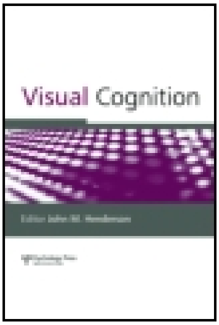

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Overt attentional prioritization of new objects and feature changes during real-world scene viewing

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Overt attentional prioritization of new objects and feature changes during real-world scene viewing

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The authors investigated the extent to which a change to an object's colour is overtly prioritized for fixation relative to the appearance of a new object during real-world scene viewing. Both types of scene change captured gaze (and attention) when introduced during a fixation, although colour changes captured attention less often than new objects. Neither of these scene changes captured attention when they occurred during a saccade, but slower and less reliable memory-based mechanisms were nevertheless able to prioritize new objects and colour changes relative to the other stable objects in the scene. These results indicate that online memory for object identity and at least some object features are functional in detecting changes to real-world scenes. Additionally, visual factors such as the salience of onsets and colour changes did not affect prioritization of these events. We discuss these results in terms of current theories of attention allocation within, and online memory representations of, real-world scenes.

Keywords: Attention; Visual memory; Oculomotor capture; Real-world scenes; Gaze control.

The guidance of the eyes through a scene is an active process of interrogating scene regions relevant to one's goals (e.g., Antes, 1974; Buswell, 1935; Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Henderson, Brockmole, Castelhano, & Mack, 2007; Henderson & Hollingworth, 1998; Land, Mennie, & Rusted, 1999; Mackworth & Morandi, 1967; Torralba, Oliva, Castelhano, & Henderson, 2006;

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Yarbus, 1967). However, in order to achieve some balance between the need to selectively focus on task-relevant stimuli and the need to be interrupted by other important events, the goal-directed control of gaze is not absolute and can be disrupted. For example, dynamic changes to visual displays such as the sudden emergence of a new object (Boot, Kramer, & Peterson, 2005b; Brockmole & Henderson, 2005b, 2008; Irwin, Colcombe, Kramer, & Hahn, 2000; Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999), the disappearance of an object (Brockmole & Henderson, 2005a), or changes to an object's colour or luminance (Irwin et al., 2000) can exogenously draw gaze, a circumstance referred to as *oculomotor capture*.[1]

The vast majority of oculomotor capture research has considered the priority given to new objects that appear in simple visual arrays of geometric shapes (Boot et al., 2005a; Irwin et al., 2000; Theeuwes et al., 1998, 1999). To take the seminal paper on the topic as an illustrative example, Theeuwes et al. (1998) presented observers with six grey circles surrounding a central fixation point. Five circles then turned red and letters were revealed in each circle. Observers were to move their eyes to the remaining grey circle and identify the letter presented within it. Critically, along with the revelation of the search target, an additional red item appeared in the display. Although this new item was never the target of search, the eyes moved toward the onset on approximately 50% of trials. Fixations on the onset were atypically brief, suggesting that the saccade to the target was programmed, but before the eye movement could be executed to this target, the onset interrupted the goal-directed eye movement.

More recent experiments have begun to consider analogous effects during real-world scene viewing. In a series of studies, Brockmole and Henderson (2005a, 2005b, 2008) asked observers to study photographs of scenes for a later memory task. During the study period, an object was added to each display. As expected, observers had a strong tendency to fixate these new objects very soon after their appearance at rates much higher than expected by chance. The degree of prioritization, however, depended on whether the new object appeared during a fixation (so that it was accompanied by a motion transient) or during a saccadic eye movement (which, due to saccadic suppression, eliminated the transient signal). New objects that appeared during fixations were fixated twice as often as those that appeared during saccades, indicating that, although low-level transient motion signals enhance the prioritization of new objects for viewing, they are not required

[1] Covert measures of *attention capture* whereby involuntary shifts of attention to dynamic singletons are measured through reaction time or response accuracy have a rich history (see Rauschenberger, 2003, and Simons, 2000, for reviews). Because our focus is on the capture of gaze, we will not review the covert capture literature in depth.

for prioritization to occur. This is not merely a quantitative distinction, however; it is also one of kind. Prioritization of new objects during saccades did not occur as quickly as it did during fixations. Additionally, prioritization of new objects during saccades, but not during fixations, was affected by manipulations of memory for the scene. These two results indicate that the effects observed during saccades are qualitatively different from those observed during fixations. Fast, exogenous, and robust oculomotor capture requires a transient motion signal, but, without such a signal, new objects are nevertheless prioritized for viewing as slower and less reliable memory processes are engaged to guide gaze. Brockmole and Henderson (2005b) termed this second mechanism *memory-guided prioritization*. Hence, the overt prioritization of new objects in real-world scenes can be mediated by both exogenous and endogenous mechanisms.

