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The timecourse of attentional and oculomotor capture reveals a common cause

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Running Head: Capture of attention and the eyes

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Abstract

Eye movements are often misdirected towards a distractor when it appears abruptly, an effect known as oculomotor capture. Fundamental differences between eye movements and attention have led to questions about the relationship of oculomotor capture to the more general effect of sudden onsets on performance, known as attentional capture. This study explores that issue by examining the timecourse of eye movements and manual localization responses to targets in the presence of sudden onset distractors. The results demonstrate that for both response types, the proportion of trials on which responses are erroneously directed to sudden onsets reflects the quality of information about the visual display at a given point in time. We conclude that oculomotor capture is a specific instance of a more general attentional capture effect. Differences and similarities between the two types of capture can be explained by the critical idea that the quality of information about a visual display changes over time, and that different response systems tend to access this information at different moments in time.

Keywords: Eye movements, visual search, attentional capture, oculomotor capture, voluntary and reflexive attention

Selective attention is typically characterized as having two distinct subtypes: one subtype is variously named reflexive, exogenous, bottom-up and stimulus-driven attention, and the other subtype is referred to as voluntary, endogenous, top-down, and goal-directed attention.  The bifurcation of selective attention into these subtypes has been supported by distinct function (e.g., Posner, 1980; Posner and Cohen, 1984; Lu and Dosher, 2000; Taylor and Klein, 1998) and underlying neurophysiology  (e.g. Corbetta and Shulman, 2002; Friedrich, Egly, Rafal and Beck, 1998; Serences, Shomstein, Leber, Golay, Egeth and Yantis, 2005) associated with reflexive and voluntary attention.

Selection by reflexive attention is driven by inherently attractive stimulus properties. Voluntary attention, in contrast, is often characterized as a goal-directed filter that uses expectations about the target's perceptual features to enhance certain visual channels over others in order to isolate the target from the rest of the display. An important question that is the subject of heated debate in the literature is how reflexive and voluntary attention function during search of the environment for a specific visual item, particularly in the face of a range of distracting events. The attentional capture paradigm is typically used as a method for measuring the relative contributions of reflexive and voluntary attention to visual search by measuring the efficiency of search for a given target when it is paired with specific kinds of distractors.

Several studies have emphasized the role of stimulus properties in guiding attention. Some have argued that unique visual features in the environment are able to "capture" attention reflexively, without being relevant to task goals. For instance, a single red item among green ones will interfere with search for a specific shape, even when color is irrelevant to the task (Theeuwes, 1992). Theeuwes argues that this is because attention is initially allocated to the most perceptually salient visual event in the display. Similarly, others have shown that abrupt onsets

attract attention regardless of the task goals (e.g., Yantis and Jonides, 1984). The current

explanation for the special status of abrupt onsets is that they represent the appearance of a new

object, and thus have automatic priority for the system that orients attention (e.g., Enns, Austen,

Di Lollo, Rauschenberger and Yantis, 2001, but see also Franconeri, Hollingsworth, and Simons,

2005; von Mühlenen, Rempel, and Enns, in press). Thus, when a sudden onset appears, attention

is automatically drawn to its location. Manual detection or discrimination responses are

consequently slower in the presence of an onset, because they await the allocation of attention to

the target location before they can be executed.

Other studies have emphasized the role of voluntary goals and strategies in determining

what kinds of distractors will and will not interfere with search. Attention tends to be distracted

by items that share some perceptual feature with the target (e.g. Jonides and Yantis, 1988). This

kind of distraction effect can be thought of as a byproduct of the attempts of voluntary attention

to use available visual features to home in on a subset of goal-relevant items in the environment.

In fact, there is some evidence that voluntary strategies are behind capture of attention by

seemingly irrelevant singletons. Bacon and Egeth (1994) demonstrated that when the target is a

unique item (singleton), subjects tend to adopt a "singleton detection" strategy, and thus other

singletons are distracting because they share with the target the characteristic of being unique,

regardless of whether or not they share any specific features with the target. When the singleton

detection strategy is no longer viable for finding the target, singleton distractors no longer

impede search performance. There is also some debate about whether capture by sudden onsets

can be considered purely reflexive, because the extent to which performance will be impeded by

onsets depends on what has been defined as the target (e.g., Folk, Remington and Johnston,

1992; Folk, Remington and Wright, 1994).  Folk and Remington (1998) have suggested that

delayed responding in the presence of sudden onsets does not necessarily mean that attention has

been allocated to the onset location. They propose that in the presence of irrelevant events,

voluntary attention imposes a filter on the visual display in order to detect the target among the

increased noise, and the imposition of this filter slows the detection of the target. According to

this model of visual search, there is no allocation of spatial attention directly to the onset

location.

One barrier to understanding how attention functions in visual search is that the debate is

mainly concerned with covert visual orienting, that is, orienting attention in the absence of any

overt movement of the eyes and/or head. The locus of covert visual attention must be inferred

using differences in the reaction time of manual discrimination responses. In recent years, many

visual search studies have begun measuring eye movements as well as, or in place of, manual

responses, to better understand how covert attention is allocated during search for a target.

Among the first of these, Theeuwes, Kramer, Hahn, and Irwin (1998) and Theeuwes, Kramer,

Hahn, Irwin and Zelinsky (1999) required participants to make a saccadic eye movement from

the center of the display to a color singleton target. On half the trials an irrelevant onset suddenly

appeared at the same time as the target was revealed.  Theeuwes et al. observed that the eyes

were frequently directed towards the sudden onset first, and then redirected towards the target, a

phenomenon known as oculomotor capture. They suggest that a reflexive shift of attention to the

onset initiates the programming of an eye movement there, at the same time as an eye movement

program to the color singleton is initiated in response to voluntary attention allocated to the

target location, and whichever eye movement program is completed first wins control over the

eye movement system. One of the assumptions of Theeuwes et al. (1999) is that the cause of

oculomotor capture is the reflexive orienting of covert attention to the sudden onset. If the delay

in responding associated with sudden onsets in manual tasks were due to the voluntary

implementation of an attentional filter, one would not expect error saccades to be systematically

directed towards the onset. Thus the existence of oculomotor capture supports the notion that

attention is captured reflexively by sudden onsets.

There is reason to question the assertion that oculomotor and attentional capture reflect

the same underlying processes, however. Theeuwes, Kramer, Hahn and Irwin (1998) note that

they ". . . assume that the reflexive shift of attention to the new object also initiated the

programming of a saccade. . .to the location of the new object." (page 383). But covertly

attending to a specific location in space does not necessarily elicit the programming of a saccade

to that location (e.g., Hunt and Kingstone, 2003a; Juan, Shorter-Jacobi and Schall, 2005), and

saccades and manual responses have been shown in several instances to produce very different

patterns of results (e.g. Hunt and Kingstone 2003b; Hunt and Klein, 2002; Posner, Nissen and

Ogden, 1978; Sailer, Eggert, Ditterich, and Straube, 2002).  Indeed, the architecture of the

saccadic eye movement system supports the possibility that oculomotor capture is a saccade-

specific phenomenon. A branch of the optic tract feeds directly into the superior colliculus (SC),

a midbrain structure known to be involved in eye movement control. Moreover, based on

evidence from oculomotor capture experiments, recent studies concluded that the integration of

competing saccade programs takes place within the SC (Godijn and Theeuwes, 2002; Hunt, Olk,

von Mühlenen and Kingstone, 2004). This notion that the SC plays an important role in

oculomotor capture is difficult to reconcile with the assertion that oculomotor capture is tapping

into the same attentional mechanisms as manual discrimination responses.

Whether or not attentional and oculomotor capture reflect the same underlying processes

is not yet known. Three studies to date have specifically addressed this issue. Wu and Remington

(2003) systematically compared oculomotor and attention capture, and found that eye

movements were captured by sudden onsets but not by color singletons, while manual responses

demonstrated attentional capture (that is, slower reaction time to discriminate the target) in the

presence of both color singleton distractors and sudden onsets. They also note that the

methodology used by Theeuwes et al (1998; 1999) encourages the use of a singleton-detection

strategy, which brings to light the possibility that oculomotor capture is not a purely reflexive

phenomenon. When the target itself was no longer a singleton, they observed smaller capture by

sudden onsets among eye movement responses, and no capture among manual responses. They

conclude that oculomotor capture by abrupt onsets is not mediated by the same underlying

mechanism as attentional capture measured by manual responses. Interestingly, Theeuwes, de

Vries, and Godijn (2003) found a parallel dissociation during search for a specific target feature.

Here an irrelevant singleton distractor was found to slow manual reaction time (that is, produce

attentional capture) without affecting eye movements. Ludwig and Gilchrist (2002) similarly

concluded that capture is influenced by the required response. They demonstrated that capture by

abrupt onsets does occur for manual mouse movement responses, but not for manual button-

press responses like the ones used by Wu and Remington (2003).  Their results suggest that

attentional and oculomotor capture are similar when both are measured using directional

localization responses. It is not quite accurate to say that they are the same, however, because

capture for manual responses was observed in reaction time differences, and saccadic capture

was always observed in the direction of saccadic responses, but never in reaction time. This

difference in the effect of the distractor on these two kinds of responses is representative of the

oculomotor and attentional capture literatures as a whole, with oculomotor capture typically

observed using the landing position of eye movements, and attentional capture measured using

reaction time. These two measures make it difficult to directly compare capture for the two conditions. Indeed, Prinzmetal, McCool & Park (2005) have suggested that accuracy and reaction time effects may reflect different underlying processes of attention.  They propose that accuracy effects in attentional cueing experiments reflect the enhancement of perceptual processing caused by the voluntary allocation of attention. Reflexive attention, in contrast, does not influence response accuracy, because it does not affect perceptual processes. One might be tempted to infer based on this hypothesis that oculomotor capture reflects voluntary attentional orienting, while attentional capture reflects response competition brought on by purely reflexive processes. However, Prinzmetal et al. do note that the divergence of voluntary and reflexive attention in terms of their effect on accuracy may require a specific set of circumstances: there must be no pressure on reaction time, there must be no uncertainty about the target location, and the eyes must be monitored to ensure that it is covert, and not overt, attention that is being measured. Given that attentional and oculomotor capture experiments tend to violate most, if not all, of these conditions, it is not clear whether their conclusions apply to attentional capture and oculomotor capture investigations.

