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Oculomotor capture by irrelevant onsets with and without color contrast

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It is widely known that irrelevant onsets (i.e., items appearing in previously empty locations) can automatically capture attention and attract our gaze. Some studies have shown that onset capture is stronger when the onset distractor matches the target feature, indicating that onset capture can be modulated by feature-based (top-down) tuning to the target. However, it is less clear whether and to what extent the perceptual saliency of the distractor can further modulate this effect. This study examined the effects of target similarity, competition between target and distractor, and bottom-up color contrast on the ability of onset distractor to capture the gaze, by varying the color (contrast) and stimulus-onset asynchrony of the onset distractor. The results clearly show that competition and feature-based attention modulate capture by the irrelevant onset to a large extent, whereas bottom-up color contrasts do not modulate onset capture. These results indicate the need to revise current accounts of gaze control.

Keywords: visual search; onset capture; oculomotor capture; color contrast; SOA

Introduction

In everyday life, we may have the impression that we have perfect knowledge and control over our attention and eye movements, such that we automatically know which objects we are attending to, and are always able to ensure that our gaze does not stray into unwanted territory. This impression may even be true when we know everyone's location and the location of the most important objects. In these situations, we can also covertly attend to items outside the current gaze focus "out of the corner of our eyes."[1] However, when we are actively searching for a person or an object, and the location of a sought-after object is unknown, the situation drastically changes. First, whenever we move our eyes, attention and eye movements are tightly linked, so that we cannot dissociate the locus of attention from the gaze.[1–3] Second and more important, our control over our attention and gaze behavior seems severely limited when we do not know the location of an object.[4] In instances in which we have to rely on other features of objects (e.g., color or shape), attention cannot be successfully biased to a specific object, but only to single elementary features such as a specific color and/or a specific orientation or shape (e.g., looking for a red object; see Refs. 5–7). Our visual environment is, however, often cluttered with similar-looking objects, resulting in frequent visual-selection errors. For instance, when looking for a woman with a red hat, we may erroneously look at a woman with a red umbrella or a red dress. Apparently, we can preset attention to specific feature values such as red or green,[8,9] but are unable to successfully single out compound features that differ only in a conjunction of features from the surround (e.g., simultaneously considering the color and shape to distinguish a red dress from a red umbrella; see Refs. 6 and 7). Hence, when looking for an item, we are prone to select irrelevant items that share the target's features. In other words, irrelevant items can involuntarily capture attention or the gaze if they match our top-down control settings.[8,9]

In addition to these instances of *top-down–contingent capture*, attention and gaze behavior are also affected by bottom-up, stimulus-driven

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factors.[10] Among the stimuli that can strongly affect gaze behavior are sudden onsets. These are suddenly appearing stimuli that can attract our attention and gaze even when they are irrelevant to the task and dissimilar to the target.[10–13]

Another class of stimuli that can potentially attract attention and the gaze involuntarily are visually salient objects, such as stimuli with a high color or luminance contrast.[14–16] Although the underlying mechanism is not fully understood, it is plausible that high-contrast stimuli enjoy a relative advantage over other stimuli because items of the same color are mutually inhibited via lateral inhibitory connections in the visual cortex (for a review, see Ref. 17).[18] Among a homogeneously colored array of stimuli, an odd-looking item will therefore be the only item that is not inhibited and thus will pop out.[19]

Is it possible that capture by onsets is based on a similar mechanism? On the one hand, it may seem plausible that onsets would pop out in a similar fashion from other items, because the sudden appearance of an object can be a visually salient event, especially when the onset is accompanied by a unique transient or unique temporal change.[20–24] According to this view, onsets could capture attention and the gaze in a similar manner as other highly salient stimuli, by competing for attention with the target (within a single attentional priority map that determines attention and gaze shifts (see, e.g., Refs. 21, 25, and 26)).

A probably more widely held view, however, is that onsets modulate attention and eye movements via a separate system that is dedicated to detecting the appearance of new objects (see, e.g., Refs. 27–29; but also see Refs. 21, 22, and 30). Interestingly, Mulckhuyse and Theeuwes additionally proposed that onsets exert their effects at a very early stage of visual processing—before a stage where color contrast or information about specific colors (e.g., red) could affect attention.[31] In fact, a similar two-window account has been proposed for other stimulus-driven instances of capture, with the bottom-up saliency of stimuli always affecting attention before top-down controlled processes, which can modulate visual stimulation only at a later stage of visual processing, via a feedback loop.[32–34] In the following, this hypothesis will be referred to as the *dual-stage account* of onset capture.

