Sustained attention to objects' motion sharpens position representations: attention to changing position and attention to motion are distinct

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In tasks where people monitor moving objects, such the multiple object tracking task (MOT), observers attempt to keep track of targets as they move amongst distracters. The literature is mixed as to whether observers make use of motion information to facilitate performance. We sought to address this by two means: first by superimposing arrows on objects which varied in their informativeness about motion direction and second by asking observers to attend to motion direction. Using a position monitoring task, we calculated mean error magnitudes as a measure of the precision with which target positions are represented. We also calculated perceptual lags versus extrapolated reports, which are the times at which positions of targets best match position reports. We find that the presence of motion information in the form of superimposed arrows made no difference to position report precision nor perceptual lag. However, when we explicitly instructed observers to attend to motion, we saw facilitatory effects on position reports and in some cases reports that best matched extrapolated rather than lagging positions for small set sizes. The results indicate that attention to changing positions does not automatically recruit attention to motion, showing a dissociation between sustained attention to changing positions and attention to motion.

Introduction

Multiple object tracking (MOT) tasks are frequently used to explore visual attention. This type of task requires participants to track a number of indicated targets as they move around a screen amongst distracters. At the end of a trial the participant is typically asked to indicate whether one of the objects appearing on the screen is a target or not. Pylyshyn and Storm (1988) originally proposed that we have an architectural constraint on tracking based on a fixed number of pointers or FINSTs which can be used to track targets. We now know however that the limit on performance is not set by a fixed number of slots (e.g. Alvarez & Franconeri, 2007; Howard & Holcombe, 2008) but rather depends on a host of factors including speed (Holcombe & Chen, 2013) and inter-object spacing (Franconeri, Jonathan and Scimeca, 2010).

One issue under debate in the literature is whether or not motion information is used in one way or another during attentional tracking and attention to moving targets. In multiple object tracking tasks, motion information might be useful since it may increase the distinctiveness between objects on the basis of their different motion characteristics, as other visual aspects of distinctiveness have been shown to aid tracking (Makovski and Jiang, 2009). In traditional MOT tasks and more generally in attentional tracking of moving objects, it is possible that motion processing may facilitate the mechanism by which we represent the changing positions of objects. Position and motion are encoded in overlapping but non-identical areas of the brain. Primary and secondary visual cortices process spatial information such as position, and motion is also thought to be processed in these areas, as well as higher order areas such as V3 and V5/MT: Zeki et al. (1991) used PET to show that motion perception recruited areas V1/V2 and V5. From this, is it not clear whether position monitoring would automatically recruit the neural systems subserving motion processing, nor whether directing attention to motion would facilitate processing of positions of objects as they move.

How might attention to motion facilitate position monitoring? One possibility is that it may increase activation or sensitivity in position processing areas of cortex. In an fMRI study, Büchel et al. (1998) used a speed change detection task to engage attention to motion, showing that attention to motion increased activation in V3/V5 and the V1/V2 border over and above the activity seen for passive motion viewing. In this study, it is of note that attention to motion increased activation in the earlier areas of V1 and V2 and this may reflect a neural substrate of the facilitatory effects of attention to motion on position perception. This conjecture is supported by the fact that in the study by Zeki et al. (1991), expectations about motion appeared to modulate V1 activity even when the stimulus was static: more V1 activity was recorded for static stimuli when participants knew they would be viewing motion on subsequent trials than when they were expecting non-motion (colour) stimuli. If attention to motion facilitates lower-level spatial vision such as position perception, then it could be the case that this comes about by enhancement of cortical responsiveness in primary and secondary visual cortex.

Another way in which motion information may be used by the visual system is to support extrapolatory processes. There are several reasons why a mechanism that predicts near future states of objects may be helpful in MOT and position monitoring more generally. If the visual system could take account of the current trajectories of objects, then it may be able to compensate for neural delay incurred by the processing of visual information. Additionally, because of the demands on attention during tracking, there may be occasions where attention lapses momentarily, when targets and distracters become in danger of being confused, and where attention may switch between targets. In all these cases, it would be beneficial if the tracking mechanism were able to anticipate where targets would be after a brief interval of attention lapse or other failure to update the representation of target positions. Whether or not the tracking mechanism is able to, or routinely does make use of motion information to perform these extrapolatory processes is still unresolved.

Howard and Holcombe (2008) and Howard, Masom and Holcombe (2011) observed in a position report MOT paradigm that when asked to report the final position of targets, observers tend to report slightly out-of-date positions. In other words, position reports exhibited perceptual lag. In these experiments, observers tracked a varying number of objects under a range of speed, trajectory parameters and tracking region conditions, and observers consistently reported final positions that were more similar to positions occupied in the moments leading up to display offset than they were to the position displayed on the final frame before offset. However, Iordanescu, Grabowecky and Suzuki (2009) observed the opposite result, that responses were more likely to lie ahead of the final position of objects that in other directions. Atsma, Koning and van Lier (2012) used a probe detection task to assess the distribution of attention around moving targets and found better performance ahead of the targets' current positions. However, participants are very likely to have adopted a strategy of attending to the region around targets and therefore these data must overstate the diffuse spread of attention around targets. However, the fact that performance was better ahead of the position than behind does lend support to arguments for the role of extrapolation in MOT. The reason for the discrepant results between these studies is not currently clear.

Some studies have used motion trajectories of varying predictiveness in order to assess whether or not motion information may be used to extrapolate near future positions of objects. The results of these studies are also somewhat mixed. Howard, Masom & Holcombe (2011) varied predictability of objects' motion in a position report tracking task. In one condition, objects moved with constant speed and direction of motion unless they collided with each other or with the tracking region boundaries, and in another condition, the vertical and horizontal components of their accelerations were constantly and randomly changing. This had no effect on performance or on perceptual lag, suggesting at most a limited role for extrapolatory processes. Similarly, Vul, Frank, Tenenbaum and Alvarez (2009) varied the inertia of objects' motion during tracking. They found that performance was not affected by this manipulation of predictability. In contrast, Howe and Holcombe (2012) varied the predictability of objects' motion using two or four targets. In the predictable condition, objects travelled in straight lines until they collided with the edges of the display. In the unpredictable condition, they changed direction of motion randomly and with unpredictable frequency. They observed better performance in the predictable than the unpredictable condition, but only for tracking two targets. This suggests that direction of motion information was useful in some way but only for a limited number of targets. The main difference between this study and the previous two that did not report predictability effects is that in this study only direction of motion predictability was manipulated and not speed variability. Speed changes may therefore be less susceptible to extrapolatory processes. Another possibility is that the sudden direction changes may actually have attracted attention as they have been shown to under some circumstances (Howard and Holcombe, 2010). This may be detrimental to performance when changes occur in distracter objects. In any case, the evidence for whether or not trajectory predictability plays a role in performance is as yet unresolved.

Several recent studies have introduced motion to the surface texture of objects in order to investigate the role of motion information in tracking performance. If motion information is used to predict near future trajectories of targets during tracking, then introducing any motion

that is not consistent with the direction of travel should disrupt performance. It seems reasonable to suggest that motion information may be used in this way since it could aid in target recovery during brief tracking failures or switching of attention between targets.
An advantage of this method is that this surface motion can be manipulated independently of the motion of the object around the tracking space. St. Clair, Huff and Seiffert (2010) conducted several experiments using this technique of varying the direction and speed of surface motion relative to the translating motion of objects undergoing MOT. They reported poorer performance when the surface motion moved in the opposite direction to object motion, and to a lesser extent, when surface motion was orthogonal to object motion, than when surface motion was consistent with the actual direction of travel of objects. Interestingly, manipulations of surface motion speed had no consistent effect on performance.

