Oculomotor capture by transient events: A comparison of abrupt onsets, offsets, motion, and flicker

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Attentional and oculomotor capture by some salient visual event gives insight into what types of dynamic signals the human orienting system is sensitive to. We examined the sensitivity of the saccadic eye movement system to 4 types of dynamic, but task-irrelevant, visual events: abrupt onset, abrupt offset, motion onset and flicker onset. We varied (1) the primary task (contrast vs. motion discrimination) and (2) the amount of prior knowledge of the location of the dynamic event. Interference from the irrelevant events was quantified using a discrimination threshold metric. When the primary task involved contrast discrimination, all four events disrupted performance approximately equally, including the sudden disappearance of an old object. However, when motion was the task-relevant dimension, abrupt onsets and offsets did not disrupt performance at all, but motion onset had a strong effect. Providing more spatial certainty to observers decreased the amount of direct oculomotor capture but nevertheless impaired performance. We conclude that oculomotor capture is predominantly contingent upon the channel the observer monitors in order to perform the primary visual task.

Introduction

A visual event that triggers a covert or overt orienting response despite being irrelevant for the immediate behavioral task at hand is generally said to have captured attention (Egeth & Yantis, 1997; Ludwig & Gilchrist, 2002; Theeuwes, 1992; Theeuwes, Kramer, Hahn, & Irwin, 1998; Yantis & Jonides, 1984). The phenomenon is of interest because it provides insight into what dynamic signals the visual system is sensitive to and the kinds of tasks the system has evolved to serve. Over the past 3 decades, the capturing potential of a catalogue of visual events has been examined, including—among others—abrupt onsets (Enns, Austen, Lollo, Rauschenberger, & Yantis 2001; Yantis & Jonides, 1984), color singletons (Theeuwes, 1992; Turatto & Galfano, 2000), motion onset (Abrams & Christ, 2003; Franconeri & Simons, 2003; Mühlenen, Rempel, & Enns, 2005), and luminance changes (Enns et al., 2001; Rauschenberger, 2003). These studies typically use a visual search task in which the target display is preceded by a preview display containing a number of masks. At or around the time the target display is revealed, one of the existing items undergoes some change (e.g., it starts moving) or a new object appears in a location that was empty during the preview (abrupt onset). Capture is inferred from impaired target detection or discrimination in the presence of an onset or change elsewhere in the scene and/or improved performance when the target and changing item coincide. This pattern is thought to arise because the processing of the irrelevant onset or change is prioritized, interfering with the central task when the irrelevant change and target are separated but aiding performance when they coincide.

A number of different theoretical perspectives on why capture occurs have been put forward. One view is that attention is drawn to the most salient region in the image, regardless of the current behavioral goals of the observer (Theeuwes, 1992; Yantis & Jonides, 1984). For instance, in search for a target that has a unique shape, like a circle among squares, Theeuwes (1992) reported reaction time interference from a uniquely colored distractor item. Yantis and Jonides (1984) demonstrated efficient search if an abrupt onset coincided with the target, but inefficient search when the abrupt onset appeared elsewhere in the display. In both these examples, attending to color discontinuities or abrupt onsets did not aid observers find the target, and in this sense capture was independent of the observer's behavioral goals.

Folk et al. (Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994) proposed that capture is contingent upon the observer having established an attentional set for some visual feature or event. For capture to occur, the distracting

event must in some way be consistent with that attentional set. These authors used a cueing paradigm to show that abrupt onset cues only captured attention when the observer is set to respond to an onset target. A color singleton cue only captured attention if color is the target-defining dimension. Proponents of this theory hypothesize that when a color distractor disrupts search for a shape target (Theeuwes, 1992), it is because the attentional set has been configured to aid detection of unique visual events (or singletons) in general (Bacon & Egeth, 1994). Contingent capture has been elaborated to include visual events that do not aid the detection or localization of the target per se, but that signal the appearance of the target display and therefore the beginning of the search epoch in a trial (Atchley, Kramer, & Hillstrom, 2000; Gibson & Kelsey, 1998).

A third view is offered by those who hold that capture may occur independent of attentional set when a visual event constitutes a "new object" (Enns et al., 2001; Rauschenberger, 2003; Yantis & Hillstrom, 1994), which requires the observer to establish a representation or object file (Kahneman, Treisman, & Gibbs, 1992) for that item. According to this view, abrupt onsets have special status and are prioritized over other kinds of visual changes (such as changes in luminance) that involve merely updating an already established object representation. This view has been challenged by reports of capture by changes to existing objects, such as the onset of motion (Abrams & Christ, 2003; Franconeri & Simons, 2003), and of failure to find capture when the onset of a new object is not associated with a local luminance transient (Franconeri, Hollingworth, & Simons, 2005).

Orienting is generally done overtly by moving the eyes, head, and body (Land, 2004; Land & Hayhoe, 2001). With regard to saccadic eye movements, it has been firmly established that abrupt onsets can capture the eyes under a range of conditions (Boot, Kramer, & Peterson, 2005; Godijn & Theeuwes, 2002; Irwin, Colcombe, Kramer, & Hahn, 2000; Ludwig & Gilchrist, 2002, 2003a; Theeuwes et al., 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999; Wu & Remington, 2003). A number of these studies have attempted to compare oculomotor capture by abrupt onsets with other visual events. Wu and Remington (2003) showed that, as with covert attention, oculomotor capture was influenced by the search mode or set adopted by observers. However, capture by abrupt onsets was never quite eliminated in conditions in which the contingent capture view predicts it should not occur. Irwin et al. (2000) compared the extent of oculomotor capture by abrupt onsets with that elicited by transient color and luminance changes. They reported that abrupt onsets were especially effective. Finally, Boot et al. (2005) compared capture by abrupt onsets and offsets and showed that the disappearance of an item did not elicit an inappropriate saccade even though the two events are similar in terms of the magnitude of sensory change. Thus, there is some evidence that abrupt onsets have special status where the

eye movement system is concerned. Indeed, within oculomotor research a prevalent assumption is that the saccadic system is highly sensitive to rapid changes in luminance (Lennie, 1993).

In the present study, we sought to further address this issue by comparing capture by abrupt onsets with a number of other visual events that occurred in pre-existing objects. Specifically, we aimed to choose non-onset events that could be expected to activate the same early visual mechanisms as abrupt onsets, yet according to the published literature differed in their behavioral relevance (Boot et al., 2005; Franconeri & Simons, 2003). The events chosen were the abrupt offset of an existing item, the onset of motion, and the onset of flicker. Abrupt offsets have been studied by Boot et al. (2005) and were found not to interfere with goal-directed saccadic eye movements. Oculomotor capture by motion and flicker onset has to our knowledge not been reported.

The aim to compare events that are known or could be expected to activate similar visual mechanisms led us to use grating patterns that are frequently used to character-ize the response properties of cells in striate cortex (Albrecht, Geisler, Frazor, & Crane, 2002; Müller, Metha, Krauskopf, & Lennie, 2001). In addition to forming a reasonable description of the spatial tuning of V1 receptive fields, Gabor patterns allow for the parametric manipulation of target (and, for that matter, distractor) properties such as contrast (Experiments 1 and 2) and opponent motion energy (Experiment 3). The advantage of such parametric manipulations is that the effect of an irrelevant transient visual event can be expressed in units related to the target discrimination. In the region of the discrimination threshold, this scale is approximately linear so that the effects of different events may be compared on a more meaningful numerical scale. For example, if one event requires an additional 5% contrast in the target and another event requires an additional 10%, we have some indication that the latter is twice as disruptive as the former.

