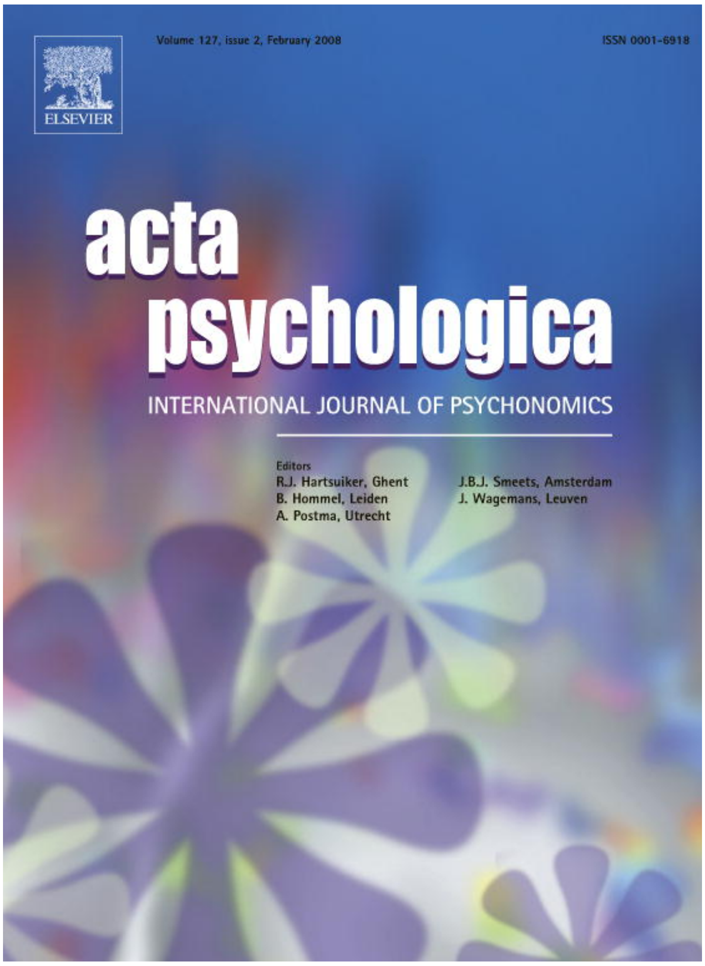
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Change detection: Evidence for information accumulation in flicker paradigms

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Abstract

Change detection in rapidly alternating pictures separated by a blank frame has been shown to be very difficult (e.g., [Rensink, R. A., O'Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. *Psychological Science, 8*, 368–373]). The three experiments reported here focus on the mechanism behind detection. More specifically, we explored whether information about the stimulus material accumulates in visual memory and thereby improves change detection. For that purpose the first experiment varied the number of repetitions of the original and modified stimulus version. Results showed that detection improved with more repetitions. The second experiment demonstrated that repetition performance improved more when both the original and the modified picture were repeated. Finally, the third experiment strengthened these findings by showing poorer detection performance when the repetition sequence was randomized. Together, our findings suggest accumulation of information in memory over picture presentations and moreover improved performance when both picture types were repeated. These results underline the importance of developing representations for both picture versions in change detection.

PsycINFO classification: 2323; 2343

Keywords: Change blindness; Visual memory; Scene Perception

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1. Introduction

Most of us feel that every gaze provides us with plenty of information about our visual surrounding in a very detailed fashion. Contrary to this intuition, recent research results indicate that under certain circumstances changes from one image to the next are difficult to detect (e.g., Grimes, 1996; Rensink, O'Regan, & Clark, 1997). Grimes (1996), for example, asked participants to study photographs of natural scenes for 10 s in what they thought was a recall task. During this presentation time a detail of the scene changed while the participant made a saccade. Although the pictures were studied thoroughly, many changes were not detected, for instance, only half of the participants noticed when the heads of two cowboys were exchanged.

This surprising failure in change detection has frequently been referred to as 'change blindness' (e.g., Rensink et al., 1997). Research regarding this phenomenon established that global disturbances like saccades, blinks, and artificial techniques of interruption, e.g. blank frames or oscillatory motion of the whole scene can cause 'change blindness' (e.g., Blackmore, Brelstaff, Nelson, & Troscianko, 1995; Cole, Kentridge, Gellatly, & Heywood, 2003; O'Regan, Deubel, Clark, & Rensink, 2000; Phillips, 1974; Rensink et al., 1997; Schofield, Bishop, & Allen, 2006; Simons & Levin, 1998). In addition, 'change blindness' has been

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reported when only localized disturbances occur, e.g. several small splashes displayed superimposed on a scene (Rensink, O'Regan, & Clark, 2000) or when the changes occur very slowly, so that no local transients are generated (Simons, Franconeri, & Reimer, 2000).

The phenomenon of 'change blindness' has been explained in terms of visual transients. In an uninterrupted visual display a sudden onset of a stimulus captures attention involuntarily (Remington, Johnston, & Yantis, 1992) and is detected very fast and with almost 100% accuracy. This is because a local change in the visual field like the appearance and disappearance of an item normally leads to a visual transient, which is easily detected. In contrast, saccades or complete disruptions of picture presentations cause a global transient, because from one view to the next every object signals a local transient or change. It seems that this global transient masks the local one, and therefore, change detection becomes difficult (Simons & Levin, 1997).

One of the most commonly used methods to explore 'change blindness' is the flicker technique (Rensink et al., 1997). Here, one view of the original picture (A) is presented briefly followed by a short blank frame. Next, the modified version of the picture (B) is presented, again followed by a short blank frame (see Fig. 1). This cycle is repeated until the participant detects the change. In a typical example of this method, Rensink et al. (1997) explored whether detection performance depends on the importance of the object of change. They used photographs of common scenes and changed either details of objects of marginal interest or details of objects of central interest. Photographs were presented for 240 ms followed by a blank frame of 80 ms in an AABB cycle. The authors found that participants needed fewer alternations of pictures when objects of central interest were changed than when objects of marginal interest were affected.

In recent years these and other similar change detection paradigms have been used to study the phenomenon of 'change blindness'. Much information concerning the content and timing of representations has been gathered by exploring which type of changes are detected fastest. Together, it seems that the gist of the scene is represented earliest (Simons & Levin, 1997; Tatler, Gilchrist, & Rusted, 2003), followed by the appearance or disappearance of an object (Mondy & Coltheart, 2000), and then changes in spatial locations and color (Aginsky & Tarr, 2000). Participants are also more likely to detect probable than improbable changes (Beck, Angelone, & Levin, 2004).

Another focus of research has been the mechanism behind change detection and related to this, the degree of information integration across the interrupted but repeated pictures. One possibility is that over repeated presentations of a detailed scene, representations build up in long-term memory, which then allow an effective comparison (i.e., the completed change is detected). Another possibility is that change detection is similar to visual serial search and mainly based on attentional processes with only sparse representations in visual short-term memory (dynamic change detection). The distinction between completed vs. dynamic change detection has been introduced by Rensink, 2002 (see also Simons & Rensink, 2005). Whereas attention is the main mechanism governing dynamic change detection,

Fig. 1. Example cycle of a typical trial in the AB condition. In this example the "Trading" sign above the shop entrance appears and disappears.

completed change detection is mainly based on visual long-term memory.[1]

The importance of attentional processes for the detection of change has been demonstrated in a number of experiments (Aginsky & Tarr, 2000; Pringle, Irwin, Kramer, & Atchley, 2001; Rensink, 2000; Rensink et al., 1997; Scholl, 2000). For example, in addition to the investigation of detection differences between central and marginal objects – as mentioned above – Rensink and colleagues (1997) also explored the effect of focal attention. They used three different types of changes: An object either changed its color, its location, or its presence (i.e., it was either present or absent). All changes were relatively large and judged as easy to notice. At the beginning of each trial, a cue was presented to manipulate focal attention for a certain type of change. Cues could be either valid or invalid. Change detection was faster in the valid cue condition than in the invalid cue condition for all change types. This, and the finding that objects of central interest were more easily detected indicate the importance of attention in change detection (for a similar conclusion with a different approach, see Pringle et al., 2001).