This effect has since been replicated and shown even when different objects within a display possess different surface motion characteristics. Meyerhoff, Papenmeier and Huff (2013) introduced a condition in which some objects' surface texture moved in the same direction as object motion, and some had texture which moved in the opposite direction to travel. Individual targets with opposite motion were shown to be lost more often than those with consistent surface motion. Thus it appears that whatever processes are affected by surface motion appear to operate on an object based level. Huff and Papenmeier (2013) also report that alternating motion between consistent and opposite motion results in intermediate levels of performance between performance levels seen for simple consistent and opposite motion conditions. Further, the longer the periods of consistent motion compared to opposite motion, the more performance resembled that seen in the consistent condition.

One possibility is that the effects of non-consistent surface motion are due to disruptions of extrapolatory processes. However, another possibility is that surface motion affected position representations and this interpretation is problematic for accounts of tracking that propose facilitative effects of consistent surface motion. De Valois and De Valois (1991) found that surface motion affects where people perceive an object to be, even if the object is not physically moving and not being displaced in position. Hence in all the studies that manipulate surface motion, disruption by inconsistent surface motion may actually be due to objects appearing to be displaced in the direction of the surface motion.

Several studies have used occlusion techniques to assess the role of motion information in extrapolation. Meyerhoff et al. (2013) introduced a brief flash during the motion display part of each trial, after which targets, distractors or both changed direction. Target motion but not distracter motion change impaired performance which is consistent with the presence of extrapolatory processes. However, for any design using occlusion techniques, it is possible that participants anticipate the break in visibility introduced by flashes or other occlusion events and hence deliberately attend to motion characteristics more than they might otherwise do as a strategy to overcome this.

However, despite the fact that occlusion techniques might encourage extrapolatory strategies, three studies find no evidence or mixed evidence for anticipation of future positions. Franconeri, Pylyshyn and Scholl (2012) pitted motion information against position information in an occlusion paradigm. In a number of conditions, they had objects reappear after travelling behind an occluder either in a manner that was consistent with their motion trajectory, or at a position that was closer to its pre-disappearance position. Performance was better when the object reappeared near to where it disappeared, even if this violated potential expectations based on motion, hence arguing against extrapolation. Keane and Pylyshyn (2006) introduced occlusion events lasting 300-900 ms after which objects were presented in one of several different positions along its trajectory. It could either reappear at the position it disappeared ('no-move'), at an extrapolated position predicted by its velocity and the time interval since disappearance ('move') or at a 'rewind' position which is the position it previously occupied shortly before disappearance. Performance was worse in the 'move' condition than the other conditions, again providing no evidence for extrapolation.

In a similar design, Fencsik, Klieger and Horowitz (2007) found that performance was poorer in a 'move' condition compared to either 'no-move' or 'rewind' trials. To test for the possibility that the 'rewind' condition benefitted from the fact that objects soon moved back to their original pre-disappearance positions, they included displays where objects remained stationary after reappearing. The results were somewhat mixed: for tracking five targets there was little difference in performance between conditions, but for tracking two targets, performance was better in the 'no move' than the other conditions. They also investigated the extent to which viewing this pre-disappearance movement benefitted performance. For tracking one target, viewing this pre-disappearance moving trajectory benefitted participants, but was no help when tracking four targets. In summary, the only result of theirs that supports the idea of participants extrapolating is that viewing pre-disappearance trajectories helped when there was only one target. However, this is also consistent with participants deliberately encoding motion information when they know it will be helpful and when the tracking load is low enough to enable this.

In summary, evidence from studies using position report, surface motion and occlusion paradigms is mixed in terms of whether or not observers appear to use motion information when keeping track of moving objects. We here use a position monitoring task to assess the mechanism by which observers can attend to the changing positions of objects since this is a fundamental task of the human visual system and also one of the component aspects of the multiple object tracking task. Previous surface motion manipulations in tracking tasks carry the inherent risk of observing apparent extrapolation due to the known effects of local motion signals on position perception. On the other hand, occlusion studies which yield mixed results appear to encourage deliberate adoption of extrapolatory strategies. To avoid these pitfalls and to isolate the role of information about direction of motion, we use arrows of varying informativeness to evaluate their effect on position representations. We use these high level cues to isolate this type of information and to assess their possible contribution to position monitoring, thus avoiding the pitfalls of surface motion techniques which likely affect position judgements and occlusion techniques which likely encourage extrapolation strategies. Whether or not observers can and do make use of this type of information will be tested here both in terms of position monitoring performance and perceptual lags versus extrapolation in position reports. Of course, if this high level motion information does not aid performance here, it would not necessarily mean that motion information can never aid in position monitoring, only that high level information of this type does not appear to be used in this way. In addition, to directly encourage attention to motion direction, we introduce a dual task where in some conditions, observers are asked to report both the final position and the final direction of motion of targets. In doing so, we assess the effect, if any, of attention to motion information over and above the effect of attention to position. Note that although motion and change in position are identical constructs in physics, whether or not attention to changing position and attention to motion are separate cognitive processes remains an empirical question. In akinetopsia, for example, motion perception is compromised (typically after damage to area MT, see Zeki, 1991), but position perception even as it unfolds over time is relatively spared. Therefore just as perception of changing position and perception of motion are not identical processes, we ask whether attention to changing position and attention to motion are identical, and if not, whether attention to motion can facilitate position monitoring.

We will test whether or not attention to position as it changes over time necessarily entails attention to motion. If attention to motion has no effect on the efficacy of attention to position, then there would be two possible interpretations: first, that attention to changing position necessarily entails attention to motion, and therefore there is no additional effect of a direct instruction to attend to motion, or second, that the two attention types are distinct, but that attention to motion does not affect position monitoring. If attention to motion affects position monitoring, then it is logically undeniable that attention to motion is a separable type of attention from attention to position (since one entity cannot affect itself, a priori). If motion information can be used to enhance position representations, then attention to motion would be expected to aid performance in the position monitoring task in terms of precision of reports and potentially in overcoming perceptual lags. This would add weight to arguments made by others (e.g Huff & Papenmeier, 201; Meyerhoff et al., 2013; Meyerhoff, Papenmeier & Huff, 2013; St. Clair, Huff & Seiffert, 2010) that motion can aid in tracking-type tasks, but without recourse to add artificial texture motion or use of occlusion techniques to the display.

Experiment 1

Method: Overview

All experiments reported here were carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). In all experiments all observers gave informed consent prior to participation.

In Experiment 1, we investigated whether directly encouraging attention to motion information would assist with position monitoring. In this experiment, we used a dual task paradigm where in addition to position monitoring, observers were also asked on some trials to attend to the direction of motion of discs. We also investigated whether the presence of information about direction of motion, in the form of arrows, would assist with this position monitoring task.

Observers completed 50 trials in each block. Each block covered one of the four conditions in a 2x2 design varying task type (single task: position report only, dual task: both position and direction of motion report) and direction of motion information (randomly oriented arrows, arrows facing forward direction of motion). Observers completed these blocks in a random order. Trials with two or four targets were randomly intermixed within blocks. At the start of each block, observers were told whether the following trials would all be single task or dual task trials. Observers were given practice trials until they were comfortable with the task, usually fewer than 10 trials.

Method: Stimuli

A computer programme written in Python using the VisionEgg library (Straw, 2008; www.visionegg.org) displayed stimuli on a CRT screen at 1024 x 768 pixel resolution refreshing at 85 Hz. Observers viewed the display at a distance of 0.4 m in a dimly lit room.