Although the research described above demonstrates how gaze control is affected by the appearance of new objects in a visual display or scene, it is less clear how gaze might be affected by changes to the surface features of *existing* objects that are visible throughout the viewing period. In the present study, we investigated whether and under what conditions sudden changes to an existing object's colour can attract gaze, and if so, whether this attraction can be driven by oculomotor capture and/or memory-guided prioritization. By investigating the extent to which each of these mechanisms is sensitive to changes to surface features of objects in real-world scenes, we aimed to determine the extent to which the overt attention system is tuned to identify and prioritize scene changes that do not involve the appearance of a new object, and the nature of the object feature information retained in online memory representations that is functional in detecting dynamic scene changes.

OCULOMOTOR CAPTURE

The evidence reviewed above indicates that transient motion signals lead to oculomotor capture when they coincide with the appearance of a new object. One goal of this study was to determine whether these transient signals lead to oculomotor capture when they are correlated with feature changes to existing objects. If new objects play a special role in oculomotor capture (cf. Yantis, 1993, 1998, 2000; Yantis & Gibson, 1994; Yantis & Hillstrom, 1994; Yantis & Jonides, 1996), then changes to surface features of existing objects such as their colours may not attract gaze. Only one previous study has used an oculomotor capture paradigm to investigate this question. Irwin et al. (2000) presented observers with four red circles around a central fixation cross. After a short delay, letters were revealed in the centre of each circle while one circle simultaneously turned grey and an additional red circle was onset. In separate conditions, observers were to report the letter contained within either the grey circle or within the onset. When the target was defined by the colour singleton, the presence of the onset captured gaze. When the target was in the onset, the colour singleton also captured gaze, but only if colour singletons were previously used as targets in the experiment. These results suggest that, while onsets capture gaze regardless of an observer's task or prior experience, transient colour changes do not attract gaze automatically, but can be induced to do so if they were previously related to the observer's goals.

Irwin et al.'s (2000) study provided important insight into the prominence of new objects in attracting gaze, but it is limited in an important way: Colour changes always occurred concurrently with onsets. In other words, the authors examined how well transient changes to existing objects capture gaze when a suddenly appearing new object is simultaneously competing for attention. In this situation, it is impossible to ascertain the efficacy with which feature changes can independently attract gaze. Resolving this ambiguity in the context of real-world scene viewing is one goal of the present study.

MEMORY-GUIDED PRIORITIZATION

In addition to investigating the control of oculomotor capture by changes to an object's surface features, we also aimed to advance our understanding of memory-guided prioritization. According to Brockmole and Henderson's (2005a, 2005b, 2008) conceptualization of this mechanism, when scene changes are not marked by a transient motion signal, observers can compare the perceived scene with a stored memory representation derived from prior discrete views (for similar arguments for such a comparison mechanism, see Henderson & Castelhano, 2005; Hollingworth & Henderson, 2002; Hyun, Woodman, Vogel, Hollingworth, & Luck, in press; Zelinsky, 2001). According to this hypothesis, when a perceived object lacks a corresponding representation in memory, this object is prioritized for viewing. An important question to ask of this mechanism, therefore, concerns the specificity with which memory representations of objects and scenes are maintained in working memory and the degree of mismatch that is necessary for prioritization to take place. In the case of an onset, the sudden appearance of a new object generates a substantial mismatch between the perceived scene and the corresponding representation of the scene in memory. Changes to existing objects, however, are more subtle. For example, the degree to which colour changes to an object can be detected depends on how well these surface properties are maintained in the online memory representations constructed over the course of scene viewing as well as their functionality in guiding attention. Therefore, the second goal of this report was to determine the degree to which memory-based control of attention can be used to detect changes to scenes in which the featural properties of existing objects change.

VISUAL SALIENCE IN OCULOMOTOR CAPTURE AND MEMORY-GUIDED PRIORITIZATION

In addition to being visually surprising events (see Itti & Baldi, in press, for a computational modelling approach to visually based surprise), the addition of a new object or a change in an existing object's visual features is likely to alter low-level visual characteristics of a scene. However, previous work on oculomotor capture and memory-guided prioritization (at least as they operate within real-world scenes) has treated all scene changes as visual equals. Hence, although it is known that the semantic nature of sudden scene changes can influence the rates at which they are prioritized for viewing (Brockmole & Henderson, 2008), it is unknown to what degree low-level visual attributes of objects are also important. In an effort to provide insight into this question, a final goal of this report was to investigate the potential importance of *visual salience* in oculomotor capture and memory-guided prioritization.

A major theme throughout much of this Special Issue specifically, and the gaze control literature generally, is the extent to which gaze is correlated with visual salience, or the conspicuity of a scene region within the global visual context (Foulsham & Underwood, 2007; Henderson et al., 2007; Itti & Koch, 2000; Koch & Ullman, 1985; Parkhurst, Law, & Niebur, 2002; Tatler, Baddely, & Gilchrist, 2005; Torralba et al., 2006). As a means of extending this discussion to oculomotor capture, we asked whether the visual salience of the new or altered object modulates the extent to which that object is prioritized for viewing. We accomplished this goal by examining whether critical objects that either scored very low or very high in salience were differentially prioritized (details of salience calculation in methods section). If the visual prominence of an object makes it more likely to be prioritized, regardless of its identity, then gaze should be allocated to highly salient objects more than to nonsalient objects when they appear (or change) in a scene.

