The Role of Attention in Eye Movement Awareness

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# Abstract

People are unable to accurately report on their own eye movements most of the time. Can this be explained as a lack of attention to the objects we fixate? Here we reproduce the classic oculomotor capture effect, in which people tend to look at sudden onsets even when they are irrelevant. In the first experiment we find that participants are aware of these errors on about a quarter of trials. In the second experiment we aim to assess what differentiates errors that are detected from those that are not. We test both dwell time on the onset distractor, and a measure of how much attention was allocated to the distractor (the extent to which an irrelevant letter inside the onset distractor influences the time taken to discriminate a letter inside the target). Longer dwell times were associated with awareness of the error, but the measure of attention was not. The results suggest both attentional and oculomotor capture can occur in the absence of awareness, and have important implications for our understanding of the relationship between attention, eye movements, and awareness.

# Introduction

The visual world is enriched with far more information than we can possibly process. Both eye movements and attention are involved in the process of selectively sampling information from the visual array for more detailed processing, to the exclusion of other information. The functional similarity between them has led to the intuitively appealing hypothesis that covert attention and eye movements exist on a continuum, with covert attention simply being a sub-threshold eye movement (Klein, 1980; Rizzolati et al., 1987). This hypothesis has been supported by research demonstrating that covert attention tends to be allocated to the location where an eye movement is about to be executed (e.g. Shepherd, Findlay and Hockey, 1986; Hoffman and Subramaniam, 1995; Kowler et al., 1995; Deubel and Schneider, 1996). Based on these studies it was widely believed that it is not possible to move the eyes without also moving attention.

If eye movements necessarily recruit and involve attention, one might expect people’s awareness of their own eye movements to be reasonably high. However, previous research suggests this awareness is extremely limited. We used a converging methods approach and measured eye movement awareness during three tasks: visual search of a complex illustration, naming objects in a photographic image, and moving the eyes to a simple, single target (Clarke, Mahon, Irvine and Hunt, 2017). Based on the results of all three experiments, we reached the conclusion that people have many strategies at their disposal to boost accuracy when asked to report on their own eye movements, but when these strategies are not available, the accuracy of reports is close to chance. This is consistent with previous studies in which alternative strategies were available, which found people to be moderately above chance in their ability to report on their own eye movements (Foulsham and Kingstone, 2013; Marti et al., 2015). It is also consistent with the recent results from Vo, Aizenman & Wolfe (2016), who found people were no better at remembering where they just looked in a scene relative to a baseline of where they think other people would be likely to look.

Earlier research suggested participants are unaware of eye movement errors. Theeuwes and colleagues (1998, 1999) investigated erroneous eye movements executed towards task-irrelevant sudden onsets. Participants were instructed to move their eyes to a single orange circle amongst red circle distractors. On half of the trials, an additional red circle appeared between the existing circles. Eye movements were directed to this sudden onset on 30-40% of trials, even though it was irrelevant to the task. The high prevalence of eye movements to the irrelevant onset, known as *oculomotor capture*, has been replicated many times (e.g., Belopolsky et al. 2008; Born et al. 2011; Godijn and Theeuwes 2002b, 2003; Hunt et al., 2004; Hunt et al. 2007; Wu and Remington 2003). At the end of their experiment, Theeuwes et al. (1998) informally asked participants if the sudden onset affected their eye movement behaviour. Most participants reported being unaware of the abrupt onset, and no participants reported that their eye movements were affected or captured by it. Extending this further, Belopolsky, Kramer and Theeuwes (2008) used a similar task, but after each trial participants were asked if they looked directly at the target. People were able to report errors around two-thirds of the time. Although the results of these two studies are somewhat at odds (i.e. are participants unaware of *all* errors or just some of them?) they do reinforce the conclusion that people have limited awareness of their own eye movements, even when they know that they will be asked to report on them, and even when these movements are large errors that negatively impact their performance.

