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Tracking the apparent location of targets in interpolated motion

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Abstract

Under appropriate conditions, a target moving in discrete steps can appear to move smoothly and continuously even within the portions of the path where no physical stimulus is present. We investigated the nature of this interpolated motion in attentive tracking displays as well as apparent motion. The results showed that the apparent location of the target moved smoothly through space between the two discrete locations and the judgements of interpolated motion for attentive tracking and apparent motion were comparable to those for continuous motion in both the perceived path and the precision of the judgements. There were few, if any, differences between judgements for real and interpolated motion. An alignment procedure showed that the smooth change in location judgements was real and not a consequence of averaging across discrete locations actually seen on each trial. We also found that the slowest alternation rate which supported accurate location judgements corresponded to a critical SOA of about 500 ms, similar to the longest SOA which supported a subjective impression of motion in the display. Deviations from a constant velocity which were shorter than 200 ms did not register in the judged motion path, suggesting a fairly long time constant for the integration of velocity information into the perceived motion. These results suggest a specialized motion analysis which provides an accurate, explicit model of the interpolated motion path.

Keywords: Motion perception; Attention; Tracking

1. Introduction

When two nearby lights are turned on and off in alternation, observers perceive an apparent motion between the two lights. Wertheimer (1912) reported that with appropriate parameters observers sense something moving along the path between the two positions and many subsequent articles have explored the nature of this interpolated motion (Kolers & von Grünau, 1976; Robins & Shepard, 1977; Shepard & Zare, 1983). Of particular interest are displays where the alternating lights are separated by a blank interstimulus interval because during that time, motion continues to be sensed along a path in the absence of any physical stimulus.

Low-level interpretations of the phenomenon can call on spatio-temporal filtering to fill in the path as a blurred version of the discrete presentation (Watson, Ahumada, & Farrell, 1986). This interpretation in its simplest form would suggest that motion should be sensed along the path joining the two targets but it does not have any mechanism for generating impressions of the moving target at specific positions along the path. In other words, a low-level motion process can fill in motion but not features unless additional elements are added to the model of motion processing. Indeed, there are several phenomena which demonstrate the independence of motion and position information. For example, motion can be seen in the opposite direction from position displacement when the contrast of the stimulus reverses with each step (Anstis & Rogers, 1975), when an appropriate ISI field is interposed (Shioiri & Cavanagh, 1990), or when a ‘missing fundamental’ pattern is stepped by 1/4 cycle (Adelson & Bergen, 1985). On the other hand, the presence of motion can affect position judgements. Motion within a stationary window or a motion after-effect can offset the perceived position of stationary images (Ramachandran & Anstis, 1990; De Valois & De Valois, 1991; Nishida & Johnston, 1999). However, the change is a fixed, small offset, not a continuous drift which would match the

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motion which induces it. This effect of motion on position is not likely to be related to the interpolation seen over longer distances during apparent motion. Interpolations of moving stimuli over similarly small distance and short duration have been reported (Burr & Ross, 1979; Morgan, 1980; Morgan & Watt, 1983; Fahle & De Luca, 1994). For example, alignment of the relative location between two stimuli that moved stroboscopically so that only one was visible at any given time showed results to suggest that the perceived location of apparently moving objects were interpolated (Morgan, 1980). However, these experiments presented the stimuli at rates close to spatiotemporal sensitivity limits of the visual system and therefore the perceived motion was not noticeably different from continuous motion. In other words, the interpolation could again have been a consequence of spatiotemporal blurring of the physical stimulus.

Conversely, a high-level interpretation of interpolation can be based directly on feature-tracking mechanisms where an internal model of a moving target is constructed to link the two flashes of light as the end points of the motion of a single target. In this case, an internal pointer matches the position of image data when the target is present and moves smoothly between image locations when the target is not present. Wertheimer (1912) himself proposed that attention might be mediating the motion seen between the two locations, being captured by the first light and then pulled away from it by the appearance of the second light. This proposal has been revived recently by one of us (Cavanagh, 1992) in a model of high-level motion as 'attentive' smooth pursuit or tracking. In this paper, we investigate the apparent positions of the target along the path of interpolated motion in an attempt to identify its source.

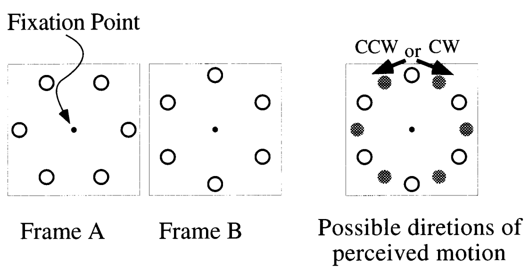

Fig. 1. Attentive tracking. When frames A and B are alternated at rates between 1 and 7 Hz, the observer can organize the alternation at will as coherent motion in either the clockwise or counterclockwise direction. The observer fixates at the center and attends to a single disk moving around the circle in one direction or the other. In the alternating sets are shown as open white disks or filled gray disks in the right figure but in the actual displays all disks were identical white on a gray background. The alternation between these locations could support a perception of motion in either direction once one disk was selected as the target to be tracked with attention. In experiments 1 and 2, six disks were displayed in each frame alternating with a second set of six disks placed midway between the disks of the first set as shown while six or four disks in each frame were used in experiment 3. Because the disks were more widely spaced in the four disk condition (by 45° compared to 30°), a given rotation rate corresponded to a 50% longer SOA between the alternating frames than in the six disk condition.

There have been a few experiments which examined whether attention itself could move smoothly through space (Shulman, Remington & McLean, 1979; Tsal, 1983; but see; Eriksen & Murphy, 1987; Murphy & Eriksen, 1987; Yantis, 1988; Sperling & Weichselgartner, 1995; Cave & Bishot, 1999). However, these experiments investigated the cueing effects of attention as its focus shifted from one location to another, a condition that may favor discrete, saccade-like shifts in attention. It is more likely that attention shifts smoothly when observers are tracking smoothly moving objects with attention, analogously to smooth pursuit eye movements.