In a different approach to examine whether memory processes in addition to attention play a role, Rensink et al. (2000) investigated whether change blindness was caused by a lack of coherence in early visual representations. They introduced a preview of the scene of 8 s before the start of an AABB flicker sequence and reasoned that if difficulties in memory consolidation were responsible for change blindness then the preview should remedy this and allow viewers to create a coherent stable representation, which subsequently would allow effective comparisons between picture versions. Thus, a change should be noticed immediately. Instead, Rensink et al. found that the number of alternations necessary to recognise the change in the preview condition was not different from the condition without preview. The authors concluded that, at an early level of processing, representations are volatile and, although we experience a detailed view of our environment, visual representations lack coherence, thus limiting our ability to detect change.

Another line of research examined change detection more directly in relation to serial visual search processes (Mitroff, Simons, & Franconeri, 2002; Rensink, 2000; Smilek, Eastwood, & Merikle, 2000). Smilek et al. (2000) used a flicker paradigm with digits as stimuli and manipulated the display size to establish whether preattentive processes rely on visual representations in memory or whether attentional visual serial search would facilitate change detection. One of the digits in the original picture would change into another digit in the modified picture. These changes could be either large or small depending on the number of segments changing from one digit to the other (e.g., digits were in block print and in this print type a change from 2 to 4 involved more segment changes than a change from 2 to 8). In both conditions the time needed to detect changes increased with display size, i.e. the slopes of response times versus number of distractors were positive. In addition, response times for small changes increased more with display size than response times for large changes, resulting in steeper search slopes for smaller compared to larger changes. The authors interpreted these results as confirmation of efficient preattentive processes and thus as evidence of information accumulation in visual long-term memory over time, with larger changes attracting more attention and therefore needing less processing time.

However, this conclusion was challenged by Mitroff et al., 2002; (see also Stolz & Jolicœur, 2004) who proposed an alternative explanation for Smilek et al. (2000) results. In their first experiment Mitroff et al. (2002) replicated the findings of Smilek and colleagues. Then, to clarify the issue, Mitroff et al. conducted another experiment, in which they randomised the display positions of every item in each cycle. They argued that accumulation of information over time should depend upon the stable spatial location of this information. Importantly, if item locations varied randomly, no build-up in memory should be possible. Thus, for these randomly displayed items, a different pattern of results than in the previous experiment was expected. Instead, the search slopes observed in this experiment were very similar to the previously observed ones. Again, response times increased with display size and were larger for small compared to large changes. The authors interpreted this as evidence for explicit comparisons under focal attention to detect the change. If the item that changes is one of the attended ones, participants are likely to detect the change in the next picture, otherwise they move on to the next set of items. This procedure reflects a serial search process. In complex visual scenes change detection can therefore take a long time. This implies that the information of one scene is not integrated with the next display to build up a detailed representation of the scene over time. Similarly, several experiments have shown that there is no integration of information from one saccade to the next (e.g., Bridgeman & Mayer, 1983; Henderson, 1997).

Smilek et al. (2000) interpretation has also been questioned by Rensink (2002). According to Rensink, Smilek et al.'s results can also be explained by a fast-decaying retinotopic buffer, e.g. iconic memory, which allows the retention of information for about 300 ms. Smilek et al.'s display had a presentation duration of 200 ms with an 80 ms blank interval, it was situated within these boundaries. This would also suggest that the interpretation of a detailed scene representation in long-term memory by Smilek et al. might be incorrect.

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[1] The distinction between dynamic and completed change detection based on attentional versus memory processes is not absolute. It is conceivable that even in completed change detection some attentional processes have to be applied to detect the change. Similarly, in dynamic change detection some memory processes are likely to be involved – at least to prevent searching for the change at the same locations twice.

Another series of experiments by Rensink (2000) used a flicker paradigm to investigate whether the attentional demands for change detection followed the same principles as the ones for complex static displays. The stimuli used in these experiments were rectangles. One of these rectangles changed either orientation or contrast polarity (change from black to white) in half of all trials, whereas no change occurred for the rest of the trials. Similar to search paradigms, display size was varied and search slopes were the main dependent variable. In one experiment, display time ranged from 80 to 800 ms in six steps while the timing of the blank frame inserted between displays remained the same. As a result, search slopes varied with display size, but processing speed per item remained similar for most of the display times tested. The increase of search slopes with display size indicates that change detection requires attention because the search for change occurs serially. In another experiment of this series, Rensink also showed that observers seem to have a memory for the location of items in the display already examined. He concluded that change detection is similar to search in static displays in that it is also based on a limited capacity process involving focused attention.

Together, this line of research indicates that for displays with a limited number of discrete items, changes are detected by attentional serial comparisons of items in the scene. In addition, it seems that if visual information is integrated from one frame to the next, its role in change detection is only a small one.

Although the evidence for change detection through purely attentional processes without coherent and stable representation in visual long-term memory is strong, other results, mainly obtained from experiments using memory tasks and not change detection paradigms, cast some doubt on this conclusion (Castelhano & Henderson, 2005; Hollingworth, 2005; Hollingworth & Henderson, 2002, 2004; Irwin & Zelinsky, 2002; Melcher, 2001; Williams, Henderson, & Zacks, 2005; Zelinsky & Loschke, 2005). For example, Melcher (2001) found evidence of information integration over brief, interrupted displays. He presented a picture of a room for a total display time of 1, 2, 3, or 4 s. In one condition, the picture was displayed continuously for the whole presentation time; in another condition, the total display duration was cut into brief views of 0.25, 1, or 2 s. In between these brief views other pictures were presented. The author tested recall memory and found no difference between continuous or interrupted scene presentations, indicating that the information displayed over repeated short viewing situations increased in visual long-term memory similarly to an uninterrupted viewing situation.

Hollingworth and Henderson (2002) tracked eye movements in a change detection paradigm with natural scenes. In one condition the scene was changed directly after participants withdrew their focus from the area of the to-be-changed item, whereas in another condition the change was initiated before the to-be-changed item was fixated. Participants detected significantly more changes when the target had been fixated before the change than when it had not been fixated. Because fixation, and therefore presumably attention in this design had been withdrawn from the target at the time of the change, the authors concluded that not only changes to items under current ongoing attention are detected more easily, but also items which were attended to previously. In addition, changes were detected with an average latency of 5.7 s from the original time of fixation, indicating an influence of long-term memory on change detection.

In a more recent experiment, Hollingworth (2005) presented natural scenes for 20 s as a preview. This was followed by the presentation of an object in isolation. In one condition the object was part of the preview and participants were asked to indicate the position of the target item. In another condition the target was not present in the preview and participants indicated where a likely position of the object would be. Localisation performance was more accurate for previews containing the object than for previews without it, indicating that both spatial context and object locations are represented in long-term memory. This conclusion was supported by findings that showed an incidental accumulation of visual scene representation over time in long-term memory by introducing unexpected memory tests following scene perception (Castelhano & Henderson, 2005; Williams et al., 2005).

In addition, Henderson and Anes (1994) provided evidence that under some circumstances integration between saccades can take place. They presented two object frames containing letters, which were positioned above each other as a preview in the periphery on one side of the visual field, while the participants fixated a point on the other side. Immediately after presentation of the preview, participants executed a saccade to a place between the two objects. During the execution of the saccade the objects in the frames were changed. As a result only one frame contained a letter, whereas the other contained a plus sign. Participants were asked to name the letter in the final display as quickly as possible. Three different changes could occur: same-frame – a letter presented in the preview remained in the same place, but the other one was substituted by a plus sign; switch-place – a letter presented in the preview moved to the other location and the other frame was filled with a plus sign; and control – none of the letters of the preview were used. The authors found a reaction time benefit for both conditions in which the target letter had already been shown in the preview. These results imply that some information can be retained from one saccade to the next.

Together, these results clearly indicate that information can be integrated from one view to the next and thus, that more detailed visual information can be accumulated in memory. But whether these findings also apply to change detection settings and in particular to flicker paradigms is uncertain. One particular problem is the necessity to distinguish between dynamic and completed change, as these types of changes might rely on different mechanisms. For the perception of changes in progress, i.e. the detection of dynamic changes, attentional processes are most likely necessary. The detection of completed changes, however, most likely requires a comparison between the original and changed object or scene, and therefore some representation of the scene in long-term memory (Rensink, 2002). Because of the potential processing differences between dynamic and completed change, experiments looking at either of these change types cannot be compared with each other. Flicker paradigms allow the investigation of dynamic changes, whereas experiments working with longer presentations probably examine completed changes. With this in mind, some of the experiments indicating the integration of information (e.g., Hollingworth, 2005) might not be comparable to other experiments using flicker paradigms, because different processes might be involved. To make sure that dynamic change is under investigation the employment of a flicker paradigm is advisable. It might also be problematic to compare naturalistic stimuli with more artificial ones. For example, Henderson and Anes (1994) evidence of integration between saccades might only apply to situations with a very limited number of items, but not to naturalistic viewing conditions. A similar argument might explain Melcher (2001) findings. He used computer-generated scenes of rooms with a limited number of items. Likewise artificial designs with a limited discrete number of items might rely on serial search processes in change detection. Thus, it is still unclear if and when naturalistic visual information presented in flicker paradigms is integrated from one frame to the next.