Four white discs (84.82 cd/m^2) were displayed against a mid-grey (16.01 cd/m^2) background and were confined within their own quadrants of the screen. On every trial, observers either attempted to monitor the position of two out of four, or all four discs. At the end of each trial, all discs disappeared, and observers were queried to report the final position of one of the target discs. However, in dual task blocks, they reported both the final position and final direction of motion of the queried disc.

Depending on the block, black (0.04 cd/m^2) arrows superimposed on discs either all pointed in the correct current directions of motion, or in random directions of motion. Observers were told at the beginning of each block about the direction of the arrows but were not explicitly directed to attend to or attempt to use this information. When discs changed direction due to collisions, the arrows changed direction accordingly. In the random condition, orientations were randomly reselected after every collision to equate this condition for frequency of orientation change.

Method: Observers

Observers were 20 undergraduates and postgraduates at Nottingham Trent University recruited though an opportunity sample from the Psychology Department research participation scheme for course credit and one staff member (14 females, 6 males, mean age = 23.3 years, range 18-37). All had normal or corrected-to-normal vision.

Method: Procedure

On every trial, one disc with a superimposed arrow appeared in each of four square areas to the upper right, upper left, lower left and lower right of fixation and each measuring 21.60 x 21.60 degrees (see Figure 1). At the start of each trial, either two randomly selected discs or all four discs flashed black for 1500 ms to indicate their status as targets for tracking. Discs were 2.88 degrees in diameter and arrows measured 0.65 x 2.16 degrees. After this period all discs moved as described in the Trajectories section within their individual square areaswith the constraint that their outer edges could not come within 0.3 degrees of a boundary, and observers attempted to monitor the positions of the targets. Between 2400 ms and 3600 ms after the start of the discs' motion, all discs disappeared.

After disc offset, observers were first prompted to indicate the final perceived position of a single queried target. The queried target was indicated by a brightening of the outer edges of its square area on the frame immediately following the end of the motion period and the disappearance of the discs. Observers used a sample black disc which acted as a mouse cursor to select the chosen position using a mouseclick. On dual report trials, immediately following this position report, a sample black arrow appeared at fixation, and observers adjusted its orientation using keypresses to match the final perceived direction of motion of the queried target. For example, to report a perceived final direction of motion of moving upwards and slightly to the right, they might adjust the arrow orientation to 17 degrees clockwise of vertical. Note that observers were exposed to arrows both during the motion phase where they were superimposed on discs, at the response stage where observers adjusted a central arrow to make direction of motion reports (during dual task trials), and also during the feedback phase at the end of the trial. After observers pressed the enter key to indicate they were satisfied with their motion direction report, all four discs reappeared in their veridical final positions with arrows indicating their veridical final directions of motion.

Method: Trajectories

On each trial, the initial positions within their square areas, speeds and directions of motion were set randomly and independently for each disc. Discs' directions of motion only changed after collisions with the edge of the square boundaries, as defined by the law of perfect elastic collisions. For all discs and on all trials, initial starting speeds and directions of motion were randomly determined within the set of constraints determined below.

Horizontal and vertical components of each disc's initial speed were set randomly and independently, with the constraint was that the initial speed was greater than 4 deg/s and less than 44 deg/s, producing a mean speed of 24 deg/s. Due to frequent collisions, directions of motion were constantly changing according to the law of perfect elastic collisions (mean number of collisions per trial for each disc 4.39, SD = 1.8).

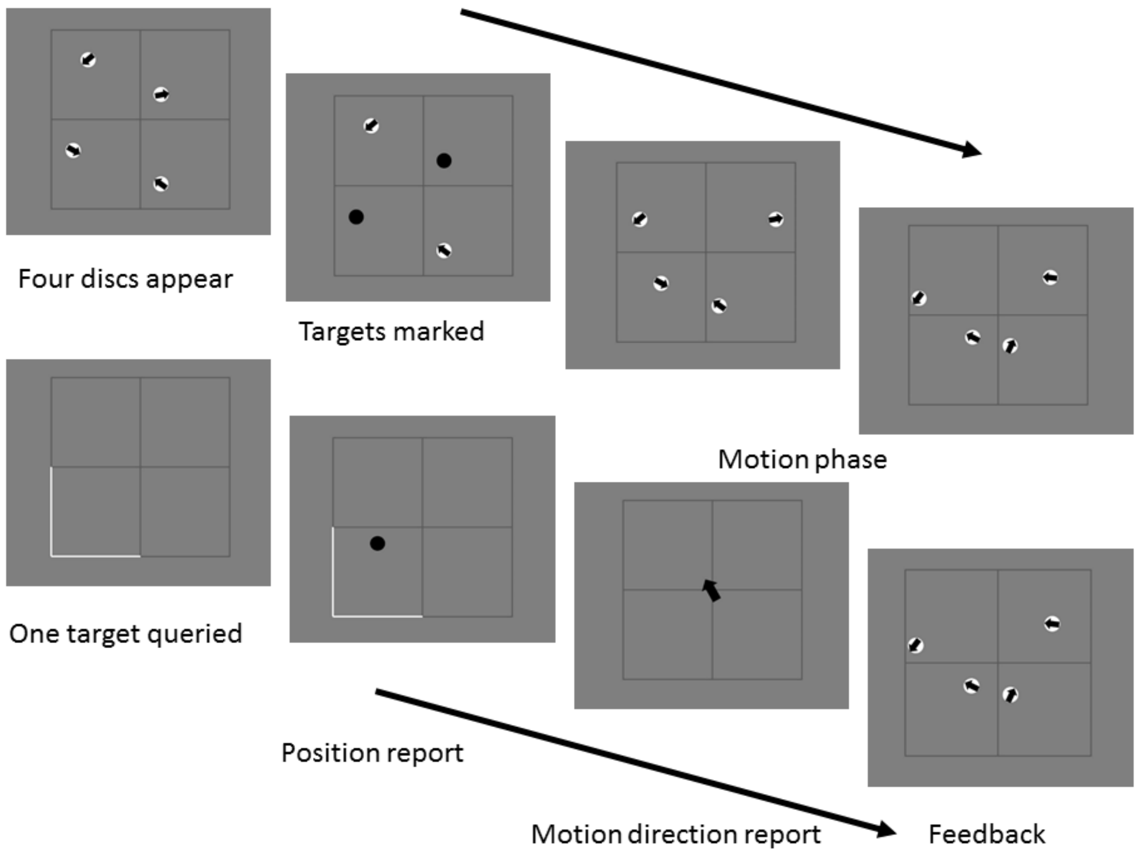

Figure 1: Trial timeline for a typical dual task trial in Experiment 1.

Results: Direction of motion reports

No single observer's mean performance produced mean error magnitudes worse than two standard deviations above the mean, therefore none were excluded from further analyses.

On every trial on which observers were prompted to give their estimation of the final direction of motion of one of the targets, we computed the mean angular error. This is the absolute difference in degrees between the reported and actual final directions of motion (see Figure 2, righthand panel). For tracking two targets with forwards motion, the mean error was 40.12 degrees (SD=16.21) and for tracking two targets with random arrow direction the mean error was higher at 63.64 degrees (SD=25.89). For tracking four targets with forwards motion, the mean error was 61.34 degrees (SD=14.52) and for tracking four targets with random arrow direction the mean error was again higher at 75.67 degrees (SD=17.30). In a 2x2 ANOVA, there was a main effect of tracking load ($F(1,19) = 33.67$, $p < 0.001$, partial eta squared = 0.64) but no main effect of the direction of arrows ($F(1,19) = 3.33$, $p = 0.084$, partial eta squared = 0.15) and no interaction ($F(1,19) = 3.62$, $p = 0.072$, partial eta squared = 0.16).