Contrary to the saliency-based view and the dual-stage account, it has also been argued that capture by onsets could be due to top-down–controlled processes. Of note, in visual-search tasks probing into capture by irrelevant items, the search target is also often a salient item; for instance, the target has a unique color (e.g., a red item among all-gray items), and observers have to ignore a distractor with a unique onset. Bacon and Egeth showed that attention can be biased rather broadly toward salient deviants when the target is a deviant on the majority of trials. Hence, an irrelevant salient distractor can capture attention even when it is featurally dissimilar to the target, in virtue of the fact that attention has been biased broadly toward deviants.[35] Adopting such a broad attentional bias is, moreover, task dependent and in this sense top down (or at least not stimulus driven): when the target can only be found by its specific feature value (e.g., red) on the majority of trials, attention is tuned to the exact feature value and a salient distractor ceases to interfere with search.[35] These results suggest that the visual system can exploit statistical regularities and flexibly adapt the search settings to optimize search.[8,9,35]

Capture by irrelevant onsets could conceivably be mediated by similar top-down factors. Of note, in visual-search studies on onset capture, the target and nontargets are often completely occluded by placeholders (masks); for instance, by presenting gray disks in the respective locations. Observers are then asked to make a fast eye movement to the stimulus that changes its color (e.g., to red, the target), while ignoring stimuli that are simultaneously presented in a previously empty location (the onset distractor; see, e.g., Fig. 1). Given that the target usually involves a color change, attention may be broadly biased to such visual transients, explaining why onset distractors have frequently been reported to attract attention and the gaze.[31,36–38] It has also been proposed that the visual system may generally become sensitive to visual transients because they signal the appearance of the target and thus can serve as a trigger to start searching.[8,9,39] In line with this view, onsets are largely ineffective in the context of a different (spatial-cueing) paradigm, which is characterized by frequent irrelevant onsets and offsets (see Refs. 8 and 9; but also see Ref. 40).

To date, several studies have probed into the possible interplay of top-down and bottom-up processes in mediating onset capture. For instance, Ludwig and Gilchrist asked observers to make a fast and precise eye movement to a red target among gray

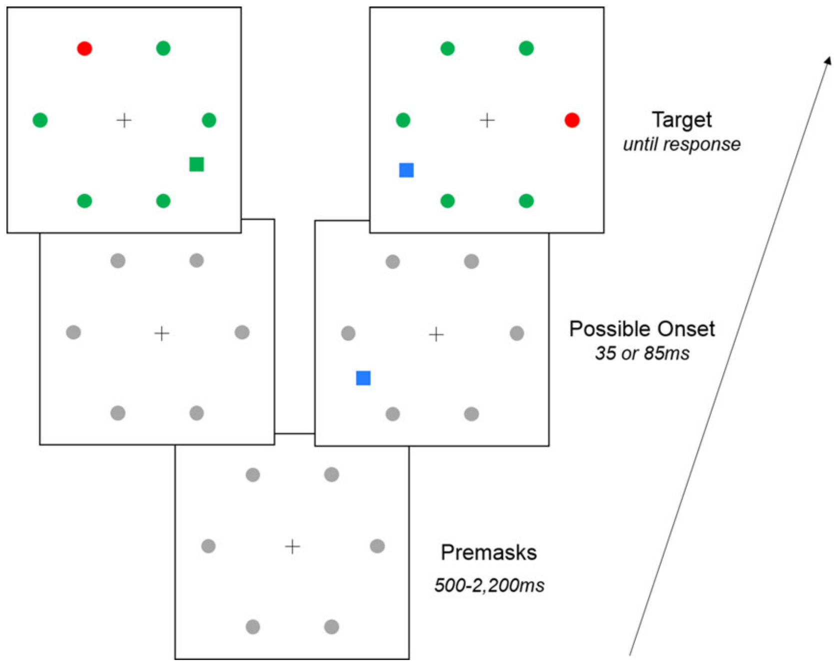

Figure 1. Example of stimuli and procedure. Each trial started with the presentation of the premask display. Depending on the SOA condition, the onset distractor (colored square) could be presented simultaneously with the target (red disk; left panels), before the target (red disk; right panels), or after the target (not depicted). The participant's task was to make a fast and precise eye movement to the target (here: red disk) and to ignore the onset distractor.

nontargets while ignoring an additional distractor that could be either presented with or without an onset, and that either had the target color (red) or a nonsalient color (gray; same as the nontargets).[26] Their results showed that target-similar onset distractors captured the gaze most strongly (49%), followed by target-similar no-onset distractors (19%) and nonsalient-onset distractors (7%: experiment 1). Similar results have been obtained in other studies[23,31] and suggest that a top-down setting to search for a particular color can modulate onset capture (but see Ref. 38). However, it is still an open question whether an irrelevant onset directly competes with the target or other irrelevant salient (high-contrast) items for attention or whether its effects would be mediated by a separate system outside this competition, as would be the case, for instance, according to the dual-stage account.

