

# Interference from filled delays on visual change detection

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Failure to detect changes to salient visual input across a brief interval has popularized the use of change detection, a paradigm that plays important roles in recent studies of visual perception, short-term memory, and consciousness. Much research has focused on the nature of visual representation for the pre- and postchange displays, yet little is known about how visual change detection is interfered with by events inserted between the pre- and postchange displays. To address this question, we tested change detection of colors, spatial locations, and natural scenes, when the interval between changes was (1) blank, (2) filled with a visual scene, or (3) filled with an auditory word. Participants were asked to either ignore the filled visual or auditory event or attend to it by categorizing it as animate or inanimate. Results showed that the ability to detect visual changes was dramatically impaired by attending to a secondary task during the delay. This interference was significant for auditory as well as for visual interfering events and was invariant to the complexity of the prechange displays. Passive listening produced no interference, whereas passive viewing produced small but significant interference. We conclude that visual change detection relies significantly on central, amodal attention.

**Keywords:** change detection, visual attention, dual-task interference, divided attention, visual short-term memory, central executive control

## Introduction

Our poor ability to detect salient changes across simultaneously or successively presented visual displays has popularized the use of change detection in studies of visual perception (O'Regan, 1992; Rensink, O'Regan, & Clark, 1997), short-term memory (Luck & Vogel, 1997; Pashler, 1988; Phillips, 1974), and consciousness (Beck, Rees, Frith, & Lavie, 2001; Landman, Spekreijse, & Lamme, 2003; Pessoa & Ungerleider, 2004). Most studies have used the flicker paradigm, where an original image and an altered version are briefly separated by a flicker of a blank screen (Rensink et al., 1997). In natural vision, however, changes are often separated by events more complex than a blank screen, during which the observer may be engaged in other cognitive tasks. For example, in the person change experiment by Levin and Simons (1997), a pedestrian was asked to give directions to one experimenter. During the conversation, several people dressed up as construction workers carried a door and cut between the pedestrian and the experimenter. After the cut, a second experimenter replaced the first, yet many pedestrians failed to notice the person change. In this setting, the change occurred across several seconds of delay, during which new visual input was presented and

the observer was busy with a cognitive task (i.e., giving directions). How is our ability to detect visual changes affected by intervening sensory input and by additional cognitive tasks? In this study, we address this question by systematically varying stimuli presented between the pre- and postchange displays and the task that observers must conduct on those stimuli. As reviewed below, this endeavor fills in a critical gap in change-detection research.

Previous studies on change detection have emphasized the role of attention. Attended objects are more likely to be noticed if they change, whether attention is directed by salient features (Wright, 2005), sudden onsets (Cole, Kentridge, & Hevywood, 2004), observers' experience and interest (Austen & Enns, 2003; Rensink et al., 1997; Yaxley & Zwann, 2005), or microstimulation of subcortical structures (Cavanaugh & Wurtz, 2004). Rensink (2000) proposed that attention is necessary to maintain a coherent representation of visual objects, without which change detection would be impossible.

Although visual selective attention to the potential change is known to modulate change blindness, other aspects of attention have received little investigation. We do not know whether change detection requires not only visual attention but also central, amodal attention. A few studies have hinted that visual selective attention during prechange encoding is not the only attentional process that

limits change detection. For example, Levin, Simons, Angelone, and Chabris (2002) showed that even central objects could lead to change blindness, suggesting that selective attention to potential changes is insufficient for change detection. Gallace, Auvray, Tan, and Spence (2006) showed that visual transients presented during the delay interval of a tactile change-detection task impaired performance, suggesting that cross-modal attention affects tactile change detection. Gallace et al. interpreted these results in terms of spatial interference: Spatial processing of visual transients may interfere with remembering the locations of tactile stimuli, yet these results could also reflect more general interference from any new input during the delay.

The goal of this study was to delineate the role of amodal, central attention in visual change detection. To this end, we employed a divided attention paradigm (Baddeley, 1986; Gallace et al., 2006) by adding a new visual or auditory stimulus that was either passively encoded or actively processed. To minimize interference on the encoding of prechange display and on the comparison between pre- and postchange displays, we restricted the secondary task to the delay interval. If attention is needed only during the encoding or comparison stages of change detection, then performance should not be affected by filled delays. In contrast, if attention is needed throughout the change-detection task, perhaps to maintain the coherence of visual

objects after their disappearance (Rensink, 2000), then change detection should be impaired by divided attention during the delay. The specific pattern of interference from visual and auditory stimuli can further reveal the roles of amodal, central attention and modality-specific visual attention.

## Experiment 1: Change detection of colors

In this experiment, participants performed a primary change-detection task of colors. We used the single-shot presentation method, where the pre- and postchange displays were presented only once, separated by a short interval (Pashler, 1988; Rensink, 2002). To assess interference effects from filled delays, we varied the following factors. First, stimuli presented during the delay could be (1) a visual scene, (2) an auditory sound, or (3) a blank screen. Second, participants either (1) ignored the visual or auditory input during the interval or (2) attended to it by categorizing the stimulus as animate or inanimate. Finally, the complexity of the prechange display was manipulated to contain either few items or many items. Figure 1 shows a schematic illustration of the displays.

