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Has someone moved my plate? The immediate and persistent effects of object location changes on gaze allocation during natural scene viewing

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In this study, we investigated the immediate and persisting effects of object location changes on gaze control during scene viewing. Participants repeatedly inspected a randomized set of naturalistic scenes for later questioning. On the seventh presentation, an object was shown at a new location, whereas the change was reversed for all subsequent presentations of the scene. We tested whether deviations from stored scene representations would modify eye movements to the changed regions and whether these effects would persist. We found that changed objects were looked at longer and more often, regardless of change reportability. These effects were most pronounced immediately after the change occurred and quickly leveled off once a scene remained unchanged. However, participants continued to perform short validation checks to changed scene regions, which implies a persistent modulation of eye movement control beyond the occurrence of object location changes.

When viewing naturalistic scenes, we tend to be quite insensitive to changes that occur while we move our eyes or that are masked by transients such as a blank screen or a blink (for a review, see Simons, 2000). Such *change blindness* has been taken as evidence for the inability of the visual system to store detailed scene representations across space and time. However, there have been quite different theoretical positions regarding the nature of scene representations, ranging from theories that suggest that no detailed visual representations accumulate as attention is oriented from one view of a scene to another (e.g., Horowitz & Wolfe, 1998; O'Regan, 1992; O'Regan, Rensink, & Clark, 1999; Rensink, 2000) to theories that propose that, indeed, very detailed visual scene representations can be stored (e.g., Deubel, Bridgeman, & Schneider, 1998; Hollingworth & Henderson, 2002; Melcher, 2006; for a review, see Hollingworth, 2006). In the study presented here, we set out to investigate whether stored scene representations—established from repeated scene viewings—are detailed enough to allow for the detection of spatial location changes of a critical object from one presentation of a scene to another. We were particularly interested in whether these change effects on eye movement control would *persist* beyond the introduction of a change during ongoing viewing of naturalistic scenes.

In order to detect object changes without transient motion signals, the current view of a scene has to be matched to an existing, actively maintained memory representation that has been generated over the course of scene viewing (for a review, see Hollingworth, 2006). Accordingly, Brockmole and Henderson (2005a, 2005b, 2008) found that in stationary scenes, new objects modified eye movement behavior even when presented during a saccade. Recent work by Ryan and colleagues (e.g., Ryan, Althoff, Whitlow, & Cohen, 2000; Ryan & Cohen, 2004; Ryan & Villate, 2009) has provided further evidence that stored scene representations allow for the detection of spatial location changes across different views of a scene, prolonging gaze toward the changed regions. Ryan and Cohen, for example, examined the effect of spatial location changes on implicit and explicit change detection by subsequently presenting pairs of scenes in which objects were deleted, added, or moved. Gaze toward changed objects was increased even when these changes were not accessible for verbal report (see also Hayhoe, Bensinger, & Ballard, 1998; Henderson & Hollingworth, 2003; Hollingworth, Williams, & Henderson, 2001; but see Smith, Hopkins, & Squire, 2006). Although these findings support the view that changes to stored scene representations are able to exhibit control over eye movement behavior, it remains unclear how long these effects persist.

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In their surprise model, Itti and Baldi (2005, 2009) related the detection of change to eye movement control by proposing that increased gaze is allocated toward *surprising events*, formalized as the mismatch of prior and posterior beliefs about the world. A *forgetting factor* ensures that new surprise reactions can occur once the previously surprising event is no longer stored. Although the theory is applicable at many levels of abstraction, so far its implementation has been a low-level visual model, which simulates early sensory neurons in areas such as V1, MT, and so forth, with only short time scales in the range of seconds (see Müller, Metha, Krauskopf, & Lennie, 1999). By using the mismatch between prior and posterior beliefs, the model therefore predicts strong effects on eye movement control immediately at the occurrence of change, although these should rapidly level off thereafter. However, a surprise detector operating on higher level and possibly less volatile internal representations of scenes may operate at much longer time scales, which would allow effects to persist. In addition, mismatch signals would have to be computed with regard to the context in which a change occurred to allow continued change monitoring across multiple intervening scenes.

In the present study, we therefore repeatedly presented participants with a set of scenes in randomized order, with the task being to view all scenes for later questioning. On the seventh presentation of each scene, we introduced an unannounced location change to a critical object in the scene, which was then returned to its original location for all subsequent presentations of the scene. Beforehand, the participants were told neither that changes would occur nor that they would be asked to indicate, at the end of the experiment, which objects within the presented scenes had changed their location. Since the changes occurred without transient motion signals and the different scenes were presented randomly, we increased the dependency of change detection on memory processes, due to the need to process and store multiple scene representations throughout the experiment.