THE CURRENT STUDY

Observers viewed photographs of real-world scenes for 10 s each (Figure 1). As a cover task, observers were instructed to memorize each scene for a later memory test (in actuality, no such test was given). During viewing, a change to each scene was effected during a fixation (to explore oculomotor capture) or a saccade (to examine memory-guided prioritization) after 5 s had elapsed

Figure 1. An example scene used in this study for both before (left panels) and after (right panels) the scene change: (A) Onset, (B) Colour change. To view this figure in colour, please see the online issue of the Journal.

since the beginning of a trial. Within each scene, a critical object was selected (e.g., the recycle bin in Figure 1). For one group of observers, the critical object was added to the scene either during a fixation or during a saccade (Figure 1A), replicating Brockmole and Henderson (2005b). The data from this group provided a baseline against which the behavioural consequences of colour changes on gaze could be contrasted. For a second group of observers, the same critical objects were present in the scene from the beginning of the trial, but changed colour mid-way through scene viewing (Figure 1B).[2] If transient changes to a scene are prioritized either via attention capture or memory-guided prioritization, then the critical objects should be viewed more often than expected by chance immediately after the change takes place. By comparing the strength of the prioritization effect

[2] This method resulted in postchange scenes that were not identical in the new object and colour change conditions. However, it allowed a direct comparison between the situations where a particular object appeared in a scene and when that same particular object changed its features.

separately for both new objects and feature changes, we can determine which types of scene change are the strongest attractors of gaze as well as the conditions under which these influences are evident. By comparing the strength of the prioritization effect separately for high and low salience objects, we can determine the extent to which prioritization of scene changes is dependent on their visual conspicuity.

METHOD

Participants

Thirty-six University of Edinburgh undergraduates with normal or corrected-to-normal vision were paid £4.00 for their participation in a single 30-minute experimental session (mean age = 21.9, range 18–26). Participants were randomly divided into three equal groups (details below).

Stimuli

Stimuli consisted of full-colour photographs of 30 real-world scenes. Initially, two photographs of each scene were taken, differing only in the presence or absence of a single *critical object* (Figure 1A). Photographs were digitally edited to eliminate minor differences in shadow and spatial displacement between each shot. Local luminance was closely approximated in each scene version (on average luminance for the critical objects was slightly, but not reliably, smaller than the backgrounds in the object-absent versions). We additionally created alternate versions of these photographs in which the colour of the critical object in each scene was altered (see Figure 1B). These colour changes were produced through a series of a pixel-wise manipulations in CIE L*a*b* colour space, which represents any colour independently of luminance. Thus, we were able to change the colour of the critical object without affecting its physical luminance level.

A saliency map was generated for each scene using the salience model popularized by Itti and Koch (2000). Based on this approach, a saliency map was generated for each scene using the Saliency Toolbox for Matlab (Walther & Koch, 2006; see also www.saliencytoolbox.net) using default parameter values. For each scene, a region of interest was defined by the smallest imaginary rectangle that could surround the critical object. For each of these regions, the average saliency value within the corresponding portion of the saliency map was calculated. Fourteen critical objects were classified as “salient items” with an average salience score of .51. Sixteen critical objects were classified as “nonsalient items” with an average salience score of .05 (see Figure 2).

Figure 2. Mean salience value of pixels within the critical region within each of the 30 scenes. Sixteen scenes were considered to have nonsalient critical regions; fourteen scenes were considered to have salient critical regions.

Photographs were displayed at a resolution of 800 × 600 pixels in 24-bit colour and subtended 37° horizontally and 27.5° vertically at a viewing distance of 81 cm. Eight pictures of the scenes used in this experiment were also used by Brockmole and Henderson (2005a, 2005b) and 22 pictures of the scenes were created for this study. The new scenes replaced scenes from Brockmole and Henderson's original set in which the critical objects were black or white as these colours could not be altered without influencing their luminance. Stimuli were also replaced in which a colour change produced semantic inconsistency in a scene (e.g., a package of sausages in a freezer suddenly changing from a natural brown to an unnatural blue). In such cases, it would be difficult to separate prioritization patterns caused by colour change per se and the semantic inconsistency it would generate (see Brockmole & Henderson, 2008, for discussion of how semantic inconsistency affects attention capture and memory-guided prioritization).

Apparatus

Stimuli were presented on a 21-inch CRT monitor with a screen refresh rate of 120 Hz. Throughout each trial, the spatial position of each observer's right eye was sampled at a rate of 1000 Hz by a tower-mounted EyeLink 2K eyetracking system (SR Research, Inc.) running in pupil and corneal-reflection mode, resulting in an average spatial accuracy of 0.15°. An eye movement was classified as a saccade if its amplitude exceeded 0.2° and either (a) its velocity exceeded 30°/s or (b) its acceleration exceeded 9500°/s.