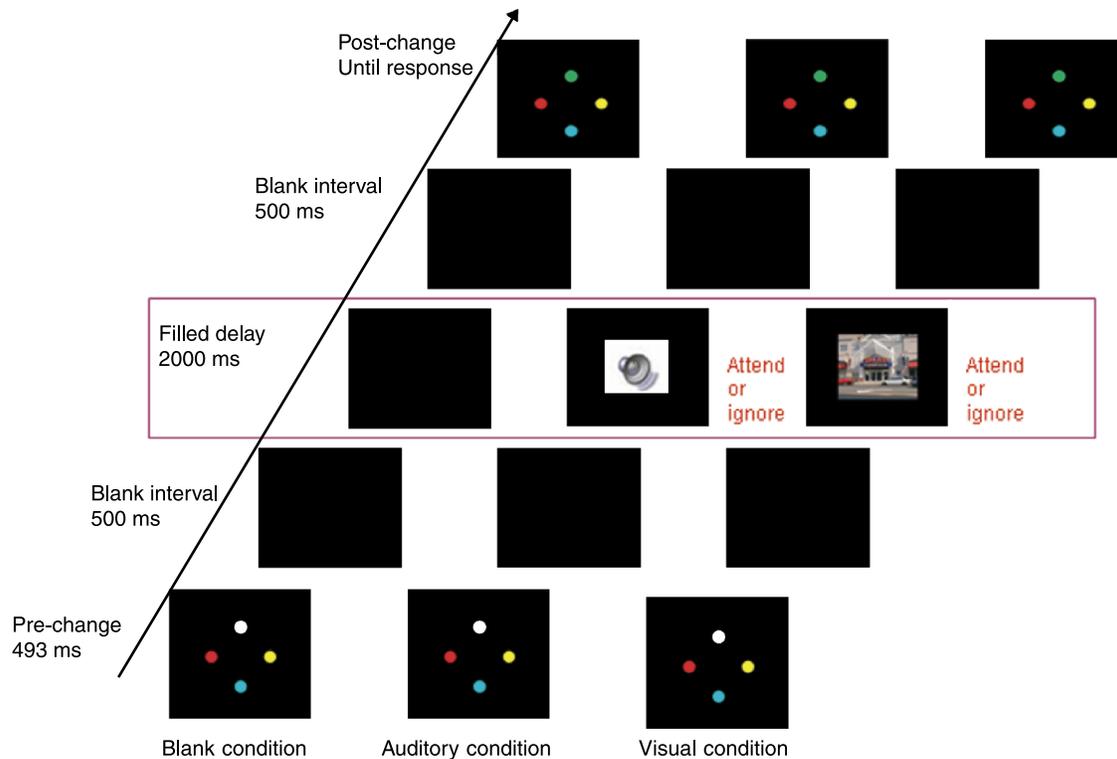


Figure 1. Sample trials tested in Experiment 1. There were two, three, or four colors on the pre- and postchange displays. During the delay interval, a blank, a scene, or an auditory word was presented and participants either ignored the new input or attended to it by deciding whether it was animate or inanimate.

These manipulations allowed us to assess whether new input presented during the interval could interfere with change detection even when no task was required on the new input. We could also test for modality-specific interference effects by comparing visual and auditory conditions and attention effects by comparing attend and ignore conditions. Additionally, the complexity manipulation enabled us to estimate the source of interference. If the filled delay interfered specifically with storing prechange stimuli in short-term visual memory, then interference should increase when there were more prechange items. Alternatively, if the filled delay interfered with central executive processes, then interference should be independent of the number of items on the prechange display.

## Method

### Participants

All participants in this study were volunteers recruited from Harvard University and its community. They had normal or corrected-to-normal visual acuity and normal color vision. Participants received course credit or payment. There were 28 participants (18–35 years old) in [Experiment 1](#), of which 13 participated in the auditory filled-delay conditions and 15 participated in the visual filled-delay conditions.

### Change-detection stimuli

The stimuli for the primary color change-detection task consisted of two, three, or four colored circles ( $1.64^\circ$  in diameter) placed equidistant on an imaginary circle (radius =  $4.1^\circ$ ) centered at central fixation. The colors were randomly selected, without replacement, from nine possible colors: red, green, blue, yellow, white, gray, purple, brown, and azure. The pre- and postchange displays were identical on half of the trials and different in one color on the remaining trials. When a color changed, it became a new color not presented on the prechange display. Participants were asked to press “s” if the two displays were the same and “d” if they were different.

### Filled delay: Visual

Participants who took part in the visual filled-delay conditions saw either a blank screen or a natural scene ( $10.5^\circ \times 10.5^\circ$ ) during the interval between the pre- and postchange displays. A total of 10 scenes were used as filled delays, half of which contained people or animals whereas the other half were inanimate. In half of the filled-delay blocks, participants were told to ignore the natural scenes (passive). In the other half of the filled-delay blocks (attend), participants were told to press “l” if the scene contained animate information and “k” if the scene contained no animate information.

### Filled delay: Auditory

Participants who took part in the auditory filled-delay conditions always saw a blank screen during the interval between the pre- and postchange displays. However, in the filled-delay blocks, an auditory stimulus was presented during the delay. The auditory stimulus consisted of a computer-generated female voice that pronounced 1 of 10 words, half of which were animate (“boy,” “girl,” “cow,” “dog,” and “horse”) whereas the other half were inanimate (“car,” “house,” “map,” “chair,” and “table”). Similar to the visual filled-delay conditions, half of the auditory filled-delay blocks required participants to categorize the input as animate or inanimate (attend), whereas the other half involved passive listening (passive).

### Design

The secondary task modality (visual or auditory) was tested between two participant groups, whereas color set-size (two, three, or four) and filled-delay conditions (blank, passive, or attend) were manipulated within participants. To minimize task-switching costs, we tested different color set-size conditions and filled-delay conditions in different blocks, each consisting of 24 trials. Each participant completed 24 practice trials and 18 blocks of experimental trials (2 blocks per filled delay per set size). The order of the 18 blocks was randomized. Change present or absent and distractor category (animate or inanimate) were randomly and evenly selected.