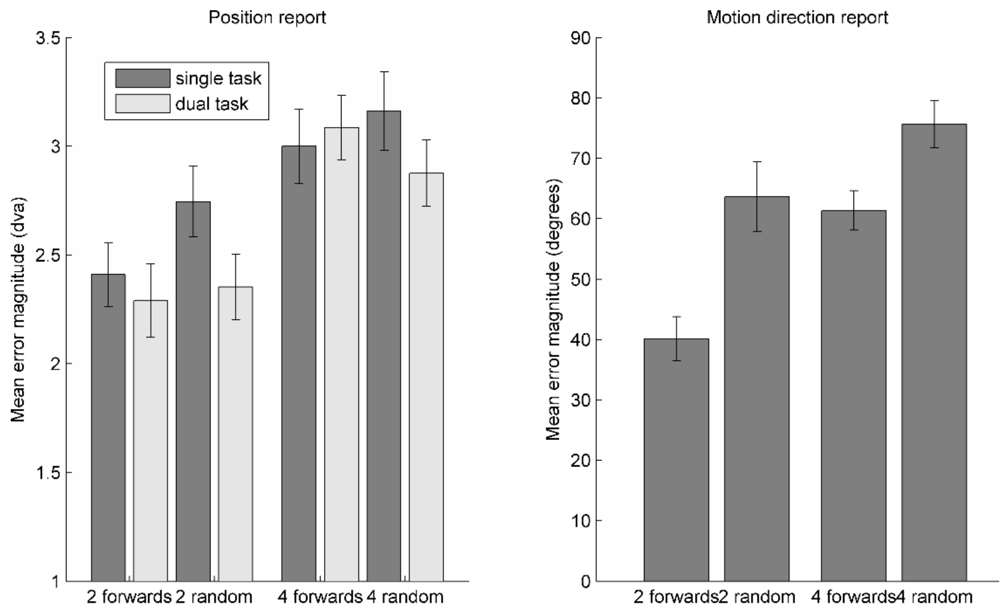

Figure 2: Position report error magnitudes (left) and direction of motion report errors magnitudes (right). Error bars indicate standard errors.

Results: Position reports

On every trial we calculated the mean error magnitude of position reports (see Figure 2, lefthand panel). For tracking two targets on single task trials, with forwards arrows, the mean error was 2.41 deg (SD = 0.66 deg), for tracking two targets on dual task trials with forwards arrows, the mean error was 2.29 deg (SD = 0.76 deg). For tracking two targets on single task trials, with randomly oriented arrows, the mean error was 2.75 deg (SD = 0.73 deg), for tracking two targets on dual task trials with randomly oriented arrows, the mean error was 2.35 deg (SD = 0.68 deg). For tracking four targets on single task trials, with forwards arrows, the mean error was 3.00 deg (SD = 0.77 deg), for tracking four targets on dual task trials with forwards arrows, the mean error was 3.09 deg (SD = 0.67 deg). For tracking four targets on single task trials, with randomly oriented arrows, the mean error was 3.16 deg (SD = 0.81 deg), for tracking four targets on dual task trials with randomly oriented arrows, the mean error was 2.88 deg (SD = 0.69 deg).

Smaller set sizes produced more precise position reports, as did the dual task condition when observers were also attending to direction of motion. These effects were confirmed by a 2 (load: two vs four targets) x 2 (direction of arrows: forward vs random) x 2 (task: single vs dual task) ANOVA, where there was a significant effect of load ($F(1,19) = 35.60$, $p = < 0.001$, partial eta squared = 0.65) and of task ($F(1,19) = 5.35$, $p = 0.032$, partial eta squared = 0.22) but not of direction of arrows ($F(1,19) = 0.35$, $p = 0.560$, partial eta squared = 0.02). There was no significant interaction between load and arrow direction ($F(1,19) = 2.70$, $p = 0.120$, partial eta squared = 0.13), between load and task ($F(1,19) = 0.65$, $p = 0.430$, partial eta squared = 0.04), between arrow direction and task ($F(1,19) = 1.63$, $p = 0.220$, partial eta squared = 0.08) nor any 3-way interaction between load, task and arrow direction ($F(1,19) = 0.08$, $p = 0.792$, partial eta squared = 0.01). It should be noted that on dual task trials, there was visual similarity between the arrows superimposed on discs during the motion phase and the arrow used to make direction of motion reports. This might have primed observers to pay more attention to the arrows during motion, but this appears not to have been the case. There was also evidence of a bias away from the centre of the screen (as previously reported by Howard & Holcombe, 2008) since on average, 57.82 % of responses were further from the centre of the screen than a simulated guess located at the centre of the individual square boundary of the queried target. We also tested for whether there was evidence of learning throughout the experiment as a result of practice with feedback but found no improvement in the second half of testing compared to the first ($t(38) = 0.43$, $p = 0.670$).

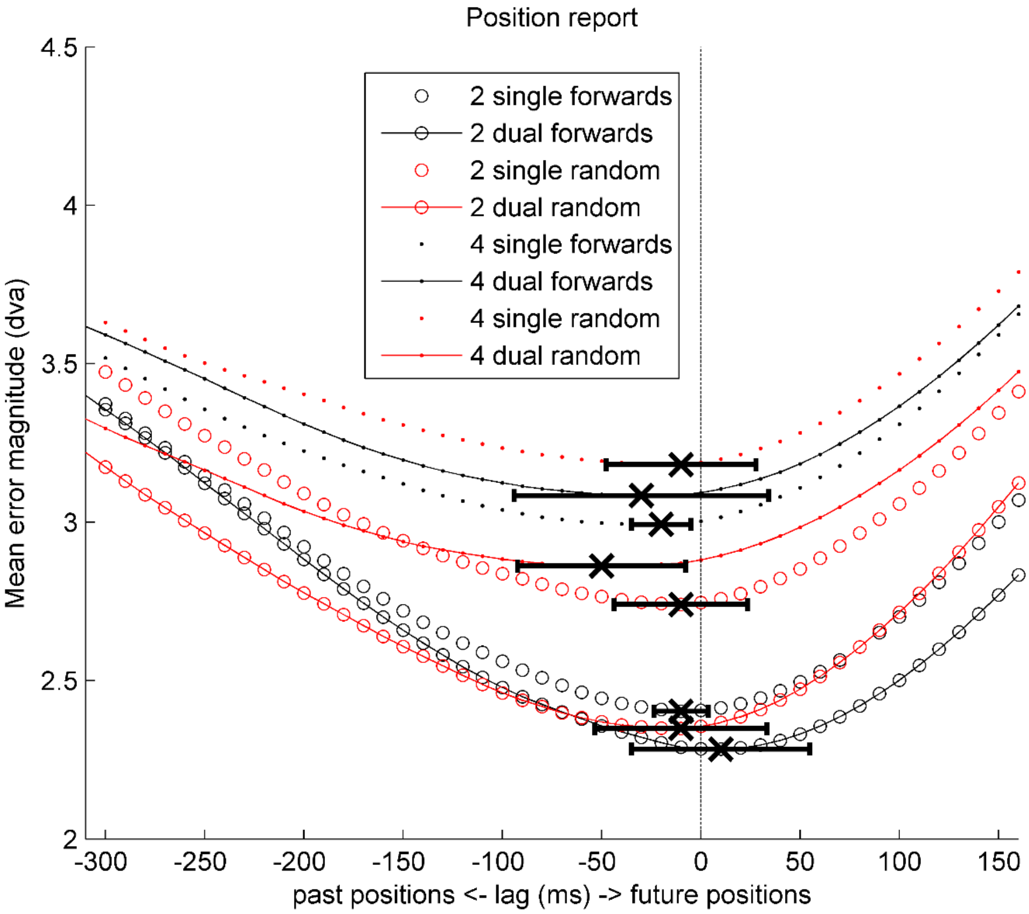

Figure 3: Perceptual lags. Error bars indicate standard errors.