Abrupt onsets and salient events tend to capture not only our eyes (e.g. Theeuwes et al., 1998, 1999) but also our attention (e.g. Yantis & Jonides, 1984; Jonides & Yantis, 1988; Theeuwes, 1994, 1995, 1999). The oculomotor capture paradigm grew from a previous paradigm developed by Theeuwes (1991a, 1992, 1994), commonly referred to as the “irrelevant singleton” (Yantis & Egeth, 1999) or “additional singleton” paradigm (e.g., Simons, 2000). Similar to the oculomotor design, an irrelevant distractor singleton is shown with a relevant target singleton. To the extent that the distractor has captured the participant’s attention, they should produce slower reaction times towards the target singleton compared to no distractor trials, and this is indeed the case (Theeuwes, 1991; 1992; 1994; 2000; Theeuwes & Godijn, 2001). The conclusion that attention is reflexively drawn to the irrelevant singleton was reinforced by Theeuwes (1996) and Theeuwes, Atchley & Kramer (2000), who both manipulated the congruency of characters presented within the distractor and target singletons. Reaction times to identify the character in the target were slower (by about 20-30ms) when the character inside the distractor was incongruent than when it was congruent, suggesting spatial attention had been allocated to the distractor on at least some of the trials.

Coming back to oculomotor capture, why are participants aware of their eye movement errors on some trials but not others? At least two factors may be important. First, awareness could simply be a function of the dwell time on the distractor: that is, the longer the participant fixates the distractor, the more likely they are to notice/report having fixated it. Increased fixation duration on an erroneously fixated stimulus was related to increases in error awareness in studies by both Mokler and Fischer (1988) and Belopolsky et al (2008). However, in both studies the distributions of dwell times overlaps, with some unreported errors having longer dwell times than reported error dwell times. Moreover, it is not possible to determine the causal direction of this effect: were participants aware they were making an error because they fixated the distractor for longer? Or did participants fixate on the distractor for longer because they were aware they were making an error?

The second potentially important determinant of eye movement error awareness could be attention. It has previously been asserted that attention *necessarily* precedes all eye movements. If this is the case, attention should precede erroneous eye movements to the same extent as goal-directed eye movements. Whether or not the participant reports awareness of the error on a particular trial should have no relationship to the extent to which attention was allocated to the distractor (as measured by congruency effects). However, some studies have suggested eye movements can be executed in the absence of attention (e.g. Stelmach, Campsall and Herdman, 1997; Van der Stigchel and DeVries, 2015). An error might go undetected on trials where the eyes, but not attention, went to the onset. In this case, awareness of an error may be related to the extent to which attention was allocated to the distractor.

We use a variation of the oculomotor paradigm used by Theeuwes et al., 1998 to elicit both oculomotor and attentional capture and measure awareness of that capture. In Experiment 1 we simply asked participants to report, after each trial, whether or not the eye movement they made on that trial was “good”, meaning it went directly from the central fixation to the target. The purpose of this experiment was to confirm we would obtain oculomotor capture in our setup and to estimate the extent to which people are aware of these capture errors. In the second experiment, we repeated the experiment, but now asked participants to make a speeded response to the orientation of the C presented in the colour singleton target. We also presented an irrelevant C inside the onset distractor. To the extent that attention is allocated to the onset distractor, the direction of the C inside the onset should influence responses (accuracy and reaction time) to the C inside the target. We can relate the size of this interference effect, as well as dwell time on the onset, to awareness of the error. If attention is necessarily allocated to a saccade target, we should see a similar interference effect irrespective of whether participants are aware of the error.

# Experiment 1: Oculomotor Capture

Participants in the original oculomotor capture experiment (Theeuwes et al., 1998) were reported to have been unaware of their eyes persistently being misdirected towards irrelevant sudden onsets. This conclusion was based on subjective reports collected from simply asking participants during debriefing if they were aware of their errors during the experiment. Later, Belopolsky, Kramer and Theeuwes (2008) conducted an oculomotor capture experiment in which they asked participants if they looked directly to the target after each trial, and found they were in fact able to report the error on around two thirds of trials, contradicting the original conclusion. However, capture rates were quite low (~16%) compared to the original study (~40%), so it is possible that a rarer capture event is more noticeable. In Experiment 1 we therefore sought to clarify the extent to which participants are aware of their own erroneous saccades.

Given that participants are required to provide binary responses about whether their eye movement was “good”, a simple accuracy measure such as percent correct is not suitable for characterising performance. This is because each individual participant will make a correct eye movement on a different number of trials. Each participant will also have their own particular response bias (e.g. to usually say the eye movement was good). We will therefore present our results using two statistics commonly used in the classification literature: precision and recall. If we are trying to classify "error" saccades from "good" saccades, then the definitions are as follows:

• Accuracy: the proportion of all items successfully classified.