The present study

The aim of this study was to assess whether onset distractors modulate search independently and/or in a different time window than other factors known to guide attention, such as bottom-up color contrast and top-down settings. Among the factors that we varied were (1) the similarity of the onset distractor to the target and the nontargets, (2) the color contrast of target-dissimilar onset distractors against the nontarget background (or background of masks), and (3) the timing of target and distractor events (i.e., the distractor was presented before the target, simultaneously with the target, and after the target).

As in previous studies, participants had to make a fast eye movement to a target marked by a color change, while ignoring an irrelevant onset distractor.[23,31,36,37] Moreover, we changed both the color of the target and the nontargets, to ensure that the target could only be found by attending to the specific target color change (not to visual transients per se). Moreover, the onset distractor was presented simultaneously with the target and nontarget color change, or 35 or 85 ms before or after the color change, so that the appearance of the onset distractor did not signal the presence of the target.[8,9,39] With this, observers had no incentive to attend to onsets or their transients, ensuring that capture by the onset would not be a by-product of deliberately attending to onsets (or their characteristics), but purely bottom-up or stimulus-driven (for the criteria of probing into bottom-up, stimulus-driven capture, see Refs. 11 and 14).

As in previous studies, onset capture was inferred by measuring the observers' eye movements during visual search, and in particular, saccades to the onset distractor. Thereby, not every eye movement to the onset distractor can be interpreted as an instance of onset capture, because eye movements are prone to errors, and are occasionally directed to a nontarget object or empty locations owing to other factors interfering with gaze control.[41] Hence, capture by the onset distractor was inferred only when the onset distractor was selected more frequently than any of the inconspicuous nontargets (i.e., the nontarget-selection rate served as a baseline; see Refs. 42–45 for a similar criterion).

Since eye movements are also prone to speed–accuracy trade-offs,[46] we additionally assessed the latencies of first saccades that were directed to either type of distractor. If, for instance, higher selection rates of one distractor is due to the fact that it triggered eye movements earlier in time, this would be reflected in shorter saccade latencies for this type of distractor.[31,42–45]

In the experiment, the premasks indicating the target and nontarget positions were all gray disks. For half of the participants, the target consisted of a color change to red, while the nontargets changed to green disks, and for the other half of the participants this was reversed (i.e., the target changed its color to green, while the nontargets changed to red). The onset distractor always appeared in a previously empty location, and in addition, it was always a square (to allow discriminating the target-similar onset distractor from the target). Five different onset distractors were used. The *target-similar* onset distractor had the same color as the target (red or green, in the different groups). The *dissimilar* distractor was blue and thus always had a high color contrast (both with respect to the gray masks and the green nontargets). The *nontarget-similar* distractor had the same color as the nontargets (green or red), and the *premask-similar* distractor was always gray. In addition, we included a *no-onset* condition that could serve as a baseline. Each distractor could be presented simultaneously with the target (and nontargets), or 35 or 85 ms before or after the target, yielding five different stimulus-onset asynchrony (SOA) conditions for each distractor. Depending on the point in time in which the distractor is presented, it can also either have a high or low color contrast (i.e., before target: nontarget-colored distractor among gray premasks is salient but premask colored distractor is nonsalient; after target: premask-colored gray distractor among nontargets is salient but nontarget-colored distractor is nonsalient). Table 1 provides an overview of salient and nonsalient color/SOA conditions, and Figure 1 provides examples of the sequence of color changes in the simultaneous onset (SOA 0) condition (left panels) and an early onset SOA condition (right panels).

The main research question was whether information about specific color values (e.g., red/green) and color contrast (i.e., onset distractor has color contrast or not) would modulate capture by the irrelevant onset. If knowledge about the target color modulates onset capture, we would expect more capture by the target-similar onset distractor than the nonmatching onsets. Moreover, if the nontarget color is suppressed, the nontarget-colored onset should be selected less frequently than the dissimilar blue onset and the premask-colored gray onset.

As mentioned earlier, the onset distractors also differed in color contrast, namely, whether they had the same color or a different color than the other irrelevant items (nontargets or premasks), which could vary depending on the SOA (see Table 1 for an overview of salient and nonsalient onsets). Hence, if color contrast modulates onset capture, we would expect more capture by the salient onsets, which are the blue and nontarget-colored onsets in the early SOA conditions (SOA –35 and –85 ms), and the blue and premask-colored onset in the later SOA conditions (SOA 0, 35, and 85 ms).