This study sought to investigate whether detailed information about the depicted scene in a flicker paradigm and therefore, in a dynamic change setting, is accumulated and facilitates change detection. Using a flicker design enabled us to make more valid comparisons with research focusing mainly on attentional processes. In order to examine integration of information between scenes, we increased the number of presentations of the original scene and the modified version before and after the change. Surprisingly, such variations in change sequence within the flicker technique have not been explored systematically. To our knowledge, only Rensink and colleagues have manipulated the change sequence (Rensink, 2000; Rensink et al., 1997). In one condition, Rensink et al. (1997) presented the original scene twice, followed by two presentations of the modified scene, each displayed for 240 ms (AABB cycle). Each picture was interrupted by an 80 ms blank. In another condition, they merged the presentation time for original and modified versions including the blank. This led to an AB cycle with 560 ms presentation time per picture. Rensink et al. argued that if the previous short presentation time hindered the consolidation of a representation in memory, then this longer amount of time should result in better performance because Potter (1976) had previously provided evidence of memory consolidation for pictures presented for around 400 ms. Unexpectedly, Rensink et al. found no difference in change detection between these two conditions and therefore concluded that consolidation of the scene representation did not influence change detection.

In light of the above-described evidence in favor of memory involvement (Castelhano & Henderson, 2005; Hollingworth & Henderson, 2002; Irwin & Zelinsky, 2002; Melcher, 2001; Williams et al., 2005; Zelinsky & Loschke, 2005) it seems possible that the prolongation of presentation time was not substantial enough to find a potential improvement in performance. It is also conceivable that a prolongation of presentation time, as described by Rensink et al. (1997), made the original flicker paradigm more similar to static search displays, because participants had more time per presentation to search the display. This might have led to a stronger emphasis on focussed attention, rather than the build-up of visual representations in memory. This argument could also account for Rensink (2000) findings for display time variations from 80 to 800 ms. Thus, an increase in the number of pictures before the change, while keeping the individual display times short, might still affect change detection. In our first experiment, we therefore manipulated the number of frames presented before and after the change to investigate a potential integration of visual information in memory.

Related to this manipulation, we explored in a second experiment, whether repetition of both picture types – original and modified version – compared to repetition of only the original version, impacted on change detection performance. As far as we know, this aspect of flicker paradigms in change detection has not been investigated yet. Several studies presented a prolonged preview of the original picture (e.g., Hollingworth, 2005; Rensink et al., 2000), but the presentation time of the modified picture was not expanded. If a comparison between accumulated visual representations of the original and modified picture takes place in order to detect change, it is only reasonable to assume that the number of replications for both versions of the display is important.

Finally, in a third experiment we focused on the effect of regularity for repeated picture versions. Accumulation of information from the original and the modified picture version should be easier if both pictures alternate regularly (i.e. in AABB cycles) compared to irregular changes between both pictures. Thus, change detection should be easier in the former compared to the latter case if it relies on accumulated visual representations.

2. Experiment 1

The goal of this experiment was to investigate whether visual information of a scene would be integrated to form a more detailed representation across frame presentation in long-term memory. Previously, Rensink et al. (1997) and Rensink (2000) have found no evidence for such an effect on detection performance when increasing viewing time within a flicker paradigm and accordingly, have only assumed a small memory impact of short-term memory in change detection. Results obtained from scene presentations, however, (e.g., Castelhano & Henderson, 2005; Hollingworth & Henderson, 2002; Irwin & Zelinsky, 2002; Melcher, 2001) suggest that such accumulation can take place. One reason for this discrepancy might be the method of prolongation of presentation time used by Rensink et al. (1997) and Rensink (2000). It is possible that different processing mechanisms take place when the picture versions are presented for a longer duration. In contrast, a repetition of several original and modified versions of the display scene would ensure that the nature of the flicker paradigm is preserved. It may be that accumulation in long-term memory facilitates change detection under these conditions. To investigate this question we used original and modified versions of natural scenes and varied the number of frames presented before and after the change occurred. In one condition only one picture was displayed before the change (AB cycle), in a second condition one scene was presented twice before the change (AABB cycle), and in a third condition, pictures were presented five times before the change occurred (AAAAABBBBB cycle). In all cases, the number of original and modified versions displayed was the same. We considered RT to detect the change as well as number of changes that occurred until change detection. If participants were able to create a complete representation in long-term memory, then RTs for change should be the same regardless of the cycle type involved, and the number of changes required to detect a change should be less in the AAAAABBBBB cycle than in the AB and AABB cycle. In contrast, if changes were detected based on serial search and information accumulation played no role, then the number of changes required to detect a change should be similar for all three cycle types.

A secondary goal was to explore whether accumulation of information, if it occurred at all, differed across different change types. Previous research has found that the appearance or disappearance of an object is easiest to detect, followed by changes in spatial locations and changes in color (Aginsky & Tarr, 2000; Mondy & Coltheart, 2000). Aginsky and Tarr (2000), for example, explored the effects of precues on different types of change in a flicker paradigm when only minor details were changed in naturalistic scenes. Changes could involve the color, location, or presence of an object or image detail. In one condition the type of change was cued with 100% validity; in another no cue was presented. They found that cuing was only beneficial for changes concerning the color of an object. Thus, directing attention towards color changes improved change detection. In contrast, location and presence changes did not gain from cuing. Aginsky and Tarr interpreted this as evidence that in contrast to color, location and presence features are encoded automatically into visual short-term memory. We used the same three change types in our experiments: change of color, change of location, or the presence of an item to explore whether differences between change types would occur. For instance, it might be that information accumulation in memory becomes more important for changes regarding color because they are more difficult to detect.

2.1. Method

2.1.1. Participants

In this experiment 18 students (3 males) from the University of Würzburg, Germany took part in an individual session of approximately 30 min. They were between 18 and 39 years old (mean age 22.3). Their participation was part of an undergraduate course requirement. All of them reported normal or corrected-to-normal vision. No participant took part in more than one experiment.

2.1.2. Apparatus and stimuli

Stimulus presentation and collection of responses were performed by an IBM-compatible computer with a 17-in. VGA-Display controlled by E-Prime (Schneider, Eschman, & Zuccolotto, 2002). Responses were collected with a standard keyboard. The photos used as material for all the experiments were a subset of the material used by Aginsky and Tarr (2000)[2]. The photos were originally collected from a PhotoDisc CD Sampler (PhotoDisc, Inc., Seattle, WA) and modified by Aginsky and Tarr to create modified versions of the original pictures. Changes looked very natural and affected minor details of the picture. In total 60 pictures displaying natural scenes were used. The size of the images ranged between 9 and 15.5 cm in width and between 10 and 13.5 cm in height. Each picture existed in two versions, which differed either according to color details, location of an object, or presence of an object. Three of the pictures were used for training trials. The other 57 photos were subdivided into three picture sets, with set 1 containing 7 color changes, 5 location changes, and 7 presence changes, set 2 containing 7 color changes, 6 location changes, and 6 presence changes, and set 3 containing 6 color changes, 6 location changes, and 7 presence changes.

2.1.3. Design and procedure

The approximate viewing distance was 60 cm. Presentation times per picture were 240 ms. In between scene pictures a black blank frame was inserted and displayed for 80 ms. The same durations have been used successfully in previous change detection experiments to create flicker paradigms (Aginsky & Tarr, 2000; Rensink et al., 1997).

Three different versions of a flicker paradigm were used. In the first condition the original and modified version of one scene alternated, resulting in an AB cycle. Fig. 1 shows an example of a typical AB cycle. In the second condition both the original and modified version was repeated twice, resulting in an AABB cycle. In the third condition, the number of frames of the original and modified versions was extended even more, with 5 frames of each type

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[2] We thank Aginsky and Tarr for making their material available.

presented before the change. This resulted in an AAAAABBBBB cycle. In all conditions the number of original and modified pictures was the same, but the sequence of frames and thus the frequency of changes differed between conditions.

