The Importance of Attention in the Twinkle Goes Effect

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Abstract

How do we perceive the location of moving objects? The position and motion literature is currently divided. Predictive accounts of object tracking propose that the position of moving objects is anticipated ahead of sensory signals, whilst non-predictive accounts claim that an anticipatory mechanism is not necessary. A novel illusion called the *twinkle goes effect*, describing a forward shift in the perceived final location of a moving object in the presence of dynamic noise, presents a novel opportunity to disambiguate these accounts. Across three experiments, we compared the predictions of predictive and non-predictive theories of object tracking by combining the twinkle goes paradigm with a multiple object tracking task. Specifically, we tested whether the size of the twinkle goes illusion would be smaller with greater attentional load (as entailed by the non-predictive, tracking continuation theory) or whether it would not be affected by attentional load (as entailed by predictive extrapolation theory). Our results failed to align with either of these theories of object localisation and tracking. Instead, we found evidence that the twinkle goes effect may be *stronger* with greater attentional load. We discuss whether this result may be a consequence of an essential, but previously unexplored relationship between the twinkle goes effect and representational momentum. In addition, this study was the first to reveal critical individual differences in the experience of the twinkle goes effect, and in the mislocalisation of moving objects. Together, our results continue to demonstrate the complexity of position and motion perception.

Keywords: twinkle goes effect, position and motion, predictive extrapolation, tracking continuation, attention, multiple object tracking

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Glossary

Theory/Term	Definition
Backward displacement	Describes an object localisation error <i>behind</i> the object's final location, relative to the object's final direction vector.
Extrapolation	Describes a prediction about the future location of a moving object which forms the basis of that object's perceived location. Thought to compensate for neural delays between retinal stimulation and visual cortex activation.
Forward displacement	Describes an object localisation error <i>ahead</i> of the object's final location, relative to the object's final direction vector.
Lag	Synonymous with <i>backward displacement</i> .
Offset transient	Abrupt change in luminance caused by the sudden disappearance of a moving object.
Predictive extrapolation theory	The perceived location of a predictably moving object is based on a prediction about that object's future position. Does not implicate any role for attention.
Tracking continuation theory	Non-predictive theory of object tracking developed alongside the discovery of the twinkle goes effect. States that when offset transients are disguised, attentional object tracking continues, producing a percept of continued movement to a location beyond the true disappearance position. Thought to be attention dependent.
Transient correction hypothesis	Extension of predictive extrapolation theory. Entails that predictions are 'deleted' when contradicted by later visual information, thus bringing perception to the true location of object disappearance.

Note. These terms will also be defined in the introduction.

The Importance of Attention in the Twinkle Goes Effect

How do drivers navigate traffic? How are cricketers capable of catching fast moving balls? For a plethora of behaviours, humans rely on their visual systems to signal the position of objects in their environment. Remarkably, the visual system has evolved to perform this function in a dynamic world, where environmental stimuli are continually moving relative to our eyes. Despite the critical importance of object localisation and tracking, the mechanisms underlying this key visual process remain mysterious.

Theories of Single Object Tracking

Whilst impressive, our ability to track moving objects is fallible. Visual motion illusions demonstrate discrepancies between the perceived and physical locations of moving objects (e.g., Fröhlich, 1923; Freyd & Fink, 1984). Such illusions inform us about the spatial and temporal information used to track moving stimuli and have laid the foundation for theories of object tracking. Such theories diverge into two broad categories: predictive and non-predictive accounts. The debate between these approaches is largely unresolved.

Predictive (Anticipatory) Extrapolation Account of Object Tracking

Predictive extrapolation theory (Nijhawan, 1994) stipulates that the position of a predictably moving object is anticipated ahead of the location signalled by the retina, to compensate for the 80-100ms delay between retinal stimulation and visual cortex activation (De Valois & De Valois, 1991). This theory was proposed to explain the flash-lag effect (FLE), a visual phenomenon where a flashed static stimulus is perceived behind a moving stimulus, despite the two being presented in alignment ([Figure 1A](#)). Congruent with predictive extrapolation theory, the discrepancy between perceived locations of flashed and moving objects equates to approximately 70-90ms of object movement (Nijhawan, 1994; Linares et al., 2009).

Predictive extrapolation provides a potential explanation of the FLE, but the theory is less equipped to account for other findings in the position and motion literature. In particular, the FLE is not observed when objects cease to move or disappear at the time of the flash (flash-terminated condition; see Figure 1B), or reverse direction following the flash (Eagleman & Sejnowski, 2000; Whitney & Murakami, 1998). These effects implicate an important role for post-flash object movement, yet predictive extrapolation explains the FLE solely using pre-flash events.

Figure 1

The Flash-Lag Effect and Flash-Terminated Condition

Note. **A.** Schematic of the flash-lag effect (FLE). In the basic FLE experiment, a moving object is perceived ahead of a flashed object, despite the two being presented in alignment. **B.** When the moving object ceases to move (or disappears) at the time of the flash, the FLE is not observed.

Non-Predictive Accounts of Object Tracking

The results which contradicted predictive extrapolation theory were foundational to *non-predictive* accounts of object tracking (Eagleman & Sejnowski, 2000; Brenner & Smeets, 2000). Non-predictive theories of object tracking commonly propose that the perceived

position of a moving object at the time of an internal trigger (e.g., a purposeful decision to sample the location of an object) or external trigger (e.g., a flash) is a product of object location after that trigger. Thus, these theories clearly predict that the FLE should be affected by events after the flash, such as object disappearance or object reversal. These theories are also attractive since they can be explained as natural consequences of known visual mechanisms, such as discrete processing of sensory information (Schneider, 2018), without relying on additional predictive processes.

An Updated Predictive Account: The Transient Correction Hypothesis

Nijhawan's (1994) original predictive extrapolation proposal was incapable of explaining the lack of FLE in flash-terminated and object reversal conditions. In response, Nijhawan (2002) proposed the *transient correction hypothesis*. According to this hypothesis, when visual input contradicts previous predictions, this engages a correction-for-extrapolation mechanism. Namely, in the FLE paradigm, when objects stop moving or reverse directions, it is thought that post-flash visual information corrects for the prior prediction, disguising the typically observed FLE (Maus & Nijhawan, 2006). To further illustrate this corrective mechanism, Nijhawan (2002; 2008) discussed in detail the variation of the flash-terminated experiment where objects disappear simultaneously with the occurrence of the flash. It was proposed that the abrupt change in luminance caused by the offset of the moving object (known as an *offset transient*) deletes the prior prediction at a low level of visual processing (Nijhawan, 2002; 2008).

The transient correction hypothesis is essential to predictive extrapolation theory, yet the evidence for this phenomenon is tenuous. Maus and Nijhawan (2006) demonstrated that fading (i.e., decreasing in luminance contrast) moving objects were perceived as disappearing 175ms ahead of their physical disappearance point. This finding was taken as evidence for extrapolation in the absence of offset transients, but the study failed to account for the

sensory uncertainty associated with fading low-luminance objects. Specifically, participants may have reported perceiving the object ahead of the physical disappearance point due to being unsure whether the object was still faintly present. In another study, Maus and Nijhawan (2008) found that moving objects which disappeared just inside the retinal blind spot were perceived as disappearing at a point further within the blind spot. The authors considered this finding to be evidence for extrapolation in the absence of offset transients, since there could be no visual signal from within the blind spot. However, this study failed to account for the well-researched phenomenon of ‘filling in’, where *static* visual stimulation adjacent to the blind spot can create a percept within the blind spot (e.g., Spillman et al., 2006), without need for motion prediction.

The debate between predictive and non-predictive theories of object tracking remains unresolved. The limited evidence for the transient correction hypothesis and the simplicity of non-predictive accounts have left some sceptical of the need for prediction in object tracking (Schneider, 2018). Others still believe that predictive extrapolation offers the best explanation of object tracking (Hogendoorn, 2020), especially given its alignment with popular brain-wide theories of prediction (e.g., Rao & Ballard, 1999; Friston, 2010).