### Procedure

On each trial, the prechange display was presented for 493 ms, followed by a 3,000-ms interval, and then, the postchange display was presented until participants’ response or until 5 s had passed, whichever came earlier. The prechange presentation duration was longer than that used in the flicker paradigm but within the typical range used in one-shot change-detection tasks. The long duration of encoding minimized the possibility that a change-detection failure would be caused by inadequate encoding of the image. In the blank condition, there was no visual or auditory input during the 3,000-ms blank interval. In the filled-delay conditions, after a 500-ms blank interval, a visual scene (2,000 ms) or an auditory word (on average, each word lasted for 840 ms, followed by 1,160 ms of silence, for a total of 2,000 ms) was presented. Participants either ignored the filled delay completely or made an animate or inanimate judgment. The postchange display was presented after another 500 ms of blank interval (see [Figure 1](#)). The response to the secondary task must be registered during the delay for it to be considered correct (timed-out trials were infrequent). Participants received feedback (in the form of a brief computer system

beep) about their accuracy in the filled-delay task during the delay interval and feedback about the change-detection task after the change-detection response.

**Dependent measure  $\log[p(\text{correct})]$**

Just like other change-detection studies, the performance was measured in percentage correct. A significant novel aspect of our dependent measure is that we performed a log 10 transformation on  $p(\text{correct})$ . We subsequently tested the interaction of prechange set size, filled-delay interference, and modality using  $\log[p(\text{correct})]$  as the index. The logic is as follows: Suppose X and Y are two sequential events and  $p(X)$  and  $p(Y)$  are the corresponding probability of success in each event. The probability of success after the occurrence of X and Y,  $p(XY)$ , equals  $[p(X) \times p(Y)]$  only when X and Y are independent. Thus, two independent events should show multiplicativity in percentage correct but show additivity in RT. It follows that the log transformation on  $p(X)$  and  $p(Y)$  should be additive if X and Y are independent (see Schweickert, 1985, for mathematical proof and empirical discussions).

The  $\log[p(\text{correct})]$  is superior to more commonly used measures such as  $d'$  and  $A'$  in that these last two measures are not linear in scale (e.g., the difference between  $d'$  of 2 and 3 is not equivalent to the difference between  $d'$  of 1 and 2); hence, they are not suited for interaction test. Nonetheless,  $d'$  and  $A'$  are typically considered measures

of sensitivity, independent of response bias ( $\beta$ ). We thus also analyzed  $d'$ ,  $A'$ , and  $\beta$ . The same statistical pattern was observed on  $d'$  and  $A'$  as on  $\log[p(\text{correct})]$  in all experiments, showing that the results were robust to any violation of linearity in  $d'$  and  $A'$ .

**Results**

**Secondary filled-delay task**

In the secondary animate/inanimate categorization task, participants were highly accurate both in the attend-auditory condition (87%) and in the attend-visual condition (94%). The difference was significant ( $p < .05$ ), suggesting that the auditory task was more difficult.

We analyzed the color change-detection data including all trials. We also analyzed the data, excluding trials where the secondary task was incorrectly performed. The two methods led to the same statistical pattern in this experiment and in the subsequent ones. Here, we report results from all trials.

**Color change-detection task**

Figure 2 shows accuracy on a log scale as a function of color set-size and filled-delay conditions, separately for visual and auditory filled delays. Passive interference was measured by the difference between the blank baseline and the passive conditions. Active interference was