Each picture was presented once per participant. Whether a picture was presented in the AB, AABB, or AAAAABBBBB condition was counterbalanced across participants because the assignment of picture sets to flicker condition was counterbalanced. The sequence of pictures, and thus the order of change frequency conditions were pseudo-random because in each trial a picture was drawn randomly without replacement.

Participants started each trial by pressing the space bar. Then the respective frame sequence was presented until the participant pressed the space bar to indicate detection of the change. Response times were measured from the first change that occurred in a flicker sequence to the onset of the response. Participants were requested to detect the change and to type in a short description of the changed detail. This allowed us to verify whether participants really detected the change and not just pressed the space bar to end the trial. If participants were not able to detect a change in a given trial, they were allowed to abandon the search and to self-terminate the trial by pressing the space bar. In this case, they were asked to type "..." instead of an item description.

At the beginning of the experiment, participants were informed that each picture contained a color, a location, or a presence change. To familiarize participants with the trial procedure, three pictures in an AB cycle, each containing one of these different types of change were presented as practice trials. Participants were not informed that the frequency of changes differed. That is, they were not aware that changes could occur after different numbers of frames. Practice trials were followed by the 57 experimental trials presented in random order, thus the experimental conditions were not blocked.

2.2. Results

Statistical tests were conducted using repeated measurements analysis of variance (ANOVA) and for post-hoc pairwise comparisons, the least significant difference test (LSD) was used. For all experiments reported here the assumption of normality of the RT distribution was confirmed (Kolmogorov–Smirnoff test, $p's > 0.20$).

Only trials with correct responses were included in the analysis. Taken together, participants did not detect the changes correctly in 10.8% of all trials. In most of the error trials (90.9%), participants had not seen any change. That is, they either gave up to search for the change or they pressed the space bar erroneously without having seen a change. False descriptions of the change were given only in 9.1% of the errors, that is, in 1.0% of all trials. None of the participants reported change detection before the actual occurrence of a change in the sequence. Errors were more common in the AAAAABBBBB change condition (17.4%) than in the AABB (10.4%) and the AB condition [4.6%, $F(2,34) = 12.67$, MSE = 2,225.7, $p < 0.001$]. Errors also occurred more often for color changes (14.2%) than position changes (11.0%) and presence changes [7.2%, $F(2,34) = 4.87$, MSE = 665.1, $p < 0.05$]. Mean RTs for failures were 44,831 ms in the AAAAABBBBB change condition (range 12,428–117,336 ms), 44,413 ms in the AABB change condition (range 3,927–166,228 ms), and 40,812 ms in the AB change condition (range 9,656–127,853 ms). Thus, we can rule out that participants abandoned change detection earlier in the AAAAABBBBB condition than in the other conditions. Furthermore, the observation that participants terminated error trials with similar RTs irrespective of change frequency conditions, suggests that participants simply decided to abandon the search after a certain amount of time. Number of changes did not play a role here, presumably because participants were not aware that change frequency was varied.

Mean detection time and mean number of changes required before detection were calculated and averaged across participants and are displayed separately for each change frequency condition and type of change condition in Figs. 2 and 3, respectively.

An ANOVA of change detection time with the within subject factors of change frequency and type of change revealed significant main effects of both factors. Change detection time differed significantly across the three change frequency conditions [$F(2,34) = 21.26$, MSE = 1,107,842,828.2, $p < 0.001$]. Pairwise comparisons showed no difference between the AB and AABB cycle ($p = 0.17$), but a large difference between AB and AAAAABBBBB cycle ($p < 0.001$) and AABB and AAAAABBBBB cycle ($p < 0.001$). In addition, there was a main effect of change type [$F(2,34) = 10.92$, MSE = 498,634,700.0, $p < 0.001$]. Pairwise comparison for this factor revealed that presence changes were detected faster than position changes

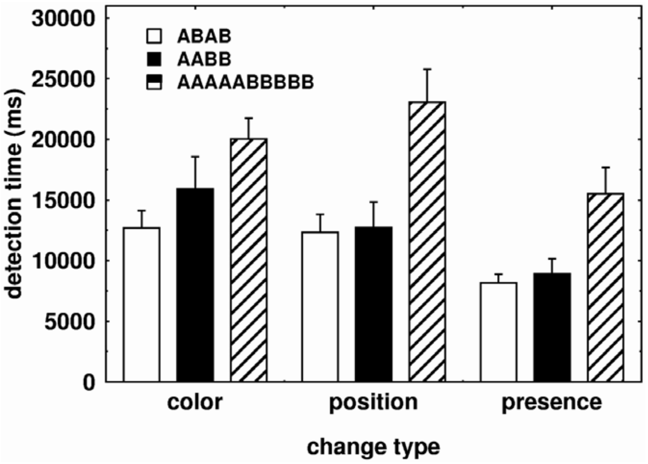

Fig. 2. Mean change detection time as a function of change frequency (AB, AABB, AAAAABBBBB) for the three change type conditions in Experiment 1. Error bars indicate one standard error.

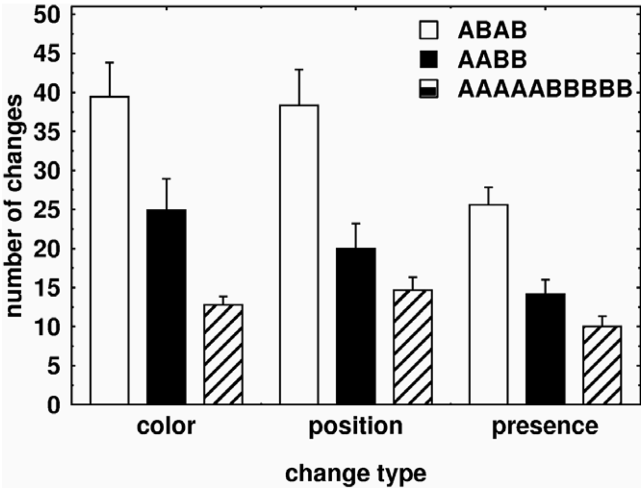

Fig. 3. Mean number of changes needed for detection as a function of change frequency (AB, AABB, AAAAABBBBB) for the three change type conditions in Experiment 1. Error bars indicate one standard error.

($p < 0.001$) and color changes ($p < 0.001$) but there was no reliable difference for position and color changes ($p = 0.90$).

The interaction between the factors change frequency and change type did not yield significant results [$F(4,68) < 1$].

The same class of ANOVA on number of changes needed before a change was detected also showed a significant difference across the change frequency conditions [$F(2,34) = 52.63,\ \mathrm{MSE} = 6{,}794.4,\ p < 0.001$]. The number of image alternations required to detect the change fell as the number of repetitions between alternations increased (see Fig. 3). Pairwise comparisons showed that the number of changes presented until detection was larger in the AB than AABB and AAAAABBBBB conditions and it was larger in the AABB than the AAAAABBBBB condition (all p's < 0.001). In addition, the different types of changes had a significant effect on the number of changes needed before participants detected the change [$F(2,34) = 12.36$, $\mathrm{MSE} = 1{,}302.6,\ p < 0.001$]. Pairwise comparisons of this factor showed that presence changes were detected faster than position changes ($p < 0.001$) and color changes ($p < 0.001$) but again performance for position and color changes ($p = 0.53$) did not differ significantly.

As for detection time, the interaction between both factors was not significant [$F(4,68) = 1.36,\ p = 0.26$].

The first experiment showed that participants needed fewer changes to detect the change when several frames of one picture version were shown than when fewer frames were shown. If change detection relied only on attentional effects without any memory involvement, then the number of changes until detection should be the same in each condition. The fact that participants needed fewer changes when each picture version was repeated five times, indicates that visual information accumulated over time. However, results also reveal that information accumulation when disrupted by blank frames is not perfect. If complete coherent representations could be accumulated in long-term memory, RTs for change detection should be the same in each condition because participants could search for the change based on their coherent scene representation. Instead, participants needed more time to detect change and also made more errors in the AAAAABBBBB condition, which suggests that this condition was also more difficult than the shorter-cycle conditions.

Regarding the type of change, our results confirm several other findings (e.g., Aginsky & Tarr, 2000; Mondy & Coltheart, 2000) in so far as changes concerning the presence of an object were detected faster than location or color changes. But unlike Mondy and Coltheart, we failed to find a significant difference between location and color changes. More importantly, however, the lack of an interaction between change type and change frequency indicates that at least slight variations of difficulty to detect a change had no influence on the effects of chance frequency.

