, & Johnston, 2003). However, because cell phone use involves several task components (e.g., verbal working memory, reasoning, sentence comprehension, imagery), it is not clear what aspects of the phone conversations impaired visual performance. More critically, since awareness of the visual scene was assessed at the end of the driving simulation, long after the critical stimuli were in view, it is unclear whether the observers truly failed to detect these items or whether they consciously perceived the stimuli but the cell phone conversation impaired their ability to remember that information.

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Here, we investigated whether central executive forms of attention, as opposed to visuospatial attention, can induce IB. For this purpose, we employed a working memory (WM) task that engages attention at central stages of information processing. According to the multiple-component model, WM can be subdivided into independent subordinate systems responsible for the maintenance of modality-specific information and a central executive system that manipulates and supervises the information contained in these subordinate systems (Baddeley, 1986). In recent work, we found that the simple maintenance of information in visual WM can induce IB (Todd, Fougnie, & Marois, 2005). This effect could conceivably result from modulation of visuospatial attention, since the latter has been implicated in visual WM maintenance (Awh & Jonides, 2001). By contrast, in the present study, we determined whether a task that specifically engages the executive system of WM—namely, manipulation of information in verbal WM (D'Esposito, Postle, & Rypma, 2000)—can impair the conscious detection of an unexpected, task-irrelevant visual stimulus. Manipulation of items in WM is a well-studied executive function known to involve separable neural networks from simple memory maintenance (Cornoldi, Rigoni, Venneri, & Vecchi, 2000; D'Esposito, Postle, Ballard, & Lease, 1999; D'Esposito et al., 2000; Postle, Berger, & D'Esposito, 1999; Tsukiura et al., 2001). Since executive WM tasks affect the deployment of goal-driven attention (Han & Kim, 2004), we reasoned that it may also affect stimulus-driven attention and, thereby, interfere with conscious detection of unexpected, task-irrelevant visual stimuli.

EXPERIMENT 1

In Experiment 1, we compared the ability of two verbal WM tasks that differed in executive demands to induce IB. One group of participants performed a verbal WM task that simply involved rehearsing five consonants, whereas a second group was required not only to rehearse the five letters, but also to rearrange them in alphabetical order. Since both verbal WM tasks involved maintenance of information but only one involved manipulation of information, any differences in visual detection performance between these two tasks would be likely to originate at executive stages of processing (D'Esposito et al., 1999; Postle et al., 1999).

Method

Participants

Sixty-seven young adults (30 males) with normal or corrected-to-normal visual acuity participated for financial compensation or class credit.

Procedure

Five consonants were presented through headphones at an interstimulus interval of 500 msec (360-msec spoken duration and 140-msec gap), for a total stimulus presentation time of 2,500 msec. The consonants were randomly selected without replacement from a list of 10 letters: FGKNQPRSTX. One group of participants was instructed to memorize the letters in the order in which they were presented (*maintain* condition), whereas the other group was instructed to rearrange the letters into alphabetical order (*manipulate* condition). After a retention period of 4,000 msec, memory was tested with a single probe display: A single letter was presented above one of five horizontal lines arranged in a row (line length, 0.5º; distance between lines, 1º; total distance, 6.5º). For the maintain condition, the five positions corresponded to the order of stimuli presentation (left to right). For the manipulate condition, the five positions referred to the alphabetical order of the stimuli (left to right). The participants indicated by buttonpress (unspeeded responses) whether the probe letter correctly matched the verbal WM stimulus at that position (50% matched trials). In nonmatching trials, the probe contained either a letter from the verbal WM set but presented in another position or a letter that was not part of the verbal WM set (equal probability of both nonmatched trials). The participants were instructed to maintain fixation on a central dot that appeared throughout all the trials. Ten participants from each verbal WM condition performed the experiment while being filmed on video camera, to monitor for eye movements or blinks.