The combination of a typical oculomotor capture paradigm to test the interference from 4 different dynamic events with a parametric manipulation of the target properties called for a more psychophysical approach than has been used to date in this domain. Thus, in each experiment, we tested three individual observers exten-sively. This approach contrasts with the typical practice of testing larger groups of observers (typically between 10 and 30) and averaging the data across this population. Both methodologies have their advantages and disadvan-tages. A psychophysics approach enables more detailed description of individual observer's results, allowing the reader to obtain greater insight in the stability of some experimental effect across observers. We believe this is a valuable contribution to a field in which such individual differences tend to be averaged out. Clearly, however, our ability to generalize our findings to a wider population is limited to the extent that our observers behave in the same manner.

A wider aim of this work, beyond the immediate scientific questions of interest, is to introduce some of the methods, language, and models from visual psychophysics to the study of oculomotor capture. In this way, we hope to stimulate research into and discussion of the involvement of previously well-characterized basic visual mechanisms (Graham, 1989) in mediating capture (as has happened in the field of visual search more generally; cf. Eckstein, 1998; Najemnik & Geisler, 2005; Palmer, Verghese, & Pavel, 2000). This study can be regarded as a step in this direction.

Experiment 1

Methods

Stimulus generation

Displays were generated with the Psychophysics Toolbox (version 3; Brainard, 1997; Pelli, 1997). The output of a Radeon X600 VGA graphics card was fed through a BITS++ digital video processor (Cambridge Research Systems Ltd.) to create 14-bit resolution. Displays were presented on a 21-in. gamma-corrected CRT monitor (EIZO FlexScan T965), running at 75 Hz. with a spatial resolution of 1152×864 pixels. Viewing was binocular from a distance of 57 cm.

The stimuli consisted of a number of Gabor patches with a spatial frequency of 2 cycles/deg. The standard deviation of the Gaussian window was $0.5°$. The patterns were arranged equidistant from a central fixation cross at an eccentricity of $8°$. There were 8 possible pattern locations with an angular separation of $45°$ (starting at 22.5°; 0° is aligned with the right horizontal meridian). Four of these locations were occupied at the start of the trial. The four locations were chosen pseudorandomly, with the constraint that there was at least one pattern in each quadrant. The target always occurred in one of the four locations filled in the "preview display" at the start of the trial. At the time of target presentation, in what will be referred to as the "test display," a transient event occurred on 80% of the trials. In the onset condition, a fifth pattern was added to the test display in a previously empty location. In the remaining three transient conditions, the dynamic event occurred at the location of one of the four pre-existing items. The transient event was constrained to occur at an angular separation of at least 90° away from the target to avoid the ambiguity in saccade classification that might have arisen at small separations due to global effect saccades (Theeuwes et al., 1998). A schematic illustration of the display layout and the experimental conditions appears in Figure 1.

The luminance of the background was fixed at 38.9 cd/m^2. The contrast of the preview Gabors was fixed at 0.25. The transient events were created as follows. In the onset condition, an additional Gabor with the non-target contrast was added to the display with an abrupt onset (i.e., a temporal step function). In the offset condition, a Gabor would disappear abruptly. Thus, in terms of the physical contrast change, the onset and offset conditions are equivalent. The motion onset was created by drifting the carrier at a temporal frequency of 5 Hz behind the fixed Gaussian window. The direction of motion was (arbitrarily) determined by the side of the display the transient occurred: Motion onsets in the left visual field drifted rightward, and vice versa for motion onsets in the right visual field. The contrast of the moving Gabor was 0.25.
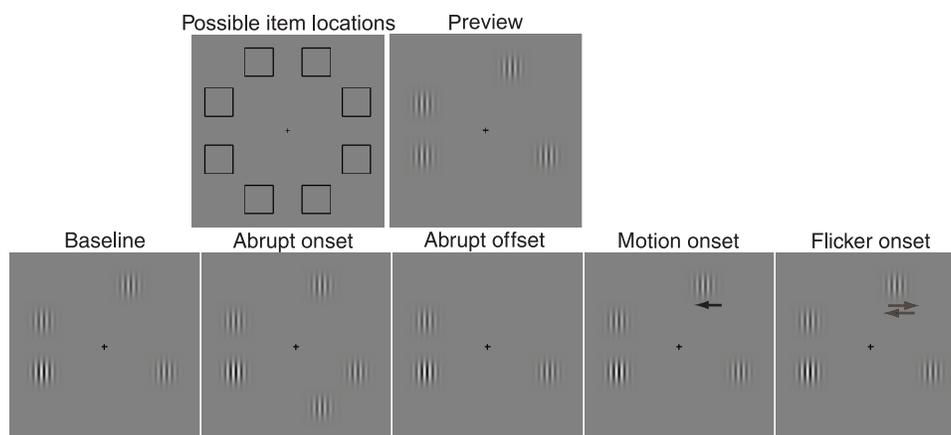

Figure 1. Stimulus arrangement and displays (Experiment 1). In the preview display, 4 out 8 possible stimulus locations were filled with Gabor patches. The preview was replaced by a test display in which the target contrast was increased (briefly). Test displays were of the following types (bottom row, from left to right): (1) baseline—no irrelevant transient occurred; (2) abrupt onset—at the time of peak target contrast, an additional pattern was introduced in one of the 4 empty locations; (3) abrupt offset—one of the non-targets disappeared; (4) motion onset—one of the non-targets started moving. The pattern location remained fixed: It was the carrier sinusoid that was shifted in phase behind the fixed Gaussian window; and (5) flicker onset—one of the non-targets started to flicker (counterphase, again behind a fixed window).

Flicker was created by overlaying two Gabors drifting in opposite directions (Levinson & Sekuler, 1975). In order to keep the overall contrast the same as that of the motion onset (and the other non-targets), the contrast of each component Gabor was halved (i.e., 0.125). The phase of the carrier (components) of the moving and flickering patters was updated every video frame to create a smooth time-varying signal.

The behavioral task was contrast discrimination. After some temporal delay, the contrast of one of the four patterns in the preview display was briefly incremented by a variable amount. The temporal profile of the contrast increment was Gaussian, with a standard deviation of 25 ms. The contrast pulse was completed in 9 video frames, with the peak contrast occurring on the 5th frame. The transient event was started at the time of peak target contrast. In case of the motion and flicker onset, the motion and flicker continued for the remainder of the trial (for a total of 50 frames, i.e., ~667 ms).

Procedure

Each trial began with a black, central fixation cross, which remained visible throughout the trial. As soon as fixation was stable, the observer initiated the trial, which started with presentation of the preview display. Preview duration was distributed according to a shifted and truncated exponential distribution: it ranged from 20 to 95 frames, with a mean foreperiod of approximately 43 frames (~573 ms). Target presentation was accompanied by a 500-Hz, 110-ms tone, included to signal target onset to the observer in cases where the target signal was small (and could therefore easily be missed). Observers were asked to aim for the target with their first saccade.

Prior to the experiment, observers were extensively trained with the basic discrimination task (i.e., just baseline trials; no transients were presented at all). Training was necessary to ensure that observers' discrimination performance had stabilized and increased monotonically with signal strength. Oculomotor discrimination performance is more susceptible to stimulus-independent noise (analogous "finger errors" in standard psychophysics) and many human observers need some training to produce stable "oculometric" functions (Ludwig & Gilchrist, 2006). In addition, the training served to obtain insight into an individual observers' discrimination threshold to promote efficient sampling of an individual's oculometric function.