We also calculated perceptual lags as per Howard and Holcombe (2008) and Howard, Masom and Holcombe (2011), shown in Figure 3. To calculate perceptual lags, we compared position reports with the positions of targets in final frames of the display leading up to its disappearance. In Figure 3, the points where the curves cross the dotted vertical line is the mean difference across all trials between the reported and actual final positions of the queried target.

The points on the curves immediately to the left of this indicate the difference between reported positions and the position of the queried target one frame (12 ms) before display offset. Each successive point further and further to the left indicates the difference between reported positions and positions earlier in the trial. Points to the right of the dotted line indicate the difference between position reports and extrapolated hypothetical future frames had the target continued moving at its final speed and direction of motion. Minima on these curves are the times at which position reports best match the stimulus i.e. perceptual lags. These minima are indicated with crosses on the curves for each condition. Mean lag magnitudes (see Figure 3) were between 10 ms and 60 ms in all conditions except for the two target, dual task condition with forwards arrows, where extrapolation was seen of magnitude 10 ms, indicating that on average in this condition, reports best matched the positions that the queried target would have occupied had it been displayed for 10 ms longer after the actual moment of disappearance.

The effects of load, arrow direction and task on lag were assessed by a 2 (load: two vs four targets) x 2 (direction of arrows: forward vs random) x 2 (task: single vs dual task) repeated measures ANOVA, where there was a significant effect of load ($F(1,19) = 7.07$, $p = 0.015$, partial eta squared = 0.27) but no effect of task ($F(1,19) = 1.52$, $p = 0.232$, partial eta squared = 0.07) nor direction of arrows ($F(1,19) = 0.22$, $p = 0.639$, partial eta squared = 0.012). There was no significant interaction between load and arrow direction ($F(1,19) = 1.35$, $p = 0.260$, partial eta squared = 0.07), between load and task ($F(1,19) = 0.51$, $p = 0.484$, partial eta squared = 0.03), between arrow direction and task ($F(1,19) = 0.77$, $p = 0.392$, partial eta squared = 0.04) nor any 3-way interaction between load, task and arrow direction ($F(1,19) = 3.00$, $p = 0.099$, partial eta squared = 0.14).

Lags were not significantly different from zero for the two target forwards single task ($t(19) = 1.57$, $p = 0.132$),for the two target forwards dual task (($t(19) = 1.00$, $p = 0.329$), the two target random single task ($t(19) = 2.00$, $p = 0.060$) nor two target random dual task ($t(19) = 1.82$, $p = 0.085$). For the four target conditions, lags were in all cases significantly more negative than zero for the forwards single task ($t(19) = 2.73$, $p = 0.013$) for the forwards dual task ($t(19) = 2.49$, $p = 0.022$), for the random single task ($t(19) = 2.51$, $p = 0.021$) and the random dual task ($t(19) = 2.20$, $p = 0.041$).

Experiment 2

Method: Overview

In Experiment 2, we sought to replicate the facilitatory effects of the dual task motion direction reporting on position reporting with a fuller range of set sizes and without the superimposed arrows which did not affect performance in Experiment 1. Observers participated in four blocks of trials. Each observer participated in two single task blocks and two dual task blocks. Blocks were completed in a random order. In single task blocks, observers reported the final position of the queried disc and were provided with feedback by means of the queried disc appearing in its final veridical position (with the addition of a superimposed arrow indicating the final direction of motion, although direction of motion was not directly task-relevant on these trials). In dual task blocks, observers attempted to monitor the changing positions and directions of motions of the target discs, and were prompted to report the final position, and then the final direction of motion of the queried target disc. As in the single task, after the reports had been made, the queried disc appeared in its final veridical position as feedback along with a superimposed arrow indicating the final veridical direction of its motion.

Experiment 2 was identical to Experiment 1 except for the following differences. Each block contained 48 trials. On each trial there were either 1, 2, 3 or 4 out of the four objects as targets for tracking, selected on each trial with equal probability. Discs were 1.2 degrees in diameter and their motion was constrained such that their outer edges could not come within 0.5 degrees of a boundary. Arrows were used for observers to make their direction reports and for direction feedback although they were not present during the period of discs' motion.

Method: Observers

Observers were 22 undergraduates and postgraduates recruited though an opportunity sample from the Psychology Department research participation scheme for course credit and two staff members at Nottingham Trent University (12 females, 10 males, mean age = 24.3 years, range 18-36). All had normal or corrected-to-normal vision.

Results: Direction of motion reports

One observer's mean position monitoring performance produced mean error magnitudes greater than two standard deviations above the mean, therefore this observer was excluded from further analyses (before removal mean = 2.18 deg, SD = 0.95, after removal mean = 1.94 deg, SD = 0.53).

Direction report errors are shown in Figure 4, righthand panel. Direction of motion error magnitudes were smallest for one target trials (mean = 22.00 deg, SD = 17.49) and became progressively larger for tracking two targets (mean = 36.70 deg, SD = 19.33), tracking three targets (mean = 47.63 deg, SD = 20.72) and tracking four targets (mean = 57.19 deg, SD = 19.97). A one way repeated measures ANOVA confirmed this effect of load ($F(3,60) = 38.05$, $p < 0.001$, partial eta squared = 0.67) and post hoc tests showed significant differences between tracking one and two targets ($t(20) = 4.75$, $p < 0.01$), between tracking two and three targets ($t(20) = 3.56$, $p < 0.01$) and between tracking three and four targets ($t(20) = 1.68$, $p = 0.11$).

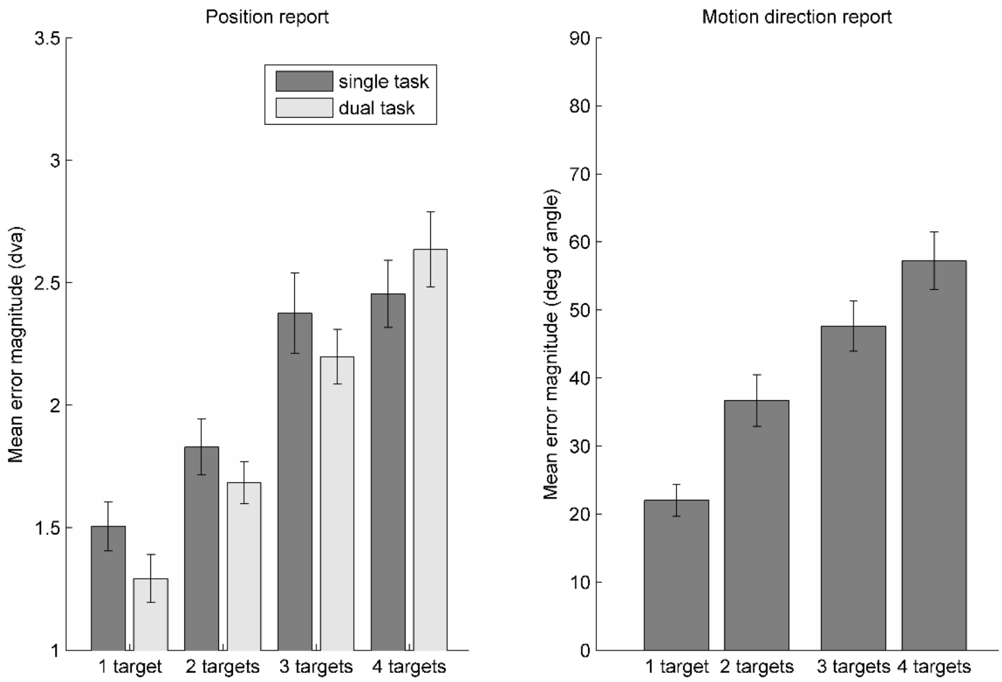

Figure 4: Position report error magnitudes (left) and direction of motion report errors magnitudes (right). Error bars indicate standard errors.

