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The onset repulsion effect

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Abstract—There have been many previous reports of mislocalization associated with moving objects (e.g. flash-lag effect, Fröhlich effect, representational momentum). Across four experiments, a new form of mislocalization — the onset repulsion effect (ORE) — is explored in which the error is always back along the observed path of motion. That is, when observers are asked to localize both the initial onset *and* the final offset positions of a moving object, by far the largest and most systematic error they make is in placing the onset point too early along the correct path of motion. Errors orthogonal to the path of motion and errors in localizing the offset point are minimal by comparison. Errors are also very small when motion is implied rather than continuous. The ORE can be observed with and without fixation, and as with other mislocalization effects, shows some dependence on direction and velocity. As the most obvious prediction in these studies, based on previous reports of mislocalization and the known properties of the visual system, would be for *forward* rather than *backward* errors, discussion will focus on the type of mechanism that may have given rise to the observed pattern of results.

Keywords: Object localization; flash-lag effect; Fröhlich effect; representational momentum.

INTRODUCTION

Successfully interacting with moving objects is an important part of everyday life. Whenever we drive a car, cross a busy street or manoeuvre through a crowded shopping mall, we rely on our visual system to accurately guide our actions. The fact that we can function in such a dynamic world suggests that we are well adapted to cope with the visual consequences of object motion. However, at least in the laboratory, it has been possible to show that we sometimes make mistakes. That is, our attempts to localize moving objects are sometimes accompanied by small but consistent errors (e.g. Fröhlich, 1923; Freyd and Finke, 1984; Nijhawan, 1994; Müsseler and Aschersleben, 1998; Whitney and Cavanagh, 2000). The purpose of the current paper is to describe a new type of localization error — the onset repulsion

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effect (ORE) — where the perceived starting point of a moving object is located too early along its path of motion, in a position that was never physically occupied.

The initial motivation for this work came from a study of memory for dynamic events (Thornton, 1999). In a series of experiments, observers watched a moving dot as it traversed a relatively complex path, changing direction and speed on several occasions. Observers were taught to use a simple interface to *reconstruct* the event they had just witnessed as accurately as possible. The interface allowed observers to map out the spatial path and assign the correct velocities to each segment. While the aim of the reconstruction was to assess how memory for dynamic events might change over time, by far the largest and most systematic error that observers made was in placing the initial onset point too early along the correct path of motion. Actis Grosso *et al.* (1996) had noted very similar patterns of error when they asked observers to watch a dot moving in a variety of curved and straight trajectories.

The four experiments reported in this paper used a very simple event — dot motion along a single, straight trajectory — to explore this form of onset error in more detail. While the focus of this work will be to introduce the ORE and to document some of the conditions under which it occurs, it is hoped that, as with other forms of mislocalization, a consideration of possible underlying mechanisms may eventually lead to a better understanding of how motion processing is accomplished by the visual system. Studies of representational momentum, for instance, where the final stopping point of an object is misremembered as being too far forward in its direction of motion (Freyd and Finke, 1984), have led to discussions about the internalization of physical principles (e.g. Hubbard, 1998), the contribution of high and low level mechanisms in perceptual processing (e.g. Reed and Vinson, 1996) and even the general nature of mental representation (e.g. Freyd, 1987).

Studies of the flash-lag effect (Nijhawan, 1994) have generated many hypotheses about the basic nature of motion processing in the visual system. With the flash-lag effect, an instantaneously presented flash is seen to lag behind a continuously visible moving object, despite the fact that the two objects are physically aligned. Possible explanations have invoked a range of mechanisms, including active extrapolation (Nijhawan, 1994), backwards masking and priming (Sheth *et al.*, 2000), attention shifting (Baldo and Klein, 1995), differential transduction delays (Whitney *et al.*, 2000), motion integration errors (Eagleman and Sejnowski, 2000), motion sampling errors (Brenner and Smeets, 2000) and higher-level forms of persistence (Krekelberg and Lappe, 2000).

Another well established form of mislocalization is the Fröhlich effect (Fröhlich, 1923), where the onset of a fast moving object is located too far forward in its path of motion (i.e. opposite to the ORE). This effect originally led to discussion on the processing limits for conscious awareness, the so-called ‘sensation time’ (Fröhlich, 1923). More recent explanations have focused on the role of attention and masking during motion perception (e.g. Kirschfeld and Kammer, 1999; Müsseler and Aschersleben, 1998).

In the current paper, a consideration of implications for more general motion processing will be reserved until the General Discussion, where some initial speculations about the type of mechanism(s) that could account for the ORE will be made. Prior to this, Experiment 1 demonstrates the basic effect, and introduces the general methodology. Experiment 2 investigates the role of eye movements and also explores the impact of a range of object velocities. Experiment 3 asks whether the ORE *only* occurs when both onset and offset locations are reported, and Experiment 4 examines the impact of supplying a static reference frame.

EXPERIMENT 1

In Experiment 1, observers were asked to watch a small, horizontally or vertically moving dot that appeared on the computer screen. On each trial, the dot appeared at a random location, moved at a constant speed in a single direction (either up, down, left-to-right, or right-to-left) and then disappeared. Observers were free to move their eyes and were asked to follow the entire path of motion. Once the object vanished, they used the mouse to indicate *both* the onset location, as in studies of the Fröhlich effect, *and* the offset location, as in studies of representational momentum. The main question of interest was whether the initial point of onset would be mislocalized given such a simple visual event.

Methods

Participants. Twelve observers from the Boston/Cambridge community were paid for their participation in this experiment. All had normal or corrected to normal vision, were right handed and were naïve as to the purpose of the research. Data from one observer was not included in the analysis as they did not follow instructions and consistently indicated the point of offset before indicating the point of onset.

Equipment. All experiments reported in this paper were conducted on a Macintosh computer connected to a 17″ monitor with a refresh rate of 75Hz and a resolution of 832 × 624 pixels. Software was custom written using routines based on work by Steinman and Narwot (1992), Pelli and Zhang (1991) and Rensink (1990). The experimental room was dimly lit and the immediate surroundings, including the monitor frame, were always clearly visible.

Stimuli. On each trial, a small dot moved from one position on the screen to another. The dot was drawn in black on a middle gray background and measured 10 by 10 pixels. At a viewing distance of 50 cm, the dot subtended 0.41° visual angle. At the start of each trial the dot could appear anywhere within a 4° viewing square centred on the middle of the screen.

On 50% of trials the dot appeared and immediately began to move in one of four directions, either up, down, left-to-right, or right-to-left from the random point of onset. On these trials, motion was smooth and dot speed was constant at 3°/second. The dot travelled along this path for a random, variable distance of between 3° to 6° and then immediately disappeared.

On the remaining 50% of trials, motion was implied rather than actual. That is, the dot appeared at a random location and remained visible for 250 ms. It then disappeared, reappearing at a time and location that would have been consistent with smooth motion in one of the four directions for a random path length. The dot again remained visible for 250 ms. These 'implied motion' trials were included as a baseline condition to assess the accuracy of localizing two points in the absence of smooth motion.