A Novel Method for Investigating Extrapolation: The ‘Twinkle Goes’ Illusion

With the object tracking literature divided, a new illusion from Nakayama and Holcombe (2020) presents an exciting opportunity to test the implications of predictive and non-predictive theories of object tracking. Originally demonstrated through an alignment judgement task, the *twinkle goes* effect (Figure 2A; Supplementary Movie 1) describes a shift in the perceived location of a moving object in the direction of motion, when dynamic noise is present at the time of disappearance. This illusion appears to be caused by the concealment of offset transients by dynamic noise. Thus, the *twinkle goes* effect could be interpreted as evidence for the transient correction hypothesis. However, the authors instead implicated a

non-predictive process, where attentional tracking continues beyond the point of object disappearance when there is no offset transient, creating the percept of continued movement. According to their *tracking continuation theory*, the twinkle goes effect is dependent on attentional resources (necessary for attentional tracking to occur), and thus should be reduced with greater attentional load. Conversely, predictive extrapolation theory does not implicate attention in the forward displacement caused by extrapolation, presenting a testable difference between these two accounts. In an initial attempt to consider the role of attention, Nakayama and Holcombe (2020) provided evidence that the twinkle goes effect is smaller when individuals perform an alignment task while attending to four objects compared to two (Figure 2B). However, this experiment used rotational motion, despite the greater attentional constraints for rotational compared to linear motion (Thornton & Gilden, 2001; 2007). In addition, it is unclear whether the visual system would be as good at predicting rotational motion as linear motion, an important consideration for both predictive extrapolation and tracking continuation theories. Thus, it is unknown how attentional load would influence the magnitude of the twinkle goes effect in a linear motion task.

Figure 2*The Twinkle Goes Illusion*

Note. **A.** The original demonstration of the twinkle goes effect. In an alignment judgment task, objects that disappear in alignment with the vertical meridian are perceived as overshooting this point. **B.** When performing an alignment task while tracking four objects (thus increasing attentional load) the size of the twinkle goes effect is reduced compared to when tracking two objects. Adapted from “Hallucination of moving objects revealed by a dynamic noise background” by R. Nakayama and A. O. Holcombe, 2020 (<https://www.biorxiv.org/content/10.1101/2020.08.21.262170v1>). Adapted with permission.

Multiple Object Tracking as a Method of Manipulating Attention

Multiple object tracking (MOT; Pylyshyn & Storm, 1988) is a useful paradigm for manipulating attention during object tracking, and critically, involves linear rather than rotational motion. The basic MOT paradigm requires participants to track a subset of moving objects (‘targets’) among other identical objects (‘distractors’), and identify which objects were targets at the end of the trial. Attentional load is assumed to be manipulated through the number of targets participants must track (Meyerhoff et al., 2017).

Testing for Extrapolation in MOT

Several studies have tested for predictive extrapolation with increasing attentional load using MOT, but none have accounted for the implications of the transient correction hypothesis. Keane and Pylyshyn (2006) first considered whether extrapolation occurred during MOT with the target recovery paradigm. This variation of the classic MOT task had objects disappear and reappear at random points during each trial. It was suggested that if extrapolation was to occur, observers should be most accurate when disappearing targets reappeared at an extrapolated position (i.e., 80-100ms further along their trajectory). Contrary to this proposal, accuracy was predicted solely by the distance between disappearance and reappearance locations (i.e., smaller distance, higher accuracy), a finding which has been replicated several times (Horowitz et al., 2006; Fencsik et al., 2007; Franconeri et al., 2012). This result was used by these studies to suggest that extrapolation does not occur when tracking multiple objects. Critically, however, the sudden disappearances of moving objects were also associated with offset transients. Thus, according to the transient correction hypothesis, extrapolation should have been corrected for by these transient signals. Predictive extrapolation theory therefore expects that performance should be best at the disappearance location, as was found in the experimental results. As such, without accounting for offset transients, the target recovery paradigm employed by these studies was incapable of testing for predictive extrapolation.

The target recovery paradigm also relies on target identification as an indirect measure of the relationship between real and perceived locations of moving objects. To measure this relationship directly, Howard and Holcombe (2008) designed a MOT experiment where all objects disappeared at the end of each trial and participants reported the final location of targets. However, the authors identified that observers would rely more on their working memory when reporting the locations of multiple targets. This introduced the

potential influence of representational momentum, a phenomenon where the disappearance location of a moving object is shifted forward after a delay between object disappearance and responding (Freyd & Fink, 1984). Representational momentum would thus be particularly evident when there were more targets, since it would take longer to respond, independent of the effect of attentional load. To avoid this confound, the authors divided the display into ‘cages’, with one object per cage, so that the final location of a single target could be queried at the end of a trial, independent of the number of targets cued at the beginning of the trial (see [Figure 3A](#)). Using this methodology, Howard and Holcombe (2008) demonstrated that reported final target locations ‘lagged’ behind physical final locations, in the last direction of target movement. In addition, lag was greater with more targets. This result was used to suggest that predictive extrapolation does not occur in MOT. Instead, it was posited that with increasing attentional load, the perception of moving object location lags further behind the object’s physical location. Variations of this experiment have been inconsistent in their replications of this finding (Iordanescu et al., 2009; Howard et al., 2011), but crucially, none of these studies have considered how the presence of offset transients (resulting from object disappearance at the end of each trial) may have influenced their results.

Rationale for the Current Study

This study aimed to shed light on a fundamental question of visual perception; how do we perceive the location of moving objects? Specifically, we aimed to understand whether the relationship between real and perceived locations of moving objects differed according to attentional load when accounting for offset transients in a linear motion task. To test this, we employed a MOT task and considered how manipulations of attentional load (i.e., number of targets observers tracked) affected the magnitude of the twinkle goes effect. Our methodology allowed for a novel comparison between predictive extrapolation and tracking continuation theories. Specifically, we tested whether increased attentional load reduces the

size of the twinkle goes illusion (as predicted by tracking continuation theory), or whether increased attentional load has no effect on the size of the illusion (as predicted by predictive extrapolation theory). Additionally, we considered whether overall forward displacement occurs when disguising offset transients, an implication of predictive extrapolation theory.

Finally, this study considered all effects at the individual-level, providing novel insight into the individual differences associated with object localisation and tracking. This approach also allowed us to consider how individuals differ in their experience of the twinkle goes effect, further characterising this novel illusion. In sum, the aims of this study were to:

1. *Compare predictive extrapolation theory and tracking continuation theory, primarily by considering how attentional load affects the magnitude of the twinkle goes effect.*
2. *Examine how individuals differ in object localisation and tracking, especially with regards to the twinkle goes effect.*

For reference to the key theories and terms mentioned in this introduction, see the [glossary](#).

Experiment 1

Experiment 1 considered whether the twinkle goes effect could occur in a MOT task, and whether it was dependent on attentional load. As in previous studies, a method of querying the location of a single target was necessary. The current study implemented a cage design similar to Howard and Holcombe's (2008), but with only four cages, and two objects per cage ([Figure 3B](#)). Using a maximum of one target per cage, it was possible to query the location of a single target by indicating the cage it was in. The larger cages also increased the minimum area participants had to attend, a critique of the original cage design (Iordanescu et al., 2009).

Another consideration for the current experiment was the quantification of localisation errors. First, we considered absolute error between the real final location of the target and the clicked location of the target, calculated as Euclidean distance ([Figure 4A](#)).

This measure allowed us to compare accuracy across participants and conditions and confirm that our target number manipulation influenced participants' localisation ability. In addition, we used the 'distance from the finish line' measure implemented by Howard et al. (2011), referring to the magnitude and direction of displacement purely on the axis of final movement (Figure 4B). This measure allowed us to consider our key theoretical variable of interest: forward/backward displacement.

Figure 3

Schematics of Cage Designs for Cuing a Single Target Following Multiple Object Tracking

Note. Circles with 'T' represent targets. Arrows represent object movement. **A.** Original cage design used by Howard and Holcombe (2008) with one object per cage. **B.** Refined cage design used in Experiment 1. Four cages, two objects per cage. Maximum of one target per cage. Single target is queried by indicating its cage.