The SOA variation could also affect onset capture more directly, because it affects (1) the relative saliency of the onset, and (2) the temporal order of target and distractor events, which can modulate competition.[21,24,47] First, the visual transient of the onset may be masked by the simultaneous color change of target and nontargets in the SOA 0 condition, so that the onset is relatively more salient in all other SOA conditions.[20] This may produce less capture by the onset when it is presented among multiple other color changes.[20] Second, the temporal order of target and distractor events affects whether and to what extent the onset distractor competes with the color target. If the sudden appearance of

Table 1. **Saliency/color contrast of onset distractors in each SOA condition**

	SOA				
	SOA –85 ms	SOA –35 ms	SOA 0 ms	SOA 35 ms	SOA 85 ms
Target-similar	**Salient**	**Salient**	**Salient**	**Salient**	**Salient**
	91%***	**79%*****	**57%*****	**32%*****	**7%****
Dissimilar	Salient	Salient	Salient	Salient	Salient
	37%***	17%***	8%**	7%**	2%
Nontarget–similar	Salient	Salient	Non-Sal	Non-Sal	Non-Sal
	20%***	6%	3%	2%	0%
Premask-similar	Non-Sal	Non-Sal	Salient	Salient	Salient
	29%***	9%*	5%*	2%	0%

NOTE: "Salient" and "Non-Sal" depict cases in which the onset distractor had a different color versus when it had the same color as the irrelevant items in the display (nontargets or pre-masks). The shaded areas represent instances in which the onset was presented before the target, and areas printed in bold highlight the condition in which the onset was similar to the target. Values represent the proportion of first eye movements to the onset, and asterisks indicate whether these values were significantly higher than the nontarget–selection rates in this condition, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, as per two-tailed t-test.

an object is indeed processed faster than color information, as proposed by the dual-stage account, then all onset distractors should interfere with target selection at the early SOAs (SOA –85, –35, and 0 ms), and probably still when the onset is presented slightly later than the target (SOA –35 ms).[31–34] On the other hand, if information about color changes and onsets is available at the same time, capture by irrelevant onsets should be eliminated when the target is presented simultaneously with the onset and at all later SOAs.

Method

Participants

Twenty-four participants from the University of Queensland, Australia, participated in the experiment. Of the 24 participants, 9 were male and 15 were female and their mean age was 25 years (range: 18–52; SD = 7.35). All participants had normal or corrected-to-normal vision. Testing protocols were approved by the ethics board of the University of Queensland and were in line with the Declaration of Helsinki.

Materials

A Dell Optiplex 745 computer (Dell, Texas) and a BenQ 19" LCD color monitor (BENQ, Taipeh) were used for the experiment. All stimuli were presented on a monitor with a resolution of 1280 × 1024 pixels and a refresh rate of 75 Hz. A video-based eye tracker (Eyelink 1000, SR Research, Ontario, Canada) recorded eye movements with a spatial resolution of 0.1° and a temporal resolution of 500 Hz. A standard mouse was used to record responses while observers viewed the screen from a distance of 65 cm. Presentation software (Neurobehavioral Systems) controlled the sequence of trials in the experiment and provided performance feedback during the experiment.

Stimuli

The premask display consisted of eight gray disks (diameter: 1.9 cm) that were placed on the 1, 3, 5, 7, 9, and 11 o'clock positions 11.4 cm from a central white fixation cross that measured 0.3 cm × 0.3 cm. In the search display, one of the gray premasks was replaced with the color target (red or green), and the remaining disks were replaced with nontargets of the opposite color (green or red). On distractor-present trials, an irrelevant colored square was presented at the 2, 4, 8, or 10 o'clock position that was not previously occupied by a premask. The colors were matched for luminance with a hand-held colorimeter and had the following RGB and CIE (1976) values: red, RGB: 240, 0, 0, $Lu'v'$: 17.9, 0.325, 0.547; blue, RGB: 81, 81, 255, $Lu'v'$: 17.4, 0.149, 0.356; green, RGB: 0, 130, 0; $Lu'v'$: 17.8, 0.090, 0.569; gray, RGB: 105, 105, 105; $Lu'v'$: 17.9, 0.148, 0.513.

Design

Half of the participants searched for a red circle, whereas the other half searched for a green circle. The square-onset distractor could have one of four different colors, yielding a target-similar onset (red or green), a dissimilar onset (blue), a nontarget-similar onset (green or red), and a premask-similar–onset distractor (gray). The color of the onset distractor was varied randomly within the experiment, so that each distractor was present on 20% of the trials, and onsets were absent on the remaining 20% of the trials. The target and distractor position were chosen randomly on each trial, with the provision that the onset was never placed at a position directly adjacent to the target (see Ref. 31 for a similar design).

Distractors were presented at five different SOAs relative to the target, either simultaneously with the target, or 35 or 85 ms before or after the target. The SOA was chosen randomly on each trial, so that each onset distractor could be presented before, simultaneously with, or after the target. The experiment consisted of 800 trials, with regular breaks in between.

Procedure

Participants were seated in a normally lighted room, with their head fixated by the eye tracker's chin and forehead rest. Participants were instructed to make a fast and precise eye movement to the target and to press a mouse button while they were still fixating on the target. Participants were fully informed about the presence and characteristics of possible onset distractors and were instructed to ignore them as much as possible.