Another major obstacle for interpreting differences between manual and saccadic responses is the time required to execute these two responses under most circumstances. Manual responses tend to be hundreds of milliseconds slower than eye movement responses. It is therefore plausible that by the time a manual response is initiated, the representation of the target location has changed from the time an eye movement would have been executed. As time passes, information about the visual display gradually accrues, which could have important influences on the response that is ultimately executed. Indeed, even within the eye movement domain, fast eye movements have been shown to be qualitatively different from slower movements in terms

of how they respond to targets in the presence of salient distractors (Van Zoest, Donk and Theeuwes, 2005).

To overcome these limitations, the current study contrasts attentional and oculomotor capture using manual localizing responses, rather than detection responses. Using an 8-way joystick, the manual response task is matched as closely as possible to the oculomotor localization task. If oculomotor and attentional capture effects are reflections of the same underlying visual search processes, manual localization responses should be similar to oculomotor responses observed in previous studies (e.g. Theeuwes et al, 1998). That is, responses should be directed toward the onset, particularly when they are executed soon after the target and onset are displayed. On the other hand, it is possible that eye movements and manual responses are distinct, and the effect of the onset is different for the two response types. If onsets have a special status for eye movements but not for attention, as Wu and Remington's (2003) results suggest, manual responses would show effects in reaction time because of the imposition of an attentional filter in the presence of onsets (Folk and Remington, 1998), but no systematic bias to respond in the direction of the onset.

Experiment 1

In Experiment 1, oculomotor capture was compared to joystick localization responses under the same conditions, and measured within the same group of participants. Because a digital 8-way joystick was used to record manual responses, the number of circles presented in the initial display was 4, instead of the more typical 6. Previous research using four locations (e.g. Irwin, Colcombe, Kramer and Hahn, 2000) has found capture similar to that using six (e.g.

Theeuwes et al, 1998), suggesting that the use of 4 locations is not likely to greatly influence the

pattern of oculomotor responses relative to previous experiments.


Methods

*Participants.* Nine undergraduate volunteers received credit in a psychology course to participate

in Experiment 1.  All had normal or corrected-to-normal vision.

*Apparatus.* The experiment was displayed on a 17-inch 80Hz monitor, viewed from a chinrest

57cm away. The position of the left eye was recorded every 4ms using an EyeLink eye tracker

(SMI research). Saccades were detected with a velocity criterion of at least 30˚ per second.

Before each block, participants underwent a nine-point calibration sequence. Each participant

was seated alone in a small room, and the experimenter monitored performance and the quality

of the eye movement calibration from a display situated in an adjacent room. Joystick responses

were recorded using a symmetrical, arcade-style, 8-way digital joystick.  The joystick

(manufactured by Happ Controls, part number 50-7608-16) has the freedom to move in any

radial direction, but inside the joystick there are four switches to record when the joystick is

moved to each of four positions. When two adjacent switches are both depressed the position is

recorded as between two positions, giving it a total of 8 discrete directions. The joystick was

built into a metal box, 6cm high, which was affixed to the table directly in front of the

participant, who was instructed to use the dominant hand to respond.

*Stimuli and Procedure.* Examples of a typical onset absent and onset present trial are illustrated

in Figure 1. At the beginning of each trial, four orange circles, 3.7˚ in diameter, were presented

12.5˚ from the central fixation crosshair and evenly spaced around the circumference of an

imaginary circle. The circles in the initial display could have one of two possible configurations,

in the shape of either a diamond (as in Figure 1) or a square. After 1000ms, all but one of the

orange circles changed to red. On half the trials an additional red circle was added to the display

at the same time as the color singleton was revealed. Participants were told that the onset was

irrelevant to their task and they should ignore it. The onset present and onset absent trials

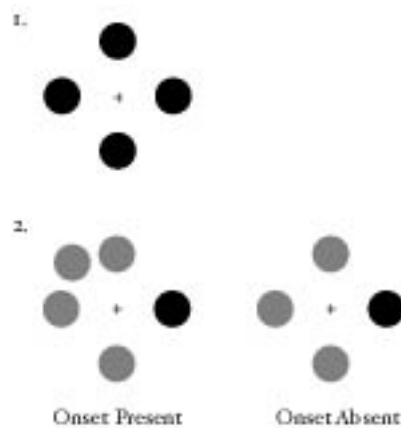occurred equally often and were randomly intermixed.



**Figure 1. Illustration of the onset absent and onset present conditions. The initial display (1) was presented for 1000ms before being replaced by one of the two displays shown below. The diamond configuration is shown here; note that the display was also shown rotated 45˚ on half the trials. What was actually orange in the experiment is shown as a black target here, and the red distractors are represented in grey.**

Each participant completed one eye movement block and one joystick block, each with

216 trials. The order of blocks was counterbalanced across participants. A brief instruction and

practice session of 10-15 trials was used to introduce each block. Participants were instructed to

move their eyes to the orange singleton in the eye movement block, and to move the joystick

toward the orange singleton in the joystick block. All participants were asked to be as fast and as

accurate as possible. In the eye movement block, participants fixated the central crosshair to

trigger the onset of the trial, and the color singleton target was displayed 1000ms after a stable

fixation was detected. The destination and latency of the first eye movement executed after the

target was presented was recorded and analyzed. In the joystick block, participants again fixated

the central crosshair to trigger the onset of the trial, but instead of moving their eyes to the target

they responded by using their dominant hand to move the joystick in the direction of the orange

target. Participants were instructed to keep their eyes fixated on the center fixation during trials

in the joystick block. When participants did not follow this instruction, the experimenter paused

and re-instructed them to remain fixated on the center.

The introduction of a digital joystick to the oculomotor capture methodology highlights a

problem with a typical capture experiment, which is that participants can eliminate, in advance, a

subset of responses as always incorrect. As can be seen in Figure 1, each trial begins with 4

circles already in place, and the target always appears in place of one of these circles. It is easy to

imagine that participants would quickly learn that the target appears only in a subset of possible

locations, and that a residual subset of responses would therefore never be correct. This

knowledge could reduce capture effects because, regardless of whether or not an onset is

presented, it would discourage participants from executing those responses that are always

incorrect. This is a particular concern because it has been shown that spatially pre-cueing the

location of an impending target eliminates capture (Theeuwes et al., 1998), and the display

inherently pre-cues a subset of locations as incorrect.

One way we addressed this design issue was to randomly intermix displays in which the

four initial circles are laid out in a diamond configuration with displays in which the four initial

circles are laid out in a square configuration, ensuring that all eight responses are made equally

likely across the experiment. However, this change alone does still allow for the strategy of

eliminating a subset of possible responses on a trial-by-trial bases, because participants know

that only positions occupied by a circle at the beginning of the trial will represent the set of

possible correct responses. To ensure that each of the eight locations was equally likely to

contain the target, a third and fourth condition were added to the typical onset present/absent

conditions in all four experiments in this study. In the third condition, as the four circles changed

to red, an orange circle was added to the display. The sudden-onset circle was also the orange

singleton, and therefore the target. In the fourth condition, as the four circles changed to red, two

additional circles were added to the display, one red and one orange. The target was again the

orange sudden-onset circle. Randomly intermingling all four conditions in equal numbers (that

is, the two original conditions shown in Figure 1 and the two new conditions, in which the target

was an onset) makes all positions equally likely to contain the target, and ensures that the red

onset distractor circle is still presented on half the trials. For simplicity, however, data from the

third and fourth conditions, in which the target was an onset, were not included in the analysis[1].

*Analysis.* Responses were classified as directed towards the target, the onset, or elsewhere. For

the joystick, this classification process was straightforward because there are 8 discrete responses

and the mapping between the response and the target location was clear. In the eye movement

block, however, the eyes' landing position was continuous, and was generally scattered around

the target or onset location. To classify saccades, the display was divided into eight 45˚ wedges,

and if the saccade landed in the 45˚ wedge centered around the target, it was classified as a

saccade to the target, if it landed in the 45˚ wedge centered around the onset, it was classified as

a saccade to the onset, and if it landed anywhere else, including nontarget circles or empty

locations, it was classified as "elsewhere".

The proportion of elsewhere responses for each subject in the onset condition was divided by six and used as an estimate of *general error* for comparison to the proportion of onset responses[2]. The proportion of responses directed towards the onset had to be significantly greater than general error in a paired t-test to conclude that responses were captured by the onset. In addition, when comparing the percent of capture across conditions, the estimate of general errors was first subtracted from the proportion of capture to control for changes in the general accuracy of responses across conditions.