Chin and forehead rests stabilized head position and kept viewing distance constant.

Design and procedure

Observers were randomly assigned to one of three conditions: The *onset condition*, the *colour condition*, and the *control condition*. The task in all conditions was the same; observers were instructed to memorize each scene in preparation for a subsequent memory test (in actuality, the test was never given). In the onset condition, a single critical object was added to the scene, whereas in the colour condition the colour of the critical object (present from the start of the trial) was altered. These scene changes occurred after 5 s had elapsed from the beginning of a trial (details later). In the control condition, these same critical objects were visible throughout the trial. This control condition allowed us to determine the baseline rate at which the critical objects were fixated when they were not suddenly added or changed during viewing. No explicit instructions regarding scene changes were given to observers in any condition.

All observers began the experimental session by completing a calibration routine that mapped the output of the eyetracker onto the display position. Calibration was constantly monitored throughout the experiment and was adjusted when necessary (a drift correction was applied at the start of each trial). Observers began each trial by fixating a dot in the centre of the display. When they were ready to view the stimulus, a photograph was displayed for 10 s. For observers in the onset and colour conditions, new objects were added or altered while an observer was studying a scene by seamlessly switching the photograph presented on the display with its associated counterpart that contained either the additional object or the altered colour (depending on the observer's condition assignment). Furthermore, critical objects were added or altered during either a saccade or a fixation. These scene changes were yoked to the first saccadic eye movement that occurred after 5 s had elapsed from the beginning of the trial. When scene changes were to occur during a saccade, their occurrence coincided with the detection of this saccade (*saccade trials*). By contrast, when scene changes were to occur during a fixation, they were executed 100 ms after the start of the first saccade launched after 5 s of viewing time. This 100-ms delay was long enough to allow the critical saccade to terminate but short enough that a subsequent saccade could not be launched before the scene change (see Brockmole & Henderson, 2005a, 2005b, 2008, for successful use of this method). Thus, the eyes were stable when scene changes occurred (*fixation trials*). The successful trial-by-trial application of these principles was examined post hoc (see below).

RESULTS AND DISCUSSION

Linking onsets and colour changes to saccadic eye movements required a liberal threshold for saccade detection. As well as enabling us to execute these scene changes during saccades on the majority of saccade trials, this procedure also led to false alarms by the saccade detection algorithm. New objects were successfully onset during a fixation on 96% of fixation trials and during a saccade on 67% of saccade trials. Colour changes were successfully executed during a fixation on 92% of fixation trials and during a saccade on 69% of saccade trials. All remaining trials were excluded from the reported analyses. Two types of analysis were conducted (see Brockmole & Henderson, 2005a, 2005b). First, we determined the probability that the critical object was fixated after its appearance or colour change relative to the probability that it was fixated when it did not suddenly appear nor change colour. Evidence for prioritization requires that the critical objects be fixated more than expected by chance. Second, we examined the speed with which the critical object was fixated following its appearance or alteration in the scene. Prioritization based on oculomotor capture should be evident sooner than that based on memory-guided prioritization.

New objects

Probability of fixating the new object. For each scene, a region of interest was defined by the smallest imaginary rectangle that could surround the critical object. Fixations were sorted based on whether they fell within or outside these regions of interest. We restricted our analysis to the first four fixations following the appearance of the new object (denoted as *ordinal fixation positions* 1, 2, 3, and 4, respectively). Fixation 1 denotes the termination of the first saccade launched after the critical change occurred to the scene. Therefore, it is the first fixation that could be influenced by the change. If the new object captures observers' gaze, then observers' eyes should be quickly directed to the location of the scene change with greater-than-chance probability. This chance level was obtained from the control condition where, on average, 7% of fixations were localized on the critical object. We refer to this probability as *the baseline rate of viewing*. After a new object appears, the probability of fixating the critical object should exceed this baseline rate if it draws attention.

Initial analyses considered the probability that the critical object was fixated as a function of trial type (fixation vs. saccade), ordinal fixation position (Fixations 1–4), and salience (salient items vs. nonsalient items). In the corresponding repeated-measures analysis of variance (ANOVA), the main effect of salience was not reliable ($p = .45$), nor did it interact with any other factor (all $ps > .13$). Our remaining analyses, therefore, collapsed across this factor and are illustrated in Figure 3 (refer to Table 1 for breakdown of performance as a function of salience).