Each trial started with the presentation of the fixation display, presented for 500 milliseconds. Immediately afterward, the premask display was presented. Stable and accurate tracking was ensured by a fixation control: participants were instructed to maintain fixation on the fixation cross in the premask display, and the trial started only when the gaze was within 50 pixels of the center of the cross, for at least 500 ms, within a time window of 2000 milliseconds. Otherwise, participants were calibrated anew (nine-point calibration). The minimum fixation duration was 500 ms plus a random period of up to 200 ms, so that the premask display was visible for at least 500 ms, up to 2200 ms (depending on when participants started to fixate on the cross). Immediately after this period, the target display and/or onset distractor was presented (depending on the SOA condition).

After each response made by participants, a feedback display appeared on screen that informed participants about the saccade latency (i.e., the time from the onset of the target to the point in time that the first eye movement started). If participants took more than 300 ms to make the first eye movement, the warning "TOO SLOW" additionally appeared below the saccade-latency feedback on the monitor (see Ref. 31 for a similar procedure).

Results

Data

Eye movements were parsed into saccades, fixations, and blinks, using the standard parser configuration of the Eyelink software, which classifies an eye movement as a saccade when it exceeds a velocity of 30°/s or an acceleration of 8000°/second. The first eye movement on a trial was attributed to the nearest stimulus (target, distractor, or nontarget) when it was outside the fixation area of 200 pixels around the fixation cross. Saccade latencies were computed from the onset of the trial to the point in time when the saccade started, according to the velocity and acceleration criterion.

Data were excluded from all analyses when the first saccade had been an anticipatory eye movement (less than 50 ms after the onset of the target) or a delayed response (more than 500 ms after target onset). This resulted in a loss of 0.35% of the trials. Additionally, 5.24% of data were lost because the end point of the first saccade could not be assigned to a stimulus (e.g., because the first saccade was still inside the fixation area).

Proportion of first saccades to the distractor

The vast majority of first eye movements was directed to the target or the distractor (>95% of first saccades across all conditions). As shown in Figure 2, the most important factor driving distractor selection was whether the distractor color was similar to the target (red line) or not. SOA also had a profound effect on distractor-selection rates, with more first eye movements directed to the distractor when it was presented before the target. This effect was most pronounced for the target-similar distractor, which was selected on 91% and 88% of all trials when it was presented before the target (SOA –85 and –35 ms, respectively). Interestingly, the target-similar distractor strongly competed with the target

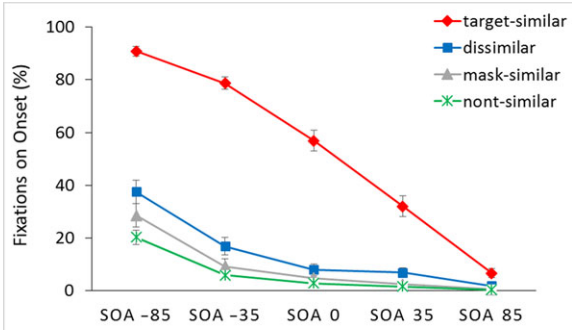

Figure 2. Proportion of first eye movements to the distractor. The proportion of first eye movements to the onset distractor, depicted separately for each SOA condition and distractor type. Error bars depict ± 1 standard error of the mean (SEM).

even when it was presented simultaneously with the target (SOA 0 ms) or slightly afterwards (SOA 35 ms), whereas the target-dissimilar distractors ceased to compete for selection at this point, and were selected only infrequently (less than 10% of the trials).

The results were confirmed by a 4 × 5 analysis of variance (ANOVA) comprising the variables distractor color (target-similar, dissimilar, nontarget-similar, premask-similar) and SOA (–85, –35, 0, 35, 85 ms) computed over the distractor-selection rates. The results revealed significant main effects of the distractor color ($F(3,69) = 450.3$, $P < 0.001$, $\eta^2 = 0.95$) and SOA ($F(4,92) = 165.5$, $P < 0.001$, $\eta^2 = 0.88$), as well as a significant interaction ($F(12,276) = 53.8$, $P < 0.001$, $\eta^2 = 0.70$). To formally assess whether distractors captured attention, the proportion of distractor fixations was compared to the proportion of nontarget fixations in each SOA/distractor color condition (which were consistently below 5%).[a] The results are depicted in Table 1, and clearly show that the most important factor modulating capture by the distractor is its similarity to the target color: only the target-similar distractor was consistently selected more frequently than the nontargets, across all SOA conditions (all *t*s > 2.9, *P*s < 0.01 (Table 1)). When the distractor was presented before the target or simultaneously with it, the distractor was selected even more frequently than the search target (all *t*s > 2.3, *P*s < 0.05). None of the other distractors competed that strongly with target selection. When the distractor had a task-irrelevant color, the target was reliably selected more frequently than the distractor, including the salient blue distractor (all *t*s > 2.3, *P*s < 0.05).