• Precision: the proportion of trials classified as "bad" that did in fact contain saccade errors.

• Recall: the proportion of trials with saccade errors that are accurately classified as “bad”.

We ran a group of naiive participants and attempted to disguise the real purpose of the study by telling the participant that we were asking them to report on their accuracy so that we could remove error trials from the data. However, to determine whether awareness of the purpose of the experiment mattered for performance and awareness, we also tested two of the authors in the same experiment to see if their results would differ from the others. To foreshadow, the authors’ data looked roughly similar to naiive participants’ data both in terms of the proportion of trials on which oculomotor capture occurred, as well as the reported awareness of that capture.

### **Methods**

### *Participants*

Ten naïve participants (5 females, mean age 22.5, range = 19 - 27 years old) took part in the Experiment. Two authors of the current paper also participated. All participants were members of the academic community at the University of Aberdeen. The experiment was conducted with the signed consent of each participant and the protocol was approved by the Psychology Research Ethics Committee at the University of Aberdeen. All participants had normal or corrected-to-normal vision. Naïve participants were remunerated £5 for their time.

### *Stimuli and procedure*

Experimental scripts were created and run using MatLab with the PsychToolBox (cite) and run on a PowerMac 10.8.2. Stimuli were presented on a Sony Trimaster EL computer screen, 1080 x 1920 pixels. Participants’ heads were stabilized in a chin rest at a viewing distance of 57cm. Participant responses were recorded using an Apple keyboard. Eye movements were monitored using an EyeLink 1000 (Ottawa, Canada) in the desktop configuration.

Each trial began with a central fixation point on a blank grey screen. Participants were required to press *spacebar* to complete calibration and to begin the trial. Stimuli consisted of six orange circles (radius 0.9˚) evenly distributed in a (invisible) circle around a central fixation cross, with a radius of 7.2˚ (see Figure 1). After 1000ms, all but one of the circles changed colour from orange to red. The target circle was defined as the one circle that maintained the original orange colour. A discrimination target (DT), presented as a forwards or backwards *c,* appeared inside the target circle. Participants were instructed to look directly and as quickly as possible to the target circle. On half of trials an additional red distracter circle would appear, simultaneously with the colour change, in-between two existing circles (see Figure 1b). The target array was displayed for 800ms.

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| --- | --- |
| Macintosh HD:Users:s09ac3:Documents:EyeMovementAwareness:AttentionalCapture:preview.png | Macintosh HD:Users:s09ac3:Documents:EyeMovementAwareness:AttentionalCapture:stimulus.png |

***Figure 1***: Example of an onset-present trial. Six orange circles are presented in a circular array around a central fixation cross (left panel). After 1000ms, 5 circles change to red, and 1 remains orange (right panel). Participants must saccade to the orange target and report the direction of the C inside. As this is an onset distractor present trial an additional red circle appears at the same time as the colour change.

During the experiment, after each trial participants were asked, via a message displayed on the computer screen, “Was this a good trial?” Participants responded by pressing a ‘y’ for “yes” or ’n’ for “no” on the keyboard. Before the experiment began, participants were told that the experimenters were interested in filtering out trials in which they made eye movement errors. They were instructed that a “yes” response meant that during the previous trial their eyes went from the center of the display directly to the orange circle target, a “no” response meant their eyes did not move *directly* to the target circle. If participants responded “yes”, they were then presented with a second question: to identify if the target *c*, which was presented within the target circle, was facing either forwards or backwards, by typing ‘f’ for forwards or ‘b’ for backwards.

There were six potential target locations and six potential distracter locations, so with three replications, this gave 108 trials. We included an equal number of trials with no sudden onset distracter to give a total of 216 trials.

### **Results**

Each participant correctly identified the C orientation on at least 95% of the trials. Participants were considerably less accurate in identifying the trials in which they made a “good” eye movement. To analyse this, we categorised the distracter trials based on the total path length of the saccades made by the participant during the trial. Path length was normalised so that 1 unit represents the distance from the central fixation cross to the center of the target. We then classed trials in which the total path length was between 1-*a* and 1+*a* as “good” (*a*=0.2 unit). Figure 2 shows the number of trials that were classified as “good” and “bad” for each participant, and within each of these categories the number of trials the participant responded “yes” (good) or “no” (bad). Data from the two authors are presented as *A* and *B.*

../../Documents/AttCapAwareness/Experiments/1_Original%20Experiment/graphs/capturedAndThoughtA.pdf

Figure 2: Proportion of trials in which direct or erroneous eye movements were executed by each participant are shown above. Trials which participants identified as bad (“no”) or good (“yes”) are presented in dark and light blue respectively, inside the data bars.