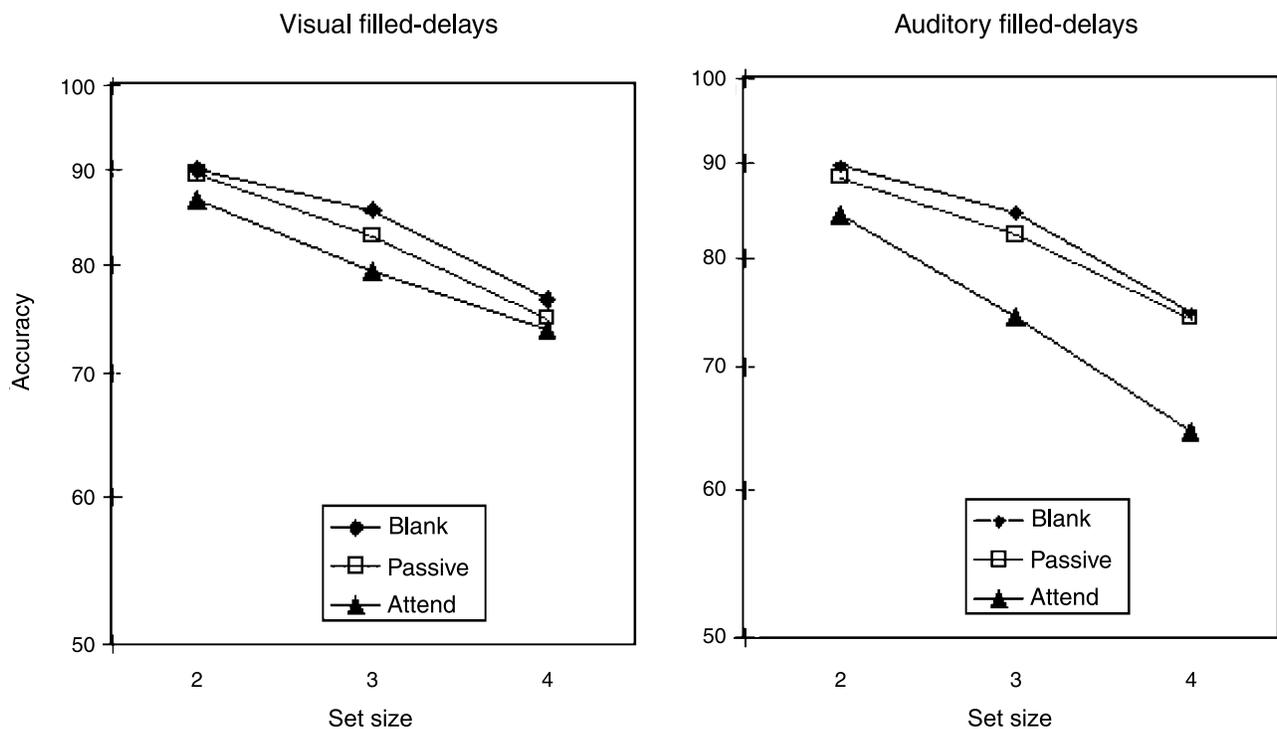


Figure 2. Results from Experiment 1 on change detection of colors: Accuracy (percentage correct) on a log scale as a function of filled-delay conditions and color set size.

measured by the difference between attend and passive conditions.

We conducted an ANOVA using filled-delay modality (visual or auditory) as a between-subject factor and using filled-delay task (blank, passive, or attend) and color set size (two, three, or four) as within-subject factors. There was a main effect of filled-delay task condition,  $F(2, 52) = 19.21, p < .01$ , suggesting that change detection of colors was sensitive to filled delays. There was also a main effect of color set size,  $F(2, 52) = 80.23, p < .01$ , with lower accuracy at higher set sizes. The main effect of filled-delay modality was not significant ( $F < 1$ ). None of the interaction effects were significant, except for the interaction between filled-delay task and filled-delay modality,  $F(2, 52) = 3.61, p < .05$ , driven primarily by a larger active interference effect in the auditory than in the visual conditions.

Follow-up analyses showed that compared with the blank baseline, the passive filled-delay task did not significantly interfere with change detection. The main effect of passive interference (passive vs. blank) was not significant,  $F(1, 26) = 2.55, p > .10$ , neither did it interact with modality,  $F < 1$ . In contrast, attending to the filled delay produced significant interference, as compared with both the blank conditions,  $F(1, 26) = 28.18, p < .01$ , and the passive conditions,  $F(1, 26) = 19.03, p < .01$ . Active interference produced by attending to the secondary filled delays (relative to the passive conditions) was greater when the secondary stimulus was an auditory sound than when it was a visual scene,  $F(1, 26) = 5.26, p < .05$ , perhaps because the auditory task was harder. However, active interference was not modulated by color set size,  $F < 1$ . Indeed, performance in the attended conditions was marginally worse than in the passive conditions even when participants only had to remember two colors for a change detection,  $t(27) = 1.99, p = .057$ .

To ensure that filled-delays affected not only response bias but also change-detection sensitivity, we verified that the above statistical pattern held for  $d'$  and  $A'$  (Table 1 shows mean  $A'$  for each condition). In both  $d'$  and  $A'$ , attending to a secondary task significantly reduced

performance ( $p < .01$ ), but passive viewing or listening did not have any effect ( $p > .14$ ). Performing a secondary task did not significantly change response bias ( $p > .25$ ).

## Discussion

Perhaps the most surprising finding from Experiment 1 was that visual change detection was significantly interfered with by an auditory task inserted between pre- and postchange displays, even when the auditory task was a simple categorization task that involved no spatial processing. The interference was largely eliminated when participants were told to ignore the filled delay. These results clearly showed that visual change detection relied on central, amodal attentional processes. In addition, they showed that focused attention was needed not only for selective encoding of the potential change but also during the delay. Notably, active interference was not reduced at smaller color set sizes when visual short-term memory (VSTM) was still not full. These results suggest that the source of interference was most likely central executive processes needed for the task, rather than memory storage capacity per se.

There was also weak but suggestive evidence for the reliance of change detection on modality-specific visual processes. Passive viewing of a visual scene appeared to produce some interference, although it failed to reach statistical significance. We will return to modality-specific interference after presenting all three experiments.

## Experiment 2: Change detection of spatial locations

Why did a filled visual or auditory stimulus interfere with change detection of colors? One possibility is that

| Set size               | Lowest (Experiment 1: 2;<br>Experiment 2: 6;<br>Experiment 3: 1) |        |         | Intermediate (Experiment 1: 3;<br>Experiment 2: 8;<br>Experiment 3: N/A) |        |         | Highest (Experiment 1: 4;<br>Experiment 2: 10;<br>Experiment 3: 2) |        |         |       |
|------------------------|--|--------|---------|--|--------|---------|--|--------|---------|-------|
|                        | Filled delay   | Attend | Passive | Blank  | Attend | Passive | Blank  | Attend | Passive | Blank |
| Experiment 1: visual   |  | .92    | .94     | .94  | .86    | .89     | .91  | .82    | .82     | .85   |
| Experiment 1: auditory |  | .91    | .93     | .94  | .82    | .89     | .91  | .72    | .83     | .83   |
| Experiment 2: visual   |  | .88    | .93     | .93  | .84    | .90     | .91  | .79    | .84     | .87   |
| Experiment 2: auditory |  | .86    | .87     | .89  | .74    | .85     | .83  | .74    | .80     | .78   |
| Experiment 3: visual   |  | .88    | .88     | .89  | N/A    |         |  | .74    | .78     | .81   |
| Experiment 3: auditory |  | .86    | .87     | .88  | N/A    |         |  | .78    | .78     | .79   |