The statistical approach used in this experiment was also of theoretical importance. To consider individual differences in object localisation, we used a repeated *N*-of-1 design. This approach involved testing participants on enough trials to understand the pattern of results at the individual level (Smith & Little, 2018). One consequence of the repeated *N*-of-1 approach was that many trials were required to gain a sufficiently reliable representation of participants' patterns of results (1000 trials for this experiment). Thus, every additional comparison would reduce our ability to see potential effects. Based on extensive piloting, it

was therefore decided to only have one and four target conditions, manipulating attention to the largest extent possible.

Figure 4

Measures of Localisation Errors

Note. Red circle represents real final target location. Blue circle represents selected final target location. Arrow represents last direction of movement. Text within square represents a possible result using the measure. **A.** Absolute error measured the Euclidean distance between physical and selected locations (in degrees of visual angle). **B.** Distance from the finish line measured how far ahead or behind the clicked location was from the physical location, with respect to the target's final direction (measured in degrees).

Hypotheses

Hypotheses for Experiment 1 differed between predictive extrapolation and tracking continuation theories. Both predictive extrapolation theory and tracking continuation theory entail that the twinkle goes effect should apply to MOT. That is, objects should be localised further along their trajectory when offset transients are disguised by a dynamic noise background, compared to when the background remains static. However, tracking continuation theory predicts the effect should be smaller when tracking four targets compared to one, since attentional load is increased. Predictive extrapolation theory does not predict a

difference between the one target and four target conditions. These theories also make different predictions about net distance from the finish line. Predictive extrapolation theory and the transient correction hypothesis entail that offset transients in the static background condition should direct perception accurately to the final target location (i.e., no net lag or extrapolation). Localisation in the dynamic background condition is predicted to be ahead of the static background condition, and thus ahead of the final object location (i.e., distance from the finish line greater than zero). Whilst tracking continuation theory does not make specific predictions about net forward/backward displacement, the attentional mechanisms described by this theory are coherent with the broader role of attention posited by Howard and Holcombe (2008). As such, this theory is consistent with lag in the static background condition, with greater lag for more targets. Tracking continuation theory does not, however, make a specific prediction about net displacement in the dynamic noise condition, except that it should be ahead of the static condition. These hypotheses are summarised graphically in [Figure 5](#).

This study was also the first to investigate the twinkle goes effect at differing eccentricities. As such, we also conducted exploratory analysis considering the effect of eccentricity on forward/backward displacement, considered at the level of the individual. We were particularly interested in whether the twinkle goes effect, like other position and motion illusions (e.g., the FLE; Linares et al., 2009), was stronger in the periphery than in the fovea.

Figure 5

Differing Hypotheses for Experiment 1 According to Tracking Continuation Theory and Predictive Extrapolation Theory.

	Tracking Continuation Theory	Predictive Extrapolation Theory
Final Target Location
Final Direction of Movement
1 Target Condition Localisation
4 Target Condition Localisation
Summary	<p>Forward displacement caused by disguising offset with dynamic noise <i>should be reduced with 4 (compared to 1) targets.</i></p> <p>Localisation in the static noise condition will lag final target location. Lag should be bigger for 4 target condition.</p>	<p>Forward displacement caused by disguising offset with dynamic noise <i>should not depend on number of targets.</i></p> <p>Localisation in the static noise condition should be accurate.</p>
*Additional Consideration	Tracking continuation theory predicts greater <i>relative</i> forward displacement for the dynamic compared to static background condition. Absolute displacement for the dynamic condition may be negative (i.e., lag behind final object location).	

Note. See [Figure 8](#) for a summary of Experiment 1 results displayed in this same format.

Method

Experiment 1 was preregistered [here](#). See [Supplementary Movie 2](#) for a demonstration of six representative Experiment 1 trials.

Participants

Five observers (1 female) participated in Experiment 1, all of whom were aware of the study's aims. Due to restrictions arising from the Sydney lock-down, it was difficult to recruit completely naïve observers. For all experiments, non-collaborator participants were

compensated at the rate of 20AUD/hr. Participants for all experiments had normal or corrected-to-normal vision and provided written consent. Experiments were approved by the University of Sydney Human Research Ethics committee.

Apparatus

In all experiments, images were displayed on participants' personal monitors, all of which had refresh rates of 60Hz. Each participant was advised to sit at a specific viewing distance (ranging between 45 and 60cm) depending on their monitor width and resolution so that one pixel occupied approximately .024 degrees of visual angle.

Stimuli

A computer programme written in Python using the PsychoPy package (Peirce et al., 2019) was used to present stimuli. Throughout all trials, one horizontal and one vertical line (14 pixels wide) were presented, passing through the centre of the display. These lines created four rectangular 'cages' that limited object movement. Eight red circular objects (28 pixel radius) were presented, two per cage, and moved around their cages at 400 pix/s (~9.7 deg/s). Red was used to reduce the likelihood participants would confuse the dynamic background for object movement.

Object trajectories were generated using custom R code (available [here](#)). Participants were given slightly different trajectories depending on the width of their monitor, such that objects would 'bounce' when they reached the edge of the screen. Trajectories were created such that objects would bounce off each other and off cage boundaries according to the law of perfect elastic collision. In addition, objects randomly changed direction every 1 to 1.5 seconds to reduce the predictability of their movement. Objects would move for a random interval between 1.2 and 3 seconds. Trajectories were also constrained such that targets did not change direction in the last 400ms.

A red fixation cross (50 pixel height and width) was present in the centre of the screen, superimposed over cage borders. Behind all stimuli, a static noise background was presented during the target identification and movement phases, composed of 4 x 4 pixel (0.1 x 0.1 deg) squares, with greyscale values chosen from a random uniform distribution between the minimum and maximum values of the monitor. Following the movement phase, all moving objects and the fixation cross disappeared. In the dynamic background condition, the greyscale values for each 4 x 4 pixel square were updated each movie frame (60Hz), while in the static background condition these values remained constant. Simultaneously to object disappearance, one cage was queried by a hollow green rectangle (14 pixels thick) superimposed over relevant cage borders. The mouse cursor was only presented when participants were selecting final object location. Since the cursor was not clearly visible against noise backgrounds, it was indicated by a transparent blue circle (28 pixel radius), centred on the mouse pointer.

Procedure

Participants completed 8 practice trials and 1000 test trials. Participants were given an optional break every 100 test trials. Each trial, participants viewed the stimulus display and fixated on the central cross. All eight objects and cage borders were superimposed over a static noise background. Target stimuli (1 or 4 objects) were cued by ‘blinking’ - alternating between their original size and twice their original size repetitively. Cuing occurred for 1 second per trial, after which time the movement phase commenced (see “Stimuli” section above). After the movement phase, one cage was queried, and on 50% of trials the background became dynamic noise. Participants then used the mouse to click the perceived final location of the target in that cage. Trials with 1 and 4 targets were randomly interleaved within the experiment.

Exclusion Criteria

Trials were excluded after analysing absolute error, but prior to analysing distance from the finish line, based on preregistered criteria: if participants made a localisation error greater than 200 pixels in Euclidean distance, or if participants clicked in the wrong quadrant before the correct quadrant. Number of excluded trials per participant for all experiments is presented in Appendix A.

Data Visualisation and Analyses

Data visualisation and analyses were conducted using R version 4.1.0 with libraries including tidyverse (Wickham et al., 2019).

Using the repeated-*N*-of-1 approach (Smith & Little, 2018), no between-subjects statistics were conducted. In addition, it was decided that the limitations of significance tests and *p*-values outweighed their usefulness (Amrhein et al., 2019), and so were not used in our interpretations (significance tests are nevertheless reported for reference in Appendix D). Instead, as is commonplace in perception research (e.g., Murai & Murakami, 2016), we interpreted the pattern of results for individual participants using plots of means and 95% confidence intervals. Specifically, we used confidence intervals to interpret the effect (or absence of effect) our results were most compatible with (as recommended by Amrhein et al., 2019).

Results and Discussion

Absolute Error

As seen in [Figure 6](#), average absolute error (i.e., accuracy) differed greatly between participants. More importantly, participants also differed in their patterns of accuracy between conditions. P2, P3, and P4 appeared to be less accurate in the dynamic background condition than the static background condition, while P1 showed the reverse effect. P5 did not show a consistent effect of background condition. Intriguingly, several participants

reported having more difficulty localising the target when there were four targets compared to one, yet this result was not supported by the data.