It is clear from Figure 2 that participants varied a great deal in terms of both their rate of capture and also how aware they were of eye movement errors. What stands out in relation to the question at hand, however, is that participants tended to erroneously report a large number of trials with saccade errors as “good”. To quantify this tendency across participants, we calculated classification accuracy scores (Figure 3). Participants have reasonably good precision scores, that is, around 75% of trials that they reported as not good were indeed trials in which they made a saccadic error. However, median recall is much lower (25%). This tells us that participants are not sensitive to most of the saccadic errors they made during this experiment.

../../Documents/AttCapAwareness/Experiments/1_Original%20Experiment/graphs/f1score.pdf

Figure 3: Classification accuracy scores. Although precision scores are relatively high, recall is low, indicating that many eye movement errors were not detected.

Previous research has suggested that awareness of the onset can either decrease or increase the incidence of capture, depending on the age of the participants (Kramer, Theeuwes, Hahn and Irwin, 2000). Chisholm and Kingstone (2014) also showed that explicitly telling participants to avoid capture can lower the rate of capture. We therefore checked whether or not awareness of capture was related to the rate of capture in individual participants and found no systematic relationship (Figure 4). Being aware of errors does not appear to lead participants to make fewer of them, at least not in our study.

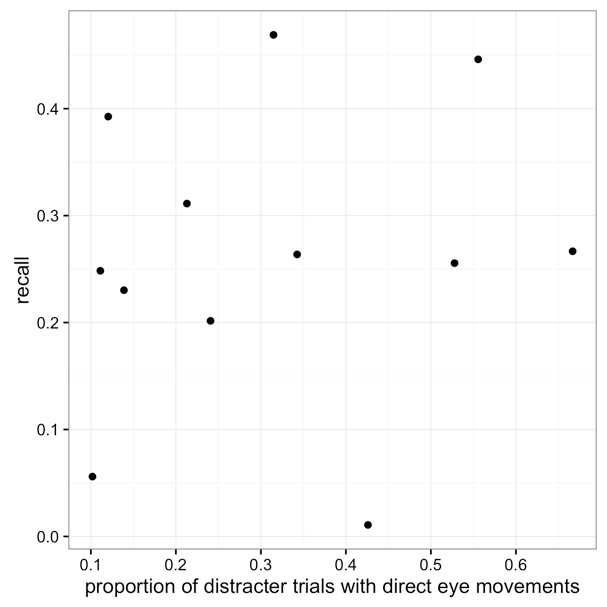


Figure 4: There is no correlation between the tendency to report one’s own errors and eye movement accuracy.

Previous research has found a relationship between dwell time on the erroneously fixated item and reported awareness of the error (Mokler and Fisher, 1999; Belopolsky & Theeuwes, 2012). Here we show the dwell time on the onset distractor on trials on which the error was correctly reported (“thought captured”) and trials on which the participant reported the eye movement was good (“thought direct”). While there is a great deal of overlap between the distributions, longer dwell times tend to occur on trials in which the error was reported.

../../Documents/AttCapAwareness/Experiments/1_Original%20Experiment/graphs/dwellTime.pdf

Figure 5: Dwell time on the distracter

### **Discussion**

In Experiment 1, oculomotor capture occurred on a large number of trials. The majority of these trials were classified as “good” by participants (median participant missed approximately 75%), consistent with the general observation of Theeuwes et al (1998) that participants are unaware of their errors. Interestingly, even the two authors, who were aware of the motivation for the experiment and the phenomenon of oculomotor capture, were largely unaware of when they were and were not captured by the distractor. Consistent with previous findings (Chisholm and Kingstone, 2014), awareness of distractors and foreknowledge about a tendency for eye movement errors appears not to reduce oculomotor capture. It also does not dramatically reduce the under-reporting of eye movement errors seen in naïve participants.