<div align="center">Results</div>

*Reaction Time.* The effect of the onset was compared within participants across eye movement and joystick blocks in a 2x2 ANOVA. The results are shown in Figure 2. Latency in the eye movement block was significantly faster than latency in the joystick block, [$F(1,8)=117.87$, $p<.001$], and there was a significant main effect of the onset [$F(1,8)=9.19$, $p<.05$]. There was also a significant interaction between response type and the effect of the onset on latency [$F(1,8)=39.59$, $p<.001$]. This occurred because there was a significant effect of the onset on the latency of correct joystick responses, with responses to the target being 547.2ms when the onset was absent and 599.3ms when it was present [$t(8)=5.33$, $p<.001$], but there was no effect of the onset on latency to saccade to the target [$t(8)=0.42$].
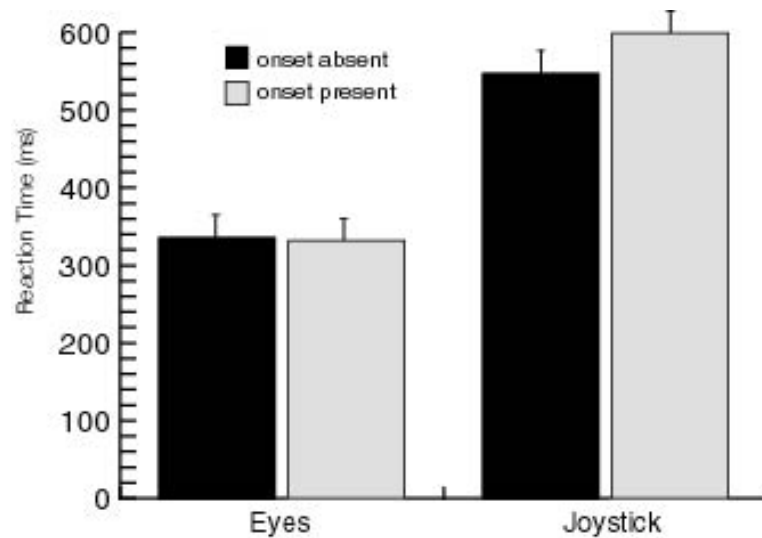
**Figure 2. The reaction time to respond to the target in Experiment 1 is shown for both eye movement and joystick responses. Error bars in this and all other graphs illustrating within-subjects interaction effects in the present study are calculated using the pooled error term of the three factors and their interactions, according to the methods for illustrating within-subjects error described by Masson and Loftus (2003). There is a significant interaction of the onset effect with response type.**

*Accuracy.* Figure 3 illustrates the accuracy of joystick and eye movement responses in both

onset-absent- and onset-present conditions. When the proportion of capture (minus general error)

was compared between response types in a paired t-test, there were significantly more responses

directed towards the onset when participants responded with their eyes than when they

responded with the joystick [t(8)=4.18, p<.01]. When the onset was presented, it captured eye

movements on 13.7% of trials. This value is less than is typically observed in oculomotor capture

experiments (e.g., Theeuwes et al., 1998; Hunt et al., 2004), but it exceeded general error by

12.7%, a difference that is significant [t(8)=4.79, p<.01]. In the joystick block, responses were

directed towards the onset when it appeared on only 2.7% of trials (see Figure 3), which, when

compared to general error, was significant [t(8)=2.36, p=.046], but exceeded it by only1.3%,

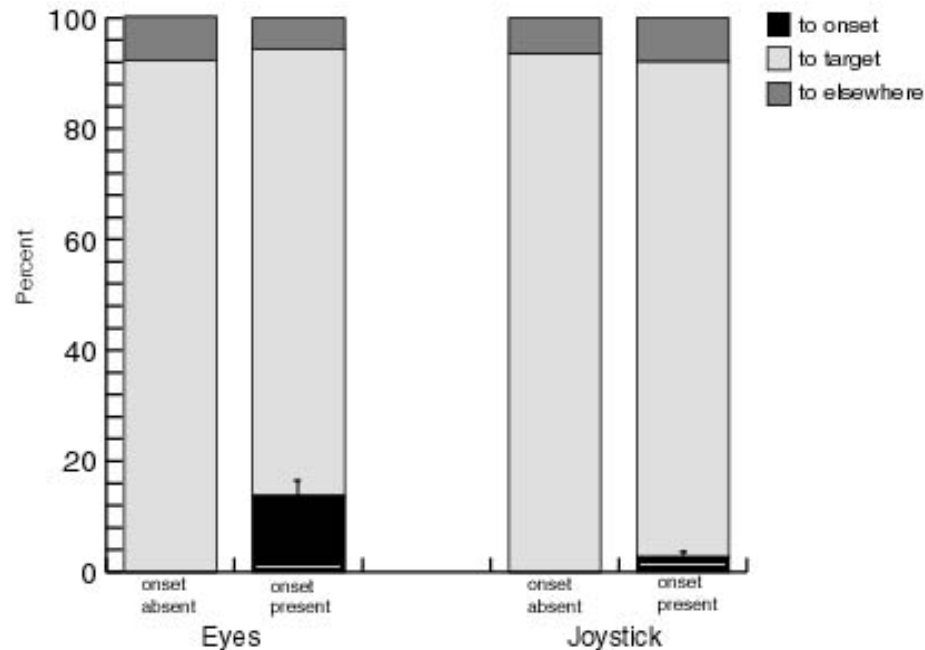suggesting consistent but not very strong capture by the irrelevant onset.[3]

**Figure 3. The proportion of responses directed towards the onset, target, and elsewhere in the display is shown for both eye movement and joystick responses in Experiment 1. There is significantly more capture for eye movement than for joystick responses. The white horizontal lines in the onset present columns here and in all subsequent graphs represent the estimate of general error (which is equal to 1/6$^{th}$ of the "elsewhere" proportion; see the methods for more details).**

Discussion

The manual results of Experiment 1 show a very small but significant effect of the onset on accuracy, and a robust effect of the onset on correct reaction time. In contrast, eye movements show no effect of the onset on reaction time, but a robust effect on accuracy. The finding from the joystick block replicates the findings from attentional capture research (which is typically measured in manual choice reaction time), and the findings from the eye movement block replicates findings from oculomotor capture research (which is typically measured in the accuracy of localization responses). It is also noteworthy that capture even among eye movements (13.7%) was quite low in this experiment relative to previous investigations (e.g. Godijn and Theeuwes, 2002; Theeuwes et al., 1999).

Joystick localization responses are much slower than eye movements in the present experiment. This is perhaps not surprising, but this observation is nonetheless important because it highlights a problem in comparing attention and oculomotor capture, even when they are both localizing responses: they are executed at different times relative to the appearance of the onset and target. The onset may slow the reaction time of manual responses because the response is withheld until attention has been allocated to the target location. Eye movements are more likely to be executed quickly, and thus errors occur in the presence of an onset because the eye movement is released before attention has been shifted to the target location. This explanation will be further explored in the next 3 experiments.

Experiment 2

In Experiment 2, reaction time feedback was introduced, and participants were urged to respond as quickly as possible. Increased emphasis on speed should increase capture in the eye movement condition (e.g., Godijn & Theeuwes, 2002). If attention and oculomotor capture are subserved by the same underlying processes, increased reaction time pressure may also influence accuracy in the joystick condition, leading to more responses directed towards the onset. In addition, participants in Experiment 2 were also no longer discouraged from moving their eyes in the joystick block, and were only told to fixate on the center point to initiate the trial. If the participant explicitly asked the experimenter where to fixate after the onset of the trial, the experimenter instructed the participant to do "whatever felt comfortable".

Methods

*Participants.* Nine undergraduates, none of whom participant in Experiment 1, received course

credit to participate in Experiment 2. All had normal or corrected-to-normal vision.

*Apparatus, Stimuli, and Procedure.* The methods of Experiment 2 were the same as in

Experiment 1, except eye movements were no longer explicitly discouraged, and reaction time

feedback was added. After each trial, participants were shown their reaction time in milliseconds

at the center of the display, and before each block, they were instructed to keep their reaction

time as low as possible.

Results

*Reaction Time.* Joystick and eye movement RT were included in a 2x2 ANOVA with response

type (eye movement versus joystick) and onset (present versus absent) as factors. There was a

significant effect of response type [$F(1,8)=129.88$, $p<.001$], with joystick responses slower than

saccades, no main effect of the onset [$F(1,8)= 1.62$], and a significant interaction between

response type and onset [$F(1,8)=7.39$, $p<.05$]. This interaction occurred because there was a

significant effect of the onset in the joystick condition, with a reaction time of 493.5ms when the

onset was absent and 524.3ms when it was present [$t(8)=3.32$, $p<.05$], and the lack of an onset

effect in the eye movement condition [$t(8)=0.11$]. Overall RT was marginally faster in this

experiment than in the previous one [404.4 versus 453.6ms, between-subjects $t(16)=1.81$,
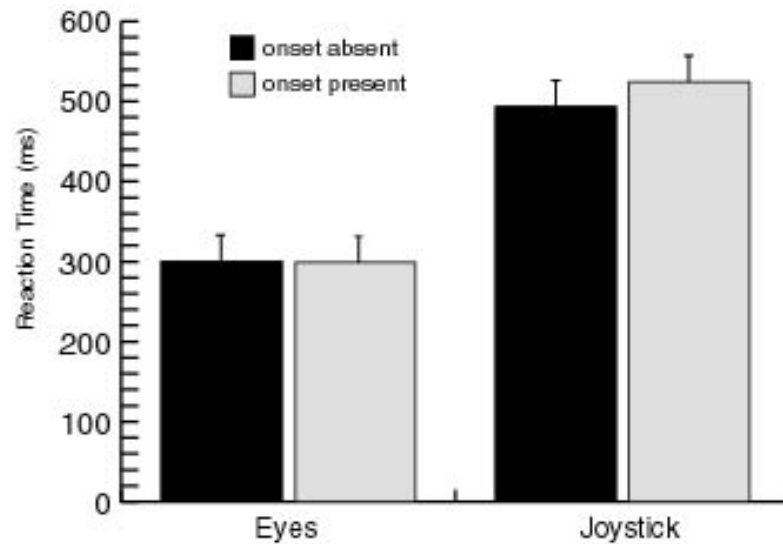
$p=.089$].