Table 1. Change-detection sensitivity (measured by  $A'$ ).  $A'$  can range from a chance level of 0.5 to a perfect performance of 1.0.  $A'$  is the nonparametric equivalence of  $d'$  (Grier, 1971; MacMillan & Creelman, 2004) and is sometimes favored over  $d'$  in studies of VSTM (Donaldson, 1993).

participants partly relied on verbal labels to remember the prechange stimulus, especially with a relatively long delay interval. Although VSTM showed only mild decay over several seconds of delay (Phillips, 1974), other nonvisual representations may start to develop with increased delay. Perhaps the filled-delay task interfered with verbal labeling of the colors, accounting for the severity of interference from auditory as well as visual secondary tasks. To test the generality of findings from Experiment 1, we carried out a change-detection task on random dot locations. Random dot locations were difficult to name; thus, the likelihood that participants would rely on a verbal strategy was reduced.

## Method

### Participants

Twenty-two participants (18–28 years old) took part in this experiment: 13 in the auditory filled-delay conditions and 9 in the visual filled-delay conditions.

### Stimulus and procedure

This experiment was similar to Experiment 1 except for the following differences. The primary change-detection task was now a dot-location change-detection task. Because dots can be grouped to form configurations (Jiang, Olson, & Chun, 2000; Phillips, 1974), people

could remember more dot locations than colors. We thus used higher set sizes on the prechange display, with 6, 8, or 10 yellow circles ( $0.82^\circ$  in diameter) presented randomly in a  $10 \times 10$  imaginary grid ( $28.7^\circ \times 28.7^\circ$ ). A change (on half of the trials) involved one dot moving to a previously empty location. The filled-delay scenes were also enlarged ( $29.8^\circ$ ) to match the size of the dot arrays.

## Results

Participants were quite accurate in the secondary categorization tasks (84% in the attend-auditory condition and 96% in the attend-visual condition; the difference was significant,  $p < .05$ ). Figure 3 shows accuracy on a log scale, separately for visual and auditory filled delays.

An ANOVA on filled-delay modality, filled-delay task, and dot memory set size revealed a significant main effect of filled-delay task,  $F(2, 40) = 23.17$ ,  $p < .01$ , suggesting that location change detection was sensitive to filled delays, and a significant main effect of dot memory set size,  $F(2, 40) = 44.51$ ,  $p < .01$ , with lower accuracy at higher memory set sizes. The main effect of filled-delay modality was also significant,  $F(1, 20) = 7.15$ ,  $p < .05$ , in that participants in the auditory filled-delay conditions performed worse overall. None of the interaction effects were significant, all  $p$  values  $> .25$ .

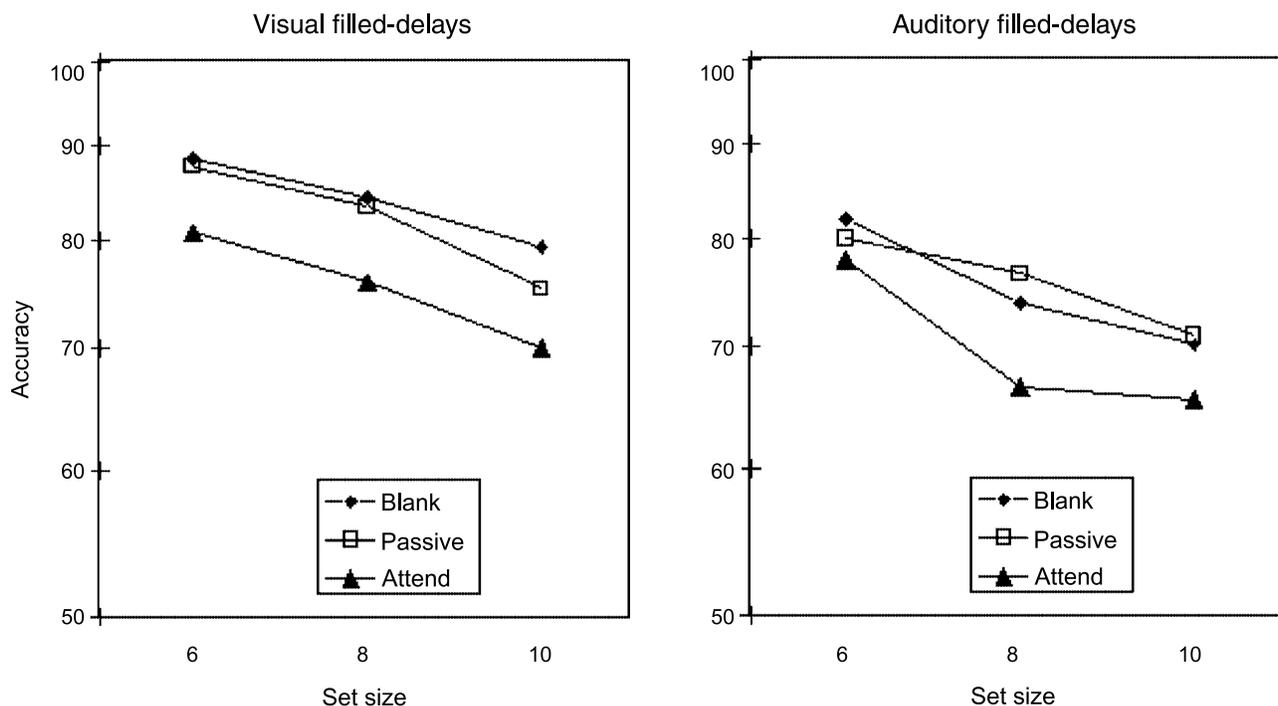


Figure 3. Results from Experiment 2 on change detection of dot locations: Accuracy rates (percentage correct) on a log scale as a function of filled-delay conditions and number of dots.