Results: Position reports

Position reports are shown in Figure 4, lefthand panel. The mean error magnitudes for tracking one target under single target conditions was 1.51 deg (SD = 0.82 deg) and under dual task conditions was numerically smaller at 1.29 deg (0.87 deg). The same pattern was seen for tracking two targets under single (mean = 1.83 deg, SD = 0.83 deg) versus dual task (1.68 deg, SD = 0.79 deg) conditions. For tracking three targets, performance was also slightly worse for single (mean = 2.38 deg, SD = 0.81 deg) than dual task (2.20 deg, SD = 0.62 deg) trials. However, for tracking four targets the trend was reversed, with better performance in single (mean = 2.45deg, SD = 0.73 deg) than dual task (mean = 2.64 deg, SD = 0.89 deg) trials.

A 4 (load, 1,2,3 or 4 targets) x 2 (task: single vs dual task) ANOVA confirmed the main effect of load ($F(3, 60) = 69.38$, $p < 0.001$, partial eta squared = 0.79) but not of task ($F(1, 20) = 2.17$, $p = 0.157$, partial eta squared = 0.10). There was a significant interaction between load and task ($F(3, 60) = 4.34$, $p < 0.008$, partial eta squared = 0.19) such that dual task conditions were better for performance under smaller loads and single tasks better for higher loads. In additional, a pairwise comparison between single and dual task conditions for the one target condition revealed a facilitative effect of the dual task (t(20) = 2.68, p =0.015) which was no longer significant for tracking two targets (t(20) = 1.84, p =0.082) nor three targets (t(20) = 1.60, p =0.125) or four targets (t(20) = 1.73, p =0.100).

As in Experiment 1, there was a bias away from the centre of the screen with on average, 59.08 % of responses lying further from the centre of the screen than a simulated guess located at the centre of the individual square boundary of the queried target. We also tested for whether there was evidence of learning throughout the experiment as a result of practice with feedback but found no improvement in the second half of testing compared to the first ($t(40) = 0.17$, $p = 0.862$).

Mean lags (see Figure 5) were between 10 ms and 40 ms for all conditions except when there was only a single target. For the one target single task condition there was extrapolation of magnitude 20 ms and for the one target dual task condition there was extrapolation of magnitude 10 ms.

A 4 (load, 1,2,3 or 4 targets) x 2 (task: single vs dual task) repeated measures ANOVA confirmed the main effect of load on lags ($F(3, 60) = 12.44$, $p < 0.001$, partial eta square = 0.40) but not of task ($F(1, 20) = 1.64$, $p = 0.216$, partial eta square = 0.08). There was no interaction between load and task ($F(3, 60) = 0.42$, $p = 0.736$, partial eta square = 0.02). However, for 1 target in the single task, the lag was significantly more positive than zero (t(20) = 2.64, p = 0.016), and was approaching significance for the 1 target, dual task condition (t(20) = 1.86, p = 0.079). For 2 targets, the lag was not significantly different from zero in either single (t(20) = 1.04, p = 0.311) or dual task conditions (t(20) = 1.32, p = 0.202). In the 3 target conditions, the lag was significantly more negative than zero for both single (t(20) = 2.98, p = 0.008) and dual tasks (t(20) = 2.70, p = 0.014). In the 4 target conditions, the lag was also significantly more negative than zero for both single (t(20) = 2.75, p = 0.013) and dual tasks (t(20) = 3.26, p = 0.004).

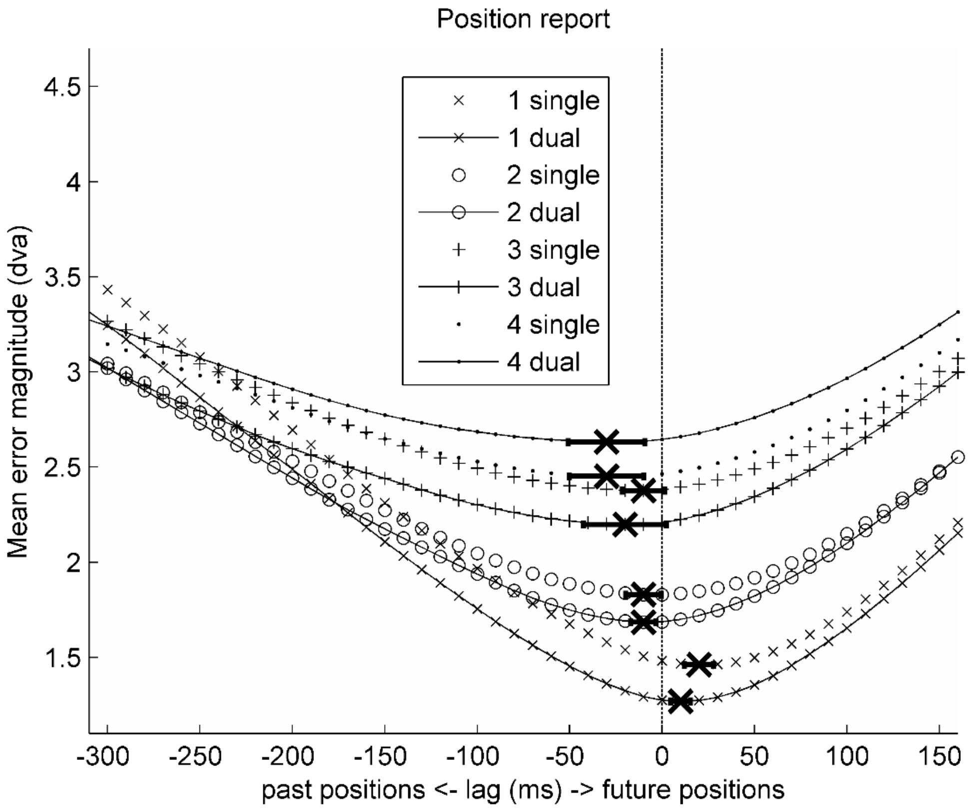

Figure 5: Perceptual lags for Experiment 2. Error bars indicate standard errors.

In a comparison between experiments, we compared performance for both direction of motion and position reports. For direction of motion reports, performance in the two target condition of Experiment 2 was better than the equivalent two target condition in Experiment 1 with random arrow direction (t(19) = 3.83, p = 0.001) but not different from the equivalent two target condition in Experiment 1 with veridical forwards arrow direction (t(19) = 0.61, p = 0.546). The same was true for four target direction of motion reporting in Experiment 2 i.e. it was better than the equivalent four target condition in Experiment 1 with random arrow directions (t(19) = 3.63, p = 0.002) but similar to the equivalent four target condition in Experiment 1 with forwards arrow directions (t(19) = 0.55, p = 0.587). In other words, direction of motion reporting in Experiment 2 resembled the forwards arrow conditions of

Experiment 1. This suggests that the presence of forwards-facing arrows in Experiment 1 did not affect performance and that the randomly oriented arrows in Experiment 1 may have distracted observers from the direction of motion monitoring task.