The participants performed a total of 12 trials. The first 6 consisted of practice trials, followed by 3 experimental trials that were identical to the practice trials. The last 3 trials consisted of the inattention, divided attention, and full attention trials. During the inattention trial, 500 msec into the WM retention interval, an unexpected critical stimulus (CS; 1º white clover drawn from Zapf Dingbats font) was presented for 60 msec, 9.9º from fixation in one of the four quadrants of the display. The participants were not informed of the presentation of this stimulus. Detection of the CS was measured 1,500 msec after its presentation by a series of questions presented on the computer screen (the WM probe was not presented on this trial). The first question assessed whether the participants had seen anything unusual during the trial. The participants responded by selecting *yes* or *no*, using separate keyboard presses. The second question asked the participants to select which stimulus they might have seen among 12 possible objects/symbols. However, because this question proved to be too difficult even under full attention (performance was at chance), it was not further analyzed. The third question asked the participants to select in which of the four quadrants the CS had appeared. In keeping with a previous study (Todd et al., 2005), CS detection was considered successful if the participants (1) reported *yes* to the presence of the unexpected stimulus and (2) correctly selected the quadrant location.

At the onset of the divided attention trial (fifth trial), the participants were explicitly instructed to both perform the memory task and detect the CS during the retention interval. This trial proceeded as described for the inattention trial, except that detection of the CS was assessed only after the full WM retention period and WM probe presentation. The full attention trial (sixth trial) proceeded as the inattention trial, except that the participants were instructed to ignore the working memory task and to pay attention only to the CS. The full attention trial established whether the CS could be seen with undivided attention.

Results and Discussion

Three participants failed to see the CS on the full attention trial and were, therefore, discarded from further analysis (Most et al., 2001; Todd et al., 2005). In addition, within the subset of participants for whom eye movements were monitored, 2 participants (1 in each WM group) were removed because they blinked or moved their eyes within a 100 msec window of CS appearance, leaving 62 participants for further analysis (31 per group). Thus, only a small proportion of the participants did not fixate at the time of stimulus presentation, and there were no differences in eye movements/blinks between the two WM groups.

Verbal Working Memory Performance

WM accuracy was analyzed for the first three experimental trials (before the CS was shown). The accuracy of the WM task was greater in the maintain than in the manipulate condition [93.5% vs. 85%; $t(53) = 2.30$, $p < .05$].[1]

Critical Stimulus Detection

Thirty-five percent of the participants in the maintain condition failed to detect the stimulus during the inattention trial ($p < .001$, relative to the full attention trial).[2] More important, an even greater number of participants (68%) failed to detect the CS in the manipulate condition than in the maintain condition (see Figure 1A; $p < .05$). In contrast, the incidence of CS detection did not differ between the two WM conditions in the divided attention trial (see Figure 1B; $p = .43$), despite the fact that the participants were still attending to the verbal WM tasks, as evidenced by similar verbal WM performance in the divided attention and the first three experimental trials (ps $> .4$). These results indicate that performing a verbal WM task may result in a failure to detect an unexpected, task-irrelevant visual stimulus. More important, they also demonstrate that adding an executive operation to the verbal WM task strongly exacerbates the incidence of IB. Finally, the results reveal that this IB is contingent on the observer's not attending to the CS, since it is severely reduced under divided attention (see also Most et al., 2001).

Because the manipulation condition was harder than the maintain condition, it could be argued that the increased IB incidence is a result of general task difficulty or arousal effects, rather than the involvement of executive processes per se. However, if it is the executive process of alphabetization that induces IB, greater IB rates should still be obtained in the manipulate condition even when that condition is equated in difficulty with the maintain condition. An executive process account also predicts that IB rates should no longer be different between the two WM conditions if the CS is shown after alphabetization is completed, even though the WM performance for these two conditions should still be different. Experiment 2 tested the latter assumption by presenting the CS at the end of the WM retention interval, whereas Experiment 3 tested the former by matching verbal WM performance in both conditions.