Follow-up analyses showed that compared with the blank baseline, passive viewing or passive listening during a filled delay did not result in any significant effect: The main effect of condition (blank vs. passive) was not significant,  $F < 1$ , neither was the interaction between condition and modality,  $F(1, 20) = 1.43$ ,  $p > .10$ . In contrast, attending to the filled delay significantly impaired change detection of dot locations compared with the blank conditions,  $F(1, 20) = 39.96$ ,  $p < .01$ , and compared with the passive conditions,  $F(1, 20) = 25.65$ ,  $p < .01$ . Active interference produced by attending to a secondary filled delay, relative to passive conditions, did not interact with modality ( $F < 1$ ) or with dot memory set size,  $F(2, 40) = 1.28$ ,  $p > .10$ . This pattern of results held for sensitivity measures ( $d'$  and  $A'$ ; see [Table 1](#) for  $A'$  values). Participants also tended to show increased change blindness (report “no change” when a change occurred) without a concomitant increase in false alarms, as prechange set size increased ( $p < .05$ ) and as a secondary task was carried out ( $p = .084$ ).

## Discussion

Taken together, results from the first two experiments indicate that change detection of color arrays or dot locations is impaired when observers also engaged in a secondary task before the presentation of the postchange display. Interference originated primarily from central attentional processes rather than from passive stimulus-driven processes. Attending to the filled delay led to more interference than merely viewing or listening to an input. Also, the auditory filled-delay task produced significant interference, and the size of the interference was not smaller at lower prechange set sizes. Given that the interference did not significantly scale with prechange set size, it seemed not to compete with short-term storage capacity per se but more with central attentional processes required by the change-detection task.

Although passive listening did not reduce change-detection accuracy compared with unfilled delays, passive viewing appeared to interfere with visual change detection. Just like in [Experiment 1](#), the passive visual interference effect did not reach statistical significance. It is weak but suggestive evidence that noncentral, modality-specific interference may have also occurred.

## Experiment 3: Change detection of natural scenes

Not all findings on memory of artificial stimuli generalize to memory of natural scene images. Visual memory, both short term and long term, is significantly

affected by the semantic gist of the image (Brockmole, Castelano, & Henderson, 2006; Potter, 1976; Standing, 1973). It is possible, therefore, that the results from the first two experiments were restricted to color arrays and dot locations that were devoid of any semantic gist. The main purpose of this experiment was to test interference from filled delays on change detection of natural scene images.

## Method

### Participants

Fifty-two participants (18–25 years old) took part in this experiment, half of whom completed the auditory filled-delay conditions whereas the other half completed the visual filled-delay conditions.

### Natural scene stimuli

We created 96 pairs of pre- and postchange stimuli from 96 different natural scenes selected from personal collection and online sources. Changes were made by changing the color, adding, deleting, displacing, or replacing a region or an object. All changes were conspicuous once pointed out. The 96 pairs of stimuli were divided into 6 sets of 16 scenes, and each set was tested in a different condition as specified below. To control for item-specific differences, we counterbalanced the assignment of the sets to conditions across participants.

Each participant was tested in six conditions, produced by orthogonal manipulation of filled-delay conditions (blank, passive, or attend) and prechange set size (Set Size 1 or 2) in a random order. The filled-delay conditions were the same as those used in [Experiments 1](#) and [2](#). Prechange set size was a tricky variable to manipulate. Unlike colored circles or dot locations that could be easily counted, the changes involved in natural scene images could not be enumerated. Some changes occurred to the background, some to more than one object, and some to parts of an object. For this reason, the changes were usually not detectable in a one-shot change-detection paradigm. Instead, these stimuli typically took participants 17 cycles to detect a change (Liu & Jiang, 2005). To manipulate set size and to make the task manageable in a one-shot paradigm, we increased the presentation duration of the prechanged scene to 3,000 ms. Although this duration was longer than that used in [Experiments 1](#) and [2](#), it was needed to alleviate encoding limitations on complex displays (Eng, Chen, & Jiang, 2005). We also cued the potential change region with one or two red squares ( $6.56^\circ \times 6.56^\circ$ ) on both the pre- and postchange scenes. At Set Size 1, the square always included the changed region on a change-present trial and a randomly selected nonchange region on a change-absent trial. At Set Size 2, the two squares were placed at mirror-reversed locations on both  $x$ - and  $y$ -axes; one of the squares would



Figure 4. A schematic trial used in Experiment 3’s natural change-detection experiment. The potential change region was cued by one or two red boxes to make the task approachable in a one-shot change-detection paradigm.

contain the change on a change-present trial. Participants were informed that on half of the trials, the pre- and postchange scenes were the same and that on the remaining trials, there would be a change that fell inside one of the two rectangular regions. Figure 4 shows a schematic sample of a trial. Participants completed 192 trials divided into 12 blocks (each scene was presented twice in the experiment, sometimes as a change-present trial and sometimes as a change-absent trial, in different blocks). Other parameters and procedures were the same as those in Experiments 1 and 2.

### Results and discussion

Overall accuracy for the secondary filled-delay categorization task was 92% in the attend-auditory condition and 95% in the attend-visual condition. The difference was significant,  $p < .05$ .

