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Visible persistence is reduced by fixed-trajectory motion but not by random motion

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Abstract. Despite the sluggish temporal response of the human visual system, moving objects appear clear and without blur, which suggests that visible persistence is reduced when objects move. It has been argued that spatiotemporal proximity alone can account for this modulation of visible persistence and that activation of a motion mechanism per se is not necessary. Experiments are reported which demonstrate that there is a motion-specific influence on visible persistence. Specifically, points moving in constant directions, or fixed trajectories, show less persistence than points moving with the same spatial and temporal displacements but taking random walks, randomly changing direction each frame. Subjects estimated the number of points present in the display for these two types of motion conditions. Under conditions chosen to produce 'good' apparent motion, ie small temporal and spatial increments, the apparent number of points for the fixed-trajectory condition was significantly lower than the apparent number in the random-walk condition. The traditional explanation of the suppression of persistence based on the spatiotemporal proximity of objects cannot account for these results. The enhanced suppression of persistence observed for a target moving in a consistent direction depends upon the activation of a directionally tuned motion mechanism extended over space and time.

1 Introduction

It has been known for many years that the visual system is able to integrate signals over time: about 120 ms for stationary stimuli under photopic conditions (Graham and Margaria 1935; Barlow 1958). More recently, Ross and Hogben (1974) showed that if a single dot is plotted sequentially in random positions on an oscilloscope screen such that the dot is physically present for only 20 μs, humans do not see just one dot at any one moment. Rather, observers report seeing as many dots as are presented within about 120 ms. That is, the images of the dot persist in the visual system for 120 ms. Ross interpreted these data as implying that the temporal integration time of the visual system is about 120 ms. This result agrees well with the temporal integration time found by Hogben and Di Lollo (1974) who used a similar technique. Thus, under conditions in which motion processors are *not* activated, the visual system integrates the images presented over about 120 ms.

Similar estimates of visible persistence have been reported for particular conditions when the stimuli were in apparent motion (Allport 1968, 1970; Efron and Lee 1971; Dixon and Hammond 1972; Coltheart 1980; Farrell 1984). However, Burr (1980, 1981) showed that the persistence of images can be reduced for stimuli that move in a constant direction. Burr sequentially presented an array of dots at a rate of 200 Hz. For each new presentation within a consecutive sequence, the array of dots was shifted slightly in a single direction to produce apparent motion. He found that if the duration of the apparent motion sequence was less than 30 ms, subjects saw a smeared line or, alternatively, observers saw several overlapping images of each dot rather than single moving dots. However, as the duration of the stimulus was increased (up to about 100 ms) the length of the smear decreased until subjects perceived unsmeared moving dots. These results have been replicated by Hogben and Di Lollo (1985).

One general finding concerning visible persistence both for moving and for stationary stimuli is that persistence is modulated by the proximity of the presented stimuli (Dixon and Hammond 1972; Burr 1980; Farrell 1984; Hogben and Di Lollo 1985; Di Lollo and Hogben 1985, 1987; Farrell et al 1990). Burr et al (1986) hypothesized that motion mechanisms with various spatiotemporal tunings could account for the suppression of visible persistence observed with moving stimuli. However, Di Lollo and Hogben (1987) argued that the involvement of a motion mechanism is not necessary and that inhibitory interactions unrelated to motion mechanisms could account for the dependence of the suppression of persistence on spatial proximity. Recently, Farrell et al (1990) have specified a simple gain-control model, using only the spatial and temporal separation and luminance as parameters, as the possible mechanism for modulating the duration of visible persistence—again eliminating the involvement of a motion mechanism.

The present study shows that there is a motion-specific influence on the suppression of visible persistence. The consistency of the direction of displacement of an object critically affects the reduction of persistence.

2 Method

2.1 *Stimuli*

Stimuli were dynamic random-dot cinematograms in which each dot moved with a constant step size. Stimuli were created by means of two types of movement algorithms. In one, referred to as the random-walk algorithm, the displacement of each dot for each frame was chosen randomly from a predefined distribution of directions and was independent of both its previous displacements and the displacements of other dots. In the other, referred to as the fixed-trajectory algorithm, once a dot had been assigned a direction from the predefined distribution, it continued to move in that direction for the entire duration of the stimulus presentation. Figure 1 shows schematic representations of both types of movement.