Task. The task of the observers was always the same. After a trial was initiated, the screen remained completely blank for 1 second. The target object appeared at a random location and either moved smoothly along its path, or remained visible for 250 ms, disappeared and then reappeared at its final location. Observers were free to move their eyes and were instructed to watch the entire path of the object so that they could indicate as accurately as possible *both* the onset and the offset locations. Once the object disappeared, observers waited during a retention interval of 1 second until the cursor appeared in the centre of the screen. This delay was introduced to reduce spurious apparent motion between the vanished object and the cursor. They were instructed to move the cursor to the remembered onset location and click the mouse. Once the onset location had been identified, observers were required to move the cursor to the remembered offset location and click again. They then pressed the space bar to record their responses and move on to the next trial.

Procedure. The task was explained to each observer and they were familiarised with the task-specific mouse and keyboard controls. They then completed 12 practice trials that were randomly drawn from the full design before completing a total of 96 experimental trials. Of these, 48 were smooth motion and 48 were implied. Within each type of motion, observers saw an equal number of up, down, left-to-right and right-to-left trials. Order of presentation was completely random across observers.

Results

Errors along the path of motion were analysed separately from errors orthogonal to the path of motion. Following a convention introduced by Hubbard and Bharucha (1988), errors along the path of motion will be referred to as M-displacements, errors orthogonal to the path of motion, will be called O-displacements. For M-displacements, positive values always indicate errors ahead of the true onset or offset point, negative values indicate errors behind these points. In the current work,

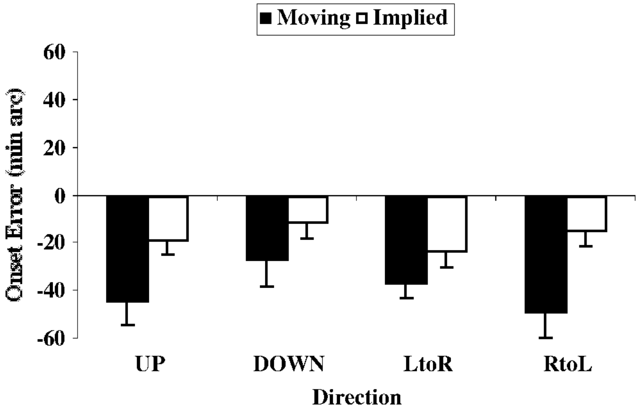

Figure 1. Average M-displacement errors for the point of ONSET for both the moving (solid bars) and implied (open bars) conditions of Experiment 1. Data are shown as function of movement direction. Errors bars show one standard error of the mean. Positive values indicate positions beyond the true point of onset, negative values indicate positions prior to the true point of onset.

positive O-displacements always indicate errors above horizontally moving stimuli or to the right of vertically moving stimuli. Negative O-displacements indicate errors below or to the left of these stimuli.

M-displacements for the perceived *onset* were analysed in a 2 (Motion Type) × 4 (Direction) repeated measures Analysis of Variance. The main finding from this analysis is illustrated in Fig. 1. Observers always tended to place the perceived onset further back along the path of motion, that is, at a point before the true onset. While this tendency is apparent in all trials, there was a main effect of Motion Type, with moving stimuli ($M = -38.8$ min arc, $SE = 5$) giving rise to consistently larger onset errors than implied stimuli, ($M = -16.6$ min arc, $SE = 3.3$), $F(1, 10) = 7.62$, $MSE = 230$, $p < 0.05$. While the graph suggests some modulation in the size of this onset error as a function of path, there was no main effect of Direction, $F(3, 30) = 1.0$, $MSE = 128$, not significant (n.s), and no Motion Type × Direction interaction, $F(3, 30) = 1.42$, $MSE = 55$, n.s. Path length was randomly varied from trial to trial in the current study. To assess the relationship between length and the size of onset errors, correlation coefficents were computed separately for each observer. This analysis revealed no significant differences from zero, either for moving ($M = -0.037$, $SE = 0.07$) or implied ($M = -0.028$, $SE = 0.057$) stimuli, all $ts < 1$, n.s.

M-displacements for the perceived *offset* were analyzed with the same ANOVA model as used for the onset errors. There was again a main effect of Motion Type, $F(1, 10) = 6.9$, $MSE = 127$, $p < 0.05$. Moving stimuli gave rise to a slight overshoot of perceived offset, ($M = 6.4$ min arc, $SE = 4.7$), while implied stimuli gave rise to a slightly larger undershoot ($M = -9.2$ min arc, $SE = 3.9$). There was no main effect of Direction, but as can be seen in Fig. 2, there was a Motion Type × Direction interaction, $F(3, 30) = 3.6$, $MSE = 25.7$, $p < 0.05$. This interaction

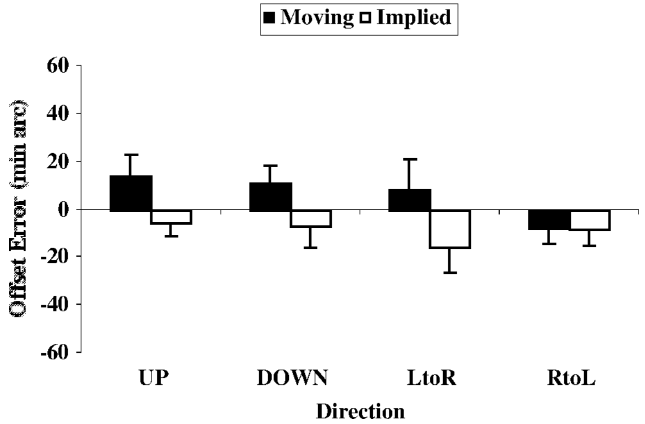

Figure 2. Average M-displacement errors for the point of OFFSET for both the moving (solid bars) and implied (open bars) conditions of Experiment 1. Data are shown as function of movement direction. Errors bars show one standard error of the mean. Positive values indicate positions beyond the true point of offset, negative values indicate positions prior to the true point of offset.

appears to be driven by the reversal in sign of the offset error for moving, right-to-left stimuli.

Generally, O-displacements were much smaller than the M-displacements. When the stimuli were moving horizontally, observers estimated the path of motion to be slightly lower on the screen than the true path, both for left-to-right ($M = -10.2$ min arc, $SE = 3.7$), and right-to-left ($M = -6.6$ min arc, $SE = 4.1$) motion. For vertically moving stimuli there was a tendency to place the path slightly to the left of its actual position. Again, this was true for both up ($M = -2.88$ min arc, $SE = 3.1$) and down ($M = -2.54$ min arc, $SE = 3.6$) motion. Separate analyses of these horizontal and vertical patterns revealed no significant effects of Motion Type, Direction or their interaction.