The main experiment was carried out in multiple sessions distributed over a number of days. An observer would typically complete 6–8 blocks of 75 trials in a single session. The number of completed trials varied somewhat across observers, and after discarding trials that did not meet our inclusion criteria (see below), the range of trials included across observers was 3,250–3,550. Within a block of trials, all 5 conditions were equally distributed and randomly intermixed.

Eye movements were recorded at 500 Hz with the EyeLink II system (SR Research Ltd.), using the EyeLink Toolbox for Matlab (Cornelissen, Peters, & Palmer, 2002). Saccades were detected using velocity and acceleration criteria of 30°/s and 8000°/s^2, respectively. The analyses reported in this article concern solely the accuracy and latency of the first saccade after display onset, provided that saccade conformed to the following inclusion criteria: (1) the starting position was within 1° of the central fixation point; (2) the amplitude exceeded 4° (half the eccentricity of the items); (3) the latency was longer than 80 ms; and (4) the direction was within 45° of a target, non-target, or transient. We collected data from naive 3 observers with normal or corrected-to-normal vision.

Results and discussion

First saccades were classified as being directed to the target, one of the non-targets, or the transient event (if present). Pooled over signal strength, we found that across observers and experimental conditions, direct oculomotor capture occurred on 3–22% of all trials. This range is comparable to that of previous studies (Irwin et al., 2000). The top row of Figure 2 shows the proportion of first saccades directed to the target, a non-target, or the transient event as a function of target contrast for one observer (#2). The data points correspond to the target-directed saccades. The stacked bars represent the remaining two categories, with the yellow portions indicating direct capture by the transient event. As expected, performance improves with signal strength in all 5 conditions. Both direct capture and saccades to non-targets are rare at the highest target contrasts. For this observer, the eyes were captured by all 4 transient events, at least to some extent. Visual inspection of the size of the yellow bars suggests that abrupt offsets and flicker were particularly disruptive. The large number of saccades directed to the location of an offset is surprising: The observer is driven to look to an empty location.

The solid curves are maximum-likelihood fits of a cumulative Gaussian to the correct, target-directed saccades. Four parameters were allowed to vary in order to accommodate the data: the upper and lower asymptotes, the mean (location), and the standard deviation (slope) of the curves. One reason we did not constrain the asymptotes to align with chance and perfect performance is that oculometric functions are frequently squashed between these theoretical limits due to stimulus-independent decisions. A second reason was that if observers have a strong bias toward looking to a transient event, this would manifest itself as below chance performance at low target contrasts (e.g., flicker onset in the top row of Figure 2).

The oculometric functions were used to define a discrimination threshold as the target contrast at which the proportion correct reached 0.55, corresponding to a d' of 1 in a 4-AFC task (Green & Swets, 1966). From
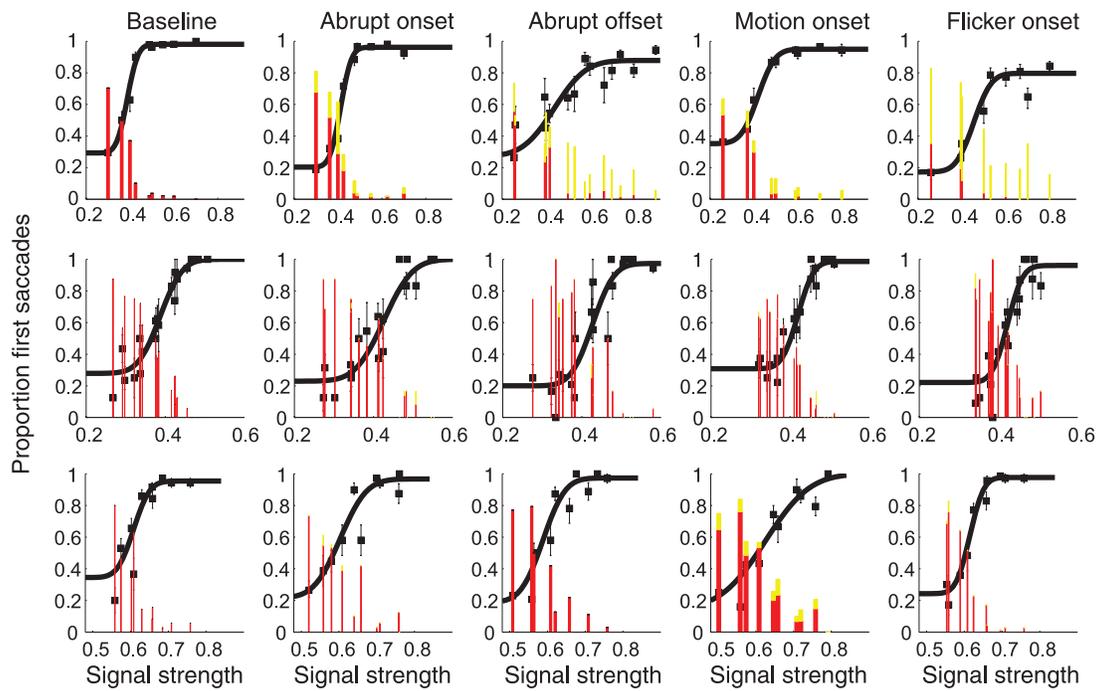
Figure 2. Probability distributions of first saccade targets as a function of signal strength. Each row corresponds to the data from one observer. Rows 1–3 correspond to Experiments 1, 2, and 3. Data points refer to the proportion of first saccades directed to the target. Error bars are bootstrap standard errors. Solid lines are best-fitting cumulative Gaussians to the data points. Stacked bars correspond to the proportion of saccades directed to non-targets (red) or irrelevant transients (yellow). Each column shows the data from one particular transient event.

Figure 2, it should be obvious that this threshold will increase with increasing numbers of saccades directed to non-targets and transient events. Figure 3 shows the
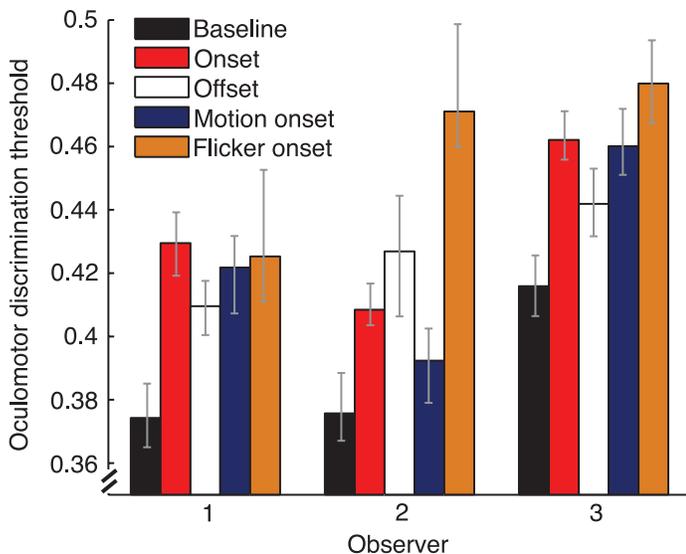

Figure 3. Discrimination thresholds derived from the oculometric functions of Experiment 1. Error bars are standard errors, corresponding to the 16th and 84th percentiles of the bootstrap distribution.

thresholds for all three observers in baseline and transient conditions. For observer 2, it is clear that the rank ordering of these thresholds follows the pattern shown in Figure 2: flicker and offsets are particularly disruptive, followed by abrupt onsets, and motion onset is least disruptive. The pattern for observers 1 and 2 is slightly different.