Stimuli were displayed on an $x-y$ cathode ray tube (CRT) display with a P4 phosphor. Observers viewed the 10 deg × 10 deg CRT screen from a distance of

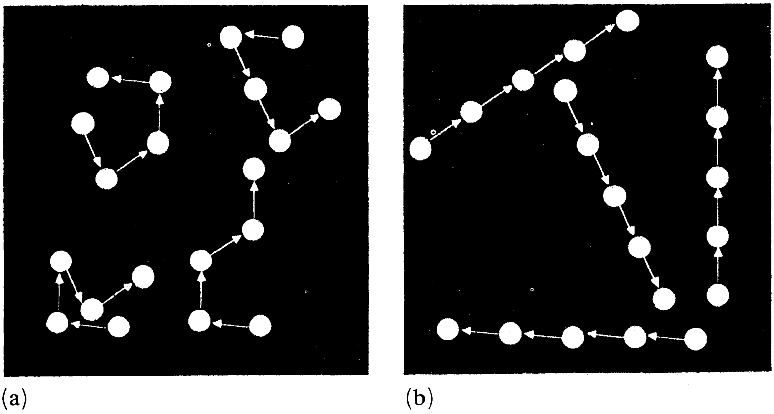

Figure 1. A schematic representation of the two moving-dot conditions. (a) Five frames (four displacements) of 'random-walk' movement for four dots. In these stimuli, dots are assigned a new direction of movement each frame, chosen randomly from a distribution of all 360°. (b) Five frames of 'fixed-trajectory' movement for four dots. The directions of movements for these dots are also chosen randomly from the same distribution of 360° as those in (a), but once a direction of movement is assigned to a dot, it continues to move in that direction for the entire duration of the stimulus. These two types of stimuli contain the same directions of motion and are identical if a two-frame analysis is performed.

57 cm, fixating a spot located at the center of the screen. The height of the CRT was set so that the center of the aperture was at approximately eye level. Stimuli were presented at a frame rate of 60 Hz, unless otherwise noted, and each stimulus dot subtended about 0.05 deg. All experiments took place with the overhead room lights on, creating a background luminance of 53 cd m^{-2}. Dot luminance varied randomly from trial to trial over the range 120 to 140 cd m^{-2}.(1) Push buttons connected to a computer initiated each trial and signalled observer responses.

2.2 *Procedure*

Observers judged the numerosity of dots within a two-alternative forced-choice, one-up and one-down staircase paradigm. Observers were presented in one interval with a random array of 50 stationary dots and in the other interval with a random array of moving dots (variable number). The observer judged in which interval more dots were perceived. Data were collected for the two types of movement, random-walk and fixed-trajectory, within the same testing session. Specifically, four interleaved staircases (one ascending and one descending for each motion type) were run simultaneously. Each staircase proceeded in the following manner. The observer was shown one stationary and one moving stimulus (order of presentation was randomized). If the observer perceived fewer moving dots than stationary dots, more moving dots per frame were plotted in the next trial; if the observer perceived more moving dots than stationary dots, fewer moving dots per frame were plotted in the next trial. An experimental session continued until at least ten reversals were recorded for each of the four staircases. Thresholds were estimated by taking the average of the reversal values excluding the first four reversals. This procedure tracked the 50% threshold, or point of subjective equality (PSE). This provided a measure of how many moving dots appeared equal in number to 50 stationary dots. In the absence of appreciable stimulus persistence, 50 moving dots should look equal in number to 50 stationary dots. If persistence lasts longer than the duration of one frame, for example if the observer perceives the dots from two frames simultaneously, then fewer than 50 moving dots will be needed to be perceived as equal in number to 50 stationary dots.

2.3 *Observers*

The author (SW), and another experienced psychophysical observer (WAM) who was naive to the purposes of these experiments, provided data for all experiments. Both observers had normal or corrected-to-normal vision. Observers were tested over a period of several months.

3 Experiments

3.1 *Experiment 1: Spatial separation*

This experiment was designed to measure how persistence is affected by the spatial separation (step size) between sequentially presented dots. Since stimuli were presented at a constant frame rate, speed increased as step size increased. Most of the previous research on persistence has shown that persistence increases with spatial separation or speed (eg Burr 1980; Di Lollo and Hogben 1985, 1987; Farrell et al 1990). The expectation for this experiment was that persistance would increase with step size and therefore the number of moving dots perceived equal to 50 stationary dots would decrease as step size increased.