Experiment 2: Attentional Capture

If covert attention and eye movements are dissociable, as some previous research has suggested (e.g. (e.g. Stelmach, Campsall and Herdman, 1997; Van der Stigchel and DeVries, 2015), errors may go unnoticed if the eyes, but not attention, are directed to the onset. To test this hypothesis, we used a paradigm similar to Experiment 1, but introduced a congruent/incongruent C to the target and distractor, as used in Theeuwes (1991). Participants were required to execute saccades directly to a target singleton and report the orientation of the C contained in the target. We expected participants to produce faster reaction times on trials with no onset distractor relative to trials with an onset distractor. On trials with a distractor, we expected participants to also respond slower when the C inside the distractor was incongruent with the target C relative to when they were congruent. As in the previous study, we should see longer dwell times when participants are aware of their errors than when they are unaware, but with a large degree of overlap. We examined the influence of both dwell time on the distractor and reaction time to the target on eye movement error awareness, using distractor interference on reaction time as a measure of the extent to which attention was allocated to the distractor. Dwell time and attention may contribute independently to the likelihood of detecting an eye movement error. Alternatively, their contributions may overlap (e.g., dwell time may increase both error awareness and congruency effects).

The hypotheses and planned analyses for this study were pre-registered on the Open Science Framework (https://osf.io/an8gj/). In the preregistered report at this link, we report the results of a pilot experiment on 16 participants which we ran in order to verify that we would be able to observe congruency effects in our paradigm, and to define, test, and refine the analyses we would apply to the new set of data from 36 participants reported below, which we had not yet seen. The Methods and Results below follow the pre-registered plan.

**Methods**

### *Participants*

Thirty naïve participants (25 females, mean age 20.8, range = 19 - 25 years old) took part in the study. We additionally include data from six undergraduate students who were non-naive (these students also helped in data collection, and are labelled a-f in figures).

*Stimuli and procedure*

The general stimuli and procedure were the same as those used in Experiment 1, with two changes. 1.) On distractor trials an additional *c* was presented within the onset distractor. The C in the distractor faced forwards or backwards (randomly determined) 2.) The order of the questions presented at the end of each trial were swapped, with participants identifying the direction of the *c* presented within the target circle first, without being prompted by an onscreen question. They were told to press the key corresponding to the C direction (left arrow for backward, right arrow for forward) as quickly as possible. If they did not respond within 1500ms, the screen displayed the message “too slow” and the trials ended (and was recycled). Following a successful response to the orientation within the deadline, participants were then asked, via a question presented on the screen, whether they executed a “direct eye movement”. In total the experiment included 577 trials, with half of trials not including a distractor. In distractor trials, the *c* within the distractor was congruent with the discrimination target *c* in the target circle on half of the trials.

*Analysis*

Analyses were primarily carried out using mixed-effect models (lme4 x.xxx library for R vx.xx). 95% confidence intervals on parameter estimates were calculated via parametric bootstrapping using the confint function. All analysis code will be publically released with the data upon publication. Following advice from Barr et al (2013), results are reported from models containing the largest random effects structure that can be support by the data.

*Modifications from the pre-registered plan*

This experiment was pre-registered on the open science framework (link). Relative to our pre-registered plan, we made two modifications:

1. We reduced proportion of no-onset trials from 50% to one third. A total of 465 trials was completed by each participant.
2. To clarify what we were asking participants to report, we changed the question about their eye movements from asking whether the eye movement was “good” to asking whether the eye movement was “direct”. As can be seen by comparing the results below to the pre-registered pilot data, this change did not have any substantial effect on reporting of eye movement errors.

### **Results**

### *CAPTURE RATE AND ERROR AWARENESS*

As in Experiment 1, data presented to illustrate awareness of errors includes all error types (because participants were asked to report whether their eye movement was “direct”, any deviations from that are considered errors). To examine dwell time and attentional capture we selected only those error trials on which the eyes landed on the onset distractor.

Figure 6 shows the number of trials with eye movement errors (using the same criteria as in Experiment 1) and trials with accurate eye movements to the target for each participant. Within each of these categories the number of trials the participant responded “yes” (direct) or “no” (error) is shown.

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**Figure 6.** Proportion of trials in which direct or erroneous eye movements were executed by each participant are shown above. Trials which participants identified as indirect (“no”) or direct (“yes”) are presented in dark and light blue respectively, inside the data bars.