3. Experiment 2

Experiment 1 showed that participants needed fewer changes to detect a change when both picture versions were repeated frequently. This suggests that participants were able to accumulate visual information across presentations. In contrast, Rensink et al. (2000) found no benefit of an 8 s preview that was presented before the start of an AABB flicker sequence. These contradictory findings can be reconciled with each other, if one assumes that not only the repetition of the original picture, but also the repetition of the modified picture, is important for change detection. Maybe both picture versions need to be represented in memory to facilitate change detection.

Our second experiment explored this possibility by manipulating the number of presentations per picture version. In one condition we presented a cycle, in which both original and modified picture versions were presented equally often (AAABBB cycle). In another condition we used a cycle in which the original picture was repeated, but not the modified version (AAAAAB cycle). In both conditions, the frequency of changes were the same because changes occurred twice in six frame presentations. If repetition of both the original and the modified picture version is important, change detection should be easier and faster in the AAABBB cycle than in the AAAAAB cycle.

As in Experiment 1, the type of change was varied across cycle conditions.

3.1. Methods

3.1.1. Participants

Sixteen new volunteers (aged 21–34, mean 24.8, 4 males) took part in an individual session of approximately 30 min either in fulfillment of course requirements or in exchange for payment. All of them reported having normal or to-normal-corrected vision, and were not familiar with the purpose of the experiment.

3.2. Stimuli and procedure

In this experiment the frequency of original and modified picture versions was manipulated. In one condition participants were presented with an equal number of both scene types in form of an AAABBB cycle; in another condition they received more original scene pictures than modified scene pictures in form of an AAAAAB cycle. Thus, the number of changes in both conditions was the same while the amount of repetitions of original and modified pictures varied. The type of change was varied within the repetition frequency conditions. Fifty-six pictures were taken for the experimental trials and subdivided into two stimulus sets each containing 10 color changes, 10 presence changes, and 8 position changes. The assignment of picture sets to flicker condition was counterbalanced over participants. All other aspects of this experiment were the same as in Experiment 1.

The experiment started with three practice trials in the AAABBB cycle, each containing one of the different types of change. Then 56 experimental trials followed in which the repetition frequency conditions occurred in random order. Again, participants were not informed about the different conditions.

3.3. Results

As before, only trials with correct responses were included in the analysis. Errors occurred in 3.9% of all trials. In most of the error trials (94.3%), participants had not seen any change. That is, they either gave up searching for the change or they pressed the space bar erroneously without having seen a change. False descriptions of the change were given only in 5.7% of the errors (i.e., in 0.2% of all trials). Errors occurred more often in the AAAAAB repetition condition (5.4%) than in the AAABBB [2.4%, $F(1,15) = 5.16$, MSE = 211.5, $p < 0.05$] and tended to differ across change type [$F(2,30) = 3.26$, $MSE = 81.3$, $p = 0.052$]. Post-hoc tests revealed that errors were more common for color changes than presence changes ($p < 0.05$) but showed no differences between color and position ($p = 0.136$) or position and presence changes ($p = 0.333$). Mean RTs for failures were 56,398 ms in the AAAAAB repetition condition (range 22,972–101,277 ms) and 60,532 ms in the AAABBB repetition condition (range −918 to 148,759 ms; the negative value resulted because one participants pressed the response key 122 ms after the trial had started, which was 918 ms before the first change would have occurred; the second smallest RT was 36,140 ms). Thus, except for one premature key press, in which no change detail was provided, we can rule out that participants abandoned change detection early.

For this experiment only mean detection times are reported because the number of changes in both conditions are directly reflected in the detection time (number of changes for similar detection times in both conditions can maximally vary by 1 change because changes occurred 640 ms earlier in the AAABBB cycle than in the AAAAAB cycle). Mean detection time was calculated and averaged across participants and is displayed separately for frame sequence and type of change conditions in Fig. 4.

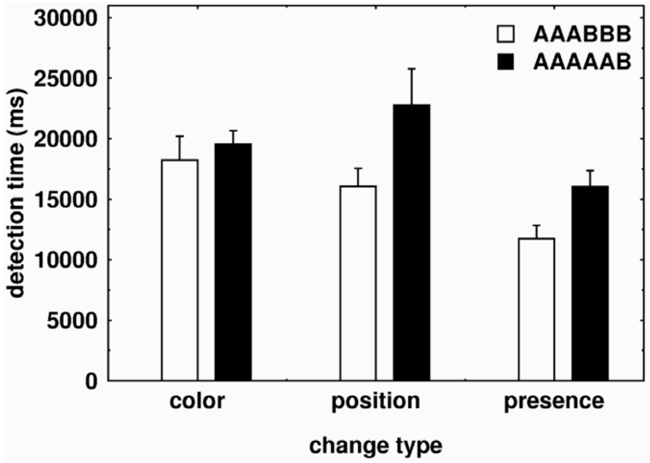

Fig. 4. Mean number of changes needed for detection as a function of repetition frequency (AAABBB and AAAAAB) for the three change type conditions in Experiment 2. Error bars indicate one standard error.

Change detection time differed significantly across repetition frequency conditions [$F(1,15) = 13.57$, MSE = 404,351,286.7, $p < 0.01$], with participants needing longer to detect the change in the AAAAAB than in the AAABBB condition. As in Experiment 1, change type differed significantly [$F(2,30) = 7.63$, MSE = 298,014,536.1, $p < 0.01$]. Again, presence changes were detected faster than position changes ($p < 0.01$) and color changes ($p < 0.001$). There was however, no difference between position and color changes ($p = 0.78$).

The interaction between the factors repetition frequency and change type was not significant [$F(2,30) < 1.09$, MSE = 58,499,334.4, $p = 0.35$].

The results of this experiment suggest that the advantages observed for more frequently repeated pictures in Experiment 1 were due to repetition of both the original and the modified versions of the picture. It seems that information can accumulate over time and that forming a representation of both pictures is more beneficial for change detection than forming a representation of only one of the pictures involved. This assumption may account for the discrepancy between our results in Experiment 1 and the Rensink et al. (2000) findings. In Rensink et al.'s study, participants saw only one picture version in the 8 s preview phase and this did not facilitate change detection.

The finding that both original and modified versions of the picture are important for change detection poses the question of how the visual system can build up two picture versions without knowledge of the change. It is conceivable that the instruction to detect a change led participants to establish two picture representations, however, further research is necessary to answer this question.

As in Experiment 1, presence changes were easier to detect than color or location changes. Again, no interaction between change type and repetition frequency manipulations was found, thereby confirming that variations in difficulty to detect the change had no impact on the effects of frequency manipulation.

4. Experiment 3

The previous results suggest that participants develop two representations – one for each version of the picture. If this assumption is correct then one would expect participants to perform better in a change detection situation with a regular cycle (AABB) than in a random cycle. We would expect this because it should be easier to develop two representations of scenes in a regular AABB cycle compared to randomly presented scenes.

The third experiment was designed to explore this possibility. In one condition we presented participants with an AABB cycle, while in the other condition we used a random sequence. In both conditions, the expected average rate of change was the same. If regularity has an effect on performance then change detection time should differ between the two cycle types. This would provide further evidence of the importance of developing two different representations.

4.1. Methods

4.1.1. Participants

In this experiment, 16 new volunteers (aged 19–24, mean 21.4, 2 males) took part. Individual sessions lasted approximately 30 min and participation was either in fulfillment of course requirements or in exchange for payment. Vision was normal or corrected-to-normal. None of the participants were familiar with the purpose of the experiment.

4.1.2. Stimuli and procedure

The stimuli and procedure in this experiment closely followed those used in Experiments 1 and 2, with only the differences described here. Instead of manipulating the frequency of change, or the frequency of repetition, the regularity of change was varied. In one condition participants received an AABB cycle; in the other condition they received a random drawing from an equal AB distribution. We chose to use this short cycle to keep the number of changes in both conditions similar. Overall, the frequency of change was therefore the same in both conditions, but they differed in the regularity of the change. As before, the type of change varied. The same two picture sets as in Experiment 2 were used. Each set contained 10 color changes, 10 presence changes, and 8 position changes. Pictures were assigned to the two change conditions and counterbalanced across participants.

The experiment started with three practice trials in the AABB cycle, each containing one of the different types of change. Then the 56 experimental trials followed in which the change regularity conditions occurred in random order. Again, participants were not informed that change regularity varied.