There are several reports in the literature focused on interpolation or extrapolation of motion with durations of several hundred ms or even longer (Wertheimer, 1912; Robins & Shepard, 1977; Bocheva, Yakimoff & Mitrani, 1984; Peterken, Brown & Bowman, 1991; Pavel, Cunningham & Stone, 1992; Lyon & Waag, 1995). These durations are much longer than early integration limits of the visual system and, in these cases, the stimulus is easily distinguished in appearance from a continuously moving stimulus. The results of these experiments suggested the existence of a mechanism that interpolates something, perhaps an implicit object, over the trajectory even though it is apparent that the stimulus itself is not present throughout the trajectory.

We focused on interpolations of the motion path during attentive tracking where not only is the stimulus absent over substantial spatial and temporal gaps but also the direction of motion is not present in the stimulus. This allows us to isolate the interpolation process from low-level motion signals. In the attentive tracking display, the direction of motion is ambiguous and can be reversed by the 'set and posture' of attention (Wertheimer, 1912). For example, with the alternation of frames A and B in Fig. 1, motion can be seen in either clockwise or counterclockwise directions as determined by the observer's attention (while fixating the center). Since the direction of the perceived motion is not set in the stimulus, the perception of target location within the gaps where nothing is present in the stimulus must rely on some higher-level continuing representation which codes not only location but also direction. In our displays, the discrete gaps between the locations and the flicker of the repetitive presentations were always well above the threshold of visibility. We will consider the specific role of attention in this tracking task in more detail in the Discussion. In addition to attentive tracking, we also used standard apparent motion for the purpose of the generalizing of the results.

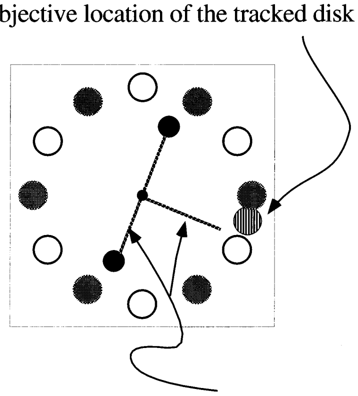

Fig. 2. Imaginary bisector probe. In order not to perturb the motion path, a technique was devised that kept all physical probe stimuli well away from the motion path. While the observer was tracking, two probe dots were flashed briefly. The observer imagined the line connecting the dots and the perpendicular bisector of the line and reported whether the apparent location of the tracked target was ahead of or behind the imaginary bisector.

As a control for both the apparent motion and pure attentive tracking, we included a single target in real motion, or at least as close to smooth as possible within the refresh rate limitations of the display (66.7 Hz). In this case, the stimulus is continuously present and minimal interpolation is required.

How can we measure the apparent location of the target during its interpolated motion, when it is not physically present? Pilot tests with probes placed near the path of motion quickly demonstrated that a probe placed anywhere along or near the path perturbed and, in essence, captured the motion onto a new path. Although a measure of the optimal disruption of motion was feasible (Shioiri, 1995), we wanted to allow the observer to point to the sensed position at different moments without disrupting the motion itself. Another problem of probes presented near the path was visible persistence. Visible persistence of the probe (or disks) sometimes created a static visual image with disks (or probes) where relative offset of physical locations between them could be seen. Since this relative offset was not necessarily the same as the apparent locations of tracked objects, we wanted to avoid the effect of visible persistence.

We developed a test which meets this criterion by using an imaginary line as a pointer. Mentally constructing this imaginary line appears at first glance to require some sophisticated geometrical analysis but it was actually an easy, intuitive task. The test probes were two briefly presented dots placed symmetrically on opposite sides of fixation. At the moment the two dots appeared, observers judged the apparent location of the target (whether visible or not) relative to the imaginary perpendicular bisector of the line joining the two probe dots (Fig. 2). The observers responded whether the target was ahead or behind of the imaginary perpendicular line. Since the probe dots were well away from the motion path, they did not interfere directly with the disks of interest. The judgements for various timings provided the estimation of the trajectory of the interpolated motion during the ISI in experiment 1.

There is a possible problem with this location measurement. When we average position judgements across trials, the estimated location may move smoothly through space even if the apparent position seen on any given trial is centered only on either of physical stimuli. If the probability of seeing one location drop smoothly over time while that for the other location rises and no other locations are seen, the estimated location will nevertheless move smoothly between the two positions. Sperling and Weichselgartner (1995) considered the closely related case where the internal representation of position was itself bimodal on *each* trial with a gradual change in the certainty of localization from entirely at the first position to entirely at the final position. Midway through the shift, both initial and final positions would have equal strengths of representation. This again could mimic the pattern of smooth motion for the averaged data of the location measurements. Experiment 2 was conducted to check this measurement artifact. We asked observers to adjust the probe dots incrementally in each trial until the imaginary perpendicular line pointed *at* the apparent location of the target. The distribution function of the adjustment data should be unimodal if the perceived location of tracked objects moved smoothly, whereas that should be bimodal if the apparent position were determined by the combination of functions distributed on either of the two locations.

The third experiment explored a variety of attentive tracking speeds to examine the relationship between the perceived motion and trajectory of the motion of tracked objects.