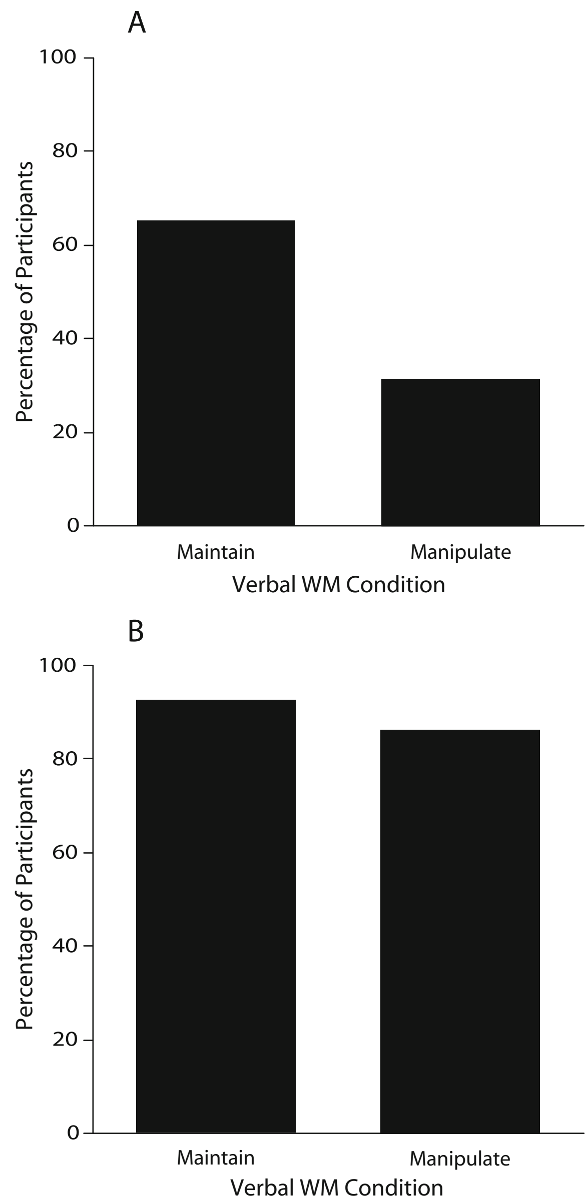

Figure 1. Experiment 1: Effect of verbal working memory (WM) maintenance (left) and manipulation (right) on the percentage of participants who detected an unexpected visual stimulus. (A) Inattention trial. (B) Divided attention trial.

EXPERIMENT 2

Experiment 2 assessed whether executive load would still induce IB if the CS was shown after the participants had rearranged the verbal WM stimuli into alphabetical order.

Method

Fifty-two young adults (23 males) with normal or corrected-to-normal visual acuity participated for financial compensation or class credit. Six participants were removed from the analysis—4 of whom failed to see the CS on the full attention trial and 2 of whom demonstrated eye movements (which were monitored for 20 participants)—leaving 46 participants (23 per group).

Pilot experiments suggested that alphabetizing was not always completed by 4 sec after letter presentation. For this reason, we doubled the retention interval from Experiment 1 to 8 sec, and the CS appeared 7.5 sec after verbal WM stimuli presentation. In all other respects, this experiment was similar to Experiment 1.

Results and Discussion

CS detection was not differentially affected by the two verbal WM conditions in the inattention trial (see Figure 2; $p = 1$). Similar results were also obtained in the divided attention trial ($p = 1$). Thus, the manipulation condition