Estimates of variability around the threshold values were derived through a non-parametric bootstrap, which involved creating 2,000 replicate data sets by resampling the original frequencies and fitting each replicate set with a cumulative Gaussian to obtain a bootstrap distribution of thresholds. The statistical significance of a difference in threshold can then be gauged by creating a distribution of difference scores and examining whether the probability of a null difference is sufficiently small (i.e., less than 0.05 in this case). We applied this logic to answer the following two questions: (1) Which events cause significant disruption of goal-directed eye movements? (2) Are abrupt onsets more disruptive than other visual events? On the basis of previous findings, we have strong directional expectations for these effects: Interference is evidenced by greater thresholds in the transient conditions than in the baseline, and an onset advantage means that the thresholds for the remaining three transients are lower. As a result, a one-tailed test is appropriate. Table 1 lists which differences were significant using this procedure for each individual observer. With the exception of motion onsets

Observer	> Baseline 95%				< Onset 5%		
	Onset	Offset	Motion	Flicker	Offset	Motion	Flicker
Experiment 1—contrast							
1	✓	✓	✓	✓	×	×	×
2	✓	✓	×	✓	×	×	×
3	✓	✓	✓	✓	✓	×	×
Experiment 2—contrast							
4	✓	✓	×	✓	×	×	×
5	✓	✓	✓	✓	×	×	×
6	✓	✓	✓	✓	×	×	×
Experiment 3—motion							
4	×	×	×	×	×	×	×
7	×	×	✓	×	×	×	×
8	×	×	✓	✓	✓	×	×

Table 1. Tests of transient interference and onset advantage across Experiments 1, 2, and 3. A tick refers to a one-tailed significant effect with $p < .05$. For observers 4–8 (Experiments 2 and 3), the relevant baseline chosen was the 5-AFC baseline.

for observer 2, all transients were disruptive, as evidenced by significant threshold elevations. With regard to the second question of whether onsets are special, it appears that only one observer (#3) showed evidence for reduced interference from offsets. For each observer, there were at least two other visual events that were just as disruptive as abrupt onsets.

It should be noted that in this experimental design the target always occurred in one of the four locations that were filled in the preview display. Given that the target never coincided with the transient event, observers may have been able to inhibit all other (unmarked) regions in the display. If this were the case, inhibition was far from perfect as abrupt onsets did capture the eyes on a substantial number of trials. However, partial inhibition may have suppressed the interference caused by abrupt onsets. Extending this logic, such spatial prior inhibition could not aid performance in the other three transient conditions, as the irrelevant events occurred in a location that could, but never did, contain the target. Note that instead of inhibiting potential transient locations, observers may have facilitated possible target locations (i.e., the four locations shown in the preview) or a combination of both. Regardless of the underlying mechanism, transients occurring at potential target locations may have enjoyed a relative advantage over abrupt onsets, resulting in apparently equal interference if abrupt onsets were, in actual fact, special.

To address this possibility in Experiment 2, we constrained the irrelevant events to only ever occur in one of two possible locations, which were the same for all transients (horizontal left and right). Likewise, the four possible target locations were also fixed and the same in all conditions (aligned with the oblique meridians). This design is similar to that used in some earlier studies on oculomotor capture (Ludwig & Gilchrist, 2002).

Experiment 2

Methods

There were four possible target locations, each of which was filled in the preview display. These four locations were situated at 45°, 135°, 225°, and 315°. The transient event now only ever occurred at 0° (right horizontal) or 180° (left horizontal). Thus, in the offset, motion onset, and flicker onset conditions, a fifth pattern was added to the preview display which would, respectively, disappear, start moving, or start flickering at the time of target presentation. In the onset condition, the fifth pattern was absent in the preview but added to the test display. An additional baseline was included in which the fifth pattern was present in both preview and test displays, but remained unchanged, just like the other three non-targets. All other stimulus characteristics were the same as in Experiment 1.

In this design, if observers are able to inhibit possible transient locations (and/or facilitate target locations), this should affect performance equally for all different transient events. Indeed, if spatial inhibition is operative in these experiments a relative advantage for abrupt onsets may now arise. Note that in order to create the offset, motion, and flicker transients, an extra item already needs to be present in the preview display. Provided this fifth element was present in the preview, observers could predict that a transient event would occur in *that* location with a conditional probability of 0.75. If the potential transient locations were empty, either no irrelevant event would occur or an abrupt onset would appear in the test display. However, this abrupt onset could appear in one of two possible, empty, locations. Thus, with an extra item in the preview, only one location needs to be inhibited; if the potential transient

locations are empty, both need to be inhibited. It seems reasonable to suggest that inhibiting one, already marked (Watson & Humphreys, 1997), location may be easier than inhibiting two empty locations. Thus, in Experiment 2, we have stacked the odds in favor of finding a relative advantage for abrupt onsets.

A different set of 3 observers took part in this experiment, one of which was the 2nd author (coded as observer 4). They were extensively trained on the baseline trials before commencing the actual experiment. Each session consisted of 6–8 blocks of 60 trials, distributed equally and randomly across the 6 conditions. The range of trials included in the analyses reported below was 2,331–3,032.

Results and discussion

The middle row of Figure 2 shows performance of one observer (#5) in the same five conditions that were shown for Experiment 1 (the second baseline is not shown here). The color coding is the same as that in the top row. It is immediately obvious that, compared to the row above, the amount of direct oculomotor capture is drastically reduced in this experiment. This was true for all 3 observers (range across experimental conditions was 0–14%). Clearly observers were able to use spatial prior information to restrict the vast majority of their movements to locations that potentially contain the target. However, despite the near absence of saccades directed to the transient event, it does appear that saccade target selection is less accurate in the transient conditions compared to the baseline (e.g., the height of the bars in the offset condition).

This impression is confirmed in Figure 4, which shows the oculomotor discrimination thresholds for all three

Figure 4. Discrimination thresholds of Experiment 2. Conventions as in Figure 3. The inset shows the thresholds from Experiments 1 and 2, averaged across the 6 observers. Error bars in the inset are within-subject standard errors of the mean.

observers. As in Experiment 1, almost all transient events interfered with target selection, as shown in Table 1. Again, there was one observer (#4) for whom motion onsets did not significantly elevate the discrimination threshold. For none of the observers did abrupt onsets interfere more than other transient events. Finally, note that performance in the two baseline conditions was roughly equivalent. This is another indication of observers' ability to inhibit a marked spatial location. Had observers been unable to use the spatial prior, this baseline condition would have been effectively treated as a 5-AFC discrimination with a corresponding reduction in chance performance (i.e., the lower asymptote of the oculometric function) and an upward shift in the threshold.

The results of Experiment 2 replicated those of the first experiment in that transient events consistently interfered with target selection, and there was very little suggestion of any systematic ordering in the extent of interference across event types. In fact, even numerically, the threshold elevations were very similar in both experiments (average transient–baseline difference was 0.05 in Experiment 1 and 0.04 in Experiment 2). Given the similarity across the two experiments, we show the discrimination thresholds averaged across observers 1–6 in the inset of Figure 4. This plot underlines the interference caused by all transient events. A one-way, repeated measures ANOVA with "transient" as 4-level factor was non-significant [$F(3,15) = 1.59$].

Providing more reliable prior information about the possible spatial locations of targets and transients had a powerful effect on performance (Theeuwes et al., 1998). Direct oculomotor capture occurred infrequently for all three observers in this experiment. Despite the drastic sensory changes occurring in the visual field, it appears relatively easy for observers to stop themselves from looking in the direction of these changes if their locations are known beforehand and remain fixed throughout the task. Nevertheless, these transients must have triggered some internal response within the system as evidenced by the threshold elevation data. We speculate that the oculomotor spatial inhibition operates at a stage closer to saccade execution and after the initial visual response. We will return to this issue in the Direct and indirect capture section.