Ninety-five per cent confidence intervals indicated that, for both fixation and saccade trials, the new object was fixated more frequently than the baseline rate of viewing at all four ordinal fixation positions. Fixation and saccade trials were contrasted with a 2 (trial type) × 4 (ordinal fixation position) repeated-measures ANOVA. On average, the new object was fixated more often when it appeared during a fixation (61% of fixations) than when it appeared during a saccade (27% of fixations), which led to a reliable main effect of trial type, $F(1, 11) = 40.9$, $p < .0001$. The new object

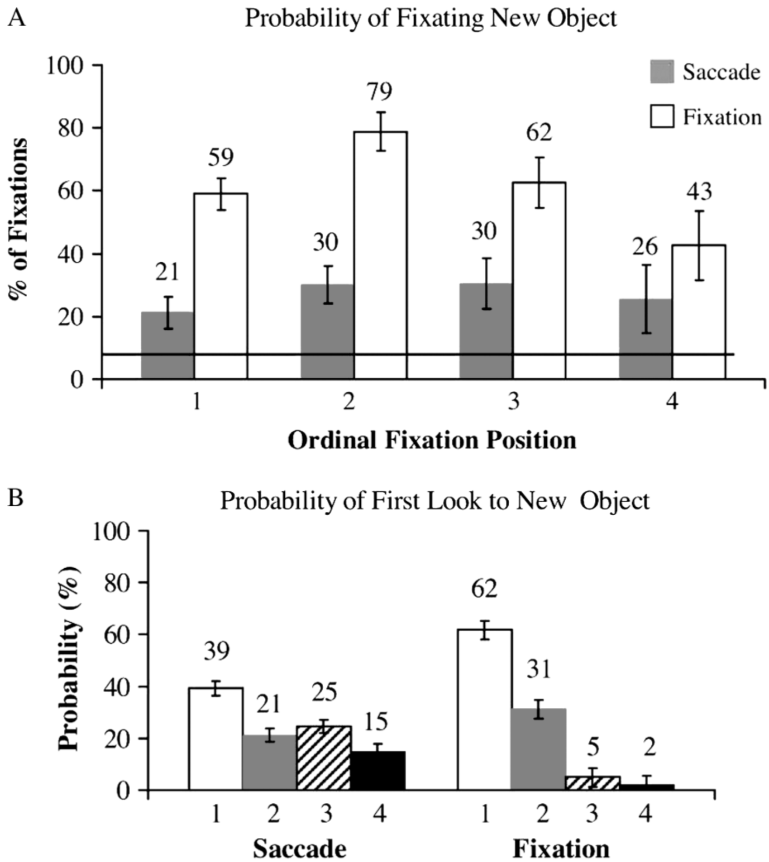

Figure 3. Results: New objects. (A) The mean probability of fixating the new object as a function of trial type (saccade vs. fixation) and ordinal fixation position (Fixations 1–4). The solid line illustrates the baseline rate of viewing (chance). (B) The probability with which the first look to the new object occurred at each of the first four fixations after its appearance. Error bars represent 95% within-subjects confidence intervals (Loftus & Masson, 1994).

TABLE 1
Mean percentage of fixations (with standard deviation) falling on new objects and colour changes broken down by ordinal fixation number, trial type, and visual salience

	Ordinal fixation number			
Trial type	*1*	*2*	*3*	*4*
New objects				
Fixation condition				
Nonsalient items	58 (5.2)	80 (3.7)	66 (5.3)	41 (6.5)
Salient items	55 (5.2)	77 (5.1)	58 (7.4)	40 (9.8)
Saccade condition				
Nonsalient items	18 (6.2)	23 (6.0)	25 (5.6)	22 (6.2)
Salient items	22 (5.8)	36 (6.9)	33 (6.2)	28 (6.6)
Colour changes				
Fixation condition				
Nonsalient items	27 (6.1)	45 (4.6)	48 (5.8)	40 (6.0)
Salient items	40 (5.2)	50 (6.1)	44 (6.4)	45 (7.6)
Saccade condition				
Nonsalient items	22 (6.0)	29 (7.4)	31 (9.3)	26 (7.2)
Salient items	15 (6.8)	40 (10)	45 (10)	37 (9.0)

was not fixated equally at all ordinal fixation positions, however, which also led to a reliable main effect of ordinal fixation position, $F(3, 33) = 7.2$, $p < .001$. For both fixation and saccade trials, the new item was fixated more often during Fixation 2 than any other fixation position. However, on fixation trials, the probability of fixating the new objects dropped dramatically from Fixation 2 to Fixation 4, whereas on saccade trials, the probability of fixating the new item remained relatively stable throughout. These distinctly different frequency patterns produced a reliable interaction of trial type and ordinal fixation position, $F(3, 33) = 5.9$, $p < .002$. These patterns qualitatively replicate those reported by Brockmole and Henderson (2005a, 2005b). Observers fixated newly appearing objects more often than expected by chance, regardless of whether they appeared during a saccade or a fixation. However, the transient signal that accompanies the onset of a new object in fixation trials drew observers' eyes more often than the appearance of a new object without such a signal (saccade trials).[3]

Number of eye movements to first fixation on new objects. Despite reliable effects of ordinal fixation position in the analysis above, it is difficult to assess the temporal trend in prioritization from fixation frequency data

[3] A similar conclusion follows from analysis of trial-level effects. The new object was fixated within the first four fixations after its appearance in the scene on 85% of trials in the fixation condition and on 40% of trials in the saccade condition, $p < .001$.

because both initial fixations and refixations are combined. The number of fixations intervening between the onset of the new object and an observer's first fixation on that object, however, does reveal how quickly the object is prioritized. On average, when occurring during a fixation, the new object was first fixated 1.5 fixations after the onset. In contrast, when occurring during a saccade, the new object was fixated 4.0 fixations after onset, $t(11) = 4.7$, $p < .0007$. On fixation trials, 98% of all first looks to the new object occurred in the first four fixations after its appearance. On saccade trials, this rate fell to 68%, $t(11) = 10.2$, $p < .0001$. These disproportionate rates of viewing indicate that new objects with transient onsets draw attention more readily than those without a transient signal.