2. Experiment 1: apparent location of the tracking object

An attentive tracking stimulus was presented with six disks alternating between two sets of positions as shown in Fig. 1. While fixating the center, observers tracked one of six disks whose identity and direction were indicated by a colored mark placed on it for the first few steps of its motion. After the identifying mark had turned off and the observers were tracking on their own, a pair of probe dots appeared and the observers reported whether the apparent location of the tracked disk was ahead of or behind the perpendicular bisector of the line joining the two dots (Fig. 2). In apparent motion, there was only a single disk but it jumped through exactly the same steps, with the same timing, as the target disk in the attentive tracking display. In the continuous motion condition, the single target disk was present on every frame moving in small steps from frame to frame. Its speed matched that of the attentive tracking and apparent motion displays. We used the accuracy and precision measured in the continuous motion case as a baseline to evaluate the quality of the interpolated motion in the attentive tracking and apparent motion stimuli.

2.1. Method

2.1.1. Subjects

Eight observers participated, three from Harvard University and five from Chiba University. All had normal or corrected-to-normal visual acuity. Three of them participated in all of attentive tracking, apparent motion and continuous motion conditions.

2.1.2. Apparatus

Two similar tracking set-ups were used in the experiment, one in Harvard University and the other in Chiba University. They were either a Macintosh IIcx or Quadra 950 with a color graphic display (Apple high resolution graphic display) of a 640 × 480 pixels resolution (66.7 Hz non-interlace). The distance between the observer and the display was 60 cm.

2.1.3. Stimulus

The stimulus was a set of disks arranged around a circle in the attentive tracking condition. The disks were divided into two group as shown in Fig. 1. Alternation of the two groups produced an ambiguous motion display. The observer saw either clockwise motion or counter clockwise motion, and the direction of motion could be selected at will by tracking one of the disks in one direction with attention. In the apparent motion condition, one disk jumped successively through the 12 disk positions of the attentive tracking display. In continuous motion condition, a single disk moved continuously, within the limitations of the video refresh rate, at the same speed as the other conditions. Three of the 8 observers participated in this part of the experiment.

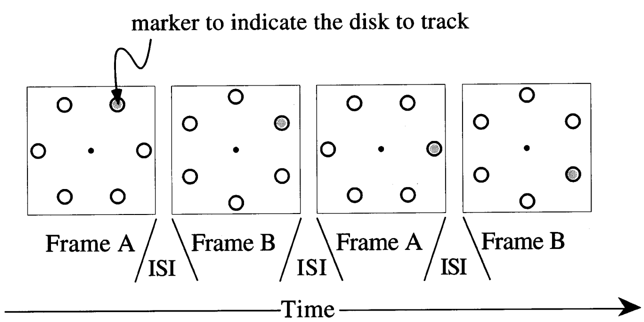

Fig. 3. Initiating tracking. To begin a trial, one disk was highlighted for ten consecutive frames (five alternations of frames A and B) indicating which disk to track and in which direction. At the end of the ten frames, the highlighted disk returned to the same state as the other disks and tracking was maintained by processes internal to the observer.

Disk luminance was 51 cd/m^2 on the background of 28 cd/m^2 and probe luminance was 0.01 cd/m^2. Disk diameter was 1.1° and the diameter of the disk array (distance between the center of the disks at opposite sides) was 14°. The probe consisted of two black dots of 0.7° diameter, which were located on opposite sides of the fixation point with a center-to-center separation of 12° (Fig. 2). The probe was used to define an imaginary line between the two dots and the observer was asked to decide if the tracking disk was ahead of or behind the (mentally constructed) perpendicular bisector of the imaginary line.

2.1.4. Procedure

The presentation duration of each frame was nominally 15 ms[1] (one refresh of the monitor) and ISI was 105 ms (seven refreshes). This corresponded to the angular velocity of 0.69 revolutions/s. In the initial five cycles of alternating frames A and B, a disk was indicated as the target to be tracked by highlighting it with a red mark as in Fig. 3. The target was identical to the other disks after the disappearance of the marker and, therefore the target remained defined only in the observer's visual system. The observer tracked the target disk for a further two cycles of alternation (without the target highlighted) before the probe was displayed. The presentation duration of the probe was 15 ms and the observer decided if the tracking disk was ahead of or behind of the location indicated by the probe at the moment it appeared. We used a short period of tracking (two cycles of alternation) in order to minimize the number of trials in which observers lost the tracking disk (these were very few). When the observer noticed that tracking was lost, the trial was cancelled and a replacement trial was added. At the moment of the presentation of the probe dots, the observer judged whether the location of tracked disk was ahead of or behind the imaginary perpendicular (see Fig. 2). Despite the complexity of stimulus, this judgement was surprisingly easy.

[1] Since the presentation lasted only one refresh of the display, its effective duration was, in fact, much shorter than 15 ms. If the presentation had lasted two refreshes or longer, the duration would have been approximated by the interval between the first and last posting of the image to the screen. Since it is only posted once to the screen, its physical duration is quite brief with a lower bound given by the phosphor persistence and an upper bound given by the time taken to post the feature from its topmost point to its bottom. For the small disks used here, the presentation duration should be taken as no more than 1 ms. The ISI, as a result, is longer than the nominal 105 ms for 7 refreshes and should be considered closer to filling the full 120 ms SOA.

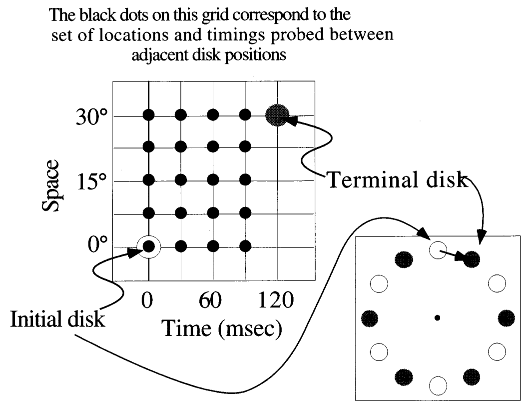

Fig. 4. Timing and location of probes. Probes were presented at four different moments during the 120 ms interval between onset of the successive frames. Five different locations were probed for each. Frequency of 'ahead' and 'behind' judgments were collected for all of the 20 spatiotemporal probe points and these data were used to track the apparent location of the interpolated motion.