**Figure 4. The reaction time to respond to the target in Experiment 2 is shown for both eye movement and joystick responses. There is a significant interaction of the onset effect with response type.**

*Accuracy.* When the proportion of capture in the joystick and eye movement blocks was compared in a paired t-test (after correcting for general error), there was significantly more capture in the eye movement block [t(8)=4.52, p<.01], see Figure 5. For joystick responses, only 3.1% of responses were directed towards the onset, a proportion that was not significantly different from general error [t(8)=0.33] [4]. Relative to the previous experiment, the proportion of responses toward the onset is greater (3.1% versus 2.7%), but general error also increased relative to the previous experiment (15.6% versus 7.9%), resulting in nonsignificant capture. Saccades were directed to the onset on 32.6% of trials in which it was presented, representing a large increase in capture relative to the previous experiment.
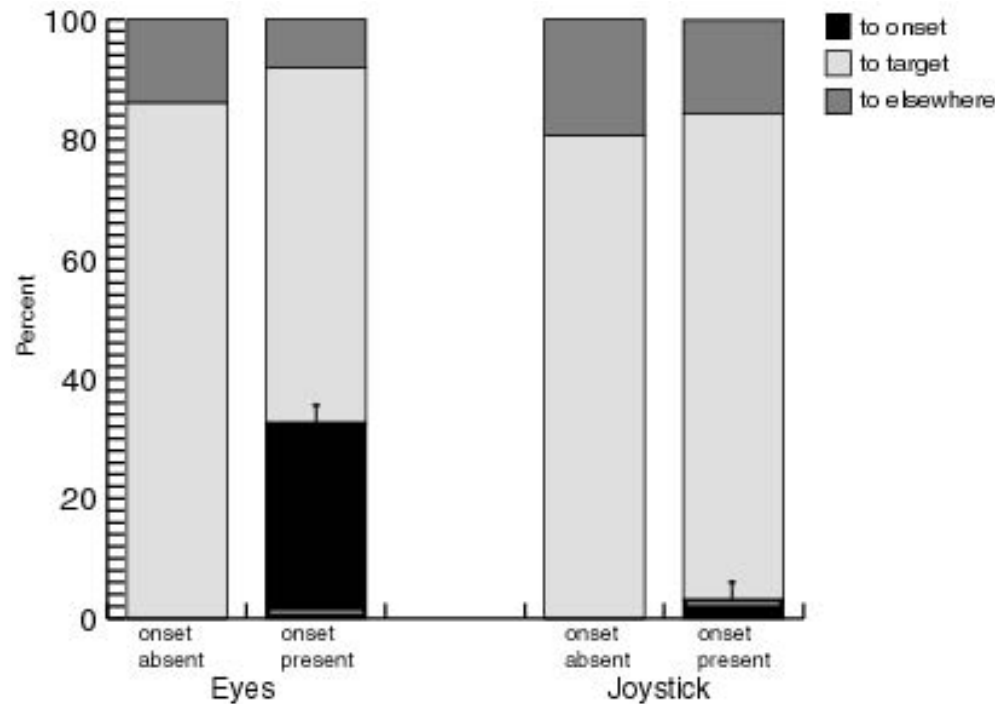
**Figure 5. The proportion of responses directed towards the onset, target, and elsewhere in the display is shown for both eye movement and joystick responses in Experiment 2. The proportion of joystick responses directed toward the onset is not significantly different from the estimate of general error (shown as the white line in the onset present columns).**

Discussion

The results of Experiments 1 and 2 taken together demonstrate a consistent dissociation between eye movement and joystick responses, whereby onsets influence the reaction time but not the accuracy of joystick responses, and onsets influence the accuracy but not the reaction time of eye movements. This observation suggests that capture as measured by joystick responses may indeed be unique from that measured by eye movement responses, in line with the observations of Wu and Remington (2003). Given that reaction time pressure had little effect on this pattern, one might be tempted to conclude that the source of the dissociation between these two response systems lies in a fundamental difference in how attention is influencing eye movements versus manual responses. However, the two types of responses have not yet been

equated for speed, with joystick responses averaging over 200ms slower than eye movement responses, even with the pressure placed on reaction time in Experiment 2. It is still possible that the difference in pattern across the two response types is due to these differences in reaction time. Generally speaking, fast responses tend to be less accurate, with accuracy increasing as responses are withheld for longer periods of time. This basic speed-accuracy trade-off function is an important consideration for any measure of performance, because it demands that reaction time and accuracy both be taken into account when assessing performance differences.

To assess the role of speed-accuracy trade-offs in differences between attentional and oculomotor capture, the effect of reaction time on the proportion of capture was examined. To accomplish this, the data from the onset present trials of Experiments 1 and 2 were divided into quartiles based on reaction time. Quartile ranges were calculated separately for each participant and for each response type. The quartile to which a given trial belonged was then used as a factor in a two-way ANOVA on the proportion of capture (minus general error), with the other factor being response type.

The results are graphically represented according to the mean reaction time for each quartile (see Figure 6).  ANOVAs from both Experiment 1 and Experiment 2 showed a significant effect of quartile and a significant interaction of quartile with response type [all ps<.01]. The source of both of these interactions is clear from Figure 6: there is a large effect of quartile on saccadic reaction time [Experiment 1 $F(3,24)=9.35$, p<.001, Experiment 2 $F(3,24)=17.39$, p<.001], similar to that observed in previous oculomotor capture research (e.g. van Zoest et al., 2004), but there is no effect of quartile on joystick capture [Experiment 1 $F(3,24)<1$; Experiment 2 $F(3,24)=2.27$].

One might once again be tempted to conclude that oculomotor capture and attentional capture are unique, because speed of response has a different effect on capture for the two types

of responses. It is clear from Figure 6, however, that another interpretation is also possible. There

is very little overlap in the reaction time distributions of the manual and saccadic responses.

Indeed, from this graphical representation of the data it is easy to imagine that manual and

saccadic responses share the same function of increasing capture with faster reaction times. That

is, oculomotor and attentional capture are in fact reflections of the same underlying process, but

fall on different points of the same speed-accuracy trade-off function.
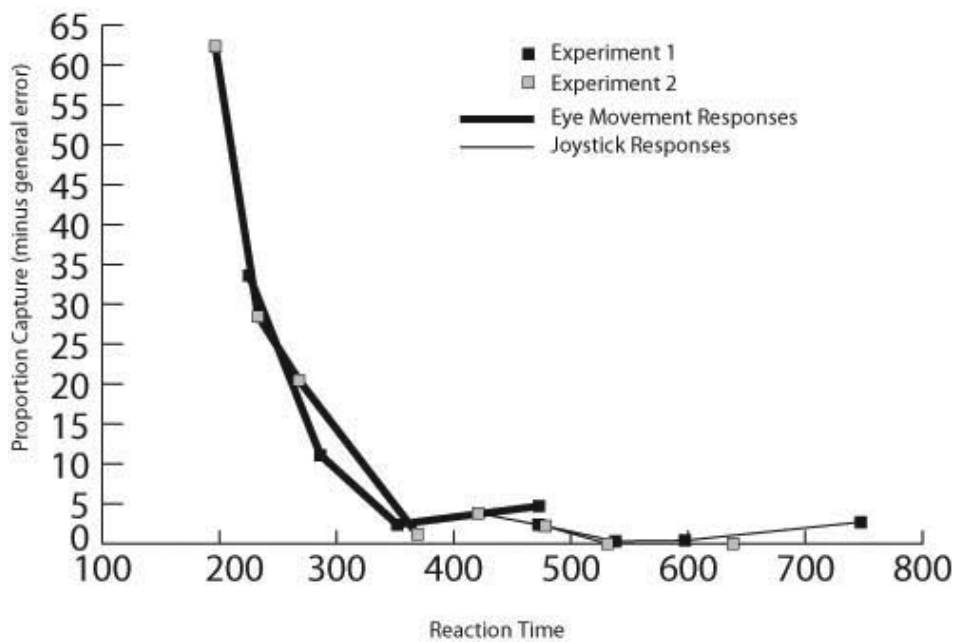


**Figure 6. The proportion of capture in Experiments 1 and 2 is shown as a function of reaction time quartile. Each square on the graph represents the mean reaction time for that quartile and the mean proportion capture for responses in that reaction time range.**

Experiment 3

The goal of Experiment 3 was to bring the reaction time distribution of eye movement

and joystick responses closer together by introducing RT deadlines. That is, participants had to

respond within a certain timeframe or their response would not be recorded and the trial would

be repeated. Faster reaction times are associated with increases in capture among eye movement

responses (e.g. Godijn and Theeuwes, 2002), but it is not known if capture among manual

responses will be influenced by pressure on reaction time to a similar extent. If the difference

between attention and oculomotor capture is due to speed-accuracy trade-offs, then when the

reaction time differences are eliminated, joystick capture should emerge in accuracy instead of

reaction time, and be similar in magnitude to eye movement capture. Alternatively, increasing

reaction time pressure on joystick responses may reduce response accuracy overall, but not

increase the proportion of joystick responses directed toward the onset. This would suggest that

attentional and oculomotor capture are not simply sampling different timepoints of the same

process, but instead measure different underlying processes.


                                                    Methods


*Participants.* Twelve undergraduate students participated in Experiment 3 for course credit.

None had participated in Experiment 1 or 2, and all had normal or corrected-to-normal vision.

*Apparatus, Stimuli, and Procedure.* The methods were the same as the previous experiment, with

the following exceptions. Each participant completed two sets of three blocks of trials. Each set

of three began with a 500ms reaction time deadline in the first block, then a 400ms deadline in

the second block, and a 350ms deadline in the final block. Half the participants completed a set

of three blocks of eye movement trials followed by a set of three blocks of joystick responses,

and the other half completed the sets of three in the opposite order, with 3 blocks of joystick

trials followed by three blocks of eye movement trials. Each block contained at least 96 trials.

As in the previous two experiments, the task was to execute a response in the direction of

the orange circle as quickly as possible. In the eye movement block, participants were instructed

to execute an eye movement from the central fixation crosshair to the target. In the joystick

block, participants moved an 8-way digital joystick in the direction of the target. After each

response, feedback was displayed for 500ms. If the response had been made within the deadline,

the feedback message said either "Wrong" (if the joystick response was incorrect, or in the

saccade block if the saccade landed outside a 45˚ wedge centered around the target), or "Right"

(if the joystick response was correct, or if the saccade landed within the 45˚ wedge around the

target). When the response was correct, the reaction time in milliseconds was also displayed

below the error feedback. If the response was executed after the deadline, the message displayed

was "Too Slow". When the response was too slow, the trial was recycled, that is, it was repeated

at some randomly-selected point later in the block. A limit of 192 was placed on the total number

of trials in a given block[5]. In the interest of making data collection under these very difficult task

conditions easier, eye movements were no longer recorded in the joystick block in this and the

subsequent experiment. Note that this was a reasonable compromise as we did not observe a

consistent relationship between joystick responses and the eye movements that occurred during

the joystick block in Experiment 1 and 2.  Because responses are under time pressure, this

experiment reduces even further the opportunity for eye movements to influence joystick

performance.