For position reports we made similar comparisons between conditions in Experiments 1 and 2 as follows. Performance in the single task two target condition of Experiment 2 was better than both the forwards arrow ($t(19) = 3.44$, $p = 0.003$) and randomly oriented arrow ($t(19) = 4.69$, $p < 0.001$) equivalent conditions in Experiment 1. Performance in the dual task two target condition of Experiment 2 was also better than both the forwards arrow ($t(19) = 2.73$, $p = 0.014$) and randomly oriented arrow ($t(19) = 3.65$, $p = 0.002$) equivalent conditions in Experiment 1. Similarly, performance in the single task four target condition of Experiment 2 was better than both the forwards arrow ($t(19) = 2.61$, $p = 0.017$) and randomly oriented arrow ($t(19) = 2.71$, $p = 0.012$) equivalent conditions in Experiment 1. However, performance in the dual task four target condition of Experiment 2 was not different from either the forwards arrow ($t(19) = 1.65$, $p = 0.117$) or randomly oriented arrow ($t(19) = 1.08$, $p = 0.293$) equivalent conditions in Experiment 1. Therefore it appears likely that the presence of arrows on discs in Experiment 1 appears to have distracted participants from the position monitoring task, since performance was better in Experiment 2 where no arrows were superimposed during the motion phase, with the exception of the four target dual task condition of Experiment 2, where performance was similar to the equivalent conditions of Experiment 1. It seems possible that under these higher task demands, distraction effects were less likely to show up in the performance data.

Discussion

Taken together, the two dual task experiments presented here show a facilitatory effect of attention to motion on position monitoring in terms of spatial precision of reports, despite the fact that dual tasks are usually associated with performance costs rather than benefits. In single task conditions, observers seem to be relying solely on attention to changing position and not attention to motion, since the benefit is only seen in dual task conditions. Therefore, position monitoring does not appear to automatically recruit attention to motion, demonstrating that attention to position and attention to motion are dissociable processes. Specifically, we find that in Experiment 1, attention to motion causes position reports to be made with greater precision. In Experiment 2, we see an interactive effect, such that attention to motion aids position report precision but only for smaller attentional loads. The fact that the effects of attention to motion interacted with load in Experiment 2 indicates a limited capacity for motion encoding in these position monitoring tasks. This is similar to previous findings of a very low capacity estimate for when motion encoding is the sole task of the observer (Horowitz & Cohen, 2010). Furthermore, in some conditions, position reports best resembled slightly extrapolated rather than lagging positions, potentially indicating a secondary beneficial effect of attention to motion on temporal as well as spatial precision.

Arrows providing information about direction of motion, in the form of relatively high-level semantic representations did not appear to affect performance either in terms of position reports or perceptual lag. In fact, between-experiment comparisons suggest that these arrows were actually in some cases a source of distraction from the task. We also replicate the finding that localisation precision depends on load, even for numbers of targets below four (Howard & Holcombe, 2008; Howard, Masom & Holcombe, 2011). These results are contrary to any fixed architectural limit of four objects (Pylyshyn & Storm, 1988) and instead are consistent with a flexible resource that that can be shared according to the number of objects attended (Alvarez & Franconeri, 2007).

Our data suggest that when observers attend to motion, this sharpens their position representations. Since this effect is seen in the dual task data we present here, the magnitude of the effect is likely to be greater than estimated in these data. Dual task aspects of the task such as holding two pieces of information in memory and preparing to execute two potential responses should, if anything, serve to decrease performance on one or both tasks, hence it is probable that attention to motion would have produced even more facilitation of position perception were it not necessary to probe both aspects using a dual task design. One possibility is that these sharpened position representations may be brought about by increased cortical responsiveness or sensitivity in early visual areas.

In addition to the facilitative effects of attention to motion on the primary measure of successful position monitoring (namely spatial precision of position reports), we report that position reports generally best resembled positions occupied by targets in the moments leading up to their disappearance rather than their final positions. That is to say, position reports frequently exhibited perceptual lag. Although perceptual lag is not the primary measure of performance in position monitoring tasks, perceptual lags are of interest since they are informative about how the visual system maintains representations with temporal precision. As previously found by Howard and colleagues (2008; 2011), perceptual lag was reduced when observers tracked fewer targets. Under some circumstances in the experiments presented here, perceptual lags numerically crossed over into extrapolation, that is to say that position reports best resembled positions that targets would have occupied had they continued moving for a few moments into the future. This was the case in Experiment 1 for monitoring two targets with forwards arrows under dual task conditions and in Experiment 2 for both one target conditions. It is not surprising that in general these cases were seen in circumstances where the number of targets was very few given the known severe capacity limit for attending to motion (Horowitz & Cohen, 2010; Tripathy & Barrett, 2004). It is also not surprising that the condition under which we see positive extrapolation values in Experiment 1 is under dual task conditions. For Experiment 2, both one target conditions produced positive extrapolation values for both single and dual tasks and this extrapolation is significantly different from zero in the single task. It is worth noting however that in Experiment 2, single and dual tasks trials were intermixed within blocks, therefore there may have been some carryover of attention to motion from dual task to single task trials –in other words, people may have attended to motion to some extent even in single task trials (if this is the case, it would further strengthen conclusions around the significance of attention to motion on position reports, since it would mean that these effects are actually underestimated here). Taken together, these positive extrapolation values seen in some conditions here contrast with the consistently lagging reports seen in previous similar position monitoring work (Howard & Holcombe, 2008; 2011). This suggests that in addition to the facilitatory effects of attention to motion on precision of position encoding, motion information may be used to compensate for various processes that cause representations to lag behind veridical states of seen objects.

Why should attention to motion cause a reduction in lags or potentially even extrapolated position reports? Given that neural processing takes time, the visual system may compensate to some extent to ensure that any actions such as eye movements or manual responses to moving targets are appropriately timed to intercept targets. Yilmaz et al. (2007) observed that flashed stimuli appear to be mislocalised towards extrapolated positions of nearby moving objects. On the basis of this observation, they suggested that motion signals are used to enhance processing of visual information slightly ahead of the current position of moving objects. They propose that a retinotopic motion map might be used to enhance the gain of position sensitive cells at extrapolated locations in a retinotopic position-map (a mechanism similar to that proposed by Verghese and McKee (2002) in which motion enhances the detectability of subsequent motion signals lying ahead the moving stimulus). In the experiments reported here, we test directly how the influence of motion processing may affect position processing when the motion and position signals are possessed by the same object. Indeed it does appear very possible that attending to motion does enhance sensitivity of position sensitive neurons lying ahead of the current trajectory of the moving object. This could then explain both the enhanced precision of position reports and presence in some conditions of extrapolatory position reports.

Evidence from studies manipulating the predictability of motion support the view that observers may be able to use motion information to aid tracking, but using a mechanism which can only support motion encoding for a very small number of objects. Howe and Holcombe (2012) showed that motion predictability only facilitated tracking performance for tracking two targets and not four targets, whilst Howard, Masom and Holcombe (2011) found no effect of motion predictability on performance for four targets. This limited capacity account could also explain the differences in effects seen between set sizes in the study by Fencsik, Klieger and Horowitz (2007) who reported an advantage from viewing pre-occlusion trajectories but only for one target. It is also consistent with our finding that the effect of the dual task was only significant in pairwise comparisons for tracking one target here, and the numerical advantage for the dual task over the single task was only apparent for tracking 1-3 targets. In fact, in the data reported here, performance is numerically worse in the dual task than the single task when tracking four targets. This suggests that a classic dual task penalty is being paid by the attentional system here, but that in smaller loads, this is masked by the facilitative effects of motion encoding on position perception. Another way to look at this is that under single task conditions, there is very little penalty in adding another target to the load from three to four targets, but under dual task conditions, performance is substantially worse going from three to four targets. In other words, at higher loads, the classic dual task penalty is observed whereby performing two tasks results in poorer performance than single task conditions. The fact this effect is absent and actually reversed at low loads shows that the facilitative effect of attention to motion is substantial enough to overcome the challenges of performing two demanding tasks concurrently.