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(1) This value was obtained by plotting a matrix of nonoverlapping dots (center-to-center spacing was 0.06 deg) at the same frame rate as used in the experiments. The luminance of this matrix was then measured with a Minolta luminance meter. Because of the decay rate of the phosphor and the high background luminance, the luminance of each dot had decreased to essentially zero within 10 ms.

3.1.1 *Results and discussion.* Data for the two observers, plotted as a function of step size, appear in figure 2a. Each point is the average of six threshold estimates. Error bars indicate ± one standard error. These data were collected with a stimulus duration of 100 ms (six frames) and an underlying directional bandwidth of 360°. There are three noteworthy features in these data. First, these graphs confirm the expected trend to smaller PSEs (greater persistance) with increments in step size. This trend is apparent for both motion types in both observers. Persistence increasing with the spatial separation between dots is in line with the results of previous research (Farrell 1984; Di Lollo and Hogben 1987; Farrell et al 1990) and underscores the importance of spatial proximity as a factor in visible persistence. Second, PSE decreases (persistence increases) monotonically up to a step size of 1.0 deg and then levels out. This suggests that persistence is not affected if dots are separated by

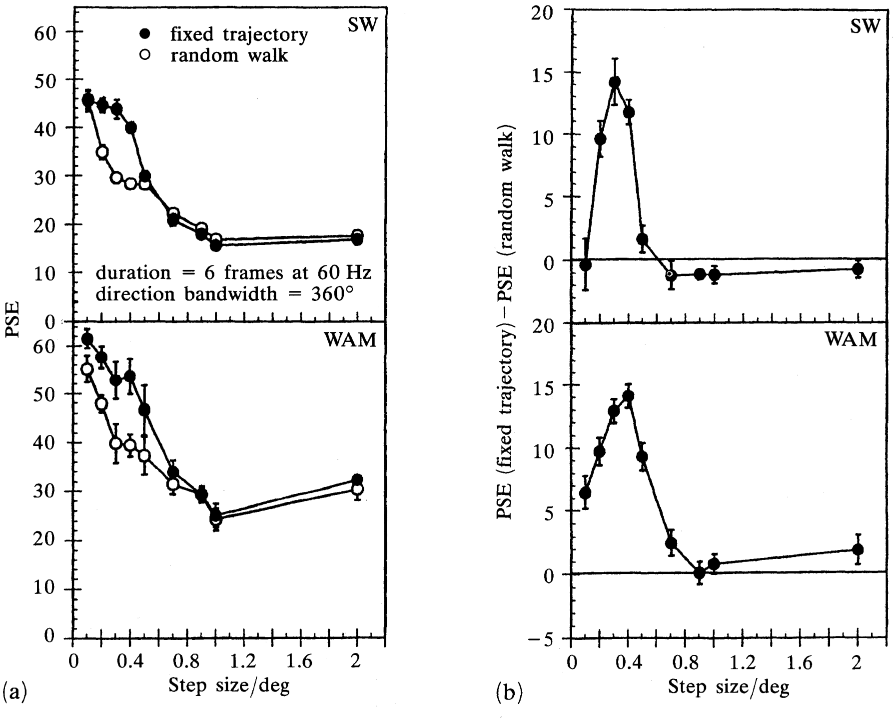

Figure 2. (a) The number of moving dots perceived equal in number to 50 stationary dots (PSE) as a function of the step size of the moving dots. Each point is the average of six threshold estimates. Error bars represent ±one standard error. In these graphs, smaller PSEs correspond to longer persistence. For each of the two observers two sets of data are plotted, one for each of the two movement conditions. Three important points about the data: (i) PSE decreases (persistence increases) as step size or spatial separation increases, (ii) PSEs asymptote at about 1.0 deg suggesting that persistence is unaffected once the spatial separation between dots is 1 deg or greater, and (iii) for step sizes between 0.1 deg and about 0.4 deg, the type of motion affects the perceived number of dots. Specifically, when dots moved with fixed-trajectories, more dots were needed to appear as numerous as 50 stationary dots than when dots took random walks which indicates less persistence in the fixed-trajectory condition. At a step size of about 0.5 deg the two curves converge, which suggests that the motion-dependent reduction of persistence disappears once the step size reaches 0.5 deg. (b) The difference between the two curves from (a) (fixed-trajectory minus random-walk) is plotted as a function of step size. Positive values mean that the fixed-trajectory condition produced shorter persistence than the random-walk condition. Points near zero indicate no difference between the two conditions. This graph clearly shows that the reduced persistence caused by dots moving in fixed trajectories acts only over a limited range of step sizes. The two observers show good quantitative agreement in the magnitude and range of the effect.