The motion of the tracked disk in this display appeared relatively smooth even though the flickering of the disks was well above the threshold. The path of motion seen appeared to be circular rather than polygonal with connecting the actual disk locations straightly. We did not consider the shape of the perceived trajectory, however, because the difference of the two cases is very small (the difference is less than 0.5% between the predictions along the two paths for motion with a constant velocity).

The timing of the probe presentation was either 0, 30, 60, 90 ms after the onset of one group of disks (either Frame A or B). The probe angle covered the range between the two successively presented adjacent disk positions in five steps (30° in orientation angle on the display, we use degrees to express the probe angle hereafter). The actual location in the display was randomly chosen for each trial so that the observer had no idea where the probe came without tracking. Forty judgements (20 for each of clockwise and counterclockwise direction) were made for each of the 20 combinations of five probe locations and four timings (Fig. 4). The actual probe locations occasionally varied for individual observers in order to bracket their perceived location in each condition, as roughly estimated by pilot observations.

The point of alignment between the perpendicular probe line and the tracked dot (present or interpolated) was determined from the function of response frequency against probe location. The probe location corresponding to 50% ahead (or behind) responses was taken as the apparent location of tracked disk after fitting a cumulative normal distribution function to data by Probit analysis. The standard deviation of the function, which corresponds to the discrimination threshold, was taken as an estimate of the precision of the judgement. We refer to the value as the JND (just noticeable difference) here to distinguish it from the standard deviation of the adjustments in experiment 2, which may or may not estimate the same precision.

2.2. Results

The point of subjective alignment was taken to be the probe angle that gave 50% of 'ahead' responses by Probit analysis based on 200 judgements for each probe timing of each observer. The point of subjective alignment were averaged across observers for each timing and plotted in Fig. 5(a). Individual results were similar to the group means and the standard error of the mean is shown when it is larger than the symbol.

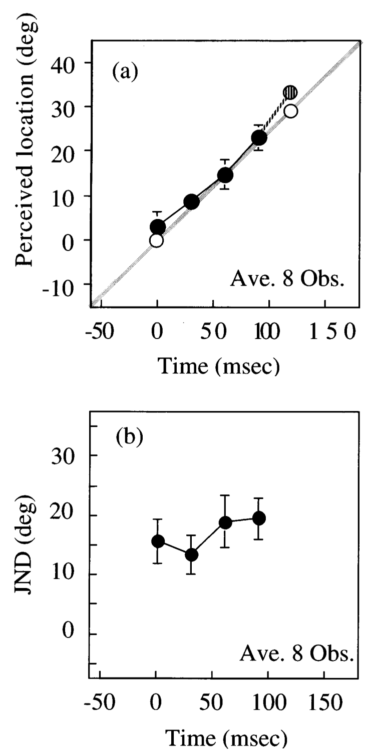

Fig. 5. (a) Apparent location of target. The gray line indicates the trajectory of linear motion between the two presented disk locations. The apparent locations, averaged over eight observers, are shown by the filled circles. The rightmost datum point shown in gray and connected to the others with a dashed line, is a repeat of the 0 ms value but now placed relative to the position of the next presented disk. Standard error of the means are shown by vertical bars. The two open circles indicate the locations of the physically presented disks. Notice that these presentations do not actually last the nominal refresh duration of 15 ms[1]. The reason is that an image feature which is presented for only one refresh cannot be considered to last the entire interval between refreshes (at least not on a CRT). Its presentation lasts at most only the amount of time taken to write the feature itself to the screen, a duration of less than 1 ms for these small disks. (b) The JND estimated from the psychometric functions, averaged over eight observers, are shown by the filled circles. Error bars represent standard error of the mean.

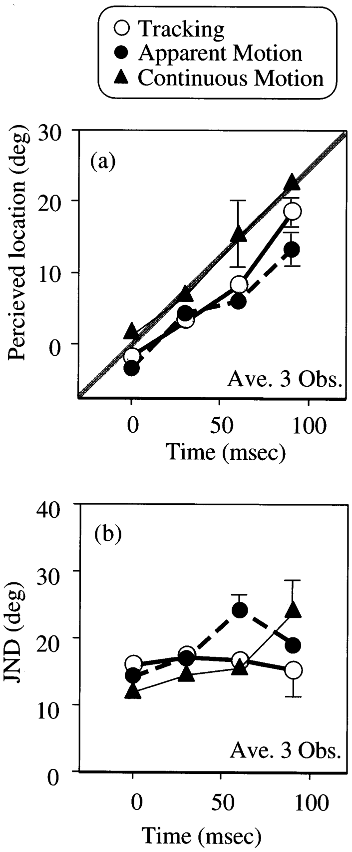

Fig. 6. (a) Perceived location as a function of time for apparent motion and continuous motion, each averaged over the three observers. Perceived location for attentive tracking is also shown. (b) The JND from the psychometric functions for three motion conditions are shown separately, also averaged over the three observers. Filled circles represent apparent motion, filled triangles represent continuous motion, and open squares represent attentive tracking. A typical standard error is shown for each condition in each panel.

The judged location moved smoothly between the beginning and end positions over a path where there was no physical stimulus. The perceived positions of the interpolated disk are very close to the path of linear motion. An ANOVA showed that none of the interpolated location estimates deviated significantly from the linear trajectory joining the two end points ($F(3,7) = 1.91$, $P > 0.05$). However, the apparent position at time zero (when actual disk was presented) was slightly ahead of its true position and this may be related to two interesting issues, although the advanced position effect is small.