The results of both contrast discrimination experiments could be taken to suggest that when different visual events are designed to activate early visual mechanisms, these events will interfere with target selection, regardless of whether the event occurs in an "old" object for which a representation has presumably already been established. As stated in the Introduction, grating patterns like the ones used in this study are frequently used to characterize the response properties of cells in striate cortex (Albrecht et al., 2002; Müller et al., 2001). Many of these neurons will respond to the abrupt onset of a pattern with a rapid burst of action potentials before gradually returning to the baseline-firing rate. Moving and flickering items will, at least in simple cells, result in the same response pattern
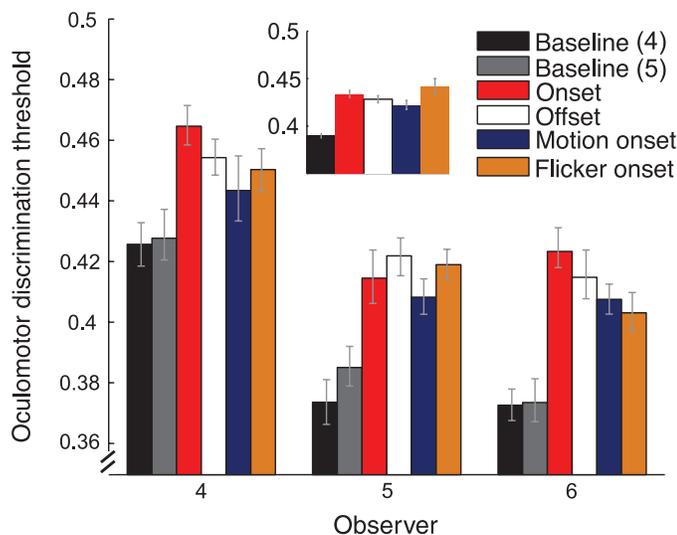
but repeated over time depending on the alignment of the light and dark bars of the grating with the cell's on and off regions. To our knowledge, it has not been tested whether offsets also activate such neurons, but given the transient nature of the response profile, it seems likely that they would (Tolhurst, 1975). Our results are in accordance with the hypothesis that such transient units are of particular importance to the eye movement system (Lennie, 1993).

However, it should be noted that the behavioral task in this experiment is to respond to brief changes in luminance contrast. Therefore, the units that we hypothesize are strongly activated by the transient visual events may be the very same ones that are also needed for the behavioral task. As a result, capture in these experiments may be contingent upon the attentional set of the observer (Folk et al., 1994; Wu & Remington, 2003). In this instance, attentional set may be regarded as the task-relevant channel that is being monitored for the primary task (Graham, 1989; Thomas, 1985). A channel may be defined as a pool of units with some response properties that are relevant for the primary task (e.g., selective for 2 cycles/deg, vertical patterns and a monotonically increasing contrast response).

To distinguish between the transients and contingent capture hypotheses, we examined the effect of the same transient events but changed the primary task to motion discrimination. After the stationary preview display that was identical to that used in Experiment 2, 3 patterns started flickering, and one pattern contained a variable opponent motion strength (see below). Observers were asked to saccade to the moving item. Transient events occurred at the same time as motion/flicker onset, and were—again—limited to the 2 locations on the horizontal meridian.

motion in the patterns that were static during the preview display. As in the previous experiments, a brief tone accompanied test display onset. Unlike Experiments 1 and 2, the target signal was present for the entire duration of the test display (55 frames). The irrelevant transient event was presented at the same time as the target signal. The contrast of all patterns was 0.25. Observer 4 from the previous experiment and 2 additional naive observers took part in this experiment after being trained on the 4-AFC baseline trials. The number of trials included in the analyses ranged from 2,625 to 3,003.

Results and discussion

The bottom row of Figure 2 shows performance of one observer (#7) as a function of target motion strength. It is clear that, qualitatively, performance was very similar to that in the previous two experiments: Target selection was more accurate as opponent motion strength increased, and there was a corresponding decrease in the number of saccades directed to non-targets or transients. As in Experiment 2, direct oculomotor capture was relatively rare (range across observers and experimental conditions was 0–7%), which is not surprising given the fixed potential target and transient locations. However, if direct capture did occur, it was mainly triggered by the motion onset transient.

As before, discrimination thresholds were derived from the oculometric functions. These thresholds are shown in Figure 5. Note that the scale is now bounded between 0.5 (flicker) and 1 (pure motion). For all 3 observers, the motion onset transients were associated with the largest threshold elevations, and the difference with the baseline

Experiment 3

Methods

In Experiment 3, the task was to saccade to the moving pattern among flickering patterns, where the flicker stimulus was created as in Experiments 1 and 2. To parametrically vary motion strength, we manipulated the amplitude of the two components of the flicker stimulus. At one end of the spectrum, a flickering pattern contains two drifting components with amplitudes (of 0.25, the non-target contrast) that are equally weighted by a factor of 1/2. At the other end of the spectrum, a pure, 100% motion stimulus can be regarded in exactly the same manner except for the unit weighting of one component and a zero weight for the opposing component. Thus, by adjusting the weight of one component over the other (from 1/2 to 1), a pattern is created that appears either more as flicker or motion. Target presentation in this experiment was signaled by the onset of the component
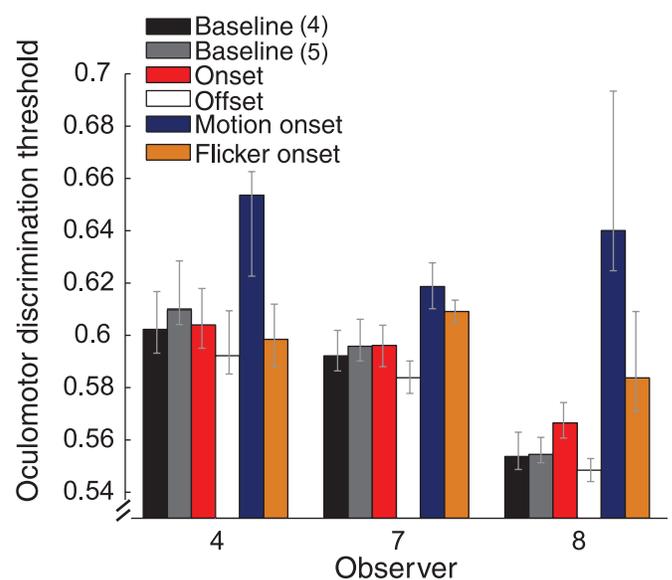

Figure 5. Discrimination thresholds of Experiment 3. Conventions as in Figure 3.

threshold was significant for 2/3 observers (Table 1). For one observer (#8), the flickering distractor was also disruptive. Apart from motion (and perhaps flicker), none of the other transients interfered with target selection. It is therefore not surprising that the null interference from abrupt onsets was no greater than that from other transient events (with exception of offsets for observer 8).