Distance from the Finish Line

Results on the distance from the finish line measure are depicted in [Figure 7](#). For P2, P4, and P5, targets were localised further along their final trajectory when the background was dynamic compared to static (averaged across number of targets). This result is indicative of the twinkle goes effect. Interestingly, there was no evidence of such an effect in P1 and P4. These results suggest important differences in the experience of the twinkle goes effect between individuals, beyond the expected inter-individual variance associated with most perceptual phenomena. Neither tracking continuation theory nor predictive extrapolation theory entail that the twinkle goes effect should only occur for some individuals.

[Figure 8](#) presents a summary of distance from the finish line results in the same format as the graphical hypotheses of [Figure 5](#). As evident in a comparison of these two figures, neither predictive extrapolation nor tracking continuation theory explain the full pattern of results for any participant. Despite the predicted role of attention posited by tracking continuation theory, there was no clear relationship between background type and number of targets for any participant. Whilst this absence of effect was implied by predictive extrapolation theory, a predictive account cannot explain the lag evident in all conditions for all participants (except P2 when the background was dynamic). Specifically, the transient correction hypothesis predicts no forward or backward displacement in the static condition and predicts extrapolation in the dynamic condition.

Effect of Eccentricity on Displacement: Exploratory Analysis

The relationship between eccentricity and distance from the finish line, divided into static and dynamic background conditions, is plotted in [Figure 9A](#). In all participants, lag was greater with increasing distance from the fovea. Contrary to expectations, this effect was

independent of background condition, suggesting that the magnitude of the twinkle goes effect is not dependent on eccentricity. This differs from other position and motion illusions (e.g., the FLE; Linares et al., 2009) that are stronger when presented in the periphery. In addition, there was no interaction between number of targets and eccentricity on lag.

The unexpected relationship between eccentricity and lag necessitated further investigation. Specifically, using the same data, we considered whether this effect depended on whether at the end of the trial the target headed towards, or away from, the centre of the screen, operationalised as ‘speed to fovea’ (the magnitude of the component of the final velocity vector directed towards the centre, where negative values correspond to movement away from the fovea). We used this measure to investigate the potential influence of a phenomenon called apparent motion (e.g., Kolers & Eysenck, 1972). Apparent motion refers to an illusory percept of movement between two static stimuli presented in rapid succession. It is possible that participants experienced apparent motion between the target and the mouse highlight that was presented at the centre of the screen, immediately following object disappearance. If this was the case, we would expect that the perceived final location of the target would be biased towards the centre of the screen, resulting in greater lag when the target was moving away from the centre, and decreased lag when moving towards the centre. Importantly, apparent motion is more evident at closer proximities to the fovea (Barfield et al., 1990), so it was also possible that the effect of eccentricity on lag was dependent on speed to fovea. As seen in [Figure 9B](#), the results we obtained were exactly the opposite of these predictions. For all participants except P5, it appeared there was greater lag when objects moved *towards* the centre. In addition, greater lag with increasing eccentricity was strongest for objects moving towards the centre.

Figure 6

Plots of Mean Absolute Error by Participant, Background Condition, and Number of Targets for Experiment 1.

Note. Error bars represent 95% confidence intervals.

Figure 7

Plots of Mean Distance from the Finish Line by Participant, Background Condition, and Number of Targets for Experiment 1.

Note. Error bars represent 95% confidence intervals. Positive values indicate forward displacement, negative values indicate lag.

Figure 8

Graphical Depiction of Experiment 1 Results by Participant, for Comparison with Graphical Hypotheses.

	P1, P3	P4, P5	P2
Final Target Location
Final Direction of Movement
1 Target Condition Localisation
4 Target Condition Localisation
Summary	No twinkle goes effect. No effect of number of targets. Lag in all conditions.	Twinkle goes effect apparent. No effect of number of targets. Lag in all conditions.	Twinkle goes effect apparent. No effect of number of targets. Lag in static noise condition, but not in dynamic noise condition (no forward/backward displacement).

Note. Results for individual participants represent a generalisation of actual results. This depiction can be compared to the predictions made by predictive extrapolation theory and tracking continuation theory in [Figure 5](#).

Figure 9

Plots of the Relationship Between Eccentricity and Distance from the Finish Line by Background (A) and Speed to Fovea (B) for Experiment 1.

Note. Since participants had differing monitor widths, ranges of possible eccentricities differed. In A, trend lines represent lines of best fit for static and dynamic conditions. In B, speed to fovea refers to the rate of which the target was approaching the centre of the screen, based on in its final direction. The blue trend line is the line of best fit independent of speed to fovea.

Experiment 2a

The absence of twinkle goes effect in two out of five participants in Experiment 1 was not predicted by either predictive extrapolation or tracking continuation theory, nor was it suggested by the prior empirical research of Nakayama and Holcombe (2020). From the perspective of tracking continuation theory, it is possible that this task was too attentionally demanding for a twinkle goes effect to occur in all participants, even in the one target condition. Specifically, the presence of distractor objects and frequent direction changes may have increased attentional load beyond Nakayama and Holcombe's (2020) original experiments.

To address this, Experiment 2a (Figure 10) considered whether a simplified MOT paradigm would reveal a more consistent twinkle goes effect. Specifically, we reduced the number of on-screen objects from eight to four (with up to two targets) and number of cages from four to two. With only four objects, there were less distractors, and with only two cages, objects had more space to travel without bouncing, and thus would change direction less often. If the twinkle goes effect could consistently occur in a MOT task, it was thought this reduction in attentional load should reveal it.

In Experiment 2a there was also an opportunity to investigate the effect of separating targets into upper/lower or left/right visual hemifields. Previous research by Alvarez and Cavanagh (2005) suggests that we have independent tracking resources for left and right visual hemifields. As such, it should be less demanding to track two targets separated into left and right hemifields than upper and lower hemifields. Tracking continuation theory thus entails there should be an interaction between the magnitude of twinkle goes effect and orientation of hemifield division, in addition to the effect of number of targets alone.

Experiment 2a was also poised to continue probing the relationship between lag, eccentricity, and speed to fovea. Whilst the results of Experiment 1 did not align with the

occurrence of apparent motion, we nevertheless reduced the potential for this effect to occur by delaying the appearance of the blue mouse highlight until after participants began to move the mouse, for completeness.

Figure 10

Experiment 2a Design.

Note. Experiment 2a involved presenting 4 objects on screen with a maximum of 2 targets. The screen was divided into either upper/lower or left/right visual hemifields, with a maximum of 1 target per half.

Method

The method of Experiment 2a was preregistered [here](#) and was the same as Experiment 1, except as detailed below. See [Supplementary Movie 3](#) for a demonstration of six representative Experiment 2a trials.

Participants

Four observers (0 female) participated in Experiment 2a, three of whom were aware of the study's aims.

Stimuli

For Experiment 2, the screen was divided into two cages. On 50% of trials a horizontal line divided the screen into upper and lower visual hemifields, and on the other 50% of trials a vertical line divided the screen into left and right visual hemifields. Two objects were presented in each half of the screen for every trial. Either one or two targets

were cued each trial, with a maximum of one per cage. Number of targets, and background at disappearance (static or dynamic) were randomly interleaved among trials. The width of the green box used to indicate the target cage was increased to 25 pixels in width (compared to 14 pixels in Experiment 1), since it was less noticeable with the larger cage size. In Experiment 2a, all participants received the same trajectories but in different orders. This meant that eccentricities were the same between participants, regardless of monitor width.

Procedure

Participants completed 8 practice trials and 1000 test trials and were given an optional break every 100 trials.

Data Analysis

As in Experiment 1, interpretations were made using graphs of means and confidence intervals, but supplementary significance tests can be found in Appendix E.

Results and Discussion

Absolute Error

Overall accuracy in Experiment 2a is plotted in [Figure 11](#). Contrary to the mixed findings of Experiment 1, all participants showed greater accuracy in the static condition than the dynamic condition, regardless of number of targets. Like Experiment 1, there was no difference in average error between one and two target conditions. In addition, there was no difference in accuracy between upper/lower and left/right divided visual hemifields, despite the previous findings of Alvarez & Cavanagh (2005).