First, the advance in the apparent position may be related to the position extrapolation which, according to Nijhawan (1994, 1997), compensates for the neural delays from the retina to the visual percept (or the temporal facilitation for moving versus flashed targets, Whitney & Murakami, 1998). Second, there is a technical aspect of our measurement procedure which may contribute to an apparent advance of judged location. To make the judgement, the observers might start with either the probe dots or the moving disk. If the observers first acquire the locations of the two probe dots, there will be some delay while they then construct the two imaginary lines, one joining the dots and then one bisecting this first line at a right angle. During that delay, the tracked disk will have moved some distance introducing an apparent advance. On the other hand, if the observer acquires first the location of the disk at the time the probe was presented and the identify the locations of the probe disks later perhaps based on the visible persistence, no delay is expected and no advance results. The inter-observer difference in perceived offsets may, therefore, be related to the strategy used.

To see the variability of the judgements of location, the JNDs estimated from the psychometric functions (given by the standard deviation of the fitted cumulative normal distribution) are plotted in Fig. 5(b), averaged over the observers. The JND is fairly constant throughout the interval, even including the initial estimate made while the disk was on during the probe presentation (0 ms). Although a numerical increase of the JND, suggesting an increase in the variability of the judgements, is found for longer SOAs, an ANOVA showed no significant difference across the time conditions ($F(3,7) = 2.67$, $P > 0.05$).

Fig. 6(a) shows the apparent target locations averaged over three observers as a function of probe timing for the apparent and continuous motion conditions. Also shown are the average results for attentive tracking for just the three observers who participated in the three conditions. The results are similar for all three conditions. For apparent motion, as for attentive tracking, the data fairly fall close to the line of linear interpolation. The position estimates for continuous motion all fall close to the actual positions as well, indicating that the measurement method is appropriate and reliable. A two-way ANOVA showed that the effect of motion conditions was not significant ($F(2,24) = 0.72$ $P > 0.05$) while the effect of the probe presentation time was significant as estimated location increased with increasing probe delay ($F(3,24) = 16.95$ $P < 0.01$ In Fig. 6(a), the estimated locations for tracking and apparent motion appear to trail the interpolated path whereas those for continuous motion appear to lead. This difference, though not significant, may be a result of individual differences since the data for these three observers were included in the results for eight observers shown in Fig. 6, and this larger group showed very little deviation of the results from the linear interpolation.

To compare the variability of the judgements among motion conditions, the JNDs are plotted in Fig. 6(b). The average JND (for the three observers) is similar among the conditions although the individual data show rather more variability with conditions. The effect of the probe presentation time is also similar for the three motion conditions. A two-way ANOVA showed that neither the motion conditions nor the probe presentation time had a significant effect on the precision of the estimates ($F(3,24) = 1.41$ $P > 0.05$ and $F(2,24) = 0.83$ $P > 0.05$) nor was there any interaction ($F(6,24) = 0.28$ $P > 0.05$). The similarity of the perceived location and variability of judgements among the three motion conditions suggests a similarity in the motion processing in three conditions.

3. Experiment 2: alignment procedure

The results of experiment 1 suggest that the apparent position of the interpolated target moves with a fairly constant velocity between the two successively flashed locations. However, it is possible to produce this pattern of data even if the target was perceived only at the two flashed locations. This can occur if the relative frequency of seeing either one or the other location changes smoothly over time with the first flash location being perceived more frequently at the early probe timings and the second flash location being perceived more frequently for later probe timings. Even though the perceived position would actually be bimodal in this case (no interpolation), the frequency of 'ahead' judgements would decrease smoothly with time between the initial and following flash. Similarly, the estimated location could move smoothly if the internal representation of position itself is bimodal on *each* trial with a gradual change in the certainty of localization from entirely at the first position to entirely at the final position (Sperling & Weichselgartner, 1995). Subjectively, observers reported fairly smooth motion, not probabilistic jumps over discrete locations or a doubling of apparent locations (Sperling & Weichselgartner, 1995) but we wanted to use a method that would demonstrate this directly.

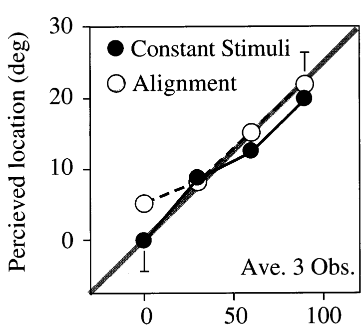

Fig. 7. Perceived location of the attentively tracked target as a function of time for the alignment procedure, averaged over the three observers. Average data from the constant stimuli procedure of experiment 1 for these three observers are also shown. The gray line shows the path of linear interpolation between the two presented locations. A typical standard error is shown for each condition.

We therefore developed a method of adjustment where the observer varied the probe angle on each trial (with a fixed timing) until the imaginary perpendicular line appeared to be aligned with the tracked target. Alignment data was collected from three observers in the attentive tracking condition. It is still possible that a bimodal distribution of position representation could mimic the pattern of smooth motion for the alignment procedure described. However, judgements of alignment midway through the path should be quite variable compared to those at the initial or final locations, as the localization representations at intermediate timings are spread out over the whole path. This was examined directly by analyzing the distribution of settings.

3.1. Method

The procedure in the second experiment was similar to that in experiment 1 with two exceptions: the probe angle presented on each trial was varied by the observer rather than being selected randomly by the computer and only an attentive tracking condition was examined. The sequence of events on each trial was identical to that in experiment 1 whereas the mode of the response was different. The observer pressed one of four keys: the first and second decreased the probe angle and the third and fourth increased it; the first and third changed the angle by the large step size (0.25 of the path length or 7.5°), and the second and fourth by the small step size (0.125 of the path length or 3.75°). The observer first adjusted the probe angle roughly using greater steps and then adjusted more accurately with the smaller steps. We chose these steps based on the psychometric function measured in experiment 1 (the responses changed rather gradually with the probe angle for steps of 7.5°). Three observers from experiment 1 (all at Chiba University) participated in this experiment. Two observers made six settings for each delay while the other observer made ten settings for each.