The second most important factor driving capture by the distractor was the temporal order of presentation: as shown in Table 1, all distractors significantly captured when they were presented 85 ms before the target, including nonsalient distractors that had the same color as the premasks.

Last, but not least, capture by the onset distractor was also modulated by task-irrelevant colors, with the strongest capture recorded for the salient blue distractor: this distractor was selected more frequently than the nontargets, even when it was presented 35 ms after the target. Moreover, with the exception of the latest SOA condition (SOA 85 ms), the salient blue distractor was selected more frequently than the nontarget-similar and premask-similar distractors (all *t*s > 2.2, *P*s < 0.05). However, inspection of Table 1 reveals that the effects of different task-irrelevant colors cannot be attributed to color contrast or the saliency of the onset distractor: before the target onset (SOA –85 and –35 ms), the nontarget-colored distractor (e.g., green) had a higher color contrast than the premask-colored distractor (gray), yet it was consistently selected less frequently than the premask-colored distractor. In the SOA –85 ms condition, the nonsalient gray

[a]The proportion of first eye movements to the nontargets was only modulated by the SOA of the distractor ($F(4,92) = 5.7$, $P = -0.001$, $\eta^2 = 0.20$), with more saccades to the nontargets in the early, –85-ms SOA condition ($M = 3.4\%$), intermediate scores in the intermediate SOA conditions ($M = 2.4\%$, 2.2%, 3.5% for SOA –35, 0, and 35 ms, respectively), and least nontarget fixations in the late, 85-ms SOA condition ($M = 1.6\%$). The color of the distractor did not modulate nontarget fixations, nor did it interact with SOA (*F*s < 2.2, *P*s > 0.05).

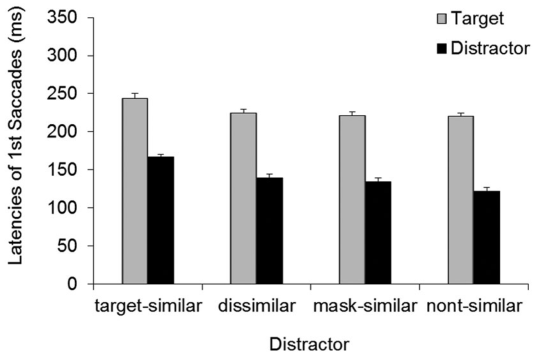

Figure 3. Mean saccade latencies of first eye movements to target and distractor. The mean latencies of first eye movements to the target (gray histograms) and distractor (black histograms), depicted separately for the different onset distractors. Error bars indicate +1 SEM.

distractor was even significantly more frequently selected than the salient green distractor ($t(23) = 2.5$, $P = 0.022$ (all other ts < 2.0, Ps > 0.06)). This renders it unlikely that more capture by the blue distractor could be attributed to its color contrast (which will be discussed in more detail below).

Latencies of first saccades

There were not sufficient data for a formal analysis of the latencies of first saccades to the target-dissimilar distractors, as only 10 participants selected the target-dissimilar distractors in the early SOA conditions, and rarely more than five times. Hence, to compare the distractor-fixation latencies with the target-fixation latencies, data had to be pooled over the different SOA conditions. Figure 3 shows the mean target- and distractor-fixation latencies for the first eye movements to the target and distractor, respectively. As shown in the graph, the distractor-fixation latencies were shorter than the target-fixation latencies, whereas this difference was slightly diminished for the target-similar onset distractor. These observations were supported by the result of a 2 × 4 ANOVA comprising the variables "selected item" (target, distractor) and "distractor color" (target-similar, dissimilar, nontarget-similar, premask-similar), which showed significant main effects of the selected item ($F(1,22) = 437.4$, $P < 0.001$, $\eta^2 = 0.95$) and distractor color ($F(3,66) = 76.5$, $P < 0.001$, $\eta^2 = 0.77$), as well as a significant interaction ($F(3,66) = 10.8$, $P < 0.001$, $\eta^2 = 0.33$). Pairwise two-tailed t-tests showed that distractors were selected significantly earlier than the target in all conditions (all ts > 17.9, Ps < 0.001).