To obtain a more fine-grain picture of prioritization speed, we analysed the probability with which the first fixation on the critical object occurred at each of the ordinal fixation positions, given that it was fixated within this temporal range. Figure 3B illustrates these probabilities as a function of trial type. The probability of the first look to the new object occurring at each of the four ordinal fixation positions differed, $F(3, 33) = 32.8$, $p < .0001$, and these differences were not equal for saccade and fixation trials, $F(3, 33) = 34.5$, $p < .0001$.[4] On fixation trials, 62% of first looks to the new object occurred at Fixation 1. This was followed by a rapid decline at each of the next ordinal fixation positions. Only 7% of these first looks occurred at Fixations 3 and 4 combined. In contrast, on saccade trials, 39% of the first looks occurred at Fixation 1. The moderate decrease followed with 21% of first looks occurring at Fixation 2, and an additional 40% at Fixations 3 and 4 combined. Compared with onsets on fixation trials, prioritization of new objects appearing during saccades was temporarily protracted. These results also qualitatively replicate those reported by Brockmole and Henderson (2005b). In conjunction with the fixation frequency analysis depicted in Figure 3A, we conclude that, like Brockmole and Henderson (2005a, 2005b, 2008), a transient signal increases both the probability that the new object is prioritized and the speed with which the prioritization takes place.

Colour changes

Probability of fixating colour changes. As with new objects, initial analyses considered the probability that the critical object was fixated as a function of trial type (fixation vs. saccade), ordinal fixation position (Fixations 1–4), and salience (salient items vs. nonsalient items). In the

[4] To avoid issues of multicollinearity introduced by expressing the number of first looks to the onset at each of ordinal fixation position as a conditional probability, we performed the ANOVA on the raw number of times the first look occurred at each fixation position (see Brockmole & Henderson, 2005b).

corresponding repeated-measures ANOVA, the main effect of salience was not reliable ($p = .15$), nor did it interact with any other factor (all $ps > .15$). Therefore, our remaining analyses collapsed across this factor and are illustrated in Figure 4 (refer to Table 1 for breakdown of performance as a function of salience).

Ninety-five percent confident intervals indicated that, for both fixation and saccade trials, colour changes were fixated more frequently than the baseline rate of viewing at all four ordinal fixation positions. A 2 (trial

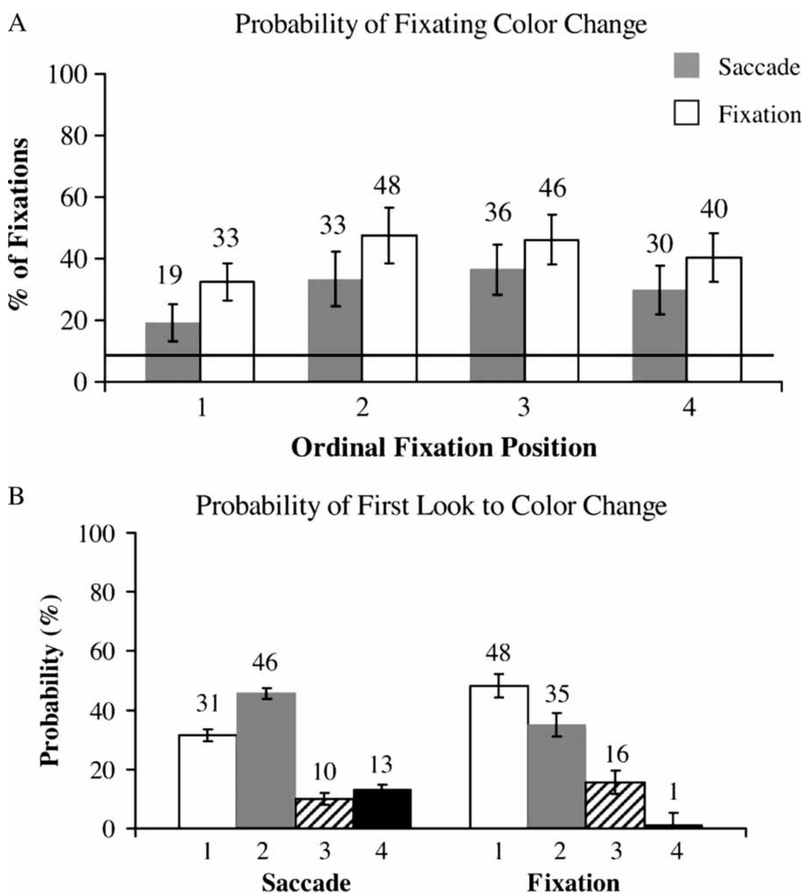

Figure 4. Results: Colour changes. (A) The mean probability of fixating the colour change as a function of trial type (saccade vs. fixation) and ordinal fixation position (Fixations 1–4). The solid line illustrates the baseline rate of viewing (chance). (B) The probability with which the first look to the critical object occurred at each of the first four fixation position after its colour changed. Error bars represent 95% within-subjects confidence intervals (Loftus & Masson, 1994).