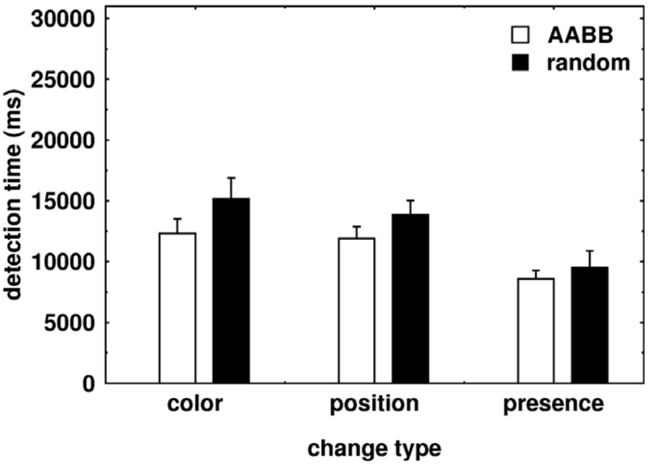

Fig. 5. Mean change detection time as a function of change regularity (AABB and random) for the three change type conditions in Experiment 3. Error bars indicate one standard error.

4.2. Results

Errors occurred in 3.6% of all trials and were excluded from the analysis. In most of the error trials (81.3%), participants had not seen any change. That is, they either gave up searching for the change or they pressed the space bar erroneously without having seen a change. False descriptions of the change were given for only 18.8% of the errors (i.e., in 0.7% of all trials). Error rates varied significantly across change conditions, with more errors in the random change condition (5.5%) than in the AABB condition [1.8%, $F(1,15) = 8.85$, MSE = 328.2, $p < 0.01$]. Mean RTs for failures were 40,563 ms in the random change condition (range 405–108,803 ms, the second smallest RT was 16,012 ms) and 28,070 ms in the AABB change condition (range 17,267–40,616 ms). Thus, except for one fast key press, which according to the participant was by mistake, we can rule out that participants abandoned change detection early.[3]

As in Experiment 2, and for the same reason, only results regarding detection times are reported. The mean detection time was calculated and averaged across participants and is displayed separately for frame sequence and type of change conditions in Fig. 5.

The main effect of change detection time across the two change conditions was significant [$F(1,15) = 9.40$, MSE = 87,110,785.3, $p < 0.01$]. Participants needed more time to detect the change in the random than in the AABB cycle. Again, the performance for the three change types differed [$F(2,30) = 13.78$, MSE = 200,442,739.5, $p < 0.001$]. Pair-

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[3] The large differences in failure RTs for both conditions are mainly due to three outlier RTs in the random change conditions: the one premature key press already mentioned and two attempts to search for the change for 107,367 and 108,803 ms.

wise comparisons for this factor revealed that presence changes were detected faster than position changes ($p < 0.001$) and color changes ($p < 0.001$). As in Experiments 1 and 2, there was no significant difference between position and color changes ($p = 0.41$).

As before, the factors change regularity and change type did not interact with each other [$F(2, 30) < 1$].

Experiment 3 demonstrated that change detection performance suffered when the flicker sequence was presented in a random sequence compared to an AABB sequence. These results are in line with the assumption that visual information is accumulated across presentations and supports the notion that picture repetition is more effective when participants are able to create a representation of each picture version – the original and the modified one.

As in previous experiments, presence changes were easier to detect than color or location changes. Again, the factor change type did not interact with change regularity thereby indicating that variations in difficulty to detect the change did not influence the effects of change regularity.

By using an AABB sequence as a comparison to a random sequence we most likely underestimated the importance of regularity. Effect sizes might have been even greater if we had compared the random sequence with a sequence with more repetitions in each cycle. Because randomness may frequently have led to long runs of one picture type followed by long runs of the other picture type, these results also emphasize the importance of regularity and not only repetition of one picture version.

5. General discussion

Attentional mechanisms play an important role in change detection (e.g., Aginsky & Tarr, 2000; Mitroff et al., 2002). However, the role of visual representations on change detection processes in dynamic change situations is unclear (e.g., Melcher, 2001; Rensink et al., 2000). The research reported in this article provides evidence that the build-up of visual representations in visual memory contributes to change detection. In addition, it seems to be beneficial to create representations not only of one version of the stimulus material, but of both.

These conclusions are based on three experiments designed to investigate whether information in dynamic change situations is accumulated over frame presentation. We explored the issue by focusing on the flicker paradigm itself. The first experiment tested whether repeated presentations of the original and the modified picture version could improve change detection. For this purpose, flicker cycles with different numbers of repetitions were compared with each other. The results revealed that an increased number of picture frames improved change detection, because with many repetitions participants needed fewer alternations to detect the change. The second experiment contrasted repeated presentations of only the original picture with repeated presentations of both, the original and modified picture version. The results showed that change detection was faster when both the original and the modified versions were repeated. The third experiment further tested the degree to which representations of both picture versions facilitated change detection by comparing detection performance for cycles using a regular schedule with those using random cycles. If representations of both picture versions are beneficial for change detection then a random cycle should impede the accumulation of information because random presentation hampers the build-up of information for both pictures. Performance was indeed better in the regular than in the random cycle, therefore supporting the conclusion drawn from Experiment 2.

For the effects observed, an alternative explanation seems possible. It is conceivable that participants chose to verify the detection of a certain change by waiting for the change to re-occur before indicating their response. Of course, the re-occurrence of a change depends on the number of repetitions in a given condition. That is, for the more frequently repeated picture version, more time has to pass before a change re-occurs. Such a verification-strategy combined with the assumption of a pure, serial visual search, might account for the results obtained in Experiment 1. However, in Experiments 2 and 3, the time needed for a change to re-occur is actually similar on average when one assumes that change detection is based on serial visual search and thus equally likely for long (e.g. AAAAA) and short (just B in the AAAAAB cycle) runs of one picture presentation. Accordingly, serial visual search combined with a verification strategy cannot account for our results.

Two main findings can be derived from our data. Firstly, the results indicate that in a flicker paradigm, information accumulates in visual memory over several brief picture presentations. It seems therefore, that visual information is integrated from one frame to the next, in a similar fashion to information integration over saccades (Henderson & Anes, 1994). These parallel findings in experiments using saccade and flicker paradigms strengthen the view that the presentation of stimulus material in flicker paradigms is comparable to natural saccades (e.g., Cole et al., 2003; Rensink et al., 1997). This is somewhat surprising as natural saccades are programmed by the visual system, whereas the flicker paradigm is imposed on the observer. For saccades, there seems to be implicit knowledge of what is expected to be seen at the landing point. This might be due to attentional shifts that precede saccades. The flicker paradigm on the other hand does not allow any preparation. Nevertheless, our results indicate information integration over frames in a flicker paradigm. This adds to previous findings reported by Brockmole, Wang, and Irwin (2002). They found evidence of integration when two parts of one display were displayed temporarily separated. Interestingly, accuracy for short blanks (below 100 ms) was low, but increased with longer blank durations. Similarly, Lleras, Rensink, and Enns (2005) observed decreased detection times in a search task when the search display was shown for a second time. Delays between first and second presentations in their experiments were longer than 900 ms. We extend these findings by showing that integration can also occur when interruptions are brief.

Secondly, our data also suggest that participants establish representations for each of the two picture versions involved because repetitions are more beneficial for change detection when they affect both the original and the modified versions of the stimulus material. This conclusion is based on the clear performance advantage for cycles in which both picture types were equally often repeated compared to cycles in which only the original picture was repeated. In addition, the third experiment demonstrated that performance suffered when pictures were presented in a random cycle compared to regular cycle presentations. Under the assumption that the repetition of both picture versions in a regular manner is important to yield an advantage in change detection, one would expect performance to deteriorate when accumulation in memory is more difficult as it was in the random cycle condition. The results of Experiment 3 therefore strengthen the possibility of a performance benefit being connected to a repetition of both picture types. This finding in particular can explain why Rensink et al. (2000) found no evidence of information accumulation in memory when presenting an 8 s preview of the original picture before the start of an AABB sequence. Our results suggest that it is necessary to prolong the presentation of both images in a pair.