3.2. Results

Fig. 7 shows the average results for three observers in experiment 2 with the results from the method of constant stimuli in experiment 1. For the three observers tested with the alignment procedure, the apparent location during attentive tracking again changed smoothly through the period of interpolated motion (during the ISI). Although there were differences between the settings in the two procedures, the nature of the differences varied from observer to observer and did not appear to have any systematic pattern. A two-way ANOVA showed that the effect of the procedures was not significant ($F(2,24) = 0.49$, $P > 0.05$) while the effect of the probe presentation time was significant ($F(3,24) = 11.62$, $P < 0.01$). The precision of

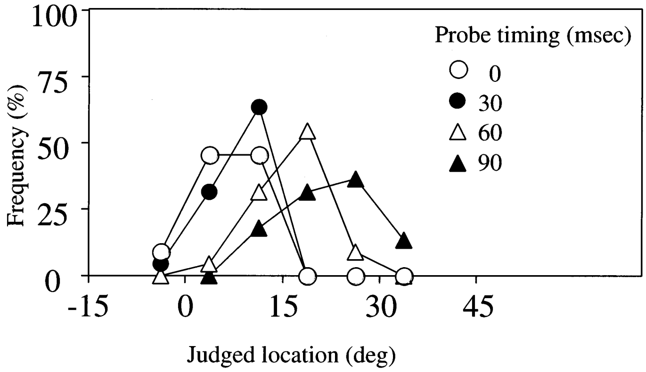

Fig. 8. Distribution functions of judged locations. The judgements for a probe presentation time were pooled over the three observers (total judgements of 22 for each conditions).

the alignment judgements as estimated from the standard deviation of the settings also remained fairly constant across time conditions (not shown), which was confirmed by an ANOVA ($F(3,28) = 1.63$, $P > 0.05$).

The values for the precision of the estimates was very different between the two procedures; 24.3° for constant stimuli and 4.6° for alignment on average. This large difference is striking because the stimulus and the observers were the same. One difference between the two procedures was the number of the trials at a given probe timing before the final judgements were made. In the method of constant stimuli, observers could not predict when the probe would appear from trial to trial and the attentive state at the moment of its appearance may have been quite variable. In the alignment method, the probe was presented repeatedly at the same timing until the observer was satisfied with the alignment.

Fig. 8 shows the distribution of the alignment settings for the data pooled over three observers at each presentation time of the probe. The frequency of the settings was obtained by pooling data in 15 ms bins in each condition. The distribution function clearly shows a single peak in all conditions with that peak shifting rightward with the probe presentation time. These results argue against either of the two discrete location coding models we described above. The width of the function tends to increase with the probe presentation time, which agrees with the slight increase of the JND found in experiment 1. This suggests that the localization judgement is slightly less variable when the physical stimulus is presented with the probe or terminated not long before the probe presentation.

4. Experiment 3: effects of speed, SOA, and exposure duration on judgements of alignment

Using the alignment method we varied the rate of motion and the SOA during attentive tracking. In the first condition, the frame duration was brief (nominally 15 ms) separated by long ISIs with no disks present. This allowed us to examine whether accurate interpolation could be based on predicted trajectories even at very long SOAs which, in this condition, produced little or no sense of motion. At these long SOAs attentively tracked objects seemed to move in steps from one location to the next with little or no impression of a motion trajectory linking the two locations. We varied the rate of motion and SOA independently by changing the number of disks around the display. Two values were used: 4 and 6. The angular jump between alternate frames was 30° for the six disk display (see Fig. 1) and 45° for the four disk display. The three rotation speeds were matched in the two displays by adjusting the SOAs appropriately. The apparent location of the tracked target during the interpolated motion was measured using the alignment procedure.

We also used a long exposure (with a short ISI, 15 ms) condition for each rotation rate where the disks would remain visible and stationary for almost the entire SOA. This condition allowed us to evaluate the interpolated motion seen for stimulus that follows an explicitly stepped or staircase path in space-time. In contrast to the short exposure condition above, this stimulus still produced an impression of motion at long SOAs (slow rates) but it was an impression of repetitive jerks or ratcheting. We expected that at high rotation rates, the accelerations of the stimulus would be smoothed out in the perceived motion whereas at some critical lower rate, the veridical, stepped or jerky velocity would be seen.

4.1. Method

With two exceptions, the apparatus and stimuli were the same as in experiment 2 and all sessions were run at Chiba University. The alignment procedure described in experiment 2 was used. The first difference was that the SOA (accordingly the rotation rate) and exposure duration of stimulus disks were varied and the second was that for half of the conditions, only four disks were present around the display rather than six. Three rotation rates were used for each display: 0.69, 0.35, and 0.18 revolution/s. The relevant SOAs for the four disk display (45 angular degree jump) were 720, 360 and 180 ms, whereas for the six disk display (30 angular degree jump) they were 480, 240, and 120 ms. In the short exposure conditions, the exposure duration of the disk frames was always one frame (nominally 15 ms) whereas in the long exposure conditions, it was the entire SOA minus 15 ms (i.e., the ISI was constant at 15 ms). The actual velocity varied substantially from zero while the disks were present to very fast during the interval spanning the ISI (5.6 revolution/s for the six disk display and 8.3 revolution/s for the four disk display) in the long exposure conditions. The timing of the probe presentation varied with SOA, keeping the relative values to the SOA (0, 0.25, 0.5, 0.75). The three observers of experiment 2 participated in the experiment. Six adjustments were performed in each condition by each observer.