Discussion

The results of Experiment 1 confirm the findings of Actis Grosso *et al*. (1996) and Thornton (1999) that observers consistently mislocalize the point of onset back behind the true onset location. Here, this error was shown to occur even with very simple motion involving constant velocity in a single direction. While this 'onset repulsion effect', was present for both moving and implied stimuli, it was much stronger in the former case where observers had to track the smoothly moving object. Even so, the presence of any form of backwards shift when only two points are presented is very interesting. It suggests that any form of trajectory, actual or implied, has the potential to elicit some level of error. The absence of direction and length effects in the current experiment further suggests that it might be the 'existence of', rather than something about the 'nature of', a path that is a necessary condition for observing the ORE.

Discussion of the possible sources for the ORE will be reserved until the General Discussion. However, the design of the current experiment would seem to rule out at least some potential explanations. As observers were free to move their eyes prior to target onset, and as onset location and direction was random on a trial-by-trial basis, it seems very unlikely that the current effect could result from some form of foveal or display-centre bias. Previous research has shown that a tendency towards a central reference point can influence patterns of localization (e.g. Osaka, 1977; Mateeff and Gourevich, 1983; O' Regan, 1984; Rose and Halpern, 1992). Also, at least for stationary stimuli, peripheral targets tend to be localized closer to the fovea than their true position (e.g. Müsseler *et al.*, 1999; Van der Heijden *et al.*, 1999; Sheth and Shimojo, 2001). Neither of these biases could account for the current results given the randomisation of position and direction. For instance, objects moving left-to-right, were equally likely to occur on the right side or left side of the screen. A central bias should lead to the appearance of an ORE when this movement occurred to the left of centre, and an equal and opposite forward shift when it occurred to the right of centre. Thus, errors arising from this sort of bias would cancel each other out across trials and a consistent underestimation should not have been observed.

Errors at the offset of motion were much smaller than those involving motion onset. Furthermore, offset errors in the moving and implied conditions behaved quite differently. For moving stimuli, the estimated offset point was slightly beyond the true stopping point. This finding is consistent with the large body of work on representational momentum (e.g. Freyd and Finke, 1984; Freyd, 1987; Hubbard, 1995). For implied stimuli, there was a slight underestimation of the offset point. As the second dot always appeared 'out of nowhere' in the implied condition, observers almost certainly had to execute a saccade in order to localize it. If the position of their eyes prior to appearance of the second dot where close the position of the initial onset, this error could represent some form of saccadic undershoot (Henson, 1978).

Errors orthogonal to motion, O-displacements, were very small in comparison to those along the path of motion, the M-displacements. The tendency for horizontally moving stimuli to be localized a little lower than their actual position is consistent with previous reports of what has been termed 'representational gravity' (Hubbard, 1995). It is not clear why there might be a slight leftwards bias for vertically moving stimuli.

In the remainder of this paper, the focus will be almost exclusively on the M-displacements that constitute the ORE. While errors in estimating the point of offset and errors orthogonal to the direction of motion will be reported, they will only be discussed in any detail when they interact with onset errors. In Experiment 2, the impact of fixation and object velocity is explored. Experiment 3 tests whether reporting *both* onset and offset locations is a necessary condition for producing the onset repulsion effect. Finally, in Experiment 4, the impact of a stationary reference frame will be examined.

EXPERIMENT 2

Experiment 1 has shown that observers systematically mislocalized the onset of a moving target back before its true starting point. In the current experiment, we manipulate two features of the displays used in Experiment 1 — speed of motion and eye position — to explore whether these features are important in determining the nature of the ORE.

In Experiment 1, the target dot always moved at 3°/second. Does the onset repulsion effect depend on such slow moving targets? It is well established that the onset of fast moving objects (>20°/second) tends to be mislocalized in the direction of motion (Fröhlich, 1923; Müsseler and Aschersleben, 1998). Will the ORE disappear as velocity is increased? To answer this question, target speed was varied between 3–15°/second, the maximum velocity possible given equipment limitations. As in Experiment 1, direction of movement was random on a trial by trial basis. Here, however, a second random factor was added so that observers never knew the speed or the direction of motion on a given trial.

The other major display manipulation involved the addition of a central fixation point. In Experiment 1, observers had been required to locate and track the target with their eyes. It is thus possible that the mechanism responsible for the onset repulsion effect is located somewhere within the eye movement control system. For example, when observers make a saccade towards a stationary target, they typically undershoot by about 10%, requiring further 'corrective' saccades to fully focus on the target (Harris, 1995; Henson, 1978). When trying to track a smoothly moving object, an initial corrective saccade is also necessary to lock onto the target, and tracking errors are constantly monitored and corrected. If target velocity is very high, such corrective saccades can occur every 200–250 ms (Alpern, 1982). Kerzel (2000) has recently suggested that localization errors, particularly towards the end of a motion path could arise, at least in part, from overtracking with the eyes (Mitrani and Dimitrov, 1978).

In Experiment 2, observers were required to maintain central fixation during the presentation of the target. The introduction of a fixation point was designed to reduce the influence of eye movements. More specifically, the goal was to remove errors that may have arisen when observers attempted to smoothly pursue the target. It should be noted, however, that eye movements were not monitored in this study and that the use of naïve observers makes it impossible to rule out all movements of the eye. For example, small drifts of fixation almost certainly occurred. Thus, while the presence of an ORE under the current conditions would be fairly strong evidence against the involvement of the pursuit system — at least assuming that observers complied with the instructions — further studies with more controlled conditions (i.e. monitoring of eye position) would be needed before the relationship between the ORE and eye movements can be fully understood.

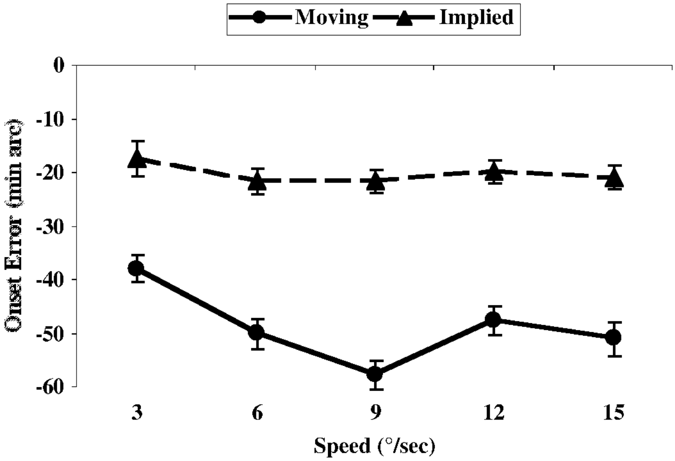

Figure 3. Average M-displacement errors for the point of ONSET for both the moving (solid lines) and implied (dashed lines) conditions of Experiment 2. Data are shown as function of target velocity, collapsed across movement direction. Errors bars show one standard error of the mean. Negative values indicate positions prior to the true point of onset.

Method

Participants. Twelve observers from the Boston/Cambridge community were paid for their participation in this experiment. All had normal or corrected to normal vision, were right handed and were naïve as to the purpose of the research. No observers had participated in Experiment 1.

Stimuli. The stimuli were identical to Experiment 1 except for the following two modifications: First, a small (30 min arc) fixation cross was constantly visible at the centre of the screen. A modification of the path generation software ensured that target objects never originated or passed within 30 min arc of this fixation point. Second, speed of motion was varied. On a given trial, the dot could move at either 3, 6, 9, 12, or 15°/second for its entire path. As in Experiment 1, the length of this path varied randomly on each trail between 3° to 6°.