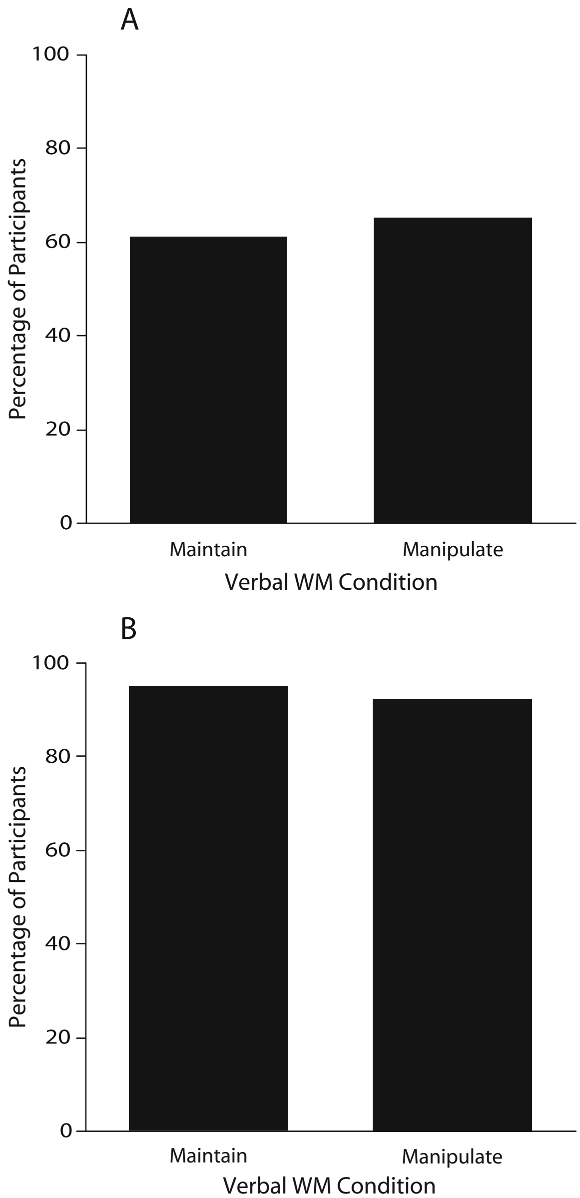

Figure 2. Experiment 2: Effect of verbal working memory (WM) maintenance (left) and manipulation (right) on the percentage of participants who detected an unexpected visual stimulus. (A) Inattention trial. (B) Divided attention trial.

no longer induced IB once alphabetical reordering was completed. Comparison of Experiments 1 and 2 revealed comparable IB rates between the two maintain conditions ($p = 1$) but lower IB rates in the manipulate condition in Experiment 2, relative to that condition in Experiment 1 ($p < .05$). This result confirms that the lack of an effect of WM condition in Experiment 2 was due to the increased rate of CS detection in the manipulate condition in this experiment. Importantly, the manipulate and maintain conditions produced similar incidence of IB despite the fact that they still differed in WM accuracy (maintain, 91.3%; manipulate, 72.5%; $p < .05$). Taken together, these results suggest that it was the executive process of alphabetizing that induced IB.

EXPERIMENT 3

By equating verbal WM performance in the maintain and manipulate conditions, Experiment 3 assessed whether executive processes can induce IB in the absence of task difficulty differences.

Method

Forty young adults (13 males) with normal or corrected-to-normal visual acuity participated for financial compensation or class credit. Four people who failed to see the CS on the full attention trial were removed from analysis, leaving 36 participants (18 per group).

Experiment 3 was performed as in Experiment 1, except for the following modifications. First, WM task difficulty was equated by presenting a different number of WM consonants in the maintain (5) and the manipulate (4) conditions. In addition, to minimize the possibility that the participants would convert the verbal WM stimuli into a visuospatial code, the visual probe used in Experiments 1 and 2 was replaced by an auditory one. This auditory probe consisted of the presentation of a number from 1 to 5 (for 360 msec), followed by a silent interval (390 msec) and by a letter (360 msec).

The participants made a *same* or *different* response indicating whether the number corresponded to the sample presentation order (maintain condition) or to the alphabetical order (manipulate condition) of the probe letter. The experiment consisted of 6 practice trials, 11 experimental trials, and the 3 CS trials. In the latter trials, the CS appeared 1 sec after verbal WM stimuli presentation to ensure that all the subjects had begun reordering the stimuli at the time of CS presentation in the manipulate condition. Finally, to further minimize the possibility that IB rates resulted from the rapid forgetting of the CS, the time interval between CS presentation and the CS detection questions was reduced from 1,500 to 500 msec.