The dependence on load and mixed findings between previous studies raises the additional possibility that use of motion information also relies on observers' use of attention to motion as a strategy during tracking. If specific attention-to-motion strategies adopted by observers are important for determining whether motion processing can be used to aid performance, then subtle differences in instructions between studies could be critical: for example 'keep track of where the targets are' versus 'keep track of the *moving* targets' could yield important differences in perceptual lags versus extrapolation. In the method used here, there was no possibility of losing track of the identity of targets and distractors if they become confused for one another by crossing one another's paths, since objects were constrained to their own areas of the screen. In a more traditional MOT paradigm, where objects can cross paths, come close together or collide, attention to motion may facilitate performance even further by allowing observers to discriminate between different objects on the basis of their motion trajectories (for example, if a participant knows a target was moving upwards, and it comes close to a distractor which they know is moving rightwards, they may be less likely to confuse the target with the distractor). However there was no possibility for such confusion to occur here, and hence attention to motion was not being used to prevent observers from losing track of targets' identities. In traditional MOT tasks therefore we might expect that attention to motion will be an important part of observers' strategy.

We consider that whether or not lag or extrapolation occurs on any given trial will be the sum of several processes. Each of these processes may vary in how much they affect responses in different experimental designs but overall will sum to produce either lag or extrapolation (for a fuller discussion, see Howard, Masom & Holcombe, 2011). In this conceptualisation, even a zero lag (or equivalently, zero extrapolation) is of interest since it indicates that these processes are overall cancelling one another out. One of these processes might be active construction of future positions of objects on the basis of their current motion trajectories. One process which may decrease lags is sensory memory. Since we did not mask the display after offset, it is possible that observers had some access to sensory memory traces that persist for a few hundred milliseconds after the disappearance of targets. Shooner et al. (2010) have shown that this is likely the case for trajectory tracking and this seems likely to have reduced the magnitude of lags here.

In addition to the fact that attention to motion appears to be very capacity limited, Zhong et al. (2014) point out that any strategy leading to extrapolation of moving targets may not always actually be beneficial to tracking performance. They conducted a computational investigation showing that extrapolating an already noisy representation of targets was in most cases actually detrimental to performance and under some circumstances slightly beneficial but only when the extrapolation is very conservatively weighted against other tracking information.

One process that will contribute to perceptual lags is temporal integration of visual signals. The visual system does not have infinite temporal resolution and hence must sum signals over a short period to produce percepts and this integration period for perception of several different visual features is estimated at around 100 ms (e.g. Gorea & Tyler, 1986; Watamaniuk & Sekuler, 1992; Kahneman & Norman, 1964). For this reason, after stimulus offset, even if observers take a moment to complete processing of the visual signal they have just seen, their position percept may reflect the summed input from a period of around 100 ms before offset. It is also possible that the duration of this integration window may be modified by attention (Motoyoshi, 2010; Yeshurun & Levy, 2003), potentially causing load effects on lag magnitudes.

Another factor which may contribute to perceptual lags is encoding perceived positions into visual short term memory (VSTM). This may be necessary in order to make these position estimates available for conscious report. Estimations for the speed with which object representations can be loaded into VSTM are 50 ms per item (Vogel et al., 2006). However, since responses are unspeeded, this consolidation into memory might be assumed to occur after stimulus offset, allowing the last perceived position to be reported without any effect on lag.

The effect of load on perceptual lag we see here is consistent with the presence of a serial element to the tracking mechanism that is perhaps either more likely to switch between targets or groups of targets when the number of targets to be tracked is greater, or parallel mechanism that is slowed by load. This idea is consistent with the presence of a serial component to the tracking mechanism as suggested by some (Oksama & Hyona, 2008; Tripathy et al., 2011). If a serial element is required to refresh representations of target positions, then the queried target will have, on average, been refreshed only recently in the past, which would give rise to the perceptual lags reported here. Further, a serial element predicts the increase in perceptual lag seen with increases in set size, as the more objects the serial mechanism must cycle through, the further in the past the queried target will have been last refreshed on average. Specifically in the MOMIT model (Oksama & Hyönä, 2008), it is identity-position bindings that are refreshed in a serial manner. However, in the work presented here, and in the position monitoring experiment reported in Howard and Holcombe (2008), this increase in lag with number of objects is also reported, despite no identity information being required other than position. Given that we find perceptual lags in most conditions across these four experiments except when attention load is low and attention to motion is engaged, attention to motion could be one such candidate for a serial process that must be switched across objects.

As stated in the introduction, evidence for extrapolation using occlusion methods (e.g. Meyerhoff et al., 2013) or introducing other breaks in visual information about target positions likely encourages observers to adopt strategies to overcome these events, and therefore may make it more likely that anticipatory processes are reported. However, even when observers know that occlusions or breaks in visual information will occur, these paradigms still often report no evidence for extrapolation (Franconeri, Pylyshyn & Scholl, 2012; Keane & Pylyshyn, 2006). It seems this could be due to capacity limitations in attention to motion or due to strategies adopted by observers that do not involve explicit attention to motion.

The method used here also differs from previous studies that have manipulated surface motion independently of the translation motion of objects around the tracking display (Huff & Papenmeier, 2013; Meyerhoff, Papenmeier & Huff, 2013; St. Clair, Huff & Seiffert, 2010). These studies find that surface motion aids or impairs performance to an extent depending on its similarity to the actual motion of objects. This is interesting since it shows that local motion signals at the positions of targets contribute to tracking performance. It remains a possibility that the tracking mechanism uses this motion information to some extent to contribute to extrapolatory processes during tracking. However as mentioned in the introduction, an alternative explanation is that surface motion produces an apparent change in the position of objects such that they appear offset in the direction of the surface motion as shown for stationary drifting gratings (De Valois & De Valois, 1991). It may be this effect on position representations that causes the benefits seen with consistent surface motion, and not the motion information itself. This view is consistent with our finding that the presence of motion information supplied by superimposed arrows was not used by the tracking mechanism and provided no benefit in terms of position reports or perceptual lag. It seems likely that these high level symbolic representations of motion were not beneficial due to the level of interpretation and semantic processing required in contrast to the effect we see for directly paying attention to the translating motion of objects.

It should be noted that we did not measure whether observers adhered to the central fixation requirement. However, there is no a priori reason why observers would use a strategy involving eye movements more in one or other of the position or direction of motion monitoring tasks. Furthermore, when there is more than one target, any benefit from fixating one target would be offset by necessarily moving fixation further away from other targets and therefore would not be an optimal strategy.

In summary, we show that the presence of high level information about motion in the form of arrows does not aid performance in monitoring moving targets. However, when motion is made task-relevant by means of explicit instructions to attend to motion, it facilitates position reports for smaller attention loads. This facilitative effect of attention to motion on position monitoring is evident despite the generally deleterious effects associated with dual tasks generally. The facilitative effect is seen both for position precision and for overcoming perceptual lags, even producing extrapolatory reports in some cases. From these facilitatory effects of attention to motion on position reporting, we can clearly infer that sustained attention to continuously changing positions does not automatically recruit attention to motion and that these two types of attention to dynamic stimuli are therefore dissociable. Attention to motion sharpens the spatial precision of target representations and may allow the position tracking mechanism to overcome perceptual lag, potentially by enhancing processing of positions that lie ahead of the current position of moving objects. The results have implications for our understanding of the neural architecture of attention to dynamic stimuli generally and in tasks such as the multiple object tracking task, as well as any real world systems that expect users to incorporate changing position or motion into their monitoring systems.

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