Results


*Reaction Time.* Reaction time data were submitted to a 3-way within-subjects ANOVA with

response (eye movement or joystick), reaction time deadline (500, 400, or 350ms) and onset

(present or absent) as factors. The results are shown in Figure 7. There was a main effect of

response [F(1,11)=41.41, p<.001], a main effect of reaction time deadline, with faster reaction

times when the deadline decreased, [F(2,22)=18.16, p<.001], and a main effect of onset

[F(1,11)=11.28, p<.001]. The main effect of onset was actually opposite to previous

experiments, with faster responses when the onset distractor was present than when it was

absent. There was an interaction of reaction time deadline with response type [F(2,22)=9.59,

p<.001], due to a larger effect of reaction time deadline on joystick reaction time than on

saccadic reaction time. There were no other significant interactions.
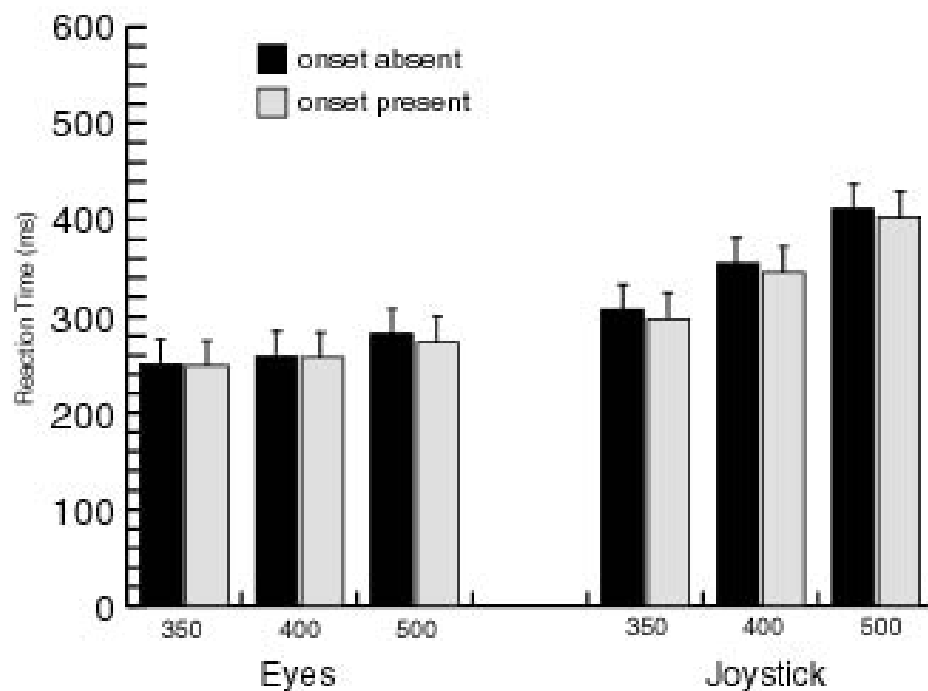


**Figure 7. The reaction time to respond to the target in Experiment 3 is shown for both eye movement and joystick responses. Responses had to be made within a deadline of 500, 400, or 350ms or the trial would time out.**

*Accuracy.* Figure 8 depicts the landing position of the first saccade executed after the target was

presented. When the percent of capture trials (with general errors subtracted) was submitted to a

2-way ANOVA, with response type (eye movement or joystick) and target deadline (500, 400, or

350) as factors, there was only a main effect of reaction time deadline [F(2,22)=5.16, p<.01],

with capture increasing with decreasing reaction time deadline. It is important to note that the effect of response type, [$F(1,11)=1.56$], and the interaction of response type and reaction time deadline [$F(2,22)<1$], were both not significant, suggesting that the pattern of increasing capture with decreasing deadline was similar for both eye movement and joystick responses[6]. The proportion of capture was significantly greater than general error in all three eye movement and joystick conditions [all $ps<.01$].
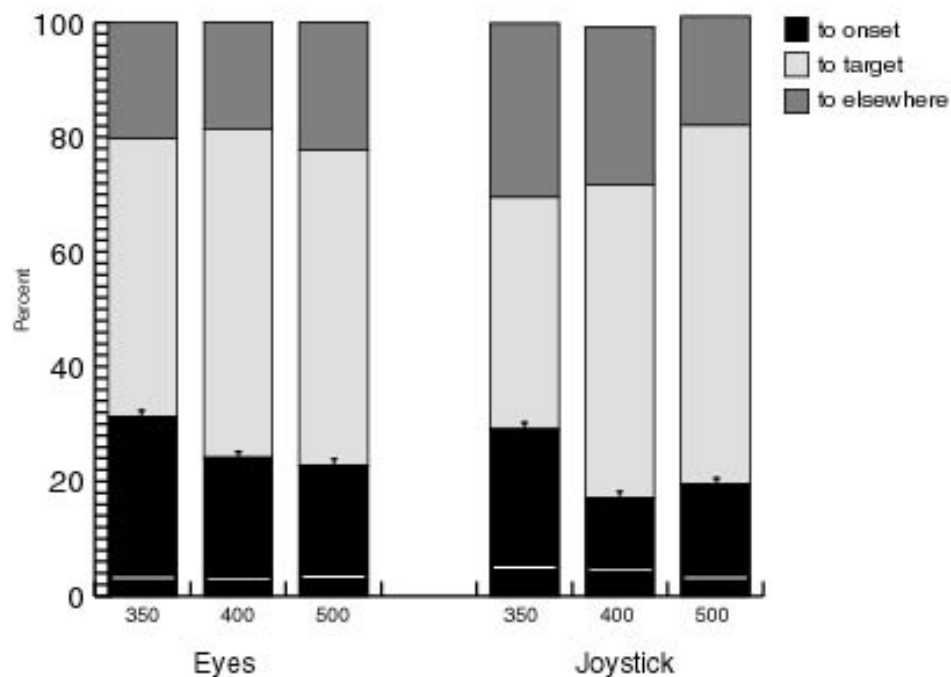


**Figure 8. The proportion of responses directed towards the target, the onset, and to other locations on onset-present trials. Both eye movement and joystick responses had to be made within a deadline of 500, 400, or 350ms.**

Discussion

The results are consistent with the prediction that the differences between eye movement and joystick capture that we observed in Experiments 1 and 2 reflected a greater bias to sacrifice speed for accuracy among saccade responses than among joystick responses. When reaction time differences were reduced by speeding joystick responses in Experiment 3, the effect of capture

on RT was not only abolished, but slightly and significantly reversed (the RT difference between

onset and no-onset conditions was 6.2ms, and there was no interaction with response type).  This

change in the RT effect was accompanied by an increase in the proportion of capture among

joystick responses, to the extent that joystick capture no longer differed significantly from eye

movement capture as it had in Experiments 1 and 2. This result suggests that the direction of

both eye movement and joystick responses is based on the same underlying representation of the

onset and target, and reflect the same locus of attention, when the response is executed within the

same time period following the appearance of the target and the onset. Importantly, this pattern is

not unique to the eye movement system, but is also observed among manual localization

responses.

Experiment 4

A response that is executed very quickly differs in at least two respects from a response

that is executed more slowly. First, when pressured to respond quickly, overt responses might be

poorly prepared, resulting in an increase in errors due to a failure in the accuracy of motor output

to accurately reflect the target location. This explanation for capture is implied in the model

developed by Godijn and Theeuwes (2001), in which information about the target location

converges onto a saccade map within the superior colliculus, where it competes with information

about the onset location.  Top-down inhibition of specific nontarget locations prevents the

automatic capture of sudden onsets by irrelevant but salient visual events, and capture occurs

when a response is executed before this inhibition has been fully instantiated. Second, the total

processing duration of the target at the point when the response is executed is shorter when

responses are executed quickly. The subsequent decrease in the amount of information about the

target location on short reaction time trials could cause an increase in responses to the onset due

to uncertainty about the target location. Experiment 4 examines the effect of target information

by shortening the target duration but no longer pressuring participants to respond within a certain

deadline. This also allows for a simultaneous exploration of the effects of target information (by

examining the effects of target duration) and response time (by examining capture effect in a

reaction time quartile analysis).

Methods

*Participants.* Thirty undergraduate students participants in Experiment 4. None had participated

in the preceding experiments, and all had normal or corrected-to-normal vision.

*Apparatus, Stimuli, and Procedure.* Experiment 4 was similar to Experiment 3, except instead of

manipulating reaction time deadline, target duration was manipulated. Each trial began with four

orange circles around a central fixation crosshair. After 1000ms, the target was revealed when

the distractor circles changed to red. After a set duration, the distractor circles changed back to

orange, making it no longer possible to discriminate the target from the other circles. There were

two groups of subjects: 12 participants completed three blocks for each response type (eye

movement versus joystick responses) with target durations  of 150, 250, and 350ms, in that

order. A second group of 18 participants completed three blocks for each response type with a

target duration of 350, 400, or 500ms, again in that order. The order of response type was

counterbalanced across participants for both groups.