Task and procedure. These were identical to Experiment 1 except that observers were required to maintain fixation until the response cursor appeared at the end of stimulus presentation. Each subject completed an experimental block consisting of 400 trials presented in a random order from a 2 (Motion Type) × 4 (Direction) × 5 (Speed) × 10 (Repetitions) design.

Results

M-displacements and O-displacements were again analysed separately. Figure 3 shows the M-displacements for the onset of target motion, as a function of speed, collapsed across direction. A 2 (Motion Type) × 4 (Direction) × 5 (Speed) repeated

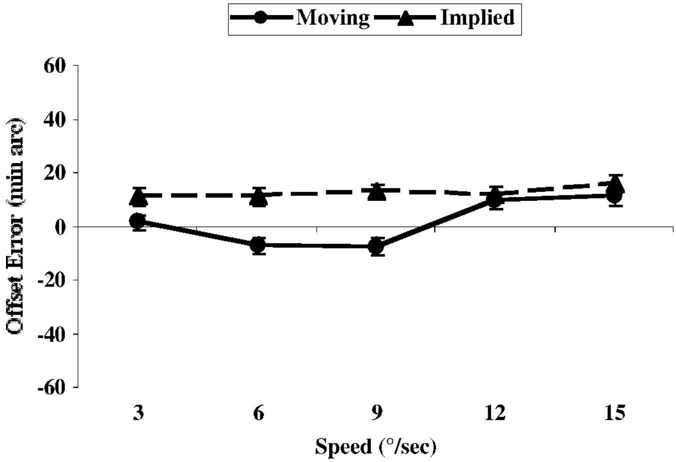

Figure 4. Average M-displacement errors for the point of OFFSET for both the moving (solid lines) and implied (dashed lines) conditions of Experiment 2. Data are shown as function of target velocity, collapsed across movement direction. Errors bars show one standard error of the mean. Positive values indicate positions beyond the true point of offset, negative values indicate positions prior to the true point of offset.

measures Analysis of Variance was used to analyse these data. As in Experiment 1, observers consistently mislocalized the onset point back behind the true starting location. While this backwards error appears for both smooth motion ($M = -48.7$ min arc, $SE = 2$) and implied motion ($M = -20.2$ min arc, $SE = 1.3$), the main effect of Motion Type again shows that the effect is consistently larger when the trial contains continuous motion, $F(1, 11) = 58.3$, $MSE = 273$, $p < 0.001$. There were no significant main effects or interactions involving direction of motion. However, there was a main effect of Speed, $F(4, 44) = 7.2$, $MSE = 42$, $p < 0.001$, and this was modified by a significant Motion Type × Speed interaction, $F(4, 44) = 2.65$, $MSE = 45.8$, $p < 0.05$. As can clearly be seen in Fig. 3, the size of the backwards shift increases across the first three velocity steps when motion is smooth, but there is little or no modulation for implied motion.

As in Experiment 1, correlation coefficents were computed separately for each observer to assess the relationship between path length and size of onset errors. This analysis again revealed no clear relationship, for moving ($M = -0.03$, $SE = 0.02$) stimuli. However, there was a very small, but still consistent, negative correlation for implied stimuli ($M = -0.1$, $SE = 0.02$), $t(11) = 4.2$, $p < 0.05$, indicating that the onset error decreased as the path length increased. Further analysis of this effect showed no influence of Speed, $F(4, 44) = 1.8$, $MSE = 0.07$, n.s, suggesting that the spatial, rather than temporal, gap between the two points is responsible for this effect.

Figure 4 shows the M-displacements for the offset point, which were again analysed using a 2 (Motion Type) × 4 (Direction) × 5 (Speed) repeated measures Analysis of Variance. There was a main effect of Motion Type, with implied motion

($M = 12.9$ min arc, $SE = 5$) giving rise to a larger overshoot than smooth motion ($M = 1.79$ min arc, $SE = 2.3$), $F(1, 11) = 9.9$, $MSE = 242$, $p < 0.01$. There was a main effect of Speed, $F(4, 44) = 6.6$, $MSE = 63$, $p < 0.001$, and a Motion Type × Speed interaction, $F(4, 44) = 2.7$, $MSE = 90$, $p < 0.05$. This interaction appears to be driven by the smooth motion condition, which remained close to zero for slower movements, before rising at the faster two velocities. As with the onset error, the implied motion offset errors remained fairly constant across all speeds. There was also a main effect of Direction for the offset errors, $F(3, 33) = 4.5$, $MSE = 197$, $p < 0.01$, and a Direction × Speed interaction, $F(12, 132) = 19.9$, $MSE = 2.0$, $p < 0.05$. Both of these effects appear to be driven by errors for upwards motion, which were generally smaller than for all other directions, showing a reversal in sign (from undershoot to overshoot) at the faster two speeds. There were no other significant effects.

Analysis of O-displacements revealed a pattern very similar to Experiment 1. Generally, the errors were very small compared to the M-displacements. When motion was smooth, there was a tendency for the position of horizontally moving stimuli to be estimated slightly lower than the true path, both for left-to-right ($M = -10.2$ min arc, $SE = 1.5$) and right-to-left ($M = -9.6$ min arc, $SE = 4.1$) motion. This was not true for implied stimuli, which showed very little error ($M = 0.07$ min arc, $SE = 4.1$), leading to a main effect of Motion Type, $F(1, 11) = 13.5$, $MSE = 69$, $p < 0.01$. For vertically moving stimuli there was very little error at all, either for moving ($M = 0.62$ min arc, $SE = 1$) or implied stimuli ($M = 1.9$ min arc, $SE = 1$). No other main effects or interactions were significant.

Discussion

The results of Experiment 2 replicate the findings of Experiment 1, showing that observers consistently mislocalize the onset of motion back behind the true starting point. It also appears that speed of motion can modulate the size of this effect. When motion was smooth, there was a modest increase in the size of the onset error up to around 9°/second. For higher velocities, the size of the error appears to stabilise at around 50 min arc. Previous research (e.g. Müsseler and Aschersleben, 1998) suggests that at very high velocities (e.g. 44°/second), the point of onset is mislocalized in the direction of motion. Further studies using velocities in this range will be needed to explore whether a reversal in sign occurs somewhere between 15° and 44°/second.

A major difference between Experiment 1 and Experiment 2, was the position of the eyes during stimulus presentation. The current results suggest that the origin of the onset repulsion effect is probably not in the eye movement control system responsible for smooth pursuit. That is, a robust onset error was still observed even when observers did not follow the object with their eyes. Eye movement related tracking errors (Alpern, 1982) would thus not appear to be responsible for the ORE. Similarly, observers were instructed not to make a saccade to either the onset or offset points until 1 second after stimulus presentation. Localising saccades during stimulus presentation would thus also not appear to be a factor.