4.2. Results

Fig. 9 shows the results for the average of the three observers (the data of 0.69 revolution/s for six disks are from Fig. 8), since the results for individual observers were quite similar. Perceived location is shown for each rotation rate for short exposure and long exposure conditions separately. The results for short exposures show that the perceived locations of the tracked objects follow the linear interpolation with reasonable accuracy at higher rotation rates (and shorter SOA) for both six and four disk displays. At the slowest rotation rate, the perceived location moves substantially more slowly on average than linear interpolation would predict. In particular, the loss of linear tracking is more extreme for the four disk display than for the six disk display and this is true for all individual observers. This result indicates that the critical factor is the SOA (720 versus 480 ms) not the rotation rate, which is matched in the two cases.

A two-way ANOVA for deviations from linear interpolation showed that the effect of SOA conditions was significant ($F(5,48) = 7.31$, $P < 0.01$) as well as the probe presentation time ($F(3,48) = 99.5$, $P < 0.01$). Further analysis for the difference between each pair of conditions revealed the difference among conditions is mostly due to the difference between the slowest SOA and each of the others ($t(48) > 5$ for all cases, $P < 0.01$), while weaker significance was found between the 360 ms condition and the 720 and 480 ms conditions ($t(48) > 3.3$, $P < 0.05$). This confirms the possible critical difference between the SOAs of 480 and 720 ms.

For the variability of the adjustments, a two-way ANOVA showed that neither the effect of SOAs nor that of the probe presentation time was significant ($F(5, 48) = 1.73$ $P > 0.05$ and $F(3, 48) = 1.19$ $P > 0.05$) nor was the interaction ($F(3, 48) = 1.07$ $P > 0.05$). The average of the standard errors was 4.7°, which is again smaller than the JND values in experiment 1. The similarity of the variability of judgements among conditions suggests that a similar mechanism contributes to the location judgements for all the conditions.

The results for long exposures of the disks revealed an important difference between slow and fast velocities. Recall that in long exposure condition, the disk remains on at a fixed location for almost the entire SOA and then jumps to the next location. An impression of motion accompanied tracking at all SOAs. However, at the fastest average rotation rates, the perceived locations fall close to the linear, constant velocity path even though the physical stimulus was moving in a jerky fashion. Clearly, the apparent velocity varied much more smoothly than the velocity of the stimulus. At the lower rotation rates, the judged locations more closely resemble the stepped locations of the stimulus. At SOAs of 200 ms or less, the discontinuous steps in the path appear to be smoothed out in the internal representation. Indeed, at SOAs of 200 ms or less the average velocity estimated from the location settings is similar or slightly faster for the short exposure than for the long exposure (the ratio is about 1.5 for all SOAs shorter than 200 ms) whereas the difference is much greater (about 2.5) for SOAs longer than 200 ms. This suggests that the internal tracking mechanism does not register departures from a constant velocity until they last more than about 200 ms.

We did not analyze the four and six disk conditions separately because there is little difference in the results for the two conditions for shorter SOAs. The effect of inter-disk distance for long SOAs cannot be accessed with the limited conditions of longer SOAs.

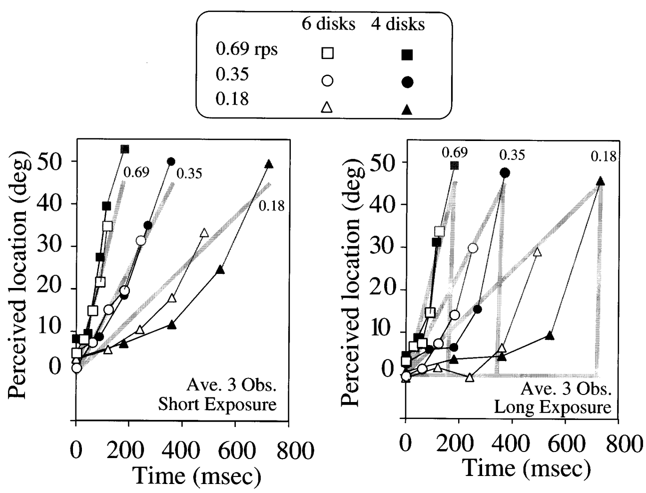

Fig. 9. Perceived location as a function of time for different rates of rotation, averaged over the three observers. The left panel is for the short exposure duration with long ISIs and the right panel for long exposure durations with the short ISI. The rightmost data points shown in gray for each condition are repeats of the 0 ms value but placed relative to the position of the next presented disk. The gray lines in each panel indicate the linear line of the average velocity for each stimulus. The hatched lines indicate the physical movements of the disks.

5. Discussion

A number of motion phenomena involve the subjective impression of an object following a path even in the absence of any physical stimulus. In apparent motion (Wertheimer, 1912), attentive tracking (Cavanagh, 1992), and path-guided motion (Shepard & Zare, 1983) there appears to be an interpolated trajectory where an object's location is moderately well defined and changing over time. This maintenance of an object token at a changing location is difficult to explain in terms of low-level processes or filling-in of a motion signal.

We found in the first experiment that the apparent location of the target moved smoothly with roughly constant velocity through space between the two presented locations. The precision of the location judgements in terms both of inter- and intra-observer variability, remained fairly constant throughout the interpolated path. Furthermore, the judgements of interpolated motion for attentive tracking and apparent motion were comparable to those for continuous motion in both the perceived path and the precision of the judgements. There were few if any differences between judgements for real and interpolated motion.

In the second experiment, an alignment procedure showed that the smooth change in location judgements was not a consequence of averaging across discrete locations actually seen on each trial. In the alignment procedure, observers attempted to make the imaginary probe line point at the perceived location. This pointing judgement moved through the interpolated trajectory in a smooth, almost linear fashion.