Data from four participants (two in each modality condition) were not included in the analysis of change-detection performance because their accuracy in one of the blank delay conditions was at chance level. Figure 5 plots the change-detection accuracy on a log scale.

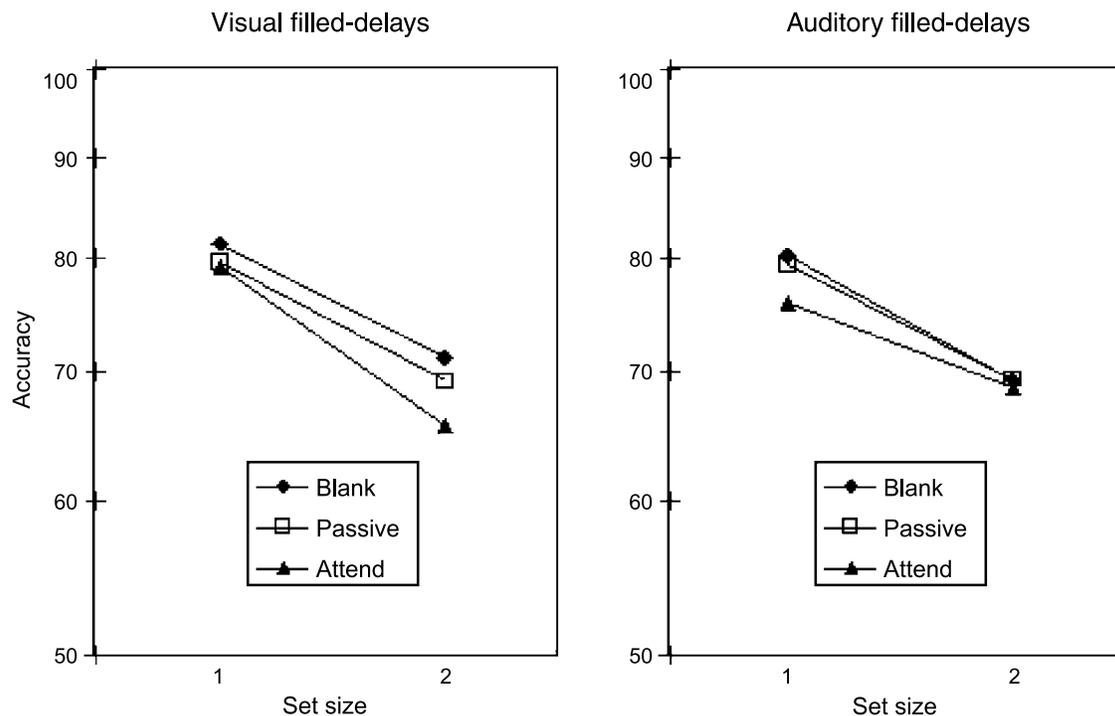


Figure 5. Results from Experiment 3 on change detection of natural scenes. Accuracy (percentage correct) on a log scale as a function of filled-delay conditions and set size. Set size refers to the number of cued regions on the pre- and postchange scenes.

We conducted an ANOVA on filled-delay modality (visual or auditory), filled-delay condition (blank, passive, or attend), and prechange set size (one or two cued regions). Once again, there was a significant main effect of filled-delay task condition,  $F(2, 92) = 5.60$ ,  $p < .01$ , suggesting that change detection of natural scenes was sensitive to filled delays, and a significant main effect of set size,  $F(1, 46) = 92.41$ ,  $p < .01$ , with lower accuracy when two regions rather than one region was cued. The main effect of filled-delay modality was not significant; neither was any interaction effect significant, all  $F$  values  $< 1$ .

Follow-up analyses revealed again that compared with the blank baseline, passive filled delays did not significantly interfere with change detection. The main effect of condition (passive vs. blank) was not significant,  $F(1, 46) = 1.76$ ,  $p > .10$ , nor was the interaction between modality and condition significant,  $F < 1$ . Paying attention to the filled delays, however, significantly impaired change detection,  $F(1, 46) = 8.83$ ,  $p < .01$ , compared with blank filled delays,  $F(1, 46) = 4.84$ ,  $p < .05$ , and compared with passive filled delays. Active interference did not interact with modality or prechange set size, all  $F$  values  $< 1$ . This pattern of results held for sensitivity measures ( $d'$  and  $A'$ ; see Table 1 for  $A'$ ). Similar to the previous experiments, participants tended to show increased change blindness (report “no change” when a change occurred), as prechange set size increased ( $p < .05$ ) and as a secondary task was carried out ( $p < .01$ ). Thus, the semantic gist in natural scenes does not make the change detection of these stimuli immune to active interference from filled delays.

## General discussion

### Central attentional interference

Whether change detection involved color arrays, dot locations, or natural scenes, performance was significantly impaired by attending to an auditory (or a visual) stimulus during the pre- and postchange interval. These results suggest that change detection across a wide range of stimuli depends on central, amodal attention. They agree with those of prior studies that showed the importance of attention in change detection (e.g., Rensink et al., 1997; Scholl, 2000). Unlike most previous research that focused on visual selective attention during encoding of prechange displays, this study showed that dividing attention during the delay interval also increased change blindness, even when attention was divided between a visual change-detection and an auditory categorization task. The fact that a nonspatial auditory task interfered with visual change detection suggests that interference did not originate from cross-modal spatial computation (Gallace et al., 2006). In addition, interference was not reduced when the pre-

change display contained fewer items, suggesting that the competition between the two tasks came primarily from central executive processes needed for the tasks, rather than from capacity limitation of VSTM (see also Klauer & Stegmaier, 1997).