However, as noted in the introduction, the contribution of eye movements during the response phase or as a consequence of poorly maintained fixation cannot be ruled out in the current study. Indeed, the appearance of a very small negative correlation between the length of the implied path and onset errors could reflect just such an eye movement effect. Further studies will clearly be necessary to more fully explore the relationship between all forms of eye movement and onset errors.

While the instruction to fixate did not have a great impact on the onset errors, the pattern of offset errors was quite different in Experiment 2. For smoothly moving stimuli, the overshoot at the point of offset that was observed in Experiment 1 was far less pronounced when observers were instructed to fixate. This reduction is consistent with recent work exploring the effect of fixation on representational momentum. Here, forward shifts for the stopping point of a trajectory were much reduced or even eliminated when target objects were not tracked (Kerzel, 2000).

Kerzel and colleagues (e.g. Kerzel, 2000; Kerzel *et al.*, 2000) have used such reductions to argue that eye movement overtracking (Mitrani and Dimitrov, 1978) together with visible persistence (e.g. Coltheart, 1980) can account for forward displacements when object motion is continuous rather than implied. Traditional explanations for representational momentum, in contrast, have emphasised the role of internalisation of environmental dynamics giving rise to anticipatory distortions of remembered positions (e.g. Freyd and Finke, 1984; Hubbard, 1998). While an eye movement and persistence account appears to be a parsimonious explanation for the reduction in errors observed by Kerzel and colleagues, it is also possible that the introduction of fixation also allows observers to exploit error-reducing reference strategies. For example, observers may be able to code an absolute or angular distance measure between the steady fixation and the point of offset.

In the current experiment, fixation also had an impact on the pattern of implied motion offset errors. In Experiment 1, implied offset errors showed a tendency to lag behind the true point of offset. It was suggested that some form of saccadic undershoot (Henson, 1978) could have given rise to this pattern. Consistent with the notion, in Experiment 2, when observers were required to maintain fixation during stimulus presentation, thus preventing an immediate saccade, a slight overshoot of the offset point was observed.

EXPERIMENT 3

Experiments 1 and 2 have shown that, for stimuli moving up to 15°/second, having to report both the onset and the offset locations gives rise to an ORE. As mentioned above, studies of the Fröhlich effect consistently find large forward shifts in estimating the point of onset. While velocity differences may prove to be a major factor in this discrepancy, another important difference is the task itself. That is, in studies of the Fröhlich effect *only* the point of onset is probed, while in Experiments

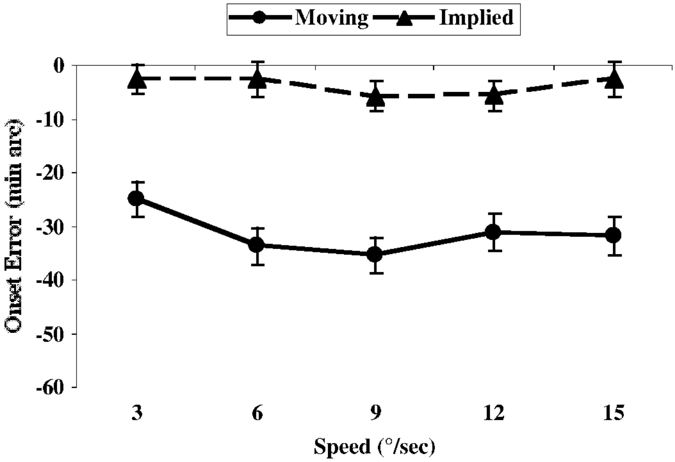

Figure 5. Average M-displacement errors for the point of ONSET for both the moving (solid lines) and implied (dashed lines) conditions of Experiment 3. Data are shown as function of target velocity, collapsed across movement direction. Errors bars show one standard error of the mean. Negative values indicate positions prior to the true point of onset.

1 and 2, observers had to report *both* the onset and offset locations. Clearly, the two tasks differ in several respects, most notably in the number of required responses and the degree to which the entire path of motion is relevant for accurate performance. In Experiment 3, we adopt a task very similar to that used for studies of the Fröhlich effect (e.g. Müsseler and Aschersleben, 1998) to examine whether the ORE can still be observed when observers are only required to report the initial point of onset.

Method

Participants. Ten observers from the Boston/Cambridge community were paid for their participation in this experiment. All had normal or corrected to normal vision, were right handed and were naïve as to the purpose of the research. No observers had participated in Experiments 1 or 2.

Stimuli, task and procedure. Stimuli and equipment were identical to those used in Experiment 2. While the procedure was largely the same, the task differed in that observers only had to report the initial onset of object motion. That is, they were explicitly told to ignore all other aspects of the trial and to focus on localizing the position where the object first appeared. As in Experiment 2, all observers completed an experimental block consisting of 400 trials drawn randomly from a 2 (Motion Type) × 4 (Direction) × 5 (Speed) × 10 (Repetitions) design.

Results

Figure 5 shows the overall pattern of M-displacements for target onset. This pattern is very similar to that found in Experiment 2, with the exception that the size of

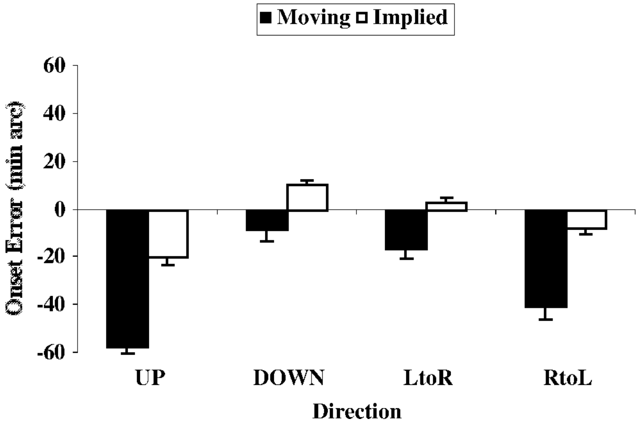

Figure 6. Average M-displacement errors for the point of ONSET for both the moving (solid bars) and implied (open bars) conditions of Experiment 3. Data are shown as function of movement direction, collapsed across target velocity. Errors bars show one standard error of the mean. Positive values indicate positions beyond the true point of onset, negative values indicate positions prior to the true point of onset.

the shift appears to be generally reduced by about 20 min arc. A 2 (Type) $\times$ 4 (Direction) $\times$ 5 (Speed) repeated measures ANOVA again showed a main effect of Motion Type, with smoothly moving stimuli ($M = -30.8$ min arc, $SE = 2.7$) giving rise to much larger errors than implied stimuli ($M = -3.6$ min arc, $SE = 1.4$), $F(1, 11) = 13.5$, $MSE = 1071$, $p < 0.01$. There was also a main effect of Speed, $F(4, 44) = 3.5$, $MSE = 68$, $p < 0.05$, which, as in Experiment 2, appears to be driven mainly by an almost linear increase in onset error over the slower three velocities for smoothly moving stimuli.