Changing the task-relevant visual dimension from luminance contrast to opponent motion had a dramatic effect on the pattern of threshold elevations caused by the various visual transients. Whereas motion onset transients were just as, or perhaps even somewhat less, disruptive as onsets and offsets in Experiments 1 and 2, they caused much greater interference than any other dynamic visual event in Experiment 3. There are two possible explanations for this finding. First, it has been reported that the potential for an abrupt onset to capture attention is diminished in the presence of other transients in the display (Martin-Emerson & Kramer, 1997; Miller, 1989; for a similar finding with motion onset distractors, see Mühlenen et al., 2005). The displays in Experiment 3 contained continuous dynamic change. It may be that these continuous transients simply swamped the signals generated by abrupt onsets and offsets. Instead, a stronger and more continuous transient signal may be needed to disrupt behavior. Although we cannot refute this explanation, there are reasons to think this is not the sole explanation for the change in performance from the contrast to the motion discrimination experiments. There was no suggestion in the data from Experiments 1 and 2 that the continuous transients (motion and flicker) were more disruptive than onsets and offsets. As a result, one cannot claim that the stronger interference from these events somehow survived being embedded in a larger pattern of transient change in Experiment 3. Together, the findings from Experiments 1, 2, and 3 suggest that motion onsets elevated the thresholds in Experiment 3 because *only* these transients strongly activated the channel that was being monitored for the primary task.

Saccade latencies

The experimental paradigm was designed to provide insight into what kinds of visual events disrupt saccade target selection, predominantly through the spatial distributions of first saccade landing positions. As a result, our inferences thus far have been based solely on selection accuracy. We now turn to the saccade latency data for two reasons. First, there is some evidence that the decision processes governing *where* to look and *when* to look there are separate (Findlay & Walker, 1999). As such, it is possible that new insights may be gained by the saccade latency data. For instance, in the contrast discrimination experiments, all transients interfered with target selection

approximately equally. However, the interference pattern in the saccade latencies may well be different and show a systematic rank ordering. Second, throughout this paper, we report that target selection essentially becomes more error-prone with the presentation of an irrelevant transient event. It is thus important to examine whether this pattern could be caused by a speed–accuracy trade-off. In other words, if there is something in the transient event that makes observers respond faster, it is no wonder they become less accurate.

Figure 6 shows, for all experiments and observers, the mean latency of the target-directed saccades as a function of target signal strength. These functions are fairly noisy, largely because some of the means are based on only a small number of trials. Nevertheless, we note the following trends. First, there is considerable overlap between the functions from the different transients conditions. Second, for many observers, mean latency decreased with signal strength (Ludwig, Gilchrist, & McSorley, 2004), although not so strongly for some (e.g., observer 1). Third, the mean latencies from the two contrast discrimination experiments (top two rows) were very similar despite their different levels of target and transient certainty. Finally, the latencies from the motion discrimination experiment (bottom row) were somewhat longer, but this may be a straightforward consequence of motion perception necessarily requiring a longer perceptual integration period. Qualitatively at least, the pattern of latencies as a function of signal strength is very similar to that obtained in the contrast discrimination experiments. As a consequence, the following analyses are based on the data across all experiments (i.e., across the 8 observers, with the contrast and motion data from observer 4 averaged).

For each observer and experimental condition, we computed a (weighted) linear regression with target signal strength as the independent variable. Although a linear fit may not be optimal for some of the functions shown in Figure 6, these fits provide useful insights in the overall trends. In particular, for most observers and conditions, the slope of the regression line was well below 0. The average slope across observers ranged from -152 (±33, 1 *SEM*) ms to -278 (±24) ms for the different experimental conditions. Thus, as signal strength increased and observers' accuracy improved, their saccade latencies decreased. In addition, we computed the mean weighted saccade latency across signal strength for each observer/condition. These means were entered into a one-way repeated measures ANOVA with condition as the experimental factor. The main effect was significant [$F(4, 28) = 3.69, p < .05$] but disappeared when the baseline condition was omitted [$F(3, 21) = 1.79$]. This analysis suggests that saccade latency was overall prolonged in the presence of an irrelevant transient, but that the increase was independent of the specific transient condition. On the whole then, the latency data tell a similar story to the accuracy/threshold data. Increasing the signal strength improved
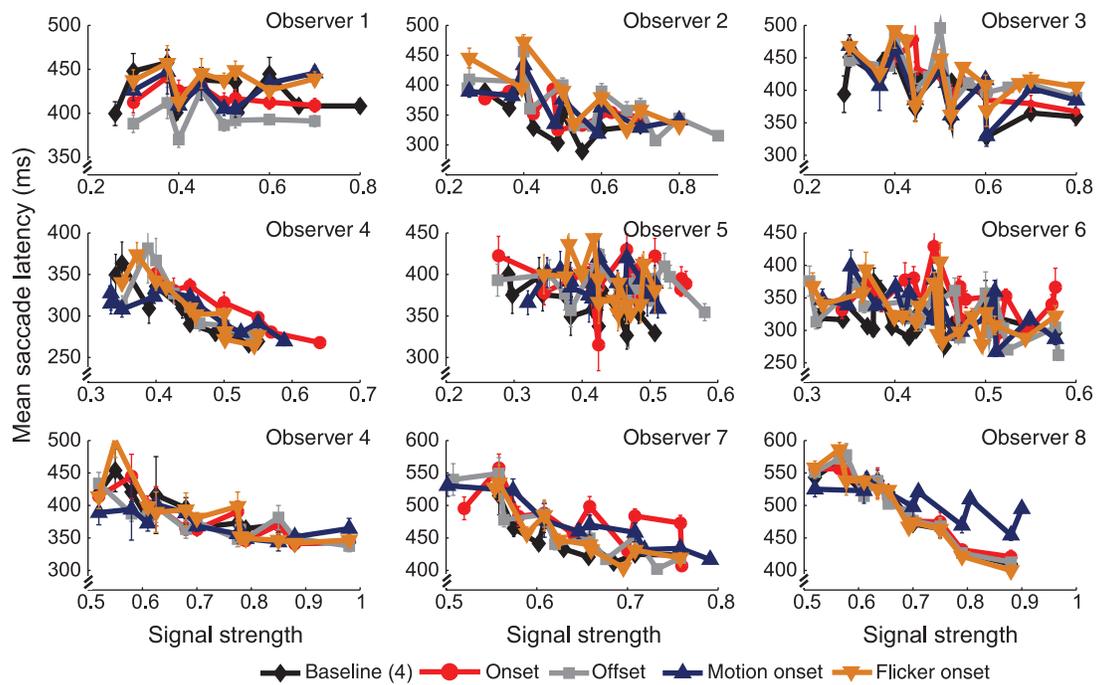
Figure 6. Mean latency of target-directed saccades as a function of signal strength. The different transient conditions are shown by different curves for each combination of observer and experiment. Rows 1–3 correspond to Experiments 1, 2, and 3. Error bars are standard errors of the mean.

accuracy and decreased saccade latency. Irrelevant transients that elevated the discrimination threshold had a similar effect on the response latency.

General discussion

In a series of 3 experiments, we systematically compared the impact of 4 different transient visual events on saccade target selection. The impact of abrupt onsets was compared to changes in pre-existing objects. Importantly, these transient events were designed so that they could all be expected to activate early visual mechanisms, yet there were good reasons to believe that their behavioral relevance might differ (Boot et al., 2005; Franconeri & Simons, 2003). Interference could manifest itself directly through capture of the first saccade, or indirectly by making saccades to potential target locations more error prone. Both forms of interference have the effect of elevating the oculomotor discrimination threshold, which is the critical metric used in this study. In addition to varying the nature of the transient visual event, we also manipulated the task-relevant dimension, or channel, for the primary discrimination task in order to test to what extent capture was contingent upon the observers' behavioral goals.