Finally, the lower bound on tracking speed seemed to be set by the SOA not by the speed of rotation. The critical SOA of about 500 ms for the upper limit of the smooth interpolation agrees with estimates for the longest SOA which supports apparent motion (e.g. Caelli & Finlay, 1981). This is also supported by a preliminary experiment. In the experiment, two new observers adjusted the longest SOA with which motion could be seen during tracking in an attentive tracking display. The average of ten settings were 716 and 693 ms for the two observers. The longest SOA for which motion is seen is therefore about 700 ms and thus the decline of motion processing starts at SOAs shorter than that.

These results indicate that there is an integration mechanism that can fill the spatial gap between physical stimulus. The mechanism is different from low-level integration by spatio-temporal filters in two aspects. First, the spatio-temporal gap is much larger than the integration limits of spatio-temporal filtering. For example, Morgan (1980) showed that the interpolation only occurred for spatial shifts less than a quarter of a degree and temporal gaps less than 50 ms when the task was the alignment of relative location between two stimuli that moved stroboscopically. In our experiments, the spatial gap was larger than 3° and the ISI was larger than 100 ms. Second, the appearance of the display in tracking and apparent motion conditions were very different from the continuous motion display. The flickering of the disks was always visible whereas no flickering was noticeable in the continuous motion display. These points suggest that low-level integration (due to early spatio-temporal filtering) could not be the sole explanation of the interpolation of the motion trajectory in our tasks.

In contrast to Morgan (1980) and others (Burr & Ross, 1979; Morgan & Watt, 1983; Fahle & De Luca, 1994), Robins and Shepard (1977) showed interpolation of motion in similar condition to ours. Although they did not show the estimated path, their data clearly demonstrated that the observers perceived something at locations between the physical stimuli of the apparent motion display. Our results confirmed their conclusion of the representation of objects along the path of apparent motion. In addition, we showed that the interpolation can be relatively linear and that the precision of the location judgements for apparent and tracking motion was as good as for continuous motion.

The performance in the actual task put to our observers could be mediated by conscious extrapolation of the path for the target given its previous speed and direction. Conversely, performance might be based on an internal model of a moving target which is updated at each brief appearance of the next position in the path. The critical difference between these two mechanisms is that the first can be a general process for noticing and predicting change which is applied to moving objects in our experiment whereas the second is a specialized process for analyzing motion and we claim that its operation is linked to the subjective impression of motion.

Evidence against conscious prediction comes from the short exposure conditions of experiment 3 where the disks are only presented briefly and the ISIs, with no disks present on the display, varied from less than 100 ms to more than 700 ms. At the faster rotation rates (short SOAs), the observers had an impression of motion and they made position settings that followed the linear interpolation trajectory fairly closely (Fig. 9, left panel, the four leftmost traces). However, in the longest SOA condition (four disks of 0.18 rps, the rightmost trace in Fig. 9, left panel), observers no longer had a convincing impression of motion and their settings deviated strongly from the linear trajectory, staying much closer to the initial disk's position. Clearly, if conscious prediction does play a role, it only does so when the target disk appeared to be moving. Parsimony suggests that it is the motion mechanism that fills in the trajectory, not conscious prediction.

The accuracy and precision of the location judgements for shorter SOAs also support interpolation by an internal model. We would expect conscious path prediction to show a clear increase in variability (JNDs for constant stimuli or standard deviation of settings for alignment) over time since the last disk presentation, to be much better for a continuously moving target than for the interpolated targets, and to change its accuracy (the deviation from linearity in short exposure conditions) only gradually as a function of physical speed. On the other hand, we expect the precision of an internal model of the motion path to be constant over the interpolated gap in time, to be similar for continuously moving and interpolated targets. Our results show all the properties expected for the second, specialized motion analysis. The constant precision over time is also seen in other results where the precision of extrapolation of the paths of moving objects declined little over short periods of time but declined remarkably with period of 1 sec or longer (Lyon & Waag, 1995; Peterken et al., 1991).

Our results among others support a specialized motion analysis that provides an accurate internal model of the interpolated motion path. It suggests that beyond the early extraction of motion energy is a representation of objects and their properties, including trajectories of motion (Kahneman, Treisman, & Gibbs, 1992). At this level, the path of motion over time is made explicit even across gaps in the presence of the physical stimulus. We claim that it is this representation which, once set in place, supports both attentive tracking in the ambiguous motion display and links the disparate flashed stimuli of an apparent motion display into a smooth position change of a single object token.

What is the role of attention in this high-level motion system? In our tracking stimulus, attention was required in order to select motion in one direction or the other and to keep tabs on the location of the target. In our apparent motion and continuous motion displays, attention was again required to keep tabs on which of the multiple display items (target and probe disks) was the target (we could think of this as a salience map, Lu & Sperling, 1995). These basic processes of attention were essential for responding in our task but they are not necessarily basic components of motion analysis. Could the motion analysis be a part of, or a consequence of, the tracking process which keeps attention on its target (Wertheimer, 1912; Cavanagh, 1992)? When attention accurately tracks a target object, the location and velocity of the attentional focus mirror the location and velocity of the object. However, there is more to our results than just reading the location and velocity of an object because in our stimuli, the object is often absent. As we have mentioned, a persisting internal representation of a moving target is necessary to explain our data and the data on apparent motion in general. The representation must code not only the current location and velocity but also the object's expected trajectory over time. This predictive internal model might be an intrinsic part of attentive tracking or it could be an independent process called upon by attention to help out in tracking. We cannot discriminate between these alternative here but we would only need to find some predictive tracking occurring without awareness to argue for an independent process which is called on by attention but is not part of attention.

In conclusion, either the control processes of attention or a predictive internal representation accessed by attention could be the source of the interpolation of the motion trajectory in our attentive tracking displays. Since the apparent motion and continuous motion displays showed similar results, the same mechanism probably contributes to the location judgements of tracked objects in general.

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