Results

*Reaction time.* The reaction time results from each group were submitted to 3-way ANOVAs,

with response (eye movement or joystick), target duration (short, medium and long) and onset

(present or absent) as within-subjects factors. For the long target duration group, there was a

main effect of response type $[F(1,17)=101.43, p<.001]$, and a main effect of onset

$[F(1,17)=4.82, p<.05]$. There was an interaction of response type and the onset effect

$[F(1,17)=6.82, p<.05]$, which occurred because the onset slowed RT among joystick responses

$[t(17)=2.67, p<.05]$ but not among eye movement responses $[t(17)=0.89]$. In the short target

duration group, there was a main effect of response type $[F(1,11)=122.64, p<.001]$ and target

duration $[F(2,22)=12.95, p<.001]$ and an interaction between them $[F(2,22)=15.15, p<.001]$. This

interaction occurred because reaction time decreased with decreasing target duration among the

joystick responses $[F(2,22)=23.81, p<.001]$ but not among eye movement responses $[F(2,22)<1]$.
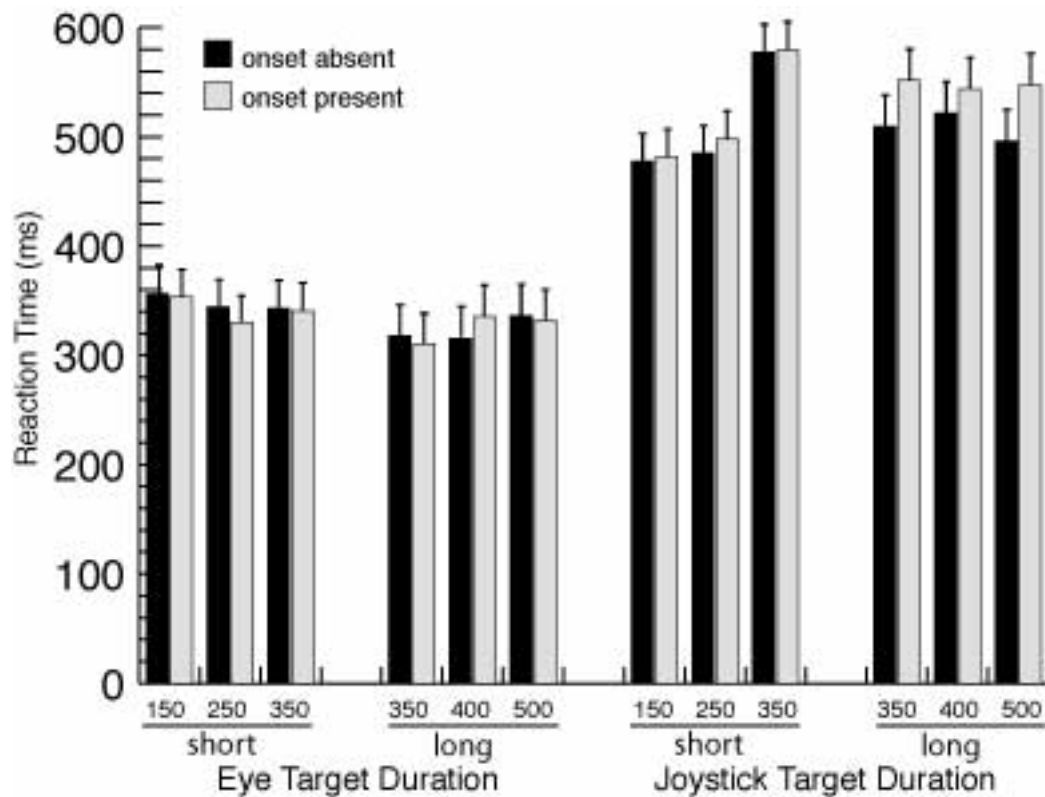
**Figure 9. The reaction time to localize the target in Experiment 4 is shown for both eye movement and joystick responses. The orange color singleton target was revealed for 150ms to 350ms (one group) or for 350 to 500ms (another group), and then the other items would turn orange as well, hiding the target location.**

*Accuracy.* The proportion of first responses directed towards the onset (with general error

subtracted) for each group were submitted to 2-way ANOVAs, with response type (eye

movements or joystick) and target duration (short, medium, and long) as factors.  In the long

target duration group, there was a marginal effect of response type [F(1,17)=4.34, p=.052], with

4.7% more capture among eye movement responses than joystick responses. In the short target

duration group, there were marginal main effects of response type [F(1,11)=3.54, p=.087], and

target duration [F(2,22)=3.39, p=.052]. The effects of response type and target interacted

significantly [F(2,22)=3.42, p=.05], which occurred because there was a significant effect of

target duration among joystick responses [F(2,22)=5.61, p<.05] but not among eye movement

responses [F(2,22)=1.00]. This is evident in Figure 10, in which the short target durations show a

pronounced effect on joystick responses but not on eye movement responses.  When compared

against general error, the proportion of capture in both the long and short target duration groups

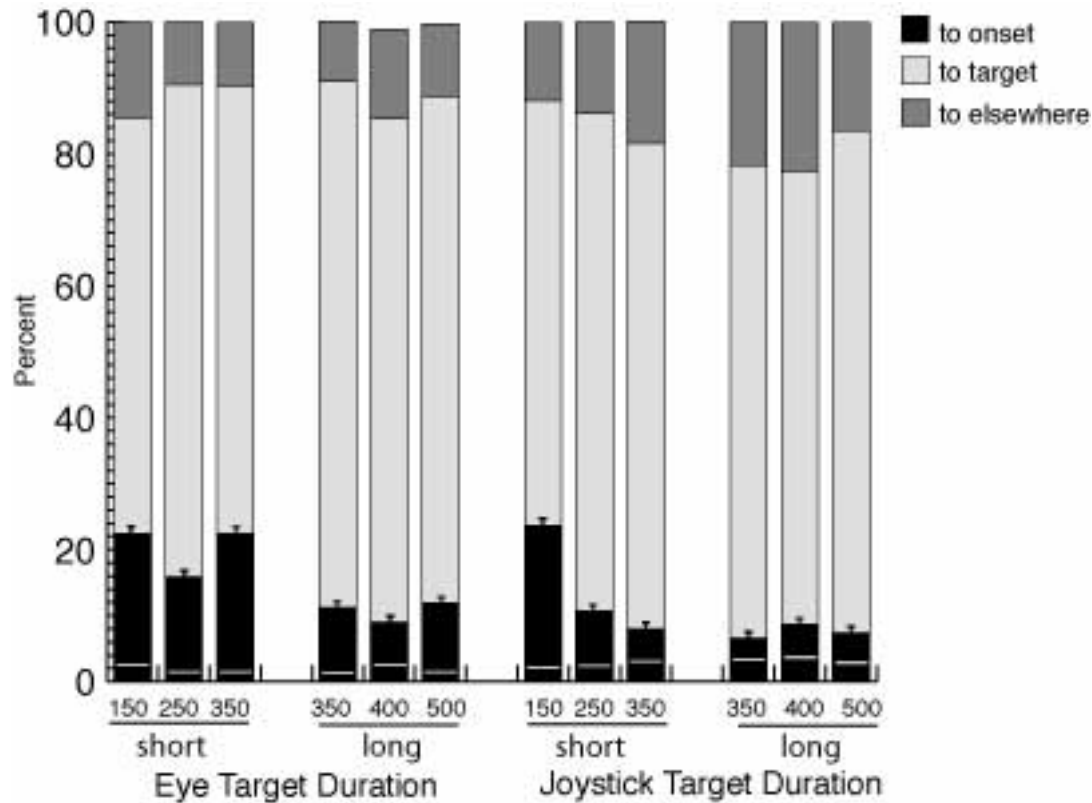were significant for both joystick and eye movement conditions [all ps<.05].



**Figure 10. The proportion of eye movement and joystick responses directed towards the target, the onset, and other locations on onset-present trials. The duration of the target was varied between 150 and 500 ms.**

*Quartile Analysis.* Capture was also examined as a function of reaction time, using the same

procedure as Experiments 1 and 2. The effect of response time and target duration were

examined together in a 3-way ANOVA with response type, target duration, and quartile as

factors. In the long target duration group, there was a main effect of quartile [F(3,51)]=6.30,

p<.001] that was involved in a 2-way interaction with response type [$F_{(3,51)}=3.25$]. This

interaction occurred because there was no effect of quartile in the joystick results

[$F_{(3,54)}=1.26$], but the main effect of quartile was significant among eye movements

[$F_{(3,51)}=6.09$, $p<.01$]. The general trend across all three target durations was that capture was

greater for shorter reaction times (see the dark squares in Figure 11).
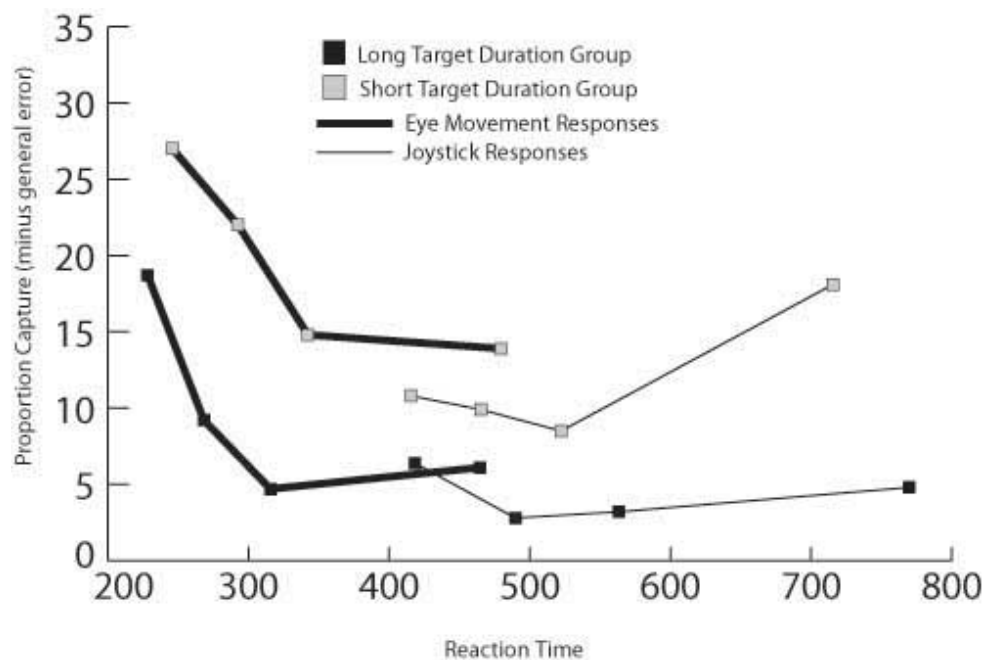


**Figure 11.The proportion of capture for joystick and eye movement responses is shown as a function of quartile and group. In the long target duration group (black squares), targets were presented for 500, 400, or 350ms. In the short target duration group (gray squares), targets were presented for 350, 250, or 150ms. Each square represents both the mean reaction time in that quartile and the proportion of capture (minus an estimate of general error).**

For the short target duration group, like in the long target duration group, there was an

interaction of quartile with response type [$F_{(3,33)}=3.30$, $p<.05$]. This occurred for the opposite

reason, however: There was a significant effect of quartile for joystick responses [$F_{(3,33)}=2.89$,

$p=.05$] but not for eye movement responses [$F_{(3,33)}=2.14$]. The quartile effect in joystick

responses reflects the fact that capture is largest for the slowest response times, which is opposite

to the significant effect of quartile for eye movements in the long target duration group, in which capture was largest for the fastest response times (see the light squares in Figure 11).