Classification accuracy scores are presented in Figure 7. As in Experiment 1, participants make a large number of eye movement errors. They have reasonably good precision scores, demonstrating that when they think they made an error they are usually correct. But median recall is low, demonstrating that are not aware of most of their errors. When we examined only the error trials where the eyes landed on the onset, the dwell time tended to be slightly longer for those trials on which the errors were reported (Figure 8). In general, these two findings closely mirror the results of Experiment 1, demonstrating the robustness of this pattern despite several modifications to the procedure (the inclusion of a speeded response to the C orientation, the delay in the report of awareness, and the change in wording of the question).

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**Figure 7.** Classification accuracy scores. Although precision scores are relatively high, recall is lower with participants showing a large variation in performance.

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**Figure 8.** Histogram depicting the dwell time on the distractor onset on trials on which the participant fixated the onset and noticed it (i.e. answering “no” to the question of whether it was “good”) vs. not noticing it (“yes”).

### *Manual responses to discriminate the C orientation*

Accuracy to discriminate the C orientation was generally high, with mean accuracies above 89% in all three conditions. Similarly, the average accuracy (over conditions) for each participant was generally high, with all but two achieving an accuracy above 80% (median participant accuracy of 95%, minimum 69%). We verified that the binomial 95% confidence interval around each participant’s accuracy was above 50%.

All further analysis is restricted to only those trials with a correct manual response in which the participant fixated both the distracter and the target (in that order). In Figure 9, we present manual reaction time to verify that the sudden onset distractor does slow manual responses, and to further verify that distractor C orientation influences responses to the target C, with incongruent orientations producing slower responses than congruent orientations.

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**Figure 9: A.** Violin plot depicting the variability of manual reaction time to discriminate the C on individual trial data (curve of violins) as well as variability of participant median RTs (points within each violin). For the congruent and incongruent trials, only trials on which participants fixated the distractor onset are included. Participants are slower when there is a distracter onset present, and slower still when that onset contains a C that is incongruent with the orientation of the target C.

The presence of the congruency effect was confirmed with a linear mixed effects model (with maximal random effects structure). As the distribution of response times is skewed, we verify that the 95% confidence interval for the congruency effect size does not contain zero, but present the results from the model with untransformed variables for ease of interpretation. We find that reaction times for incongruent trials are 25ms (95% confidence interval: 14-36ms) slower than congruent trials. This is in line with previous findings (e.g. Theeuwes, 1991).

### *predicting error awareness from dwell time and manual RT*

We now investigate which factors influence whether participants notice when they made an eye movement error. Specifically we run a generalized linear mixed-effect model with a binomial transform to see what influences the likelihood of participants correctly responding that they made an eye-movement error[[1]](#footnote-1). As predictors, we include the follow features:

* Whether the trial was congruent or incongruent, coded as a dummy (-1, 1) variable.
* *td*:Time spent fixating the distracter (dwell time).
* *t*a: Additional response time, defined as manual RT minus dwell time.

We log transform and scale td and ta so that they have zero mean and a standard deviation of 1. Only a random intercept was included in the model as models containing random slopes did not converge. The results of this model show no evidence that congruency has an effect on whether participants notice that they incorrectly fixated the target. Furthermore, none of the interactions appear to have any effect, and awareness is best explained by a weighted sum of *td* (beta = 0.80, standard error = 0.077) and *t*a (beta=1.01, standard error = 0.085).

### *Are congruency effects still observed when participants are unaware of the error?*

Finally, we investigate whether congruency effect is modulated by awareness, factoring out any effects of dwell time on the distractor. Specifically, we test whether the effect of congruency on *t*a (response time – dwell time)[[2]](#footnote-2) is modulated by whether participants were aware of their error or not. We fit a linear mixed-effect model with congruency and awareness as predictors, with random effects of awareness and random intercepts over observers. The model finds that *t*a is 38ms (95% confidence interval: 26-60ms) slower for incongruent trials (very similar to the response time congruency effect established above). As we would expect given the logistic regression above, *t*a is slower in trials in which the observers noticed that they had made an error (103ms, 76-128ms). However, there was no evidence that the congruency effect was modulated by awareness, as the effect size was -4ms, which is close to zero, with a 95% confidence interval of -34ms to 15ms. This result establishes that the size of the congruency effect is roughly equivalent whether or not participants were aware of having looked at the distractor.