In Experiments 1 and 2, observers were required to saccade to the high contrast target. In these experiments,

abrupt onsets, offsets, motion onset, and flicker onset all interfered with target selection. There was very little evidence for a special status for abrupt onsets: Across the two experiments, there was only one observer for whom the disappearance of an object was less disruptive than an abrupt onset. For all other observers, interference from changes to pre-existing items was statistically indistinguishable from that caused by the onset of a new object. In Experiment 3, observers had to select the moving target among flickering non-targets. Under these conditions, we found no interference from abrupt onsets at all, and only motion onset distractors elevated the discrimination threshold (reliably so in 2/3 observers).

These findings suggest the following conclusions. First, the saccadic eye movement system is not driven by salience or the magnitude of the response in early visual mechanisms. Although the pattern of results across Experiments 1 and 2 may be consistent with this hypothesis, Experiment 3 shows a radically different pattern of interference from *exactly the same* group of transient visual events. Second, the saccadic eye movement system is not driven by higher-level notions or representations of "objectness." That is, when distracting events are chosen to activate similar units as those that respond to abrupt onsets, these events cause similar interference despite occurring in pre-existing objects. Of course, it could be argued that the onset of motion or flicker results in a discontinuity in a spatiotemporal object file that is of sufficient magnitude for the object to be classified as new (Rauschenberger, 2003). However, for

most observers, abrupt offsets interfered almost or just as much as abrupt onsets. It would seem rather odd to classify such events as constituting new objects. Third, and finally, it appears that the saccadic system is largely driven by visual events that activate a channel that is being monitored in order to perform a behavioral task. Such events may or may not coincide with the formation of a new object representation, but as long as they trigger a response within the monitored channel, they will interfere. Thus, these experiments provide converging evidence for contingent oculomotor capture (Ludwig & Gilchrist, 2002, 2003a, 2006; Wu & Remington, 2003).

Are abrupt onsets special for the saccadic system?

As reviewed in the Introduction, previous studies of oculomotor capture have suggested that abrupt onsets may have special status for the eye movement system. For instance, Wu and Remington (2003) reported that although capture by abrupt onsets diminished when observers were set to respond to specific color targets (as opposed to color singletons), it was not eliminated. Boot et al. (2005) found hardly any capture by an offset distractor compared to that caused by abrupt onsets. Irwin et al. (2000) reported oculomotor capture by changes in luminance, but not up to the same level as that caused by abrupt onsets. Thus, aspects of our results are not consistent with these previous studies. It is worthwhile speculating as to why this may be.

One possible reason is that in our experiments the influence of the observers' behavioral goals was simply more potent in driving the saccadic machinery than in the studies cited above. In the language of the contingent capture hypothesis, it could be said that observers were able to configure and maintain a stronger attentional set for the relevant target signal. We suggest that a strong set could be adopted because our stimulus patterns were better matched to the response properties of early visual mechanisms. This is likely to enable relatively simple performance strategies that involve few computational steps. For instance, in contrast discrimination, the observer could simply monitor a pool of units with task-relevant response properties that act approximately as linear filters (e.g., cells in visual cortex that respond to approximately the correct spatial frequency, orientation, and location). The saccadic response can then be driven by whichever location triggered the largest response from the monitored pool (Beutter, Eckstein, & Stone, 2003; Ludwig, Eckstein, & Beutter, 2007). The motion discrimination experiment could involve a subset of the same units, namely, those with the relevant directional selectivity (Levinson & Sekuler, 1975), or a subsequent stage of processing that involves computing the difference between pools of units with opposing directional preferences (Adelson & Bergen, 1985). Thus, both contrast and motion discrimination are tasks that can be solved by monitoring the outputs of mechanisms early on in the visual processing hierarchy. The same is probably not true for more sophisticated attentional sets for, say, color singletons (or unique visual events in general). Thus, our choice of stimulus may have facilitated the monitoring of the correct channel(s), which would make behavior more task driven. The flip side is that this choice of stimulus makes behavioral performance in the capture paradigm amenable to computational analysis along the lines suggested above.

An additional factor that may have influenced our findings is that saccade latencies were overall relatively long (most certainly longer than in previous studies of oculomotor capture), possibly because of the use of practiced observers and/or of stimuli that may have encouraged more prolonged temporal integration (particularly in Experiment 3). It is likely that this factor contributed to the reduced capacity of transient events to override the observers' behavioral goals. There is good evidence that capture by salient events occurs when overall response latency is short (Ludwig & Gilchrist, 2003b; van Zoest, Donk, & Theeuwes, 2004).

Finally, it should be noted that our inferences have been based on the detailed analyses of individual observers' data, in contrast to previous studies in which data from a larger sample of participants were averaged. Thus, while it is true to say that for *any one* single observer we always found at least two other visual events that, statistically speaking, interfered as much as abrupt onsets, it is possible that an advantage for onsets might have appeared had we been able to test a large group of observers and averaged their data. For instance, from Figures 3 and 4, it appears likely that had we run a large-sample study comparing the influence of abrupt onset and motion distractors on contrast discrimination, we would have found a new object advantage. However, our psychophysical approach would suggest that (a) this onset advantage over motion would be fairly subtle and (b) the onset advantage would be highly dependent on which comparator event one chooses. For instance, had we chosen to pair abrupt onsets with flicker and tested the same sample size, we might have easily obtained a null effect. We believe these are useful insights that readers may wish to bear upon their interpretation of large-sample studies. Our approach should thus be seen as complementary to that typically used in the study of oculomotor capture.

Direct and indirect capture

We have reported that direct oculomotor capture decreased with increasing certainty of potential target and irrelevant transient locations, despite the discrimination thresholds remaining very similar. One can reasonably ask whether under these circumstances attention was captured, but not the eyes (whereas, presumably, in

Experiment 1 both the eyes and attention were captured; Theeuwes et al., 1999). To address this issue, it is worth considering how this pattern of performance could be generated.

Choice and RT data are frequently effectively modelled using sequential sampling models (Brown & Heathcote, 2005; Carpenter & Williams, 1995; Luce, 1986; Ratcliff & Smith, 2004). The general idea is that multiple response alternatives race each other toward some response criterion. Whichever alternative wins the race is chosen with an overt behavioral response such as a manual button press or, indeed, a saccadic eye movement. To account for variability in both choice and latency, one has to assume that the rate of accumulation varies from trial to trial, or even within a trial. The idea is illustrated in Figure 7. Consider the 4-AFC baseline condition only for now (top panel). Each of the four patterns triggers a noisy internal response that is translated into an accumulation rate. A pattern that triggers a strong internal response is associated with a fast rate and is likely to win the race to threshold. In this example, the accumulator associated with the target (black line) happens to grow fastest and ends up winning: A correct response is produced. However, this will not always be the case because the rates for all 4 accumulators are subject to random perturbations. The magnitude of these perturbations is dictated by the scale of some distribution. Example accumulation rate distributions are shown in the inset. As in standard signal detection models (Eckstein, Ahumada, & Watson, 1997; Green & Swets, 1966), the proportion correct saccades is determined by the separation between the target (black) and non-target (red) distributions when the starting level for all accumulators is equal. We envisage that with increasing signal strength the target distribution shifts further to the right, toward faster accumulation rates, producing monotonically increasing oculometric functions.