Distance from the Finish Line

As depicted in [Figure 12](#), for P1, P2, and P4, targets were localised further along their final trajectory when the background was dynamic compared to static, specifically when there were two targets. Only P4 showed evidence for such an effect in the one target condition. These results stand in direct opposition to tracking continuation theory, which

entails a *smaller* twinkle goes effect when there are more targets. In addition, this result is the opposite of Nakayama and Holcombe's (2020) finding of a larger twinkle goes effect when performing an alignment judgement task while attending to two objects, compared to four. Even in P3, who showed no clear twinkle goes effect for either one or two targets, the interaction between background condition and number of objects was in the same direction. Importantly, this effect was also not entailed by predictive extrapolation theory. Additionally, there was no consistent effect of hemifield division (left/right vs. upper/lower) on distance from the finish line.

A final interesting result from this measure was the between-participant variation in net forward/backward displacement. While most participants showed some evidence of lag (mirroring the results of Experiment 1), P2 showed strong evidence of forward displacement in all conditions. This result emphasises that object localisation and tracking may differ substantially between individuals.

Effect of Eccentricity and Speed to Fovea

As in Experiment 1, eccentricity was a strong predictor of increased lag in P1, P3, and P4 (Figure 13A), independent of background condition. In these three participants, lag also appeared to be greater when objects moved towards the fovea. Moreover, the relationship between eccentricity and lag appeared to depend on speed to fovea, such that with increasing eccentricity there was more lag specifically when objects moved towards the screen's centre (Figure 13B). Interestingly, these effects were not evident in P2.

Figure 11

Plots of Mean Absolute Error by Participant, Hemifield Division, Background Condition, and Number of Targets for Experiment 2a.

Note. Error bars represent 95% confidence intervals.

Figure 12

Plots of Mean Distance from the Finish Line by Participant, Hemifield Division, Background Condition, and Number of Targets for Experiment 2a.

Note. Error bars represent 95% confidence intervals. Positive values indicate forward displacement, negative values indicate lag.

Figure 13

Plots of the Relationship Between Eccentricity and Distance from the Finish Line by Background (A) and Speed to Fovea (B) for Experiment 2a.

Note. In A, trend lines represent lines of best fit for static and dynamic conditions. In B, speed to fovea refers to the rate of which the target was approaching the centre of the screen, based on in its final direction. The blue trend line is the line of best fit independent of speed to fovea.

Experiment 2b

The results of Experiment 2a challenged the predictions of tracking continuation theory, and to an extent, predictive extrapolation theory. Strikingly, these results also contrast with previous empirical evidence from Nakayama and Holcombe (2020) that the magnitude of the twinkle goes effect is reduced when attending to four objects, compared to two, in an alignment judgement task. It is feasible that the results of Experiment 2a were due to random variation, or due to the specific characteristics of the sample. These possibilities deserved particular attention given the absence of *a priori* theoretical and empirical predictions of such a result. Experiment 2b was conducted as a necessary replication of Experiment 2a, with a new sample of naïve observers. This experiment aimed to improve conclusions about the generalisability of Experiment 2a's findings to the population, whilst also continuing to be informative about differences in the occurrence of the twinkle goes effect between individuals.

Method

Experiment 2b was an exact replication of Experiment 2a and was preregistered [here](#).

Participants

4 observers (2 female, 0 collaborators) participated in Experiment 2b, none of whom were aware of the study's aims.

Data Analysis

As in Experiments 1 and 2a, interpretations were made using graphs of means and confidence intervals, but supplementary significance tests can be found in Appendix F.

Results and Discussion

Absolute Error

Overall accuracy in Experiment 2b is plotted in [Figure 14](#). P1 and P2 appeared to be more accurate in the static condition than the dynamic condition. P3 and P4, however, did not

show any strong difference between the two background conditions. Again, there did not appear to be a difference in average error between one and two targets, or between upper/lower and left/right divided visual hemifields.

Distance from the Finish Line

The primary purpose of Experiment 2b was to see if a larger twinkle goes effect occurred for the two-target condition than for the one-target condition. As evident in [Figure 15](#), this effect is compatible with the results of P4, and potentially for P3, but is not evident in P1 or P2. Importantly though, only P1 showed an effect in the *opposite* direction, such that there was a greater twinkle goes effect in the one-target condition. Considering these results in conjunction with those from Experiment 2a, it appears that for at least some individuals, the twinkle goes effect is greater when tracking two targets than tracking one (using this paradigm). However, the opposite effect in P1 suggests this result may not occur for everyone.

These results also provide additional evidence that net forward/backward displacement differs substantially between individuals. Specifically, P2 showed evidence of forward displacement in all conditions, while P4 showed evidence of lag in all conditions, and P1/P3 did not show evidence of overall lag or forward displacement.

Finally, the orientation of hemifield division (upper/lower vs. left/right) had no consistent effect on distance from the finish line.

Effect of Eccentricity

The effect of eccentricity in Experiment 2b was similar to that discovered in Experiments 1 and 2a ([Figure 16](#)). Specifically, with greater eccentricity, all participants showed evidence of greater lag, independent of background condition. In addition, targets moving in the direction of the fovea at disappearance showed greater lag, and the relationship between lag and eccentricity again appeared to depend on speed to fovea.

Figure 14

Plots of Mean Absolute Error by Participant, Hemifield Division, Background Condition, and Number of Targets for Experiment 2b.

Note. Error bars represent 95% confidence intervals.

Figure 15

Plots of Mean Distance from the Finish Line by Participant, Hemifield Division, Background Condition, and Number of Targets for Experiment 2b.

Note. Error bars represent 95% confidence intervals. Positive values indicate forward displacement, negative values indicate lag.

Figure 16

Plots of the Relationship Between Eccentricity and Distance from the Finish Line by Background (A) and Speed to Fovea (B) for Experiment 2b.

Note. In A, trend lines represent lines of best fit for static and dynamic conditions. In B, speed to fovea refers to the rate of which the target was approaching the centre of the screen, based on in its final direction. The blue trend line is the line of best fit independent of speed to fovea.

General Discussion

This study aimed to examine how we perceive the location of moving objects – a fundamental question of visual perception. We approached this question by examining the occurrence of the twinkle goes effect in a novel MOT paradigm. Using this approach, we found an intriguing relationship between the perceived location of moving objects and their visual eccentricity, as well as speed to fovea. Our novel approach, considering effects at the individual level, also revealed substantial differences in the experience of the twinkle goes effect between participants. Most importantly, however, this study presented results across three experiments that were incompatible with both predictive extrapolation and tracking continuation theories of object tracking, the implications of which will be discussed in the following sections.

The Effect of Eccentricity and Speed to Fovea

A surprising finding across all experiments was that participants consistently showed greater lag with increasing eccentricity (i.e., distance from the centre of the screen) and increasing speed to fovea (i.e., the rate targets moved towards the centre of the screen in their final moments). In addition, there was a strong interaction between these two measures, such that the effect of eccentricity on distance from the finish line was stronger when objects moved towards the fovea. Interestingly, none of these effects depended on background condition. To understand why these results are surprising, it is important to appreciate our rationale for considering these variables. It has previously been demonstrated that some position and motion illusions, such as the FLE (Linares et al., 2009), are stronger in peripheral vision. With poorer spatial acuity in the periphery, it is thought that the brain relies more on visual heuristics, therefore causing larger illusions (Kanai et al., 2004). However, in the current study, the twinkle goes illusion did not depend on eccentricity. Instead, we found independent effects of eccentricity and speed to fovea on lag. One explanation for greater lag

at higher eccentricities may come from a serial processing perspective, where it is thought that attention rapidly switches between attended objects (e.g., D'Avossa et al., 2006). Specifically, it may take longer for attention to rapidly switch between targets that are at the extremities of the screen (i.e., higher eccentricity), meaning that perception lags further behind the object's physical location. However, this cannot explain why greater eccentricity was associated with more lag in the one target condition, where participants did not have to switch between multiple targets.