## Discussion

The manipulation of target duration in Experiment 4 revealed that capture increases among shorter target durations. This pattern mirrors the increase in capture among shorter reaction times observed in Experiment 3, and suggests that the amount of available information about the target location is a critical factor in whether or not capture will occur. As can be seen from Figure 10, shorter target durations did not systematically increase the number of general errors, but specifically influenced the proportion of responses directed towards the sudden onset. This pattern is also illustrated in Figure 11, with increased capture when the target duration is short (light squares) relative to when the target is presented for a longer period of time (dark squares).

It is also evident from Figure 11 that eye movement capture decreases steeply as reaction time slows. Joystick capture, in contrast, reveals the opposite pattern, with capture increasing as reaction time slows. When plotted together, the proportion of capture for eye movement and joystick responses generates a U-shaped function across reaction times. This pattern can be accommodated by the notion that the total amount of available information about the target location is a critical factor in whether or not capture will occur. Faster responses are captured because information about the target location has not yet had time to accrue, while slower responses are captured because the target location information has decayed significantly. This decay pattern is particularly evident in the short target duration conditions. Consistent with the notion that changes in information over time shape the differences between oculomotor and

attentional capture observed previously, this suggests that the longer a target has been absent from the display by the time a response is executed, the higher the probability that onset capture will occur. An alternative consideration, however, is that these slower responses might represent trials on which the target location was not detected at all, and this uncertainty caused subjects to respond more slowly and direct their responses to the onset location. The more central point for the current investigation is that the different timepoints in the buildup of information sampled by the saccade and manual responses are responsible for the previously-observed differences between these response types.

At shorter target durations, the decrease in capture across reaction times that was observed for eye movements in the longer target duration group is no longer a reliable pattern. This result is also easily interpreted in terms of available information: when the target location information is removed very quickly, there is no longer any benefit to be gained by withholding a response, because no further information about the target location can be gathered during this interval.

General Discussion

The results of the current study suggest that a fruitful approach to understanding capture is in terms of the acquisition of information about the target location over time. As Posner (1978) describes in his seminal work *Chronometric Explorations of Mind*, a fundamental assumption of reaction time studies is that information about the visual environment is accrued over a measurable period of time, and the observer is able to access this information at different points in this accrual process. Thus a response executed soon after a target is displayed is more likely to be inaccurate, and later responses are more likely to be correct. A basic function describing this

speed-accuracy trade-off process is shown in Figure 12. As time passes, the quality of

information increases, until it reaches asymptote and there is no longer any benefit to accuracy
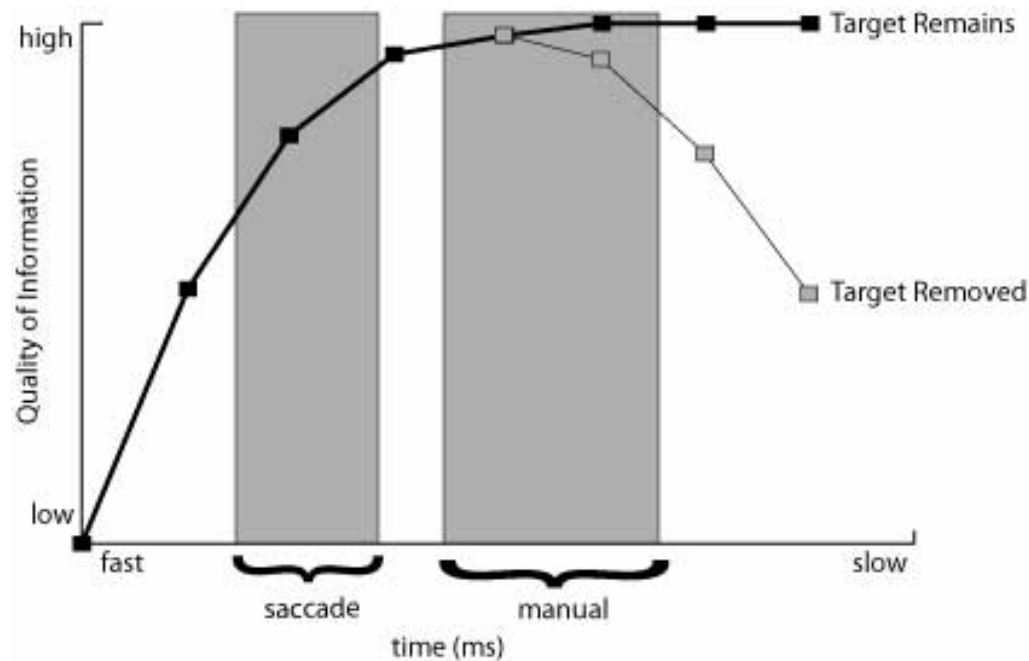
associated with slower reaction times.



**Figure 12. Function describing changes in information over time. As time passes, information about the target location accrues, and then remains at asymptote, unless the target is removed. In most circumstances, saccades tend to be executed earlier in this curve than manual responses (their response time distributions along this curve are represented by the large gray bars).**

Experiments 1 and 2 demonstrated that joystick responses show consistent capture in

latency, and eye movements show consistent capture in accuracy. This pattern replicates the

general state of the literature, where attention capture tends to be measured in manual reaction

time differences, and oculomotor capture tends to be measured in eye movement accuracy. The

gray bars in Figure 12 represent the reaction time distribution of saccadic and manual responses.

Eye movement responses are initiated based on less information about the target location than

manual responses, and as a result tend to be faster but less accurate. Manual responses tend to be

executed at a point in the curve at which there is sufficient information about the target location

that the response is reasonably accurate. The difference between manual and saccadic responses in terms of the curve shown in Figure 12 also illustrate why, in Experiments 1 and 2, eye movement responses showed an effect of response time quartile, and manual responses did not. Saccadic responses are executed at a point when the accrual of information about the target is still taking place, and thus small changes in reaction time will have a large effect on accuracy. Even very fast manual responses are typically executed after asymptote has been reached, and thus slower reaction times do not lead to increases in accuracy. This interpretation is especially evident in Figure 6, in which manual and saccadic capture are plotted as a function of reaction time.

When forced to be executed faster, as they were in Experiment 3 of the present study, the manual response distribution moves leftward on the curve and becomes less accurate, and more similar to saccades. This result demonstrates that both manual and saccadic responses are directed toward the onset when they are executed soon after the target and onset appear, supporting the assertion that both effectors respond based on the same information, but that this information produces different results when it is accessed at different points in time. When the duration of information about the target is manipulated directly, as it was in Experiment 4, an increase in capture under conditions of lower quality of information is observed. At long target durations, eye movements showed more capture in accuracy and joystick responses showed more capture in reaction time, similar to the pattern observed in Experiments 1 and 2. In general, shortening the target duration produced an increase in capture. As illustrated by the dotted line in Figure 12, when the target is removed, the quality of information about its location begins to decay. This produces a U-shaped function of the proportion of capture across reaction time, with higher proportions of capture at very short and very long reaction times, like that observed in

Figure 11 (although, as noted earlier, the data are equivocal as to whether the information was perceived and then decayed, or was never perceived at all).

The current results are relevant to the ongoing debate about the source of performance costs in attentional capture experiments outlined in the introduction. One class of explanations of attentional capture suggest that the more detailed and therefore slower filter needed to detect the target in the presence of a visually-salient distractor is responsible for the cost to reaction time associated with the onset (e.g., Folk and Remington, 1998). The other class of explanations suggest that attention is literally captured by the sudden onset, and that performance is impaired because attention must be re-allocated to the target location before a response can be executed (Theeuwes, 1992). The results from oculomotor capture studies have been used as evidence for the latter explanation for the capture effect, because the eyes presumably follow attention and are therefore captured by the sudden onset (e.g., Theeuwes et al., 1998). Our current findings provide additional support for this hypothesis by demonstrating that once different responses have been equated for reaction time and information accrual, both saccadic and manual responses are literally captured by the sudden onset. The nonspatial filter hypothesis, in contrast, would predict an increase in manual response errors under conditions of reaction time pressure or limited target information, but it would not predict that erroneous responses would be directed toward the onset more than toward other locations. Thus, the observation that manual responses, as well as oculomotor responses, were directed towards the sudden onset, is consistent with the notion that both the eyes and the hand reflect the locus of a central attention mechanism which is captured by the onset. Further support for this interpretation comes from the observation that, as in previous oculomotor capture experiments (e.g., Theeuwes et al., 1998), we observed greater capture when the target and distractor were close together, not just for eye movements (with an

average near-far difference of 7.6% across all the experiments), but also for manual responses

(with an average difference near-far difference of 7.9% across all the experiments). This is also

consistent with the notion that a shared attentional mechanism underlies both types of capture.