However, faster selection of a distractor than the target could simply reflect that erroneous saccades are made earlier and that it takes more time to execute a saccade correctly.[47] To assess whether onset distractors actively attract eye movements, especially early in search, we compared the onset-fixation latencies to the nontarget-fixation latencies. Across all distractor conditions, nontargets were selected on average within 190 ms after the start of the trial. Two-tailed t-tests comparing the onset-fixation latencies to the nontarget-fixation latencies showed that, indeed, saccades to the onset distractors started significantly earlier than saccades to a nontarget (all ts > 3.7, Ps ≤ 0.001).[b]

The target- and onset-fixation latencies were, moreover, clearly modulated by target similarity, with the target-similar–onset condition showing significantly longer latencies than the other conditions (dissimilar, nontarget-similar, premask-similar), both when the first eye movement went to the target (all ts > 6.9, Ps < 0.001) and when it went to an onset (all ts > 7.6, Ps < 0.001). The speed of selecting the target or an onset distractor was, however, not clearly modulated by color contrast: the salient blue onset did not elicit the shortest saccade latencies, but had in fact longer latencies than the nontarget-similar onset ($t(22) = 4.9$, $P < 0.001$).

To examine whether the high-contrast distractor may have delayed target selection without eliciting an eye movement in a subset of the SOA conditions, we assessed the latencies of first saccades to the target for each onset and SOA condition. Figure 4 depicts the results, with the dashed red line indicating that there were insufficient data in the SOA –85 ms condition with the target-similar–onset distractor (only 6.8% of first eye movements went to the target in this condition). Target selection was significantly

[b]The results were the same when nontarget-saccade latencies were compared to distractor-saccade latencies within each distractor-type condition (target-similar, dissimilar, nontarget-similar, premask-similar), although the t-tests comprised only 20–22 subjects (who selected the nontargets), and were in part based on latencies derived from very few trials. Distractors were selected significantly earlier than the nontargets, across all conditions (ts > 3.4, Ps < 0.004).

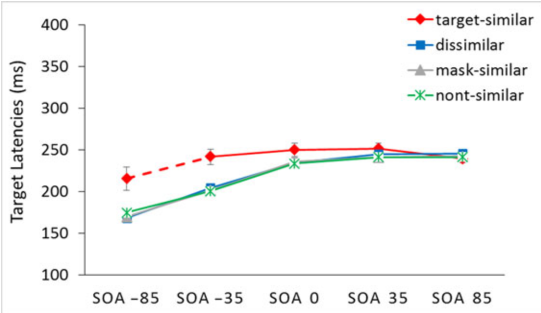

Figure 4. Latencies of first eye movements to the target. The mean latencies for first eye movements directed to the target, depicted separately for each SOA condition and distractor condition. Error bars indicate ±1 SEM.

delayed by the target-similar onset, compared to all other onsets, in all SOA conditions except the SOA 85 ms condition (all ts > 2.1, $P < 0.05$). However, the target-dissimilar onsets did not visibly differ from each other. This impression was confirmed by a 3 × 5 ANOVA computed over the dissimilar-onset–distractor conditions (dissimilar, nontarget-similar, premask-similar) and the five SOA conditions, which showed only a significant main effect of SOA ($F(4,92) = 510.8$, $P < 0.001$, $\eta^2 = 0.96$), but no effect of the onset color or an interaction (Fs < 2.0, Ps > 0.05).

General discussion

This study yielded several interesting results. First, contrary to previous studies on onset capture, we failed to observe significant capture by onsets that had the same color as the nontargets (Table 1). In the simultaneous-onset condition (SOA 0) that is traditionally used, only the target-similar onset, the dissimilar onset, and the premask-similar onset attracted the gaze, presumably because both had a high color contrast. By contrast, a plain onset distractor that had the same color as the nontargets was selected equally frequently as the nontargets (3%), indicating that this classical onset failed to attract the gaze.[c] These results deviate from previous findings of onset capture (but see Ref. 48).[26,31,38,47] The classical (nontarget-similar) onset distractor may have had a weaker effect in this study because it did not predict the onset of the target (due to the SOA variation). Moreover, in the SOA 0 condition, the onset distractor was presented among multiple transients created by the target and nontargets changing color, which may have reduced the effect of the onset distractor. In line with this explanation, the nontarget-colored onset distractor significantly attracted the gaze (20%) when it was presented 85 ms before the target. In this condition, it was the only transient in the display and there was no competition from the target. Previous studies have already shown that onsets capture attention more strongly when they have a unique onset or transient.[20,21]

Taken together, these findings are consistent with the view that onsets capture attention and the gaze in part because their appearance constitutes a visually salient event (i.e., unique change or unique transient), which usually signals the appearance of the target (in experiments employing only the SOA 0 condition).[8,9,39] The finding that onset capture is reduced or eliminated in these conditions indicates that the saccade-guidance mechanism may not be particularly sensitive to the appearance of new objects,[12,13,28,29] but rather to visual transients that signal the appearance of the target.[d,8,9,20,21]

In a subset of studies, participants were discouraged from searching for visual transients by changing only the color of the nontargets, so that the target was the only display item that did not change.[31,48] However, in this condition, the target could be at a selection disadvantage because it may be easier to find a color change among nonchanging

[c]The nontarget-similar onset also failed to capture in the SOA 0 condition when selection of the nontarget-similar onset was compared to erroneous selection of a single nontarget stimulus (i.e., the nontarget-selection rates divided by 5; ($t(23) = 1.7$, $P = 0.097$).