Results and Discussion

The use of a smaller verbal WM set size in the manipulate (4 letters) than in the maintain (5 letters) condition successfully equated verbal WM performance (maintain, 90%; manipulate, 87%; $p > .4$). Yet, incidence of IB was still greater in the manipulate (61%) than in the maintain (28%) condition ($p < .05$, one-tailed; see Figure 3). These results strongly suggest that executive processes, independent of task difficulty, can induce IB.

The results are also not consistent with the possibility that IB resulted from the transformation of the verbal WM material into a visuospatial code. First, similar incidences of IB were found in Experiments 1 and 3, despite the fact that the use of an auditory verbal WM probe in the latter experiment provided a disincentive for visual recoding of the verbal material. Furthermore, analysis of reaction time (RT) data in the verbal WM task revealed not only that the participants' RTs increased with the serial position of the verbal WM probe, but also that they did so at a rate (250 msec/position) that was much more consistent with the rate of subvocal rehearsal (Baddeley, 1986) than with the rate of visual search for lists of letters (50 msec/item; Pashler & Badgio, 1985).

Interestingly, unlike in Experiment 1, the manipulate group was still impaired at detecting the CS, relative to

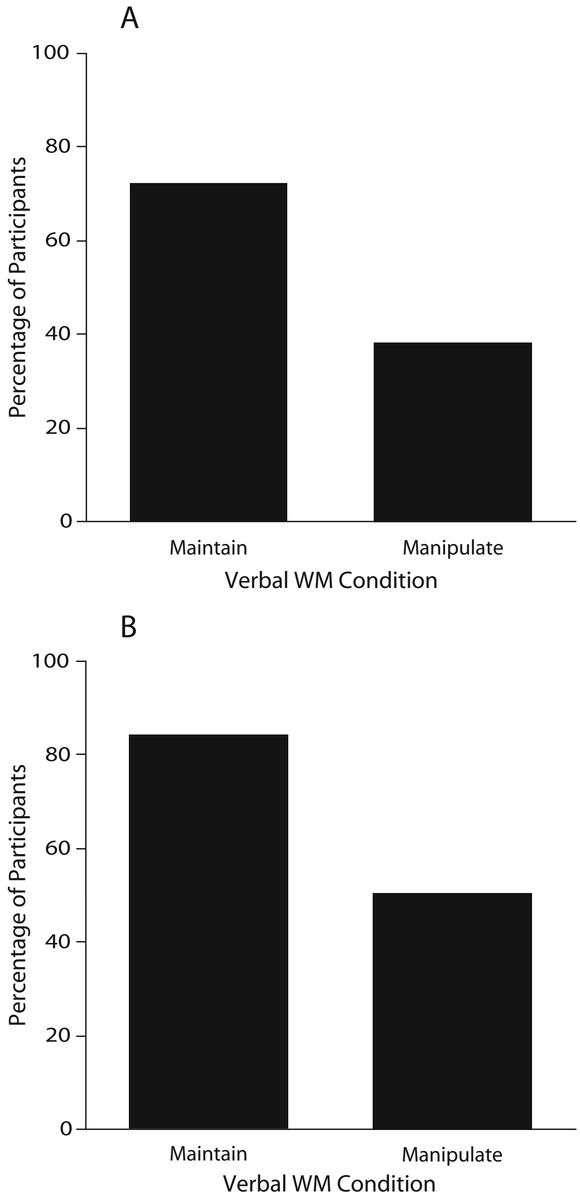

Figure 3. Experiment 3: Effect of verbal working memory (WM) maintenance (left) and manipulation (right) on the percentage of participants who detected an unexpected visual stimulus. (A) Inattention trial. (B) Divided attention trial.

the maintain group, in the divided attention trial ($p < .05$, one-tailed). The basis for this performance difference between the divided attention trials of Experiments 1 and 3 will require further investigation.