Unlike in Experiments 1 and 2, however, there was a strong effect of Direction, $F(3, 33) = 16.2$, $MSE = 390$, $p < 0.001$, as well as a significant Motion Type $\times$ Direction interaction, $F(3, 33) = 3.1$, $MSE = 136$, $p < 0.05$. As can be seen in Fig. 6, for moving stimuli there is a clear ORE for upwards and right-to-left motion, but downwards and left-to-right motion show only a very weak effect. When motion is implied, the level of error across all directions is slight. Finally, correlation coefficents between path length and size of onset errors revealed no relationship either for moving ($M = -0.02$, $SE = 0.03$) or implied ($M = -0.05$, $SE = 0.05$) stimuli, all $ts < 1$.

As in the previous two experiments, O-displacements were small in comparison to M-displacements. There was a tendency for the position of vertically moving objects to be localized slightly to the right ($M = 3.1$ min arc, $SE = 1.5$) and horizontally moving objects to be localized slightly below ($M = -13.8$ min arc, $SE = 1.4$) their true position. Analysis of these trends across type of motion, direction and speed revealed no significant main effects or interactions.

Discussion

The results of this experiment suggest that reporting *both* the onset and offset of motion is not a necessary prerequisite for observing the onset repulsion effect. While the size of the ORE for moving stimuli was much reduced relative to Experiments 1 and 2, the onset position was still consistently assessed to be behind the true starting point. Interestingly, for implied stimuli, the size of this error was very close to zero, suggesting that the shifts seen in this condition in Experiments 1 and 2 arose from observers explicitly linking the onset and offset locations.

Why should there be such a large effect of direction for moving stimuli when observers only report the onset location? Direction effects are not unusual in localization paradigms. For example, representational momentum is generally stronger for left-to-right versus right-to-left motion (Halpern and Kelly, 1993), and displacements for downwards motion are likewise generally larger than those for upwards motion (Hubbard, 1990). Similar directional asymmetries have also been reported for the Fröhlich effect (Müsseler and Aschersleben, 1998). What needs to be explained is why this effect was not apparent in Experiments 1 and 2 when both the onset and the offset locations were reported? One factor may be the influence of fixation when only a single point has to be reported. Previous studies of object localization have found that a central fixation point can have a large impact on patterns of errors (e.g. Osaka, 1977; Mateeff and Gourevich, 1983; O' Regan, 1984; Rose and Halpern, 1992; Kerzel, 2000). In the next experiment onset location is probed without requiring central fixation.

EXPERIMENT 4

Experiments 1 and 2 clearly demonstrated the tendency for observers to mislocalize the perceived onset point of a moving object back along its path of motion. In Experiment 3, evidence for such an onset repulsion effect was still found even when observers focused only on the initial onset location. However, in Experiment 3, the size of the ORE was much reduced relative to Experiments 1 and 2, suggesting that the task-relevance of the entire path of motion and/or the need to make two responses have a substantial impact on performance. Also the presence of a strong direction effect in Experiment 3 suggests that the central fixation point could have strongly influenced the pattern of results.

In the final experiment, observers again only report the onset location, but this time without the involvement of a central fixation point. Additionally, to further explore the nature of the ORE, a 'structured' environment or reference frame was introduced. More specifically, observers were asked to identify the initial position of an object that moved through the elements of a dense background grid.

Some forms of mislocalization, such as the flash-lag effect, appear to be affected very little by frames or reference objects (Nijhawan, unpublished data). Similarly, Müsseler and Aschersleben (1998, Expt. 2) only found a reduction in the size of the Fröhlich effect when a structured background was combined with central fixation. However, other forms of error, such as representational momentum, seem to be quite susceptible to such manipulations. For example, Thornton *et al.* (1996) and Gray and Thornton (2001) found that reference frames presented during the retention interval could significantly reduce or even eliminate forward displacements. Hubbard (1993) found that reference frames rotated in the direction of motion could increase forward shifts, while frames rotated opposite to the direction of motion could reduce the observed shifts.

Furthermore, Faust (1990) showed that representational momentum could be consistently observed when the motion of the target object was 'induced' (Dunker, 1929) rather than actual or implied. Here, motion of a reference frame in one direction led to the subjective impression that a target object was moving in the oppostie direction, as in Dunker's classic demonstration, but also to the appearance of target localization errors consistent with the direction of this induced motion. As observers in Experiments 1-3 of the current paper, were always able to see the computer monitor during stimulus presentation, it is possible that this 'frame of reference' had some impact on the pattern of results. Indeed, as considered more fully in the General Discussion below, an interaction between the target object and shifts in some frame of reference could provide a mechanism for the appearance of onset errors. From this perspective, increasing the strength and/or saliency of the reference frame by providing a grid should, if anything, increase the size of the observed ORE.

In the current experiment, observers were instructed to focus only on the target onset, ignoring the remainder of the path of motion. Thus, the task was essentially to 'look' at the onset position, since observers were free to move their eyes, and to indicate this grid square with the cursor once the movement was complete. The grid could thus be thought of as improving the initial accuracy of eye movements and in providing a stable reference frame to help 'remember' this position.

Method

Participants. Twelve observers from the Boston/Cambridge community were paid for their participation in this experiment. All had normal or corrected to normal vision, were right handed and were naïve as to the purpose of the research. No observers had participated in Experiments 1–3.

Stimuli. Equipment and viewing conditions were the same as in previous experiments. However, the display now contained a dense grid of 15 × 15 min arc cells which covered the entire visible area of the monitor. Target motion was generated by turning successive grid cells on and off (from gray to black and *vice versa*). Thus, motion was not completely smooth, as in Experiments 1–3, but consisted of a rapid 'jumping' from one grid square to the next. The target object filled the entire grid square (15 min arc) and could move in one of 4 directions, up, down, left-to-right, or right-to-left. Target velocity was fixed at approximately

3°/second and the initial position was constrained to be within 6° of the monitor centre. Path length was varied randomly between 3° and 6°.

Task and Procedure. The task and procedure were identical to those used in Experiment 3 with the following exceptions: There was no fixation cross, that is, observers were not required to keep their eyes fixed at any location, but were free to move their eyes to locate the target. Observers were instructed to concentrate on the initial location of the object, as this would be their only task. Once the object motion was complete, the cursor appeared at the centre of the screen (there was a 1 second delay after motion offset) and the task was simply to click in the grid square where the object first appeared. In Experiment 3, it was found that localizing a single flash (implied motion condition) was extremely accurate when observers did not also have to respond to the point of offset. In the current experiment, no implied motion condition was included. Also, as pilot data suggested that O-displacements were almost completely absent because of the grid, errors parallel to the direction of motion were not recorded.