type) × 4 (ordinal fixation position) repeated-measures ANOVA revealed a marginal difference in the probability of fixating the critical regions between fixation (42%) and saccade (30%) trials, $F(1, 11) = 4.5$, $p = .057$.[5] Like a sudden appearance of an object in Experiment 1, colour changes to existing objects were not fixated equally at all ordinal fixation positions, $F(3, 33) = 5.7$, $p < .001$, with the probability of fixating the critical object greatest at Fixation 2. However, prioritization patterns across the four ordinal fixation positions were very similar for fixation and saccade trials and the interaction of trial type (fixation vs. saccade) and ordinal fixation position was not reliable, $F(3, 33) < 1$.

Number of eye movements to first fixation on colour changes. On average, there was no reliable difference in the speed with which the critical object was first fixated when colour changes occurred during a fixation (4.0 fixations after colour change) and when they occurred during a saccade (4.7 fixations after colour change), $t(11) = 1.06$, $p = .31$. On fixation trials, 72% of all first looks to the target object occurred in the first four fixations after the colour changed, whereas on saccade trials, 67% of all first looks to the critical object occurred in the first four fixations, $t(11) = 3.2$, $p < .008$.

Figure 4B illustrates the probability that the critical object was first fixated at each of the four ordinal fixation positions given that it was viewed within this range of fixations. The probability that the first look to the critical object occurred at each of the first four ordinal fixation positions differed, $F(3, 33) = 15.7$, $p < .0001$, and these differences were not equal for saccade and fixation trials, $t(11) = 4.5$, $p < .001$. Specifically, on fixation trials, 48% of first looks to the critical object occurred at Fixation 1, which was followed by progressive decline with only 23% of first looks occurring at Fixations 3 and 4 combined. However, on saccade trials, the probability of first look peaked at Fixation 2 rather than Fixation 1, then declining to 17% at Fixations 3 and 4 combined. Although the differences in prioritization speed between fixation and saccade trials was less striking than that observed for new objects, these results nevertheless indicate that, relative to fixation trials, prioritization of the critical object was somewhat slower on saccade trails.

[5] The choice of using four ordinal fixation positions was arbitrary and was used here to parallel results presented in our prior studies (Brockmole & Henderson, 2005a, 2005b). An ANOVA considering only the first three ordinal fixation positions revealed a reliable effect of trial type, $F(1, 11) = 4.73$, $p = .05$, demonstrating a prioritization effect specific to the transient signal. The analysis of trial-level effects also supports this conclusion; observers looked to the colour change on 54% of trials in the fixation condition and on 34% of trials in the saccade condition ($p < .01$).

New objects versus colour changes

The preceding results indicate that sudden changes to an existing object's colour are prioritized. These results also suggest that memory for scenes includes not only what objects are present, but also some aspects of their surface features (i.e., colour). To more fully characterize the effects of colour change on attentional prioritization, we contrasted fixation and saccade trials across new object and colour change conditions with separate 2 (change type) × 4 (ordinal fixation position) mixed-model ANOVAs for each trial type. For fixation trials, main effects of change type, $F(1, 22) = 18.1$, $p < .001$, and ordinal fixation position, $F(3, 66) = 10.8$, $p < .001$, were observed. These factors also interacted, $F(3, 66) = 4.9$, $p < .01$. Within fixation trials, although colour changes were prioritized, new objects that suddenly appeared during scene viewing were fixated more often than colour changes. These results suggest that onsets capture attention more effectively than colour changes in real world scenes (see Boot, Brockmole, & Simons, 2005a; Gibson & Jiang, 1998; Irwin et al., 2000; Jonides & Yantis, 1988, for similar demonstrations with nonscene stimuli). For saccade trials, only a main effect of ordinal fixation position was observed, $F(3, 66) = 4.3$, $p < .01$ (all other Fs < 1). Thus, when a transient signal was not present, new objects and colour changes were prioritized with equal efficiency.

The speed of prioritization was also contrasted across the new object and colour change conditions). On fixation trials, qualitative patterns of first fixation probabilities were similar across change types, but quantitative differences were observed as a reliable interaction between change type (i.e., experiment) and ordinal fixation position, $F(3, 66) = 9.28$, $p < .01$. Although first looks to scene changes were most likely at Fixation 1 in both cases, colour changes were more likely to be fixated first later in the trial than onsets. For saccade trials, the interaction between change type and ordinal fixation position was not reliable, $F(3, 66) = 1.02$, $p = .39$. Thus, without a transient signal, new objects and colour changes were prioritized with equal speed.