Although our results clearly indicate that information accumulation facilitates change detection, it is still uncertain whether the accumulation occurs in visual short-term or in long-term memory as reported for scene presentations (e.g., Hollingworth & Henderson, 2002). Rensink (2000) proposed a theory that might explain our results on the basis of short-term memory processes only. According to his coherence theory, early visual processing establishes quickly volatile proto-objects, which contain structures of the observed visual scene. These proto-objects are lacking temporal and spatial coherence and are overwritten by any new, incoming stimuli. Attention is the link between the proto-objects and a collection point or nexus, which pools this information and maintains short-term memory. Attention in this model serves to select information from the pool of proto-objects and to create feedback between nexus and proto-objects. The interaction of nexus, links (attention) and proto-object is called a coherence field. Through this interaction, properties of proto-objects are coherent in space and time. If attention is withdrawn, the coherence field destabilises and the previously coherent properties of proto-objects become volatile again. Thus, attention is necessary to identify any change to visual properties. Rensink assumes that only a small fraction of the information that reaches the eye is accumulated through attention to a coherence field and this accumulation falls apart when attention is withdrawn. According to this theory, our findings might be explained on the basis of attentional and short-term memory effects only, without any long-term memory influence.

To examine this possibility we conducted a RT ratio analysis as described by Rensink (2000). The details of the analysis are described in the Appendix and the results are shown in Table 1. We hoped to clarify whether the amount of information accumulation is sparse and related to short-term memory, or whether it is more extended and related to long-term memory. All ratios were calculated relative to the RTs observed in the AB condition of Experiment 1. As a first step, RT ratios on the basis of purely attentional mechanisms and short-term memory involvement only were estimated. This estimation was based on short-term memory storage capacity and display time. These estimated values were then compared with the observed and for errors corrected RT ratios in our experiments. This comparison allowed us to assess whether information accumulation exceeded the short-term storage in visual short-term memory. If the observed ratios are similar to expected ratios, no additional information accumulation in long-term memory is available for change detection. If, however, the observed ratios are smaller than the expected ones, that is, if the increase in RT is less than expected under the assumption of serial search within visual short-term memory, then information accumulated in long-term memory is facilitating change detection.

In the first experiment the expected ratio for the AABB cycle was 1.0 and for the AAAAABBBBB it was 2.22. The actually observed, error-corrected RT ratios for the AABB condition were 1.35 for color change, 1.09 for position change, and 1.15 for presence change. For the AAAAABBBBB condition they were 1.86 for color change, 2.30 for position change, and 2.11 for presence change. Thus, the actually observed ratios are mostly similar to, or larger than the expected ones, thus indicating no long-term memory involvement in these conditions. An exception was the ratio observed for color changes in the AAAAABBBBB condition, which was smaller than expected and therefore suggests a contribution of long-term memory. A similar picture presented itself for the second experiment. The estimated values for the AAABBB conditions were 1.33 and 1.61 for the AAAAAB condition. The observed error-corrected ratios in the AAABBB condition were 1.40 for color changes, 1.29 for position changes, and 1.39 for presence changes. In the AAAAAB condition, they were 1.51 for color changes, 1.91 for position changes, and 1.99 for presence changes. Thus, the observed and expected ratios for the AAABBB condition and the AAAAAB were quite similar. Again, only for color changes in the AAAAAB condition, were the actually observed ratios smaller than the expected ones. In the third experiment the estimated values were 1.0 for the AABB conditions and 1.20 for the random change condition. The observed error-corrected ratios in the AABB condition were 0.92 for color changes, 0.95 for position changes, and 1.04 for presence changes. In the random change condition, they were 1.19 for color changes, 1.17 for position changes,

Table 1
Mean RT (in ms) and error rates per condition

Change frequency	Mean RT	Mean error rate	RT ratio	Correction factors	Corrected RT ratio	Expected RT ratio
Type of change						
Exp. 1						
AB						
Color	12691	0.073				
Position	12323	0.031				
Presence	8156	0.033				
AABB						1
Color	15909	0.142	1.25	1.080	1.35	
Position	12715	0.087	1.03	1.061	1.09	
Presence	8917	0.083	1.09	1.055	1.15	
AAAAABBBBB						2.22
Color	20022	0.212	1.58	1.176	1.86	
Position	23059	0.211	1.87	1.228	2.30	
Presence	15504	0.099	1.90	1.073	2.11	
Exp. 2						1.33
AAABBB						
Color	18219	0.050	1.44	0.976	1.40	
Position	16057	0.023	1.30	0.992	1.29	
Presence	11746	0.0	1.44	.967	1.39	
AAAAAB						
Color	19539	0.056	1.54	0.983	1.51	
Position	22777	0.063	1.85	1.033	1.91	
Presence	16020	0.044	1.96	1.011	1.99	
Exp. 3						1
AABB						
Color	12321	0.019	0.97	0.945	0.92	
Position	11911	0.016	0.97	0.984	0.95	
Presence	8583	0.019	1.05	0.985	1.04	
Rand AB						1.20
Color	15176	0.069	1.20	0.996	1.19	
Position	13848	0.070	1.12	1.042	1.17	
Presence	9507	0.025	1.17	0.992	1.16	

The table lists uncorrected ratios, that is RT_{cond}/RT_{AB} and ratios corrected for the error rates of each condition (see formula 1) and the expected RT ratio for each display condition. To make the computation more tractable the correction factors are listed and mean error rates and correction values are listed to three decimal places.

and 1.16 for presence changes. Thus, in Experiment 3, the amount of information accumulation did not exceed the amount of assumed short-term memory capacity because the actually observed ratios were similar to the expected ones in each condition.

All in all, the ratio analysis revealed that mainly short-term memory processes were involved in our flicker paradigms, but also that long-term structures can contribute, especially for color changes. Rensink (2000) also reported more information accumulation for color information. He speculated that color information might allow a more efficient grouping of the display, so that chunks of information can be created, which thus increased the total amount of information that can be committed to short-term memory. Of course this might be possible in our design. Nevertheless, we prefer an alternative explanation for the following reasons. Firstly, because participants did not know which change type occurred in a given trial and therefore were unlikely to develop a strategy like this. Secondly, color was much more difficult to group in our naturalistic stimulus material than in Rensink's design, which consisted of black and white rectangles. Another explanation is that different processes might be used for color. It has been shown, that location and presence features are encoded automatically, but color encoding follows a controlled process (Aginsky & Tarr, 2000). It is possible that controlled processes use different mechanisms than uncontrolled processes. Thus, it seems that at least for color change, detection relied not only on attentional processes and short-term memory but also on long-term memory. Color as a controlled process might benefit especially from a stronger build-up of representation in visual memory.

In summary, our results underlined the importance of presenting both picture versions for a prolonged time. In addition, we showed that attention and short-term memory processes are important elements of change detection performance, and that there may be an additional role for long-term memory in natural stimulus settings where color changes are involved. Thus, different processing strategies might take place depending on the particular design of the flicker paradigm.

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Appendix A

Our analysis of the RT ratios followed a similar analysis described by Rensink (2000). In his experiment, Rensink investigated change detection under visual search conditions and similar to serial visual, search slopes varied with display size with a similar processing speed per item for most of the display times (80–800 ms) tested. If items could only be compared one-by-one, processing time per item should have increased, because new material for comparison was only available later in longer display times. The fact that display time did not influence processing speed per item indicates that within one view participants could compare several items with the previous picture version. Accordingly, Rensink assumes that a certain number of items are stored in visual short-term memory and change detection occurs on the basis of these memories. Of course, the number of items held in short-term memory is limited (based on his data, Rensink assumed that on average, 5.5 items with varying orientation can be stored). Therefore, independence of change detection from display time should be restricted to a maximum display time. Theoretically, this upper limit of display time is the maximum hold of items (i.e. 5.5 items) multiplied by the processing time per item (in Rensink's data 131 ms/item – computed from the search slopes that were 7.64 item/s), thus the upper limit of display time is 720 ms. If the display time exceeds the time requirements for serially searching for changes of the items held in short-term memory, then this additional time is superfluous and consequently processing time increases (or speed per item decreases). Indeed, in his experiment this was the case for display times of 800 ms when objects changed their orientation. In contrast, for color changes, even display times of 800 ms did not influence processing speed per item.