Our findings not only highlighted the role of central, amodal attention in change detection but also placed significant constraints on the kind of inference one can make when using change detection to study visual perception and short-term memory. In visual perception, our findings suggest that change blindness can occur even when participants have adequately perceived the prechange display. Thus, change blindness cannot be equated with poor perceptual representation of the prechanged stimulus (see also Simons & Rensink, 2005; Varakin & Levin, 2006). In VSTM, our findings suggest that change-detection performance is not a pure measure of VSTM storage capacity. Even when VSTM storage capacity is not full, participants can still be blind to changes if other tasks compete with central attention (see also Triesch, Ballard, Hayhoe, & Sullivan, 2003). Because change detection has become the operational definition of VSTM, we will elaborate on the implications of our results for VSTM studies.

### Change blindness and VSTM

The concept of VSTM was widely in use long before change detection became a typical paradigm. VSTM is the short-term storage system that allows visual information to be held for a few seconds after its disappearance (Logie, 1995). It is distinguished from other visual memories in terms of storage duration (and other secondary properties such as capacity) and is distinguished from other short-term memories in the type of stimuli held (visual as opposed to nonvisual). Although VSTM is a relatively simple construct at the conceptual level, it is difficult to isolate in practice. Since the classic studies of Phillips (1974) and Luck and Vogel (1997), the one-shot change-detection task has been used as the operational definition of VSTM. VSTM researchers are well aware of contribution from other sources; hence, they usually use long delays to reduce contribution from iconic memory and use novel stimuli to reduce contribution from verbal memory and long-term memory. Change detection has thus been popularized as a measure of VSTM, and change-detection results have been used to test the storage property of VSTM, such as its capacity and its unit. The fact that central, amodal attention is involved in change detection, and that change blindness occurs when VSTM is not full, places significant constraints on what one can infer from change detection about VSTM.

Clearly, researchers should be cautious when using change detection as a measure of VSTM storage capacity as the resulted measure may underestimate VSTM capacity. For example, individuals who are good at detecting color changes are also good at detecting shape

changes (Eng et al., 2005). This finding need not imply that color VSTM and shape VSTM tap into the same storage space. Instead, it may result from the engagement of central attention by both color change detection and shape change detection. In addition, individuals who are better at detecting color changes (and are thus considered high-capacity individuals) are also better at filtering out unwanted items from entering VSTM (Vogel, McCollough, & Machizawa, 2005). This finding also does not necessarily mean that VSTM storage is correlated with attentional filtering. Instead, given that VSTM capacity is measured by change detection, it may well be that the kind of central attention involved in change detection is the same as the kind of attention needed to filter out unwanted items (Oberauer & Suss, 2000).

How should we resolve the inferential problem from change detection to VSTM? One solution is to maintain a theoretical construct of VSTM as a storage system, separate from central attention required by change detection. The other solution is to expand the construct of VSTM, such that it includes a storage component and a central attentional component (see Baddeley's model on working memory, Baddeley, 1986; Fougine & Marois, 2006). Both solutions require researchers to acknowledge that performance in change-detection tasks can be limited both by VSTM storage capacity and by central attentional processes.

## Secondary task

The secondary task used in the active filled-delay conditions involved multiple processes, including attending to the filled delay, categorizing the stimulus into animate or inanimate categories, and making an appropriate response. Any or all of these processes can interfere with change detection. In a follow-up experiment, we reduced the response-selection demand by not requiring a response on each trial. Instead, participants were asked to keep a mental count of the number of animate scenes (or sounds) and to report the sum at the end of a block. Previous studies showed that silently remembering a single number does not affect VSTM (e.g., Luck & Vogel, 1997; Morey & Cowan, 2004). However, even under this condition, the secondary task still significantly interfered with change detection. Thus, making an overt motor response on every trial was not the source of interference. Future studies that further dissect the secondary task are needed to pinpoint the exact processes involved in interference.

## Modality-specific interference

The emphasis on its central executive component does not negate a second, visual component of the change-detection task. In all three experiments, we observed a small but consistent trend of interference from passive

viewing but not from passive listening. In a final analysis, we collapsed data from all three experiments and calculated a single measure of passive interference across all set sizes (blank–passive). This analysis showed that whereas passive listening did not interfere with change detection ( $t < 1$ ), passive viewing significantly impaired change detection,  $t(47) = 2.08$ ,  $p < .05$ .

Why did passive viewing of a scene interfere with change detection? It is possible that visual change detection is susceptible to interference from new visual input, even when it is task irrelevant. Alternatively, participants may be unable to completely ignore the scene; thus, their attention was slightly captured, leading to interference. Note that these two possibilities are not mutually exclusive, and decades of research on attentional capture have shown that it is very difficult to separate purely bottom–up from attentionally guided capture effects (Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992; Franconeri, Simons, & Junge, 2004). An auditory sound may be less likely to capture attention than a visual scene, given that the primary task involves visual processing.

## Summary

Taken together, we demonstrated that central attentional demands as well as bottom–up visual information from filled delays can impair change-detection performance. This provides further evidence that information about the visual input alone cannot fully explain change-detection performance and that one must take into account other aspects of the task. Indeed, change detection is an ongoing task and performing a secondary task in the retention interval must involve executive processes in addition to memory storage processes. Given that visual and auditory secondary tasks showed the same pattern of influence on three kinds of change-detection tasks and that these effects did not interact with memory set size, we suggest that the core of that interference lies in the disruption of central executive mechanisms involved in change detection.

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