Results

The main result of this Experiment is shown in Fig. 7. Even in the presence of the reference grid, observers still systematically mislocalized the target onset as being earlier along its path of motion, with the average error being close to two complete grid squares ($M = -27.6$ min arc, $SE = 3.8$). There was a main effect of Direction, $F(3, 33) = 3.7$, $MSE = 13.2$, $p < 0.05$, with a pattern very similar to that observed in Experiment 3. *Post-hoc* analysis revealed that this effect was driven by the large 'up' error, which was consistently larger than all other directions, $F(1, 33) = 8.8$, $MSE = 116$, $p < 0.01$. No other comparisons reached significance. There also

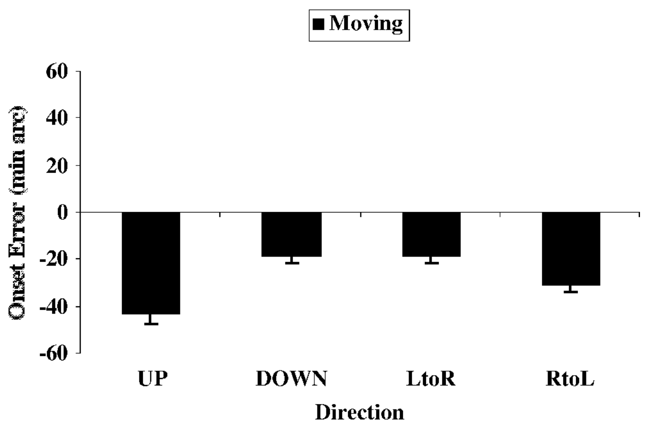

Figure 7. Average M-displacement errors for the point of ONSET in Experiment 4. Data are shown as function of movement direction. Errors bars show one standard error of the mean. Positive values indicate positions beyond the true point of onset, negative values indicate positions prior to the true point of onset.

appeared to be no relationship between path length and the size of the onset error ($M = 0.02$, $SE = 0.04$), $t < 1$.

Discussion

The results of this experiment confirm the findings of Experiment 3, that for relatively slow moving objects, even when the task is to focus just on the initial onset, a backwards shift is still observed. The appearance of a shift in this experiment is even more interesting given that motion was not completely smooth and observers had a great deal of static information that could have helped with the task of localization. While the grid did not eliminate the ORE, it also did not appear to greatly strengthen the effect. As the display conditions in Experiment 4 represent a very large change in the level of reference information available, compared to the previous three experiments, an apparent lack of modulation in the pattern of errors must cast some doubt on the role of object-surround interactions in the ORE.

Finally, the appearance of a direction effect in the absence of a central fixation point suggests that the larger errors for upwards and right-to-left motion are not a consequence of a display artefact of some kind. Rather, the replication of these trends suggests some essential difference in motion processing and/or localization ability along these paths. Further studies will obviously be needed to explore the nature of such differences.

GENERAL DISCUSSION

In four experiments, a new form of object mislocalization was explored. The onset repulsion effect (ORE) refers to the tendency for observers to localize the perceived onset of a moving object back before its true starting point. A consistent ORE was found regardless of whether observers tracked the object (Expt. 1) or maintained fixation (Expts 2 and 3). The effect increased in size as a function of velocity (up to at least 9°/second; Expts 2 and 3), was larger when both the onset and offset points had to be remembered (Expts 1 and 2), and was affected very little by the presence of a reference grid (Expt. 4).

Consistent errors at the point of offset were also observed for the smoothly moving stimuli. These errors tended to be slight overshoots of the true stopping point, consistent with the notion of representational momentum (Freyd and Finke, 1984). However, when fixation was introduced in Experiment 2, the size of this overshoot was greatly reduced. This suggests that tracking errors may play an important role in overshoot effects when stimuli are smoothly moving (Kerzel, 2000). Additionally, the introduction of a fixation point might allow observers to exploit new reference strategies (e.g. relative distance from fixation) which could also help to improve localization accuracy.

In Experiments 1–3, an implied motion condition was included to assess the baseline accuracy of localizing briefly presented stimuli. Interestingly, in both

Experiments 1 and 2, the position of the initial onset during the implied conditions was also mislocalized. The magnitude of this error was much smaller than that observed with the smooth motion condition, but the direction of mislocalization was the same, that is, backwards along the trajectory that would have joined the two points. In Experiment 3, when only the onset point was reported, this implied effect essentially vanished. The presence of any backwards shift with implied motion could suggest that at least some of the error observed in the smooth motion condition arises due to the basic computation of a direction vector and/or attempts to link the offset point with the remembered onset point rather than motion *per se*. However, while parsimony favours a single source for both implied and moving errors, it is also possible that they arise from different mechanisms. Indeed, the lack of velocity effects for the implied condition (Expts 2 and 3), its greater sensitivity to fixation (Expt. 3) and path length (Expt. 2), would all seem to hint that different mechanisms are involved. Given the current results, however, little more than speculation is possible on this point.

The goals and methods of the current work, particularly Experiments 3 and 4, are quite similar to those used to study the Fröhlich effect (e.g. Müsseler and Aschersleben, 1998). Thus, an important focus for future studies will be in trying to establish the exact conditions under which a backwards (ORE) *versus* a forwards (Fröhlich effect) shift is observed. Experiments 3 and 4 suggest that one aspect is the task itself, as a large reduction in the size of the ORE was observed when localization effort was focused only on the point of onset.

Another obvious difference between the two paradigms is speed of object motion, which is typically much higher in studies of the Fröhlich effect (e.g. >20°/second) than with the ORE (3–15°/second). Similarly, directional and positional uncertainty is much higher in the current task than is typical for Fröhlich effect studies. Not only was the onset point, relative to the centre of the screen, completely random in the current studies, but direction varied across 4 levels (left, right, up and down). Studies of the Fröhlich effect typically have a predictable linear (e.g. Müsseler and Aschersleben, 1998) or circular (Müsseler *et al.*, in press) path, with only two levels of direction varied (e.g. left/right or clockwise/counterclockwise). Thus, only onset placement within a known path is unpredictable in Fröhlich effect studies. Further experiments are planned to explore the relationship between these two effects.

The majority of mislocalization errors discussed in this paper, specifically, representational momentum (Freyd and Finke, 1984; Hubbard, 1995), the flash-lag effect (Nijhawan, 1994), and the Fröhlich effect (Fröhlich, 1923; Müsseler and Aschersleben, 1998) involve systematic shifts of position *forward* in the direction of motion. To explain such forward shifts, researchers have invoked a range of mechanisms, all sharing the common goal of trying to understand how the visual system calculates the present and/or future position of a moving object. Example explanations include, active extrapolation (Nijhawan, 1994), facilitated processing or priming of moving stimuli (Watamaniuk *et al.*, 1994; Whitney *et* *al.*, 2000), delays in the allocation of attention (Baldo and Klein, 1995; Müsseler and Aschersleben, 1998), and perceptual or cognitive anticipation (Freyd, 1987; Verfaillie and d'Ydewalle, 1991).