So, what can be concluded about the effect of eccentricity and speed to fovea on lag? Our results suggest that perception lags further behind the real location of moving objects in low acuity peripheral vision, particularly when objects move towards fixation. In addition, the non-significant interaction between eccentricity and background condition suggests that the twinkle goes effect does not differ with eccentricity. However, these conclusions require more thorough investigation. In the current study, trajectories were generated using a random geometric algorithm. It could be speculated that constraints on this algorithm, such as ensuring that objects did not change direction in the last 400ms of a trial, may have incidentally biased the final directions and locations of targets. To ensure our findings are not just an artefact of trajectory generation, future studies should directly manipulate final eccentricity and speed to fovea. In addition, research should continue to consider whether the twinkle goes effect is influenced by eccentricity. Specifically, future studies could consider whether the size of the twinkle goes effect is affected when performing an alignment judgement task at different eccentricities.

Net Distance from the Finish Line

Another interesting finding from this study was the individual variability in net distance from the finish line. Previous research considering net forward/backward displacement in a MOT task (where offset transients were not accounted for) has presented

somewhat conflicting results. Howard and Holcombe (2008) and Howard et al. (2011) suggested that perception lags behind the real location of moving objects, whilst Iordanescu et al. (2009) found that perception appeared to be ahead of the real location of moving objects. The results of the current study suggest these discrepant findings may be an artefact of the studies' samples. Specifically, for most participants in the current study, perceived locations of moving objects consistently lagged their real locations, regardless of background condition. However, there were also participants who consistently clicked a location ahead of the target disappearance point. This suggests the relationship between real and perceived locations of moving objects is subject to individual variability. It is uncertain why individuals may differ on this measure, and theoretically, it is unclear why any participant would show overall forward displacement in the static background condition (cf. [Figure 5](#)). To better understand these individual differences, future studies may wish to consider whether individuals who show overall forward displacement show similar profiles for other localisation metrics, such as absolute error.

Can the Twinkle Goes Effect be Elicited in a MOT task?

Before considering the primary research question from this study – whether attentional load influences the size of the twinkle goes effect – it is important to consider the basic question of whether the twinkle goes effect *can* occur following MOT. In Experiment 1, we explored the twinkle goes effect in a task where participants tracked either one or four targets among a total of eight on-screen objects. Results were inconsistent across the sample, with two out of five participants failing to show any evidence of a twinkle goes effect, even in the one target condition. In the less demanding MOT task of Experiments 2a and 2b, results were similarly inconsistent, with two out of eight participants (pooling the samples) failing to show evidence of a twinkle goes effect for either the one or two target conditions, and only one participant showing evidence for the twinkle goes effect in the one target

condition. In contrast, Nakayama and Holcombe (2020) found highly consistent evidence of a twinkle goes effect in all participants. These findings raise a critical question; why do some individuals show a twinkle goes effect using this MOT paradigm, while others do not? To begin answering this, future studies should compare the results of participants on both the MOT and alignment judgement twinkle goes paradigms. This would reveal whether participants who do not show a twinkle goes effect in the MOT task are simply those with a weaker twinkle goes response in the alignment judgement task, or whether there is an independent facet of our current paradigm which is causing this discrepancy (e.g., clicking the final location rather than judging alignment).

Comparing Predictive Extrapolation and Tracking Continuation Theories

The primary aim of this study was to compare predictive extrapolation and tracking continuation theories. Our main method for disambiguating these theories was to consider whether attentional load influenced the size of the twinkle goes effect. Predictive extrapolation theory entailed that the twinkle goes effect should not be affected by attentional load, whilst tracking continuation theory entailed the effect should be smaller with greater attentional load. In addition, the two theories differed in their specific predictions about net distance from the finish line, summarised in [Figure 5](#). Most importantly, the transient correction hypothesis suggested there should be no extrapolation or lag in the static background condition. In Experiment 1, our results were not consistent with either theory. There was no difference between one and four target conditions (conflicting with tracking continuation theory), and participants consistently showed lag in both static and dynamic background conditions (conflicting with predictive extrapolation theory). The findings from Experiments 2a and 2b further challenged these theories. In direct opposition to tracking continuation theory, for some participants the twinkle goes effect was bigger when tracking two targets than one. Predictive extrapolation theory, too, could not explain this finding.

These results also differed from Nakayama and Holcombe's (2020) original finding that tracking four objects was associated with a smaller twinkle goes effect than when tracking two, in an alignment judgement task. However, Nakayama and Holcombe analysed their data at the group-level, as opposed to the individual level. Thus, it is possible there were individuals in their study's sample who showed a larger twinkle goes effect when tracking more objects, but their results were concealed when averaging across the whole sample. Therefore, the differing results between our study and their study may simply be explained by differing sample characteristics and statistical approaches.

Re-Analysis of Nakayama and Holcombe (2020) Experiment 5

To test whether the differing results between our study and Nakayama and Holcombe's (2020) study may simply be explained by sample characteristics, we obtained the original data from Experiment 5 of Nakayama and Holcombe (2020) and performed a generalized mixed-effects analysis (Appendix G). As evident in our replotting of this original data in [Supplementary Figure S1](#), only three (out of 20) participants showed a larger twinkle goes illusion when attending to four objects compared to two, and for each of these individuals the effect was small. Thus, it is highly unlikely that the opposing findings between our study and their study are simply a result of sample characteristics and statistical approach.

Potential Methodological Influences on the Current Results

The next logical step in understanding the results from Experiment 2a and 2b is to consider the unique methodological aspects of our MOT paradigm, and why this may have led to opposing results to Nakayama and Holcombe (2020).

Linear vs. Rotational Motion. One of the key novelties of the current study was its manipulation of attention in a linear motion task. This was motivated by Nakayama and Holcombe's (2020) use of a rotational motion task when testing for the effect of attentional

load, despite using linear motion in their other twinkle goes experiments. It is thought that our perception of rotational motion is far more attentionally demanding than linear motion (Thornton & Gilden, 2001; 2007). Thus, the difference in attentional load required for tracking two rotating objects, compared to four, may be far greater than the difference between tracking one and two, or even one and four objects, in a linear motion task, such as our MOT paradigm. Whilst this may explain why our manipulation of attentional load did not affect the size of the twinkle goes effect in the current study, it cannot explain why for some individuals the illusion was bigger when tracking more objects.

Localisation Using Cursor Versus Alignment Judgement. In our study, we required participants to move their cursor and click the final location of a target. Importantly, it takes longer to perform this action than it does to press a single key (as required in the alignment judgement task). It is possible that the lengthened period between object disappearance and location selection may have induced a memory effect called representational momentum. Like the twinkle goes illusion, representational momentum refers to a phenomenon where the final location of a moving object is perceived ahead of its disappearance location (Freyd & Finke, 1984). Distinct to the twinkle goes effect, however, representational momentum is maximal after a longer period between object disappearance and responding (~1500ms), is not affected by offset transients, and is thought to be memory-based, not perceptual-based (De Sa Teixeira et al., 2013; De Sa Teixeira, 2016). Critically, representational momentum is increased when attention is divided (Hayes & Freyd, 2002). Thus, it is possible that the presence of dynamic noise at disappearance could simply have enhanced a representational momentum effect, which is in turn greater when attention is divided. This could potentially explain why there was a larger twinkle goes effect when tracking two objects, compared to one, in Experiments 2a and 2b. However, it is unclear why representational momentum would be greater with dynamic noise. In addition,

representational momentum alone could not explain why tracking four objects led to a smaller twinkle goes effect than tracking two in Nakayama and Holcombe's (2020) original study. In future experiments, the potential relationship between representational momentum and the twinkle goes effect could be investigated using an alignment judgement task where the length of the retention interval (time between object disappearance and responding) is manipulated. Specifically, this design would be able to consider whether the relationship between attentional load and the magnitude of the twinkle goes effect is dependent on retention interval, just like representational momentum is. However, the alignment judgement task employed by Nakayama and Holcombe (2020) is still susceptible to the potential confound of rotational motion. To avoid this, participants could perform a MOT task where instead of reporting final location, they could make an alignment judgement relative to a reference point defined on each trial (see [Figure 17](#)).