Eye movement behavior was analyzed in order to contrast the immediate and persisting effects of object location changes on gaze allocation during scene viewing. If scene representations and prior beliefs are immediately updated with each new viewing of a scene and memory for changes is limited, the effects on eye movements should be strong during change trials but short-lived. On the other hand, surprising information could persist in scene representations, marking the changed object as significant for ongoing inspection, which should result in sustained allocation of gaze toward the object even when the change is reversed.

METHOD

Participants

Twelve students (8 of them female) from Ludwig-Maximilians-Universität, Munich, ranging in age from 20 to 27 years ($M = 23.83$, $SD = 1.90$), participated in the study for course credit or for €8/h. All the participants reported normal or corrected-to-normal vision and were unfamiliar with the stimulus materials.

Stimulus Materials

Twenty 3-D-rendered images of real-world scenes were displayed on a 19-in. computer screen (resolution, 1,024 × 768 pixels; 100 Hz), subtending 28.98º (horizontal) and 27.65º (vertical) of visual angle at a viewing distance of 70 cm. All the scenes displayed about 8–10 distinct objects that, in principle, could have moved. As can be seen in Figure 1, each scene came in two versions: In the standard version, the critical object was presented in its original position within the scene, whereas in the changed version the critical object was moved horizontally relative to another object with a distance of about 3º of visual angle. The assignment of either position to the standard or the changed condition was counterbalanced, and none of the location changes resulted in improbable object locations.

Apparatus

Eye movements were recorded with an EyeLink 1000 tower system (SR Research, Canada) at a sampling rate of 1000 Hz. The position of one eye was tracked, and viewing was binocular.

Procedure

After an initial 9-point calibration and validation, the participants were informed that they would be presented with a set of repeating scenes, which they should view in preparation for questions at the end of the experiment. Each trial sequence was preceded by a drift

Figure 1. Presentations 1–6 were like the left picture above, with the critical object (vase with flowers) in its original position. Upon the 7th presentation, the scene (right picture above) was shown with the moved critical object at the changed location. Presentations 8–10 again showed the picture with the critical object back in its original position. Note that at the 7th presentation, the previous location of the object was vacant.

Table 1
Summary of Mean Values (With Standard Errors) Regarding Immediate Effects on Gaze Duration, Number of Refixations, and Time to Fixate the Changed Object As a Function of Object Change (Prechange vs. Change vs. Reversion vs. Reversion+1 vs. Reversion+2) and Reportability (Reported vs. Unreported Change)

	Change Status									
	Prechange (Presentation 6)		Change (Presentation 7)		Reversion (Presentation 8)		Reversion+1 (Presentation 9)		Reversion+2 (Presentation 10)	
Measures	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
	Reported Change									
Gaze duration (msec)	510	44	1,070	116	987	105	575	85	617	54
Number of refixations	1.37	0.08	2.37	0.21	2.10	0.19	1.62	0.14	1.54	0.12
Time to fixate (msec)	2,062	224	1,946	181	1,991	188	1,682	101	1,559	202
	Unreported Change									
Gaze duration (msec)	298	47	417	55	440	67	410	43	355	19
Number of refixations	0.95	0.06	1.28	0.17	1.25	0.08	1.34	0.10	1.23	0.11
Time to fixate (msec)	2,756	247	2,639	359	2,369	284	2,229	211	2,218	218

correction. When the fixation check was deemed successful, the fixation cross was replaced by the presentation of a scene for 7 sec. Throughout the experiment, each scene was presented 10 times in randomized order. Only on the seventh presentation was the critical object placed in a different location. The critical object was returned to its original position for all the remaining presentations. The participants viewed 10 blocks, each of which consisted of 20 randomized scenes. Note that care was taken to distribute change trials across several blocks. At the end of the experiment, an unannounced change detection task was conducted in which all the scenes in their unchanged version were presented to the participants, again in randomized order, with the instruction to indicate, via mouse click, which object had changed position during the experiment.

Data Analyses

For each scene, a *critical interest area* was defined as the rectangular box that was large enough to encompass the critical object. This allowed us to analyze the following dependent variables. *Total gaze duration* was defined as the sum of all durations for which the critical region was fixated from scene onset until scene offset, and *number of refixations* was defined as the number of times the critical interest area was revisited. *Time to fixate* the changed area was defined as the elapsed time from scene onset to initial fixation of the critical area.

For the analysis, we had to exclude 2 participants due to technical difficulties in assessing their eye movement data. The remaining raw data were submitted to two repeated measures ANOVAs with object status and change reportability as factors. In the first ANOVA, the *immediate effects* of object changes were analyzed, contrasting Presentations 6 (prechange), 7 (change), and 8 (reversion), and *persistent effects* were analyzed with a second ANOVA in which Presentations 6 (prechange), 9 (reversion+1), and 10 (reversion+2) were contrasted (for mean values, see Table 1). Significant main effects and interactions were followed up with planned *t* tests.