**DISCUSSION**

We aimed to address two key questions. First: to what extent are observers able to detect the occurrence of large eye movement errors (Experiment 1)? While there is a relatively large amount of variability across individuals, we find that the majority of people are unable to report the majority of their eye movement errors. Nonetheless, when participants do report having made an error, they are usually correct, suggesting they are sensitive to the occurrence of some errors, but not others. Following directly from this conclusion is our second question: What determines whether an eye movement error is detected or missed (Experiment 2)? We specifically tested the role of two factors: the duration of the fixation on the erroneously fixated object, and how much attention was allocated to that object, as measured by the size of the congruency effect. Fixation duration was associated with awareness of the error, but there was no association between congruency effects and eye movement awareness.

We based our experiment on previous research from Theeuwes (1991) and Theeuwes and colleagues (1998) and successfully replicated both their attentional capture and oculomotor capture effects, demonstrating that both attention and the eyes were captured by the sudden onset on a substantial proportion of trials. An interesting question that has yet to be clearly addressed is whether or not these two phenomena of attentional and oculomotor capture are one and the same, or if attention and the eyes are both independently attracted to sudden onsets. Hunt, von Mühlenen and Kingstone (2007) demonstrated that manual responses and saccades are captured by a sudden onset to a similar extent as long as they are matched in terms of response time (that is, if manual responses are performed under extreme time pressure, to make them as fast as a typical saccadic response). This suggests a central mechanism operates across multiple effectors to drive responses towards the onset. On the other hand, it is not yet clear that this central mechanism is attention. If shifts of attention *cause* capture of the eyes and other response systems, it should not be possible to observe oculomotor capture in the absence of attentional capture. If we had observed congruency effects in Experiment 2 that were reduced or absent on trials where participants were unaware that they made an eye movement to the distractor, this would have been clear evidence that attentional and oculomotor capture are dissociable phenomena, and by extension, that attention and eye movements are dissociable as well. However, we found that congruency effects are of a similar size, whether or not participants are aware that they looked at the distractor. This result does not rule out the possibility that attention and oculomotor capture are dissociable phenomena, but it is consistent with the generally well-accepted assertion that eye movements and attention tend to shift together, and provides support for the notion that a common priority map drives both attentional selection and eye movement control (e.g. Bisley and Goldberg, 2010).

Theeuwes and colleagues (1998) reported that participants were unaware that their eyes were captured by the onset, while Belopolsky and Theeuwes (2008) found that participants could report about two thirds of their capture errors. In our experiment, participants were able to accurately report about 25% of their eye movement errors, and this average was relatively consistent across the two experiments, despite several substantial differences between the experiments, including the addition of the speeded manual response, and the wording of the question about the error (i.e., whether it was a “good” or a “direct” eye movement). There was a wide variation of results across individuals in our sample, however, which could account for some of the disparity with previous findings. The existence of this individual variation reinforces the importance of obtaining relatively large samples and conveying variability in as much detail as possible when reporting and illustrating results, as we have done here. We can conclude from our results that most of our participants are capable of accurately reporting at least some of their eye movement errors. This could be taken as evidence that we have direct awareness of our own eye movements at least some of the time. However, as we argued in our previous study (Clarke et al., 2017), there are many alternative strategies available to participants that can lead to above-chance performance at reporting on their own eye movements. For example, in our previous study, we showed that participants use their memory of the existence of specific objects in a scene to indirectly infer which objects they fixated. Although the distractor objects in the current study were all circles of the same size and colour, the unique onset was a salient signal, and participants could still indirectly infer that they looked at the onset on trial on which they remember it having occurred. Consistent with this interpretation, having looked at the onset distractor for a longer duration was associated with being able to report the eye movement error (see also Mokler and Fisher, 1988; Belopolsky et al., 2008). However, the direction of the relationship between fixation duration and awareness remains to be determined: that is, do participants look at the object for a longer period of time because they are consciously aware of it? Or are they aware of the object because they looked at it for a longer period of time? Our fixation durations varied widely (see Figures 5 and 8), and this is not an exceptional finding; most studies show a similar degree of variation. A recent paper explored the temporal dynamics of saccade execution and could detect no overarching rhythmicity, and concluded a self-paced mechanism constrained by a post-saccade refractory period could best explain variations in fixation durations during periods of free viewing (Amit, Abelas, Bar-Gad & Yuval, Greenberg, 2017). In their model, a period of inhibition followed each saccade, sampled from a Gaussian distribution, and was followed by a “rebound” period of elevated saccade probability. We have shown that the fixations on the upper end of the distribution of fixation durations are more likely to be reported, but there is still a great deal of overlap between the duration distributions of aware and unaware trials left to explain.