Figure 17

Potential Method for Combining Alignment Judgement Task and Multiple Object Tracking Task Paradigms.

Note. Following object disappearance in a multiple object tracking task, participants could be asked to make a judgement of whether a queried target passed a reference line (oriented orthogonally to the last direction of object movement) rather than selecting the final location of the target. For example, participants could press the 'A' key if they thought a target

disappeared on one side of the line, and the 'L' key if they thought it disappeared on the other side.

Other Unique Methodological Features. Whilst the use of linear motion compared to rotational motion, and the cursor-selection method compared to alignment judgement method, are the two most likely reasons for differences between the current study and Nakayama and Holcombe (2020), other methodological differences warrant consideration. Firstly, in the current study, objects randomly changed direction throughout the trial. This was implemented to stop participants using a cognitive strategy to guess the final location of the target based on their memory of the target's previous location and direction. These random direction changes may have influenced the predictability of target movement, reducing the opportunity for extrapolation or tracking continuation to occur. However, it is not clear why this difference would cause a twinkle goes effect only for the two-target condition, and not the one-target condition. Another unique aspect of the current study was the use of red objects rather than black or white objects. Red was used to reduce the likelihood that movement of the dynamic noise background was mistaken for object movement. It is unclear why this colour choice would have a differential effect on the size of the twinkle goes effect for one and two target conditions, but it is worth noting since the effect of object colour on the twinkle goes effect more generally has not been thoroughly explored.

Considering Our Manipulation of Attention Alongside Absolute Error Results

An important caveat to our findings is that we operationalised attentional load as number of targets tracked, yet there was no effect of number of targets on absolute error. This conflicts with a consistent finding in the MOT literature that tracking performance is worse with more targets (Pylyshyn & Storm, 1988; Alvarez & Franconeri, 2007; Drew et al., 2011). Thus, it is important to attempt to understand why our manipulation of attentional load did

not have the intended consequence on absolute error. An obvious difference between our study and the majority of other MOT studies is the use of a cage design, and the fact participants used their cursor to select final target location, rather than distinguishing the targets from the distractors. Interestingly, however, in the original cage experiment by Howard and Holcombe (2008), participants were also less accurate when tracking more targets. The two biggest differences between Howard and Holcombe's (2008) design and our current design were the noise background, and having cages with two objects in them rather than one. Firstly, on every trial, regardless of the background at disappearance, objects were superimposed over a static noise background. Previous research by Dechterenko et al. (2020) has demonstrated that tracking performance is worse when objects are less distinguishable against their background, operationalised in their study as the visibility of moving objects against static noise. It is possible that tracking performance in the current study was so poor overall that there was no difference between one and four target conditions. This seems unlikely, however, since the objects used in this study were red, contrasting strongly to the static noise background. In addition, our reanalysis of Nakayama and Holcombe (2020) showed shallower psychometric curves for the conditions where participants tracked four objects compared to two ([Supplementary Figure S1](#)), indicative of lower accuracy. Thus, the noise background is unlikely to be the reason why number of targets had no effect on accuracy in our study. The next important difference between the two cage designs was the number of objects per cage. Specifically, in the current study we increased the number of objects per cage from one to two. By having two objects per cage, participants would be more likely to confuse targets with distractors. Whilst this is more indicative of typical MOT tasks (i.e., without cages), it is worth investigating whether the different cage design, paired with the cursor-selection task (as opposed to selecting the targets from distractors) somehow interacted to remove any effect of number of targets on accuracy.

So, what does this mean for our interpretations about the effect of attentional load on the twinkle goes effect? It could be argued that we were unsuccessful in manipulating attentional load, since there was no effect of number of targets on accuracy, and thus no conclusions should be made about the relationship between the twinkle goes effect and attention. However, number of targets tracked *did* have some effect on the present results, evident in the larger twinkle goes effect for two targets, compared to one, in Experiments 2a and 2b (even if this finding was in the opposite direction to what we expected). As such, we believe that it is still worthwhile to consider our manipulation of number of targets as a manipulation of attentional load. However, our findings should be treated with caution until we can fully understand why there was no influence of number of targets on overall accuracy.

Considerations for Future Theoretical Development

Whilst there are several findings from the current study that necessitate further investigation, our results present several important considerations for our understanding of object tracking. Across all three experiments we found substantial individual differences in net forward/backward displacement, and in the occurrence of the twinkle goes effect. Both predictive extrapolation and tracking continuation theories lack the nuanced perspective that individuals may differ in their perception of the location of moving objects. Further research will assist in clarifying the causes of these individual differences, and thus improve theoretical understanding about inter-individual variability in object localisation and tracking.

Additionally, for predictive extrapolation theory to remain a plausible explanation of object tracking, it will need to account for lag in object localisation regardless of whether offset transients are present, as exhibited in our study and previous studies (Howard & Holcombe, 2008; Howard et al., 2011).

In light of the present findings, the relationship between representational momentum and the twinkle goes effect is another important consideration for future theoretical

development. Specifically, if our hypothesis is supported that the two phenomena are related (thus explaining the bigger twinkle goes effect with divided attention in Experiments 2a and 2b), both theories would need to be adapted. Specifically, it could be posited that representational momentum is simply a special case of the twinkle goes effect, where a dynamic noise background is not required to elicit forward displacement when the retention interval is long enough. This hypothesis will, however, require further investigation.

Conclusion

This study fits into a broader literature attempting to understand a basic question of visual perception: how do we perceive the location of moving objects? Despite the simple nature of this question, and a plethora of prior research, the results from the current study continue to demonstrate the complexity of position and motion perception. Whilst we were unable to explicitly support a single theory of object tracking, our results are nevertheless critical for our progressive understanding of this domain. Firstly, we clearly demonstrated that individuals differ in their location perception of moving objects, suggesting that this variability is a vital consideration for future empirical and theoretical developments. In addition, we were able to provide important data contributing to our understanding of the twinkle goes illusion, a novel method for investigating the relationship between real and perceived positions of moving objects which may be of great utility to future research. Specifically, we demonstrated that specific methodological choices (i.e., MOT vs. alignment judgement task) may strongly impact the magnitude and consistency of this effect. Finally, we provided preliminary evidence that under certain methodological conditions, the twinkle goes effect may be larger when attentional load is higher, implicating representational momentum in the debate that surrounds moving object localisation. Together, the results of this study provide critical nuance for our understanding of position and motion and present exciting opportunities for future research.

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Appendices

Appendix A:	Excluded Trials
Appendix B:	Structure of Raw Data Files
Appendix C:	Data Visualisation/Analysis R Script
Appendix D:	Experiment 1 Supplementary Data Analysis
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Appendix A: Excluded Trials

Experiment Number	Participant ID	No. Excluded Trials
1	P1	262
	P2	155
	P3	7
	P4	155
	P5	29
2a	P1	11
	P2	47
	P3	6
	P4	5
2b	P1	7
	P2	3
	P3	14
	P4	21

Note. Criteria for exclusion was localisation error of above 200 pixels (Euclidean distance) or clicking in the incorrect cage.

Appendix B: Structure of Raw Data Files and Statistical Output

Description of Variable	Variable Name	Levels (where applicable)
Anonymised Participant ID	participant	
Trial Number	trial	
Background at Time of Disappearance	noise_present	noise (dynamic noise background); no_noise (static noise background)
Number of Targets	no_targets	Exp. 1: 1, 4 Exp. 2a, 2b: 1, 2
Clicked Location of Target X Coordinate	mouse.x	
Clicked Location of Target Y Coordinate	mouse.y	
Final Location of Target X Coordinate	obj0finalX	
Final Location of Target Y Coordinate	obj0finalY	
Orientation of line dividing the screen (only for Exp. 2a and 2b)	line_orientation	horizontal, vertical
Final Speed of Target	finalSpeed	
Error in the x plane	xErr	
Error in the y plane	yErr	
Size of absolute error (deg)	euclidean_dist	
Distance From the Finish Line (deg)	amountExtrapolation	

Outlier Trial (absolute error greater than 200 pixels)	isOutlier	true, false
Final Target Location Eccentricity (deg)	eccentricity_deg	
Speed of Object to Fovea	velocityToFovea	

Note. Only variables relevant to analysis were included in this table.