In addition to eye movement behavior with respect to changed *objects*, we were interested in whether eye movements for the previously occupied and now vacant object *position* would differ as a function of reportability. Thus, we conducted a planned *t* test for the previous object location in the changed scene for reported versus not reported changes. To account for the general finding that vacant object positions receive far fewer fixations than do locations that contain an object and to enable better comparison, we included values of 0 in the calculation of mean gaze durations and number of refixations when the vacant location was never fixated (for mean values, see Table 2).

RESULTS

Across all participants, about half of the position changes were correctly reported ($M = 56\%$, $SD = 18.68$). Note that the participants had to select the object that had changed from several other objects within a scene and indicate that the object had changed in order to correctly report a change, resulting in a baseline guess level of less than 15%. None of the participants reported using strategies to limit the number of objects likely to move.

Immediate Effects on Eye Movements

Gaze duration. With a main effect of object status [$F(2,9) = 17.13$, $p < .01$], gaze duration was prolonged for both the change and reversion conditions, as compared with the prechange condition [$t(9) = 5.79$, $p < .01$, and $t(9) = 5.33$, $p < .01$, respectively]. Reported changes were gazed at longer than unreported changes [$F(1,9) = 31.82$, $p < .01$]. There was also a significant interaction [$F(2,9) = 10.00$, $p < .01$], in that the effects of change were more pronounced for reported changes than for unreported changes: The difference between change and prechange and the difference between reversion and prechange were significantly higher for reported changes [$t(9) = 4.08$, $p < .01$, and $t(9) = 3.10$, $p < .05$, respectively].

In addition, the now-vacant object position during change trials was fixated about three times longer when the change was reported ($M = 211$ msec, $SE = 47$) than when it was not ($M = 59$ msec, $SE = 17$) [$t(9) = 5.19$, $p < .01$].

Table 2
Summary of Mean Values (With Standard Errors) Regarding Gaze Duration, Number of Refixations, and Time to Fixate the Unoccupied Object Location on the Seventh Presentation (Change) As a Function of Reportability (Reported vs. Unreported Change)

	Reported Change		Unreported Change	
Measures	*M*	*SE*	*M*	*SE*
Gaze duration (msec)	211	47	59	17
Number of refixations	0.53	0.10	0.26	0.10

Note—We included 0 values for trials on which the vacant location was never fixated. Thus, the low values of mean gaze durations and mean number of refixations on vacant locations mirror the overall finding that vacant object locations receive far fewer fixations than do locations that contain an object.

Number of refixations. Object status also affected the number of refixations [$F(2,9) = 16.43$, $p < .01$], which was increased for the change conditions, as compared with the prechange condition [change, $t(9) = 5.17$, $p < .01$; reversion, $t(9) = 6.42$, $p < .01$]. Furthermore, reported changes were refixated more often than unreported changes [$F(1,9) = 17.57$, $p < .01$]. The significant interaction [$F(2,9) = 7.34$, $p < .01$] showed that the effects of change were more pronounced for reported changes than for unreported changes: The difference between change and prechange was significantly higher for reported than for unreported changes [$t(9) = 3.33$, $p < .01$], whereas the difference between reversion and prechange was only marginally significant [$t(9) = 2.22$, $p > .05$].

Also, the now-vacant object position was refixated about twice as often when the change was reported ($M = .53$, $SE = .10$) than when it was not ($M = .26$, $SE = .09$) [$t(9) = 2.00$, $p < .05$].

Time to fixate. There was a tendency for change reportability [$F(2,9) = 4.42$, $p = .07$], but no main effect of object status and no interaction (Fs < 1).

Persistent Effects on Eye Movements

Gaze duration. There was an effect of reportability, in that previously moved but now reversed objects were looked at longer for reported than for unreported changes [$F(1,9) = 55.90$, $p < .01$]. There was neither an effect of object status [$F(2,9) = 1.97$, $p > .05$], nor an interaction ($F < 1$).

Number of refixations. In addition to increased refixation for reported changes [$F(1,9) = 13.46$, $p < .01$], object status also showed effects [$F(2,9) = 5.71$, $p < .05$], in that the participants continued to refixate previously changed objects more often, as compared with the prechange condition [reversion+1: $t(9) = 3.29$, $p < .01$, and $t(9) = 2.05$, $p < .05$, respectively], whereas reversion+1 and reversion+2 did not differ ($t < 1$). There was no interaction ($F < 1$).

Time to fixate. Although we did not find immediate effects of change on the time to fixate the changed objects, the time to fixate changed objects decreased during the later stages of scene viewing for the postchange conditions, as compared with the prechange condition [$F(2,9) = 4.02$, $p < .05$; reversion+1, $t(9) = 3.50$, $p < .01$; reversion+2, $t(9) = 3.13$, $p < .01$]. Furthermore, reported changes were refixated earlier than unreported changes [$F(1,9) = 9.40$, $p < .05$]. There was no significant interaction ($F < 1$).