[d]Of note, von Muehlenen *et al.* found that onsets captured covert attention most strongly when they were presented either 150 ms before or after the target, whereby capture did not differ between these two SOA conditions. Our failure to find onset capture at later SOAs (e.g., 85 ms) probably does not reflect an important difference between overt and covert orienting, but rather a difference in the time course of search. Note that Von Muehlenen *et al.* used a difficult, serial search task, whereas in our study, the target could be localized quickly. The unique transients of the onset distractor probably retain an ability to attract attention as long as the target has not been localized but become ineffective once the target has been localized and a saccade program initiated, which explains why onsets were ineffective at later SOAs in our study.

items rather than a nonchanging target among color-changing nontargets (similar to the well-known search asymmetry for moving items).[6,7,49] Hence, the onset distractor may have captured more strongly because the target was more difficult to detect than all other items. Changing the color of all the search items in this study probably provided a more symmetric design (see Ref. 50) that neutralized the effects of the onset's visual transients without incurring a selection disadvantage for the target. That said, it remains to be determined which of the two factors contributed most to the reduction of onset capture in the SOA 0 condition: (1) changing the color of all search items, or (2) rendering the onset nonpredictive of the target by presenting it before and after the target change.

Color contrast and top-down effects on onset capture

The most interesting finding of this study was probably that onset capture was not clearly modulated by color contrast. As shown in Table 1, the capture rates were not systematically related to the onset distractor having a high or low color contrast. Although the high-contrast blue onset was selected more frequently than the nontarget-similar and premask-similar onsets, this finding cannot be interpreted as reflecting a color-saliency effect. Of note, the nontarget-similar onset consistently captured less than the premask-similar onset, even in the early SOA conditions in which it was more salient then the premask-similar onset (see Table 1, shaded areas). The pattern of strongest capture for blue, followed by the premask-similar onset and the nontarget-similar onset, instead suggests that the colors were inhibited according to how strongly they competed with the target for selection. The nontarget color was always presented together with the target, and hence presented the strongest/most reliable competitor, and was inhibited most strongly. The gray premasks were maybe not actively inhibited, but gray onsets probably suffered from the *preview effect*, that colors of previously viewed items are automatically inhibited.[51] By contrast, the blue onset distractor was present on only 20% of all trials, and competed with the target only in the early SOA conditions (i.e., on one-third of these trials). Hence, blue items were probably not inhibited at all, so that the blue onset captured attention and the gaze most strongly.

The view that the nontarget-colored onset was actively inhibited is also in line with the finding that the target-similar onset captured most strongly, and from an early point in time. Strong capture by the target-similar onset indicates that attention was biased toward the target color. Moreover, note that the selection rates increased steeply when the onset was presented before the target (SOA –85, –35 ms). Evidently, the attentional bias for the target color modulated selection of the onset before the target and nontargets were presented, in a feed-forward manner. This finding is consistent with neurophysiological evidence showing that the expectation of a colored target object modulates the activity of neurons in the visual cortex before the appearance of any stimuli,[52,53] and is at odds with the dual-stage account, that a top-down bias emerges late in response to a visual input (within a feedback loop).[31,32] According to such a dual-stage account with delayed modulation of onsets by color, we would have expected that all onsets (target-similar and target-dissimilar onsets alike) show a similar steep increase when the onset is presented before the target. By contrast, the results showed that the increase in selection rates was significantly reduced for the target-dissimilar onsets (compared with the target-similar onset). This suggests that the visual system's sensitivity for the target color was increased before the presentation of the target, and that this modulated the visual stimulation of the onset from the earliest stage (in a feed-forward manner).

Similarly, Figure 2 shows that capture by the nontarget-colored onset distractor also increased less in the earliest SOA condition (SOA –85 ms). Although this shallower increase could also be attributed to the lower overall selection rates of this onset, it is in line with the view that the nontarget-colored onset was inhibited (see above), and that this inhibition was in place before the presentation of the target and modulated capture.

In sum, the results of this study are consistent with the contingent-capture hypothesis that orienting and gaze behavior are (most) strongly modulated by the task demands, which translate into a top-down bias for the target color (and a bias against the nontarget color).[8,9] This top-down bias seems to be in place throughout the task and modulates visual stimulation in a feed-forward manner.[8] The second most important factor for onset capture was the point in time in which the onset distractor was presented, suggesting that the temporal order is a very important determinant for competition. By contrast, onset capture was not systematically modulated by color contrast in this study, indicating that unique visual transients may tap into different saliency mechanisms than those that are sensitive to color saliency. The latter conclusion is, however, certainly speculative and would require further research.

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Conflicts of interest

The authors declare no conflicts of interest.

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