Appendix C: Data Visualisation/Analysis R Script

Available [here](#).

Supplementary Table S1

Results of ANOVA Considering the Effect of Background Condition and Number of Targets on Distance From the Finish Line for Each Participant.

Participant	Background Type		No. Targets		Background by No. Targets Interaction	
	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
P1	.185	.668	.963	.327	.351	.554
P2	14.1	<.001***	.119	.686	.990	.320
P3	4.12	.043*	2.27	.132	1.42	.233
P4	.001	.974	.124	.725	.145	.704
P5	5.54	.019*	2.36	.125	1.48	.224

Note. ^ = $p < .1$, * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Supplementary Table S2

Participant	Background Type		No. Targets		Background by No. Targets		Eccentricity		Eccentricity by Background	
	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>
P1	5.14	0.587	2.50	0.397	1.99	.501	-.076	<.001***	-.011	.497
P2	3.29	.683	.925	.708	2.46	.319	-.031	.027*	-.022	.116
P3	1.17	.883	3.06	.187	2.06	.375	-.044	.001**	-.010	.446
P4	4.61	.375	.600	.699	.336	.828	-.157	<.001***	-.009	.436
P5	2.68	.637	2.70	.107	2.14	.201	-.041	.002**	-.015	.239

Results of Regression Including the Effect of No. Targets, Background, Eccentricity, and Theoretically Meaningful Interactions.

Note. ^ = $p < .1$, * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Supplementary Table S3

Results of Regression including No. Targets, Background, Eccentricity, Speed to Fovea, and Theoretically Meaningful Interactions.

Participant	Background Type		No. Targets		Background Type by No. Targets		Eccentricity		Speed to Fovea		Eccentricity by Speed to Fovea	
	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>
P1	.020	.752	.041	.509	.052	.404	<.001	.409	.007	.813	>-.001	<.001***
P2	.187	<.001***	.030	.676	.065	.234	<.001	.031*	.204	<.001***	>-.001	<.001***
P3	.009	.700	.009	.697	.017	.471	>-.001	.006**	-.003	.823	>-.001	<.001***
P4	.108	.033*	.070	.167	.035	.493	>-.001	.266	.260	<.001***	>-.001	<.001***
P5	.098	.013*	.062	.117	.046	.244	>-.001	.248	.089	<.001***	>-.001	<.001***

Note. ^ = $p < .1$, * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Supplementary Table S4

Results of ANOVA Considering the Effect of Background Condition, Number of Targets, and Line Orientation on Distance From the Finish Line for Each Participant.

Participant	Background Type		No. Targets		Line Orientation		Background by No. Targets		Background by Line Ori.		No. Targets by Line Orientation		No. Targets by Line Ori by Background	
	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
P1	2.81	.094^	.006	.940	.345	.557	4.04	.045*	.500	.480	.011	.917	.123	.726
P2	.760	.384	.224	.637	.124	.725	3.95	.047*	1.28	.258	.050	.924	.758	.384
P3	.072	.789	.280	.597	.001	.972	1.23	.268	.378	.539	.313	.576	.557	.456
P4	26.1	<.001***	2.09	.149	.100	.752	4.14	.042*	2.08	.149	1.62	.203	2.91	.089^

Note. ^ = $p < .1$, * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Supplementary Table S5

Results of Regression including No. Targets, Background, Eccentricity, Speed to Fovea, and Theoretically Meaningful Interactions.

Participant	Background Type		No. Targets		Background Type by No. Targets		Eccentricity		Speed to Fovea		Eccentricity by Speed to Fovea	
	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>
P1	.067	.044*	.002	.044*	.047	.155	>-.001	.754	.045	.003**	>-.001	<.001***
P2	.047	.293	.038	.393	.106	.018*	>-.001	.844	.167	<.001***	>-.001	<.001***
P3	.031	.144	.005	.822	.002	.391	-.001	<.001***	-.004	<.001***	>-.001	<.001***
P4	.220	<.001***	.038	.209	.063	.039*	<.001	.749	.033	.021*	>-.001	<.001***

Note. ^ = $p < .1$, * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Supplementary Table S6

Results of ANOVA Considering the Effect of Background Condition, Number of Targets, and Line Orientation on Distance From the Finish Line for Each Participant.

Participant	Background Type		No. Targets		Line Orientation		Background by No. Targets		Background by Line Ori.		No. Targets by Line Orientation		No. Targets by Line Ori by Background	
	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
P1	2.62	.106	.723	.395	.104	.748	.397	.529	.652	.420	.070	.792	.120	.708
P2	15.1	>.001***	.600	.439	.059	.808	.214	.644	.521	.471	.512	.474	1.03	.310
P3	2.59	.108	.755	.385	1.63	.202	.468	.494	.250	.617	2.74	.098^	>.001	.990
P4	8.78	.003*	.066	.798	.022	.882	2.48	.116	.194	.660	.003	.959	.111	.739

Note. ^ = $p < .1$, * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Supplementary Table S7

Results of Regression including No. Targets, Background, Eccentricity, Speed to Fovea, and Theoretically Meaningful Interactions.

Participant	Background Type		No. Targets		Background Type by No. Targets		Eccentricity		Speed to Fovea		Eccentricity by Speed to Fovea	
	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>	<i>b</i>	<i>p</i>
P1	.080	.012*	.032	.310	.030	.350	>-.001	<.001***	.059	<.001***	>-.001	<.001***
P2	.100	<.001***	.020	.392	.008	.700	>-.001	<.001***	.048	<.001***	>-.001	<.001***
P3	.072	.019*	.026	.391	.020	.505	>-.001	.151	.095	<.001***	>-.001	<.001***
P4	.147	<.001***	.013	.723	.064	.092^	>.001	.109	.121	<.001***	>-.001	<.001***

Note. ^ = $p < .1$, * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Appendix G: Re-Analysis of Nakayama and Holcombe (2020) Experiment 5

```

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']
Family: binomial (probit)
Formula: response ~ (cue * background | participant) + (tilt | participant) + cue * background + tilt
Data: df

      AIC      BIC    logLik deviance df.resid
12056.3 12185.3 -6010.1 12020.3     9582

Scaled residuals:
      Min       1Q   Median       3Q      Max
-4.3730 -0.8708 -0.2675  0.8500  5.5266

Random effects:
Groups      Name                Variance Std.Dev. Corr
participant (Intercept)         0.115476 0.33982
           cue1                 0.016951 0.13020  0.45
           background1         0.009060 0.09518  0.26 -0.65
           cue1:background1    0.005761 0.07590 -0.11  0.68 -0.49
participant.1 (Intercept)       0.032598 0.18055
           tilt                 0.001683 0.04102 -1.00

Number of obs: 9600, groups: participant, 20

Fixed effects:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)   -0.398272   0.088234  -4.514 6.37e-06 ***
cue1           -0.112589   0.032267  -3.489 0.000484 ***
background1    0.208343   0.025748   8.091 5.89e-16 ***
tilt           0.092711   0.009577   9.680 < 2e-16 ***
cue1:background1 -0.056487  0.021738  -2.599 0.009362 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
              (Intr) cue1  bckgr1 tilt
cue1          0.364
background1   0.167 -0.505
tilt          -0.474 -0.018  0.053
c1:bckgrnd1  -0.068  0.481 -0.330 -0.017
optimizer (Nelder-Mead) convergence code: 0 (OK)
boundary (singular) fit: see ?isSingular

```

Supplementary Figure S1

Probability of Reporting that Objects Crossed in an Alignment Judgement Task by Physical Tilt, Background Condition, and Cuing Condition, for each participant. (Re-Analysis of Nakayama and Holcombe (2020), Experiment 5). [Link back to main text](#).

Note. Up response indicated that participants thought that objects crossed the centre. Vertical lines indicate points of subjective equality (PSEs). PSEs represent a 50% probability that participants would think the objects crossed (or did not cross). PSEs greater than zero indicate lag, while PSEs less than zero indicate forward displacement. In the post-cue condition participants only had to attend to 2 objects, while in the pre-cue condition participants had to attend to 4 objects.