Now consider a transient condition. For illustration purposes, we take the abrupt onset condition as an example. Suppose the following: (1) An irrelevant transient is associated with its own accumulator that competes just like the other 4 accumulators do. The validity of this assumption is self-evident as direct oculomotor does occur. (2) Because the transient is *always* irrelevant, its associated accumulator may start at a lower level than the potential target accumulators. In a simple, visually guided saccade task, the latency decrease that results from providing observers with more certainty about the probable target location has been successfully modelled as a shift in the starting level of a single accumulator (Carpenter & Williams, 1995). In addition, neurophysiological recordings from monkey superior colliculus have shown changes in baseline activity level with varying levels of prior target certainty (Basso & Wurtz, 1997, 1998). (3) A transient event that activates a monitored channel results in more noisy responses to all items in the display: The rates of all 5 accumulators vary

more from trial to trial. This final assumption is less obvious and more speculative. This proposed effect of the irrelevant transient is perhaps analogous to that of a
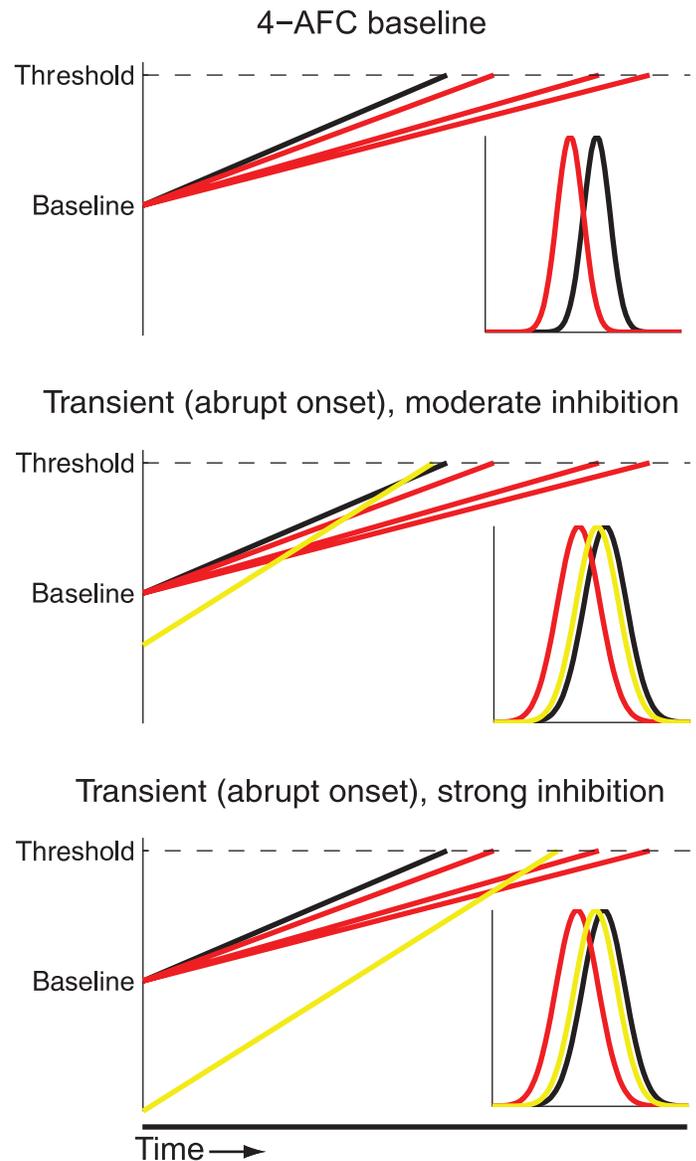

Figure 7. Schematic framework of saccade target selection. Each pattern in the display is associated with an accumulator that gathers evidence from baseline to some response criterion. The accumulator with the fastest rate wins the race and determines which pattern is chosen. The accumulation rate varies probabilistically from trial to trial (see Gaussian distributions in the insets). In this example, transient events trigger an almost similar (mean) internal response as the target. Yet we assume some form of inhibition results in a lower starting level for the accumulator associated with the transient saccade program. As a result, it will win the race to threshold sometimes (middle panel), but not always (bottom panel) depending on the variability in the accumulation rate and the amount of inhibition. Note that presentation of the transient results in more noisy responses (wider rate distributions in the insets) to all patterns.

spatially super-imposed random noise mask or background. Such effects have been modelled as an additional noise source that decreases the signal-to-noise ratio of the internal response to the target pattern (Eckstein et al., 1997; Foley, 1994).

These assumptions are illustrated in the middle and bottom panels of Figure 7. In the middle panel, the inhibition of the transient event (yellow line) is moderate. Thus, if the transient event triggers a large enough response, it might still reach the threshold before any other accumulator and direct oculomotor capture occurs. In the bottom panel, the transient has the same rate of rise as in the middle panel. However, because inhibition is stronger, it cannot make up for lost ground in time before the target reaches the threshold. In both the middle and bottom panel, the variability in accumulation rates is larger than that in the baseline condition (compare the width of the distributions in the insets across the three panels). Again, with increasing signal strength the target distribution will shift further to the right, resulting in more accurate performance and less oculomotor capture.

According to this scheme the influence of an irrelevant transient is twofold. First, it directly competes with the other response alternatives and may win the race to threshold. Second, it increases accumulation rate variability so that even when the transient does not win the race itself it makes the behavioral responses to one of the remaining patterns more random. We hypothesize that providing more spatial certainty allows observers to decrease the baseline activity associated with the transient saccade program (Carpenter & Williams, 1995). As a result, direct oculomotor capture becomes very unlikely. However, the effect on rate variability remains and results in error-prone responses directed to potential target locations. Such errors elevate the discrimination threshold in the absence of direct oculomotor capture. This scheme *does* predict a subtle decrease in the threshold with increasing spatial inhibition because responses that would otherwise (when inhibition is less strong) have been directed to the transient now at least have a chance of going to the target. However, this decrease may be too subtle to detect empirically with a realistic number of trials.

Clearly this is just one possible account of how increasing spatial certainty decreases direct oculomotor capture while keeping discrimination thresholds elevated. We have entertained this option in some detail because (a) it fits in with established models of saccadic (Carpenter & Williams, 1995; Ludwig, Mildinhall, & Gilchrist, 2007) and perceptual (Ratcliff & Rouder, 1998) decision making; and (b) such models have been used to describe and account for neurophysiological data from eye movement structures such as the superior colliculus (Ratcliff, Cherian, & Segraves, 2003) and frontal eye fields (Hanes & Schall, 1996). In addition, considering in some detail how this behavioral performance pattern could be generated provides a more solid basis upon which to theorize about the role of attention in this task. Note that the framework sketched above makes no mention of attention at all. However, it may be that attention is an underlying mechanism that controls some of the behavior of this simple system. Providing spatial certainty about the potential target and transient locations may be regarded as a form of spatial cueing (Theeuwes et al., 1998). As such, spatial attention could be the mechanism that controls the separation between baseline and threshold at various locations in the visual field (or the spatial prior; cf. Shimozaki, Eckstein, & Abbey, 2003). To return to our original question whether the decrease in direct oculomotor capture meant that attention was captured instead, it is not quite clear how this conception of attention is something that can be meaningfully captured by an irrelevant, salient event.

Conclusions

The present study makes a number of methodological, empirical, and theoretical contributions. *Methodologically,* we have introduced a more psychophysical approach to the study of oculomotor capture which involves the use of stimuli that are better matched to the response properties of the underlying visual mechanisms that, presumably, support behavioral performance. The use of such patterns opens up the possibility of parametric manipulations of target and distractor signals and of a more explicit computational specification of task performance. *Empirically,* to our knowledge this is the first report of oculomotor capture by abrupt offsets, motion, and flicker. In addition, we show that providing improved prior knowledge about potential target and distractor locations may decrease the amount of direct capture, but overall performance is still impaired by the presentation of irrelevant transient events. *Theoretically,* we have begun to sketch an account of eye movement behavior that combines aspects of statistical decision theory and sequential sampling models. This framework appears a promising avenue for the development of explicit, biologically inspired models that can account for both direct and indirect forms of oculomotor capture.

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