The onset repulsion effect presents a slightly different problem. Why would we ever expect to see a *backwards* shift? That is, what aspect of visual processing would ever lead to motion onset being perceived/remembered behind the true starting point? In the remainder of this General Discussion, five possible types of explanation are considered, namely, *Frames of Reference, Overcompensation, Misestimation, Misremembering* and *Misperception.*

Frames of reference. Relative motion between two objects or between an object and a reference frame can sometimes cause illusory or distorted motion perception (Dunker, 1929; Johansson, 1950). In the classic example of 'induced motion', Dunker (1929) showed that shifting a surrounding rectangular frame can lead to the perception of opposite motion in a completely stationary central dot. A backwards shift in perceived position could thus arise in the current work if some aspect of the display placed the onset location in opposition to a second reference event (e.g. the continued motion), reference point (e.g. onset versus offset locations) or reference frame (visible monitor frame in Expts 1–3, or the grid in Expt. 4). One appeal of this idea is that it would not necessarily require the presence of smooth motion and could thus also potentially account for the current implied motion errors.

How could such a mechanism account for the current results? One example would be if the eye movements involved in tracking the position of the dot, led to the perception of opposite shifts in the immediate surround, an effect known as the Filehne illusion (Filehne, 1922). Clearly, additional mechanisms would be needed to explain why the ORE persists, albeit at reduced levels, when observers fixate.

More importantly, to explain the ORE with such a frame of reference account, at least one further step would be needed. That is, a *backwards* shift in the perceived onset requires either that the to-be-remembered location becomes 'attached to' or is treated in the same way as the surround, and is thus shifted in the direction opposite to the continuing motion, or that some change in the perceived speed of dot motion arises because of illusory shift which then has an impact on later compensation or estimation strategies, ideas discussed in the next two points. Further manipulations of surrounding reference frames, such as adding physical, 'nulling' motion to the background, may prove a useful avenue for future research. Having said this, the apparent lack of modulation in the size of the ORE when a grid was added in Experiment 4 would seem to cast some doubt as to the central role of such a reference frame mechanism.

Overcompensation. Another possibility is that observers compensate for their uncertainty as to the true point of onset in some way. That is, if the observer realises that the true onset has been missed, this could lead to the selection of a point further back along the trajectory as a means of correction. The onset repulsion effect would thus be a form of response bias involving systematic overcompensation. A similar argument has recently been made, in the form of an optimal control strategy, as an explanation for saccadic undershoot (Engelbrecht *et al.*, 1999). Manipulating directional or positional uncertainty (e.g. by providing some form or pre-cue) might be a useful way to explore this issue.

Overcompensation could also arise due to the fact that objects in the real-world rarely appear instantaneously 'out of thin air'. Overcompensation could arise from a tendency to attribute some form of 'natural history' to the visual event. A similar argument for 'natural motions' was proposed by Runeson (1974) to explain why observers sometimes experience illusory acceleration when an object suddenly begins to move at a fast, constant velocity.

Misestimation. A third possibility is that the visual system tries to overcome the lack of precise onset information by providing mechanisms for *post-hoc* estimation of the origin. For example, given a good estimate of the total duration of an event, estimates of object velocity could be used to calculate distance travelled. The onset could then be estimated by working back from the more recently experienced offset point. Abrams and Landgraf (1990) provide evidence not only that judgements about an object's motion can be based either on estimates of absolute position or on estimates of distance travelled, but that estimates based on distance are sometimes more susceptible to some forms of error. Any secondary source of influence on perceived speed and/or distance, such as the Filehne illusion or Runeson's (1974) illusory acceleration effect, could also play a role in such estimation errors.

Misremembering. The previous two mechanisms have assumed that observers have an imprecise percept of the true onset point. An alternative is that the onset if accurately represented but becomes distorted during the delay before the report is made. The onset repulsion effect would thus result from some form of memory error. Memory distortions have been proposed as an explanation for other forms of localization error, most notably, representational momentum (Freyd and Finke, 1984). While such errors are typically forward in the direction of motion, some factors of the current display, such as the delay between onset and response (Freyd and Johnson, 1987) or the fact that the onset position is indicated relative to the offset point (Hubbard and Ruppel, 1999), could conceivably cause a backwards shift. It is also possible that some form of Boundary Extension (Intraub, 1997) is operating here. While a spatial form of this error might predict a shrinking of the remembered path, the witnessed event is inherently spatiotemporal, and thus a shifting of the event boundary would predict a backwards shift. One way to further investigate the memory aspects of the ORE would be to systematically vary the delay between observation and response. Thornton (1999), however, found very little variation in error patterns, at least, for complex paths, when retention interval varied between, 1, 5, and 10 s.

Misperception. Finally, it could be possible that observers are responding to some form of visual trace, even though this trace is not a veridical marker of motion onset. Kim and Francis (1998) recently suggested that inhibitory 'rebound' signals, designed to control visible persistence, could be used by the visual system to maintain a useful 'history' of an object's movement. They have presented computational and psychophysical evidence that 'motion lines', often used by artists and animators to convey a sense of motion in pictorial stimuli, may well have some neurophysiological reality (Francis and Kim, 1999; Kim and Francis, 1998). Their psychophysical studies of apparent motion are particularly interesting as they demonstrate that observer responses can be influenced by such traces.

Could a similar mechanism account for the ORE? The model proposed by Francis and Kim operates only at the local level (i.e. a rebound signal is generated once the target moves beyond the current feature detector). However, there is growing evidence from both behavioural studies (e.g. Watamaniuk *et al.*, 1994; Whitney and Cavanagh, 2001) and physiological studies (e.g. Berry *et al.*, 1999; Jancke *et al.*, 1999; Jancke, 2000) that the successful processing of motion requires computations that go beyond the immediate locus of stimulation.

Recently, much interest has been focused on the finding that motion processing early in the visual pathway, specifically, at the level of retinal ganglion cells, produces a wave of neural activity that appears to peak ahead of the current stimulus location. Such patterns of activation suggest some form of extrapolation or anticipation is being carried out (Berry *et al.*, 1999). At higher, cortical sites, successful non-local motion processing almost certainly relies on a complex interplay between both excitatory *and* inhibitory processes (Jancke *et al.*, 1999). If non-local inhibitory feedback is used to control and shape the spread of activation behind as well as ahead of a moving object, as suggested by recent physiological studies (e.g. Jancke, 2000), then this provides a possible mechanism for the ORE. That is, if inhibitory signals ever propagate back beyond the point of onset this could give rise to visual traces that bias observers' responses, just as in the case of Francis and Kim's local rebound signals. Establishing whether such inhibitory signals ever do cross the point of onset and, if so, what happens when they 'inhibit' previously unstimulated regions will be important questions for future research.

In the previous five sections, a range of potential mechanisms have been explored. As the current data does not provide conclusive support for any of these alternatives, it seems that only further studies will be able to provide a definitive answer as to the cause of the ORE. By way of speculation, however, the most promising direction for future research would appear to be along the lines of the 'mis-applied' inhibition explanation just discussed. This explanation not only capitalises on recent insights into the general nature of motion processing, it also lends itself to study from a broad range of perspectives, such as computational modelling and physiology.

In conclusion, the current work has introduced a new form of object mislocalization, the onset repulsion effect (ORE), and has made a first attempt at exploring some of the conditions under which it can be observed. Future studies will concentrate on exploring links to other, possibly related phenomena, and on establishing possible mechanisms. It is hoped that by further exploring this phenomenon, novel insights into how the visual system processes moving objects may be gained.

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