When we isolated only those trials where the eyes went to the onset distractor first and then to the colour singleton target, we observed slower responses to report the orientation of the C inside the colour singleton when the C inside the onset distractor was incongruent relative to congruent. It is important to note that although the congruency effect was relatively small, we pre-registered the experiment on the open science framework, and the planned analysis we conducted was based on a separate set of pilot data from 16 participants (the data from the pilot can be viewed in full in the pre-registered document here [link]). This pilot study’s pattern of results was very close to the current results, with small but significant congruency effects. Our key question was whether eye movements might sometimes be executed in the absence of attention, which would lead to both smaller (or absent) congruency effects as well as a generally lack of awareness of the error. Our logic was that there may be two subsets of trials on which a capture error occurred: on some capture trials attention was allocated to the distractor, leading to large congruence effects and a reportable error, and on other trials attention was not allocated to the distractor, leading to smaller or absent congruence effects and reports of a “direct” eye movement. However, awareness did not mediate the magnitude of the congruency effect. While this is a null result, we observed no hint of an effect across both our pilot experiment (N=16) and the current pre-registered version (N=36), suggesting it is unlikely to be due to a lack of power.

It is interesting that the impact of a distractor on subsequent processing is similar in magnitude whether or not participants are aware that they looked at that distractor. These findings are broadly consistent with assertions that attention and awareness are dissociable (e.g., Block, 2007, 2011; Cohen & Dennett, 2011; Koch, 2004; Koch & Tsuchiya, 2007; Kentridge, 2001; Koivisto et al., 2009; Lamme, 2003, 2010; Tononi & Koch, 2008). In our studies, we infer that attention was allocated to the distractor in general, on the basis of the small but significant mean difference in reaction time between congruent and incongruent trials. Our results are, therefore, clear evidence for the existence of attention effects in the absence of awareness: the effect of the distractor on reaction time was still present, even when there was no awareness that it had been fixated. As such, our experiment joins a broad range of experimental paradigms demonstrating attention in the absence of awareness, including visual masking (e.g., Kiefer & Martens, 2010; Naccache et al., 2002; Shin et al., 2009; Van den Bussche et al., 2010), crowding (e.g., Faivre & Kouider, 2011; Montaser et al., 2005), continuous flash suppression (e.g., Jiang et al., 2006; Hsieh et al., 2011) and sub-threshold presentations (e.g., Bauer et al., 2009). While the above research makes a clear case that attention can be allocated without awareness, claims of awareness without attention are more controversial (e.g., Li et al., 2002; Mack & Rock, 1998; Koch & Tsuchiya, 2007). Cohen and colleagues (2012) argue against such a “double-dissociation”, instead proposing that attention is necessary, but not sufficient, for awareness. They suggest that awareness will follow if a requisite amount of attention is allocated to an object. If this account is correct, it is puzzling that variations in reported awareness in our experiment were not associated with variations in our measure of attention. One would expect that if more attention increases the likelihood that a stimulus or event will be consciously perceived, there would be larger attentional effects associated with reported, as opposed to unreported, events. While we find no evidence that this is the case, both our measure of attention and our self-report method of determining awareness may be influenced in different ways by random trial-by-trial fluctuations in alertness or motor readiness in such a way as to mask their relationship. Our results, in showing that modulations in awareness are not accompanied by changes in measureable allocation of attention, are therefore an intriguing piece of evidence that awareness does not depend on attention, but further research establishing a similar pattern would be a welcome development for better understanding the relationship between awareness and attention.

**CONCLUSION**

Participants looked at a sudden-onset distractor on a large proportion of trials, and they were unaware of the majority of these eye movement errors. Longer fixations on the distractor were associated with a modestly elevated probability that the error would be reported, but there is a great deal of overlap between the distributions of reported and unreported error fixation durations that remains unexplained. Our measure of attention allocation to the distractor showed no difference between reported and unreported errors. The results suggest attention effects do not depend on awareness, and leave open the question of what determines whether an eye movement error will be detected or not.

# References

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1. Remember that we have already filtered the data to only include trials in which the observers fixated the distracter and then the target. [↑](#footnote-ref-1)
2. There was 1 data point (out of 3896) with a negative value for *ta*. This was removed from the analysis. After removing this point, the smallest value for *ta* was 128ms. [↑](#footnote-ref-2)