DISCUSSION

The present study investigated the extent to which changes to an object's colour are prioritized for viewing relative to the appearance of a new object. New objects appeared, and object feature changes occurred, either during a fixation so that they were accompanied by transient motion signals or during a saccade so that these transient signals were eliminated. Replicating previous findings (Brockmole & Henderson, 2005a, 2005b, 2008), new objects were powerful attracters of gaze by two separable mechanisms. When new objects appeared during a fixation, over half of the next four fixations were directed to these new objects. Furthermore, over 60% of all first looks to the new object occurred with the fixation immediately following the onset. These results indicate that transient onsets capture attention quickly and reliably. Gaze was also directed to new objects that appeared without a transient signal (i.e., during a saccade) at rates far greater than chance. However, prioritization of these objects occurred less often and more slowly than objects accompanied by a transient motion signal.

The consequence of a colour change to an existing object on gaze was qualitatively very similar to that caused by new objects. Colour changes were prioritized for viewing regardless of their transient status, but those that occurred during a fixation received more frequent and faster prioritization than those that occurred during a saccade. However, important quantitative differences were apparent between the efficacy with which a colour change draws gaze and that observed when a new object appears in a scene. With respect to oculomotor capture, transient onsets captured gaze more often than transient colour changes. This is a result that refines and extends the conclusions reached by Irwin et al. (2000) regarding the capture of attention by colour singletons. First, as in simple displays, colour changes to an existing object can capture attention in real-world scenes. Second, capture by a colour change does not require the critical object to be a singleton in an otherwise homogenous display. Third, colour changes capture attention less often than new objects even when these two types of change occur independently from one another.

With respect to memory-guided prioritization, no differences were observed between the prioritization given to colour changes and to new objects. This result has two major implications for conceptualization of online scene memory. First, object surface feature information (i.e., colour) in a display is incidentally stored in the online representations that are generated during scene viewing, extending previous demonstrations that object identity, position, and orientation are maintained in memory (e.g., Aivar, Hayhoe, Chizk, & Mruczek, 2005; Henderson & Hollingworth, 1999, 2003; Hollingworth, 2004, 2006, 2007; Hollingworth & Henderson, 2000, 2002; Smilek, Eastwood, & Merikle, 2000; Tatler, Gilchrist, & Land, 2005; Tatler, Gilchrist, & Rusted, 2003). However, this conclusion contrasts somewhat with recent arguments that colour information is not useful in the guidance of visual search for known targets through real-world scenes (Ehinger & Brockmole, 2008), although a variety of task differences existed between these studies. Therefore, determining the conditions under which colour is used to guide attention constitutes an important avenue for continued research. Second, when current views are compared to those stored in memory, a change to the colour of an object is as conspicuous as a change produced by the onset of an entirely new object. The behavioural equivalence of these conditions suggests that a sudden change to an object's colour may require an observer to create a new object file in visual working memory (Treisman & Gelade, 1980), but further research on this possibility is required (see Mitroff & Alvarez, 2007, for evidence that surface features such as colour may not determine object files).

While the prioritization of new objects can be affected by their semantic identity (Brockmole & Henderson, 2008), the results of the present study suggest that both oculomotor capture and memory-guided prioritization operate independently of at least some visual factors. Newly appearing nonsalient objects were prioritized for viewing—regardless of the mechanisms involved—just as efficaciously as highly salient objects. Similar results were obtained for colour changes. This result reinforces the prominence of a transient motion signal in the generation of oculomotor capture and suggests that the features of salient objects are no more likely to be retained in memory than those of nonsalient objects.

In summary, we can draw five general conclusions regarding the prioritization of new objects and changes in the surface features of existing objects. First, both new objects and colour changes can capture overt attention during real-world scene viewing. This finding not only supports the ecological validity of prior oculomotor capture studies but also provides clear evidence that these effects can be observed even when scene changes do not constitute singletons in an otherwise homogeneous display. Second, a strong "new object" theory of attention capture seems to be false, at least in the context of oculomotor capture during real-world scene viewing. Colour changes did not result in physically new objects in the displays, but they nevertheless captured overt attention. Third, the robustness of oculomotor capture is not equal for all types of scene change. In this case colour changes did not capture attention as efficiently as new objects. This pattern suggests that while physically new objects are not required for oculomotor capture, they nevertheless are given higher priority than feature changes. Fourth, memory-guided prioritization is not limited to the onset (or offset) of an object. When transient signals were absent, colour changes were prioritized just as well as new objects, suggesting some level of psychological equivalence between these two types of scene change. Finally, although prioritization can be influenced by semantic factors (Brockmole & Henderson, 2008), both oculomotor capture and memory-guided prioritization of new objects and colour changes are independent of visual salience.

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