This description of capture changing over time as information about the target location

accrues can elaborate existing explanations of oculomotor and attentional capture. For example,

Godijn and Theeuwes (2002) have described a competitive integration model of oculomotor

capture in which the activation associated with the sudden onset competes with the target

activation for control over eye movements in a shared map of the visual field. In their model,

activation associated with the distractor onset builds more rapidly than the target, and in the

absence of sufficient top-down inhibition, activation associated with the distractor will reach

response threshold faster than the target, and saccades to the distractor instead of to the target

will be elicited. This shared activation map is proposed to be housed within the superior

colliculus (e.g., see Trappenberg, Dorris, Munoz, & Klein, 2001), and integrates input from the

retina with other regions associated with eye movement control, such as the frontal eye fields and

the posterior parietal cortex (PPC). The current results are consistent with a competitive

integration model, in that information ("activation") about the target location accrues gradually,

and responses that are elicited early in this accrual process will be directed to the onset distractor.

But the results also suggest that the competitive integration model can be generalized beyond the

eye movement system, given that we observed the same pattern among manual responses. Thus,

our current findings suggest that  there is a more generic map involved in the integration of

signals from the environment and the biasing of certain signals over others in the interest of the

current task demands. The posterior parietal cortex is a good candidate area to support such a

map for at least three reasons. This region has been strongly implicated in spatial attention (e.g.

Corbetta and Shulman, 2002). It also represents information about object locations coded in

gaze-centered coordinates. And finally it plays a role in both eye movement and manual reach

planning (for a review, see Andersen and Buneo, 2002).  Another candidate region for shared

attention and eye movement control is the superior colliculus itself, which appears to play some

role not only in eye movements, but also in covert attention (e.g., Müller, Philiastides and

Newsome, 2005, but also see Sumner, Adamjee and Mollon, 2002) and in arm-reaching

movements (e.g. Stuphorn, Bauswein, and Hoffman, 2000).

A finding that was less central to our primary hypothesis, but is nonetheless interesting,

was the lack of any consistent relationship between the timing and direction of eye movements

and joystick responses occurring within the same trial in Experiments 1 and 2. We found no

increase in joystick capture from Experiment 1 to Experiment 2, even though the eyes were not

only permitted to move in Experiment 2, but were also directed toward the onset location on

13.2% of trials. There is some evidence suggesting that control of hand and eye are yoked to

some degree, but it is not clear that this coupling is obligatory. For example, reaches, like eye

movements, seem to be planned in eye-centered rather than motor coordinates, and these plans

have to therefore be updated whenever the eyes move (e.g., Batista, Buneo, Snyder, and

Anderson, 1999;  Khan, Pisella, Vighetto et al., 2005).  In the current study, manual responses

were not made in the same visual coordinates as eye movements, and ours may therefore

represent a special condition in which they are able to operate more independently than when

performing reaches in visual space. Importantly, although we observed an independence of

saccadic and manual responses at different timepoints in the same trial, we also observed a

similarity in their response patterns once they were equated for time. This further strengthens our

conclusion that both types of responses reflect the same process of dynamic allocation of attention over time.

This conclusion, that manual and eye movement responses seems to reflect the same underlying attentional process, will be welcome news to researchers who have been using oculomotor capture to understand the processes underlying attention (e.g. Irwin, Colcombe, Kramer & Hahn, 2000; Theeuwes et al. 1999; van Zoest, et al., 2004). Eye movements are in fact able to sample a point in the target localization process that can provide information that is usually not provided by manual responses.  This makes them a unique and valuable source of information about spatial selective attention. An important question that remains to be answered, however, is why eye movements tend to be executed based on less information, while manual localization responses tend to be delayed until uncertainty about the target location has been resolved. A plausible, albeit speculative, explanation is that a manual response represents a larger investment of energy than an eye movement, and if the hand has been guided to an irrelevant location, it takes more energy and time to correct it than an eye movement. There is also a large payoff in moving the eyes in terms of information gain, where the higher-acuity fovea allows for more detailed information to be picked up from the fixated location. Valuable information is surely also gained from kinetic and tactile information that manual manipulation provides, but the cost in terms of time and energy is large enough that this system waits until after the accrual of visual information is complete before investing in moving towards a specific target.

The current study is unique in observing that response capture of a categorical and limited manual response is similar to that observed among eye movement responses. This conclusion adds an important caveat to previous work that found that the response type influences attentional capture (Ludwig and Gilchrist, 2002; Wu and Remington, 2003) without

equating manual and saccadic responses in terms of reaction time. We have shown that bringing

the timing of manual and saccadic responses closer together reduces differences in the effect of

sudden onsets on those responses. Another question one might ask is whether bringing manual

and saccadic responses closer together in terms of the coordinates of the response space and the

spatial precision required to localize the target might also eliminate differences between the

types of responses. For example, visually-guided pointing responses in the presence of a sudden

onset might show a similar pattern in the presence of an irrelevant onset as the eye movements.

Our current conclusions predict that they will only be the same so long as they are executed at

roughly the same time relative to target onset, regardless of their spatial similarity, but this

remains to be tested.  An experiment using more continuous manual responses would also be

able to address questions about the nature of on-line error corrections in manual capture tasks,

which the current experiment was not able to address because of the discrete nature of the

joystick response.  We hasten to add, however, that the discrete nature of the joystick response

enabled us to make clear contact with the discrete button press research that makes up the bulk of

the attention capture literature, while the directional component of the joystick response enabled

direct comparison to the eye movement research that has come to define oculomotor capture.

A second important outstanding question is how exactly attention influences the accrual

of information about specific elements or features. This is a fundamental question, and

researchers exploring the effect of attention on basic visual processes have begun providing

important pieces of this puzzle. For instance, attention has been shown to enhance spatial

resolution (Yeshurun and Carrasco, 1998), accelerate visual processing (Carrasco and McElree,

2001), and inhibit the processing of unattended signals (Dosher and Lu, 2000). Experiments

exploring how selective attention influences and combines with basic perceptual processes will

likely also contribute greatly to a more complete understanding of visual search and attentional capture.

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Footnotes

1) For the curious reader, here is a general description of the results we observed in these two excluded conditions, in which the target was an onset. Across all four experiments reported here, when the target was both a color singleton and a sudden onset, responses were faster than to color-singleton only targets, by 30.3ms for saccades and by 17.5ms for manual responses. The effect of the additional sudden onset distractor was much smaller when the target was an onset, with 2.5% capture in the eye movement blocks and 1.8% in the joystick blocks. Reaction time onset distractor effects were also very small. Among eye movements, correct RT was 8.5ms slower in the presence of an onset, and among joystick responses, correct RT was 11.3ms slower. We assume the reduced effect of the onset occurred because the target onset was already such a

salient stimulus, having both a unique color and a sudden onset, that there was no opportunity for any interference from additional distractors.

2) Errors can occur because of poorly-planned responses and inattentiveness, and participants may be more prone to these kinds of errors in some conditions than in others. In the present series of experiments, on trials on which no onset is presented, there is one "correct" response, directed towards the target, and then 7 additional erroneous responses that the participant could make on any given trial. On onset trials, there is one "correct" response, one "capture" response (towards the onset) and then 6 additional erroneous "elsewhere" responses that the participant could make. If there is no tendency for participants to respond in the direction of the onset, one would expect the proportion of capture to be equal to roughly $1/6^{th}$ of the proportion of responses made toward locations that contained neither the target nor the onset.  To compare whether responses towards the onset were greater than this value, the proportion of "elsewhere" responses for each participant in the onset present condition was divided by six, and this value used as an estimate of *general error* for comparison to the proportion of "onset" responses.

3) Eye movements were also recorded in the joystick block. Subjects withheld a saccade for the entire duration of the trial on 65.6% of the trials, and this proportion was not significantly affected by the presence of an onset [t(8)=0.19]. The eyes went to the irrelevant onset on 3.1% of trials, which did not differ significantly from general error of eye movements [t(8)=1.56].When eye movements were executed towards the target, their mean latency was not significantly different from joystick latency (F(1,8)<1).

4) In the joystick block, eye movements were executed on 87.9% of the trials.  Like Experiment 1, there was no significant difference in the latency of saccades in the joystick block versus joystick responses [F(1,8)<1], with eye movements in fact slightly slower (523.4) than joystick

responses (508.9ms). The eye went to the onset on 13.2% of trials, which is significantly

different from chance [t(8)=3.90, p<.01], and significantly greater than the proportion of onset-

directed joystick responses [t(8)=4.89, p<.01]. The latency to move the eyes to the onset on these

trials was also significantly faster than the joystick response latency (325.0 vs. 602.5ms

[t(8)=2.90, p<.05]) suggesting that on these trials the eyes were directed to the onset first, and

then a joystick response to the target usually followed.

5) Six participants reached this limit, with an average of 83 trials completed within the deadline

in the 350ms deadline block (the lowest number of trials completed in this block was 48). It was

for this reason that no quartile analysis is shown for this experiment. The reduction in data for

some participants, especially in the critical 350ms joystick condition, made further division of

data into quartiles unfeasible.

6) It is in some respects surprising that there is a similar effect of reaction time pressure on eye

movement and joystick responses in this experiment. Whereas joystick responses are typically

slower than 500ms, making it difficult for participants to respond within shorter deadlines, eye

movements tend to be faster than 350ms on average, and thus reaction time pressure had little

effect on saccadic reaction time. One might have therefore expected that eye movements would

show similar capture across deadline conditions. In Experiments 1 and 2, RT pressure likewise

had no significant effect on RT for saccades, but there was an increase in the proportion of

capture from 13.7% to 32.6%. Perhaps mean saccadic latency is already so fast that subjects are

unable to respond any faster, but the overall sense of time pressure causes subjects to respond

less carefully.