GENERAL DISCUSSION

The main finding of this study is that engagement of an executive process—that is, manipulation of information in verbal WM—is sufficient to impair the detection of unexpected, task-irrelevant visual stimuli. By directly implicating executive processes as a source of IB, these results are consistent with those in studies suggesting that cognitive demands affect IB (Simons & Chabris, 1999; Strayer et al., 2003). Since manipulations of the observer's visuospatial attentional set are also known to modulate the strength of IB (Most et al., 2005; Most et al., 2001), we conclude that IB can arise from attentional demands at either visuospatial or executive stages of information processing of the primary task. Finally, together with the visual WM maintenance study of Todd and colleagues (2005), our findings demonstrate that each of the two major operations of working memory—maintenance and manipulation of information—are capable of inducing IB.

What could be the mechanism by which manipulation of information in verbal WM affects the explicit detection of a visual stimulus? One possibility is that executive load reduces activity in the visual cortex, although evidence in favor of this hypothesis is rather equivocal. Whereas some studies suggest that the ability of unfamiliar, task-irrelevant stimuli to capture attention and activate the visual cortex is attenuated under high executive load (Spinks, Zhang, Fox, Gao, & Hai Tan, 2004), others indicate that increasing the central executive demands of an *n*-back WM task does not affect neural processing of task-irrelevant background stimuli (Yi, Woodman, Widders, Marois, & Chun, 2004).

Alternatively, executive processes could suppress the neural circuit involved in attentional orienting, so as to prevent task-irrelevant stimuli from interfering with ongoing behavioral goals (Corbetta & Schulman, 2002). Consistent with this possibility, maintenance of information in visual WM suppresses neural activity in a key brain region of the stimulus-driven attentional network, the temporoparietal junction (TPJ; Todd et al., 2005). Since the very same visual WM maintenance task also induces IB (Todd et al., 2005), it is conceivable that IB could result from suppression of activity in the TPJ. It remains to be seen, however, whether executive load also suppresses TPJ activity.

A final possibility is that alphabetization and the explicit perception of novel, task-irrelevant stimuli interfere with each other because they share common neural processes. Consistent with this possibility, both visual *oddball* detection tasks and executive working memory tasks engage the dorsolateral prefrontal cortex (Ardekani et al., 2002; Petrides, 2000; Tsukiura et al., 2001). It is unclear however, what process would be common to both manipulating information in WM and shifting attention to rare or unexpected visual stimuli, although it could be related to refocusing central attention from one stimulus to another (either in working memory or in the visual scene). Clearly, determining how executive load induces IB will be an important goal of future research.

It has recently been proposed that executive WM disrupts selective attention, which results in increased processing of task-irrelevant information (Lavie, 2005). Although this proposition may appear inconsistent with our findings, there are important methodological differences between the present study and those that support Lavie's load theory of attention. In the present study, the participants were unaware that a task-irrelevant stimulus would appear. By contrast, in studies that support Lavie's load theory, distractor presentation was expected, and these distractors may have competed with task-relevant stimuli (e.g., Lavie, Hirst, de Fockert, & Viding, 2004). In that case, active suppression of distractors would improve selective processing of the task-relevant information, and the engagement of executive working memory (in a secondary task) might interfere with the ability to filter out distractor information. In our study, since the task-irrelevant stimulus was unexpected, such attentional filtering would be unlikely to be engaged. Our findings, in conjunction with Lavie et al.'s experiments, thus underline the importance of participants' task expectancies in determining the effect of executive load on distractor processing: Whether such load leads to an increase or a decrease in distractor processing likely depends on whether participants have engaged a task set to ignore these stimuli.

AUTHOR NOTE

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NOTES

1. Two-sample *t* tests were used for behavioral comparisons involving continuous data.

2. Fisher's exact probability tests for categorical data were used for all IB comparisons.

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