In sum, we found that the occurrence of a change immediately increased both total gaze durations and the number of refixations but did not immediately lead to earlier fixation of the changed scene region. The impact of object change on eye movement control was most pronounced during change and reversion trials (Presentations 7 and 8) and quickly leveled off once no further change occurred. Furthermore, we found that although gaze durations to changed objects reduced to prechange level once the change had been reversed, refixations also reduced but remained above prechange level. Persistent effects on eye movement control were also observable in the reduced time taken to fixate the changed object during postreversion trials (Presentations 9 and 10). Previously occupied and now vacant positions received increased gaze when changes were later reported, implying that especially for reported changes, participants performed validation checks to the previously occupied scene region.

DISCUSSION

In the present study, we set out to investigate whether deviations from scene representations generated across repeated viewings of the same scene would lead to increased gaze allocation to those parts of the scene that had changed and whether the impact on eye movement behavior would persist after the change was reversed. In order to detect subtle object location changes, very detailed episodic scene representations had to be established across repeated presentations of each scene. Indeed, the participants were able to identify more than 50% of all the changed objects.

In addition, eye movement control was modulated, in that critical objects received more viewing time and refixations when the object had changed position, implying that stored scene representations not only are detailed enough to enable the detection of small location changes, but also modulate ongoing viewing behavior. These effects were observed regardless of explicit change reportability, suggesting that eye movements may be a more sensitive indicator for change detection than is explicit report (see Hayhoe et al., 1998; Henderson & Hollingworth, 2003; Karacan & Hayhoe, 2008; Parker, 1978; Ryan et al., 2000; Ryan & Cohen, 2004). Furthermore, for reported changes, the effect of change was more pronounced and was accompanied by increased deployment of eye movements toward the old, unoccupied object position. Thus, even though the previous object location was unoccupied at the time of viewing—that is, there was no object to look at—the participants fixated that particular region of the scene to a higher degree when they were subsequently able to report the position change. Although these results corroborate previous findings of gaze allocation to previously occupied scene regions (e.g., Parker, 1978; Ryan et al., 2000), we provide further evidence for the modulation of change effects on gaze behavior as a function of reportability. We surmise that explicit change detection might rely on the binding of an object to its stored location by successfully reactivating position information from a stored scene representation. This subsequently allows for an extra validation check of the formerly occupied position, which might increase the probability of change reportability.

The moved object was not fixated earlier during change trials, arguing against attentional capture for the changed object. Only upon fixation did the moved object lead to prolonged gaze and an increased number of refixations. This is in line with findings by Tatler, Gilchrist, and Land (2005), who found that the detection of position changes depends on the fixation of the moved object (see also Hollingworth & Henderson, 2002). Fixation seems to be a prerequisite for associating object position information to the scene representation.

Moreover, by reversing the changed object to its original position and continuing to present participants with these scenes, we were able to investigate the immediate and persistent effects of object location changes on eye movement behavior. Object location changes immediately affected viewing behavior, in that the increase of gaze allocation was evident not only when the object changed location, but also when the object was reversed to its original position. Subsequently, viewing time on changed objects immediately dropped close to prechange level when no further change occurred in the following presentations. It seems that when the detection of change is not relevant for the current task, lingering mismatch information can be attenuated to avoid unnecessary deployment of attention to task-irrelevant events.

However, although object location changes immediately affected eye movement control, these effects persisted even when no further change occurred: The level of refixations remained slightly increased with regard to the level of prechange inspection, which might reflect the participants' performing quick control checks to previously changed objects without prolonging viewing time. Also, changed objects were fixated earlier in postchange trials than before the change had occurred.

According to the surprise model (Itti & Baldi, 2005, 2009), increased gaze is allocated toward surprising events—that is, the mismatch of prior and posterior beliefs. However, these mismatch signals are based on low-level visual features with only short-lived effects. On the contrary, our finding that previously moved objects continue to be fixated to a higher degree—despite several different, intervening scenes—implies that a surprise detector operating on higher level scene representations requires mismatch computations that not only operate over larger time scales, but also are context based. That is, mismatch computations of prior and posterior beliefs have to take place with regard to the specific context in which a change occurred—in our case, a particular scene.

We therefore propose that small changes to stored scene representations seem to be selectively updated depending on a scene's context, such that across several intervening scenes, some eye movement parameters are updated more quickly (e.g., quick recovery of prolonged gaze durations), whereas others persist (continued refixation checks and less time to fixate). Thus, stored scene representations exert control over eye movement behavior both immediately and persistently during ongoing scene viewing.

AUTHOR NOTE

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