Following this logic we analysed ratios of response times to examine whether the amount of information accumulation is sparse and related to short-term memory (as proposed by Rensink, 2000) or whether it is more extended and related to long-term memory. The observed (vs. corrected) RT ratios reported here were calculated relative to the reaction times observed in the AB condition of Experiment 1. In addition, we also computed corrected ratios to adjust the ratio values according to the different error rates in each condition (see Table 1). Errors were mostly trials in which participants abandoned search. Thus, we adjusted the RT ratio (i.e. $\mathrm{RT}_{\mathrm{cond}}/\mathrm{RT}_{\mathrm{AB}}$) for each condition by the ratio of the number of correct trials in AB to the respective condition. That is, for error correction we applied the following formula:

$$\mathrm{RT\ ratio}_{\mathrm{cond}} = (\mathrm{RT}_{\mathrm{cond}}/\mathrm{RT}_{\mathrm{AB}}) * (1 - \mathrm{error\ rates}_{\mathrm{AB}})/(1 - \mathrm{error\ rates}_{\mathrm{cond}})$$

The observed ratios were compared with estimated ratios based on display time (derived from Rensink, 2000). The calculations for the estimated ratios are based on the assumption that blanks themselves do not cause interference and that performance therefore depends on total display time only, which has been indicated in the experiments described by Rensink et al. (1997) and Rensink (2000). For example, in Experiment 1 the display time in the AABB cycle for original and modified picture is $2 \times (240\ \mathrm{ms} + 80\ \mathrm{ms}) = 640$ ms and in the AAAAABBBBB cycle display time is $5 \times (240\ \mathrm{ms} + 80\ \mathrm{ms}) = 1600$.

Further, estimated ratios are based on the assumption that: (i) change detection requires attention and therefore occurs serially with a processing time per item of 131 ms and (ii) a maximum number of 5.5 items per display can be stored in visual short-term memory and that only these items and no further information are available for change detection. Consequently, RTs for change detection should be independent of display time for display times up to 720 ms (i.e. processing time per item, 131 ms, multiplied with maximum hold, 5.5). Thus, no increase in RT is expected when comparing the AB and the AABB cycle, i.e., the expected ratio for the AABB cycle (display time 640 ms) is 1.0. When display times increase beyond 720 ms, RT ratios should increase in relation to this limit. That is, for the AAAAABBBBB cycle an increase of 2.22 (1600 ms/720 ms) is expected and for the AAABBB in Experiment 2 an increase of 1.33 (960 ms/720 ms) is expected. For the AAAAAB condition in Experiment 2, we assume an expected ratio of 1.66 (interpolated from 2.22 for 5 repeating cycles and 1.00 for one repeating cycle). For the random sequence condition in Experiment 3, we do not know how many 1 A, 2 A, 3A, 4A and so on repetitions actually happened in each trial because our program did not record the random sequences used in each trial. Therefore, we computed the expected ratio based on the probability with which each number of repetitions is expected to occur.

References

Aginsky, V., & Tarr, M. J. (2000). How are different properties of a scene encoded in visual memory? *Visual Cognition, 7*, 147–162.

Beck, M. R., Angelone, B. L., & Levin, D. T. (2004). Knowledge about the probability of change affects change detection performance. *Journal of Experimental Psychology: Human Perception and Performance, 30*, 778–791.

Blackmore, S. J., Brelstaff, G., Nelson, K., & Troscianko, T. (1995). Is the richness of our visual world an illusion? Transsaccadic memory for complex scenes. *Perception, 24*, 1075–1081.

Bridgeman, B., & Mayer, M. (1983). Failure to integrate visual information from successive fixations. *Bulletin of the Psychonomic Society, 21*, 285–286.

Brockmole, J. R., Wang, R. F., & Irwin, D. E. (2002). Temporal integration between visual images and visual percepts. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 315–334.

Castelhano, M. S., & Henderson, J. M. (2005). Incidental visual memory for objects in scenes. *Visual Cognition, 12*, 1017–1040.

Cole, G. G., Kentridge, R. W., Gellatly, A. R. H., & Heywood, C. A. (2003). Detectability of onsets versus offsets in the change detection paradigm. *Journal of Vision, 3*, 22–31.

Grimes, J. (1996). On the failure to detect changes in scenes across saccades. In: Davis, S., Atkins, K., Hedberg, N., Popowich, F., & Wright, R., (Series Eds.) & K. Akins (Vol. Ed.), Vancouver studies in cognitive science (Vol. 5). Perception (pp. 89–109). New York: Oxford University Press.

Henderson, J. M. (1997). Transsaccadic memory and integration during real-world perception. *Psychological Science, 8*, 51–55.

Henderson, J. M., & Anes, M. D. (1994). Roles of object-file review and type priming in visual identification within and across eye fixations. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 826–839.

Hollingworth, A. (2005). Memory for object position in natural scenes. *Visual Cognition, 12*, 1003–1016.

Hollingworth, A., & Henderson, J. M. (2002). Accurate visual memory for previously attended objects in natural scenes. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 113–136.

Hollingworth, A., & Henderson, J. M. (2004). Sustained change blindness to incremental scene rotation: A dissociation between explicit change detection and visual memory. *Perception & Psychophysics, 66*, 800–807.

Irwin, D. E., & Zelinsky, G. J. (2002). Eye movements and scene perception: Memory for things observed. *Perception & Psychophysics, 64*, 882–895.

Lleras, A., Rensink, R. A., & Enns, J. T. (2005). Rapid resumption of interrupted visual search. *Psychological Science, 16*, 684–688.

Melcher, D. (2001). Persistence of visual memory for scenes. *Nature, 412*, 401.

Mitroff, S. R., Simons, D. J., & Franconeri, S. L. (2002). The siren song of implicit change detection. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 798–815.

Mondy, S., & Coltheart, V. (2000). Detection and identification of change in naturalistic scenes. *Visual Cognition, 7*, 281–296.

O'Regan, J. K., Deubel, H., Clark, J. J., & Rensink, R. A. (2000). Picture changes during blinks: Looking without seeing and seeing without looking. *Visual Cognition, 7*, 191–211.

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception & Psychophysics, 16*, 283–290.

Potter, M. C. (1976). Short-term conceptual memory for pictures. *Journal of Experimental Psychology: Human Learning & Memory, 2*, 509–522.

Pringle, H. L., Irwin, D. E., Kramer, A. F., & Atchley, P. (2001). The role of attentional breadth in perceptual change detection. *Psychonomic Bulletin & Review, 8*, 89–95.

Remington, R. W., Johnston, J. C., & Yantis, S. (1992). Involuntary attentional capture by abrupt onsets. *Perception & Psychophysics, 51*, 279–290.

Rensink, R. A. (2000). Visual search for change: A probe into the nature of attentional processing. *Visual Cognition, 7*, 345–376.

Rensink, R. A. (2002). Change detection. *Annual Review of Psychology, 53*, 245–277.

Rensink, R. A., O'Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. *Psychological Science, 8*, 368–373.

Rensink, R. A., O'Regan, J. K., & Clark, J. J. (2000). On the failure to detect changes in scenes across brief interruptions. *Visual Cognition, 7*, 127–145.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-prime user's guide*. Pittsburgh: Psychology Software Tools Inc.

Schofield, A. J., Bishop, N. J., & Allen, J. (2006). Oscillatory motion induces change blindness. *Acta Psychologica, 121*, 249–274.

Scholl, B. J. (2000). Attenuated change blindness for exogenously attended items in a flicker paradigm. *Visual Cognition, 7*, 377–396.

Simons, D. J., Franconeri, S. L., & Reimer, R. L. (2000). Change Blindness in the absence of a visual disruption. *Perception, 29*, 1143–1154.

Simons, D. J., & Levin, D. T. (1997). Change blindness. *Trends in Cognitive Sciences, 1*, 261–267.

Simons, D. J., & Levin, D. T. (1998). Failure to detect changes to people in a real-world interaction. *Psychonomic Bulletin & Review, 5*, 644–649.

Simons, D. J., & Rensink, R. A. (2005). Change blindness: Past, present, and future. *Trends in Cognitive Sciences, 9*, 16–20.

Smilek, D., Eastwood, J. D., & Merikle, P. M. (2000). Does unattended information facilitate change detection? *Journal of Experimental Psychology: Human Perception and Performance, 26*, 480–487.

Stolz, J. A., & Jolicœur, P. (2004). Changing features do not guide attention in change detection: Evidence from a spatial cuing paradigm. *Psychonomic Bulletin & Review, 11*, 870–875.

Tatler, B. W., Gilchrist, I. D., & Rusted, J. (2003). The time course of abstract visual representation. *Perception, 32*, 579–592.

Williams, C. C., Henderson, J. M., & Zacks, R. T. (2005). Incidental visual memory for targets and distractors in visual search. *Perception & Psychophysics, 67*, 816–827.

Zelinsky, G. J., & Loschke, L. C. (2005). Eye movements serialize memory for objects in scenes. *Perception & Psychophysics, 67*, 676–690.