1.0 deg or more. Finally, these data show an important new result: the two types of motion produce different amounts of persistence over the range of step sizes 0.2 deg to 0.4 deg. This result cannot be explained in terms of the traditional view that the critical determining variable for duration of visible persistence is spatial proximity. In the present work, the only difference between the two motion types was the consistency of direction over time. All other spatial and temporal parameters of the displays were identical. In fact, if one looks at the spatial proximity of dots across two or more frames, dots moving in random walks are spatially closer, on average, than dots moving in fixed trajectories. This is so because dots moving in random walks tend to follow paths that often double-up on themselves and thus do not move far from their original starting position. This is direct evidence that the directional consistency of motion has a critical effect on persistence.

Figure 2b shows the difference between the PSEs for the two motion types for each observer. In these plots, positive values mean that more dots were needed (less persistence) for the fixed-trajectory motion than the random-walk motion. This can be regarded as a tuning function for the modulation of persistence due to coherent directional motion. The advantage of fixed-trajectory motion in reducing persistence is clearly seen in these plots. Notice that although the absolute values of PSEs for the two observers differ (figure 2a), when the differences between each observer's respective curves are taken (figure 2b) the resultant curves are very similar; the magnitude and the range of step sizes over which fixed-trajectory motion reduces persistence is strikingly similar for both observers.

The experimental procedure used above does not rule out the possibility that observers may have used the perceived local density as the basis of their judgments. However, because the dots in both the moving and stationary displays are randomly positioned in each trial, local density is an unreliable cue. Variability in perceived number estimates taken in different staircases should be large if this were the cue on which observers based their judgments. However, performance was stable, as evidenced by small standard deviations across staircases (standard deviations: SW, 9.1% of threshold; WAM, 16.0% of threshold), suggesting that local density was not the basis of numerosity judgments. As an additional confirmation, a second procedure was run in which there were two different standards, one with 30 and the other with 50 stationary dots, and the area over which the dots were plotted was varied randomly from trial to trial. Thus, within one test session, one staircase for each motion type had one standard number of stationary dots and the other had a different standard number of stationary dots. The data from these two different procedures were transformed by taking the ratio between the number of stationary dots and the number of moving dots at threshold. This provided a measure of persistence that was independent of the number of standard dots. An analysis of variance (ANOVA) showed that data collected with the two-standard procedure were not significantly different from those obtained with the previous one-standard procedure ($F_{1,78} = 0.377, p > 0.05$).

It has been suggested (eg Loftus and Hanna 1989) that stimulus complexity may play a role in visible persistence: the higher the complexity, the longer the persistence. Conceivably, this might apply to the present work. The rationale is that encoding of motion in the random-walk condition may be a more difficult (and hence more complex) task than in the fixed-trajectory condition because each dot moving in a random walk defines an independent complex path. This higher stimulus complexity may lead to longer persistence. As a control, data were collected on observer SW for a display in which all dots in the random-walk condition were displaced in the same direction within any one frame but the direction was changed each frame. An ANOVA showed that dots moving in random walks with coincident directions produced persistence that was not significantly different from that with the usual random-walk stimulus ($F_{1,38} = 0.799$, $p > 0.05$). The difference in persistence between the random-walk and fixed-trajectory conditions is due to the difference in the directional consistency of their local motion and not to the particular procedure used, local density differences, or stimulus complexity.

3.2 *Experiment 2: Presentation rate*

Experiment 1 provides strong evidence that a motion mechanism is involved in the modulation of visible persistence. In addition, it was found that the greatest reduction in persistence due to motion occurred at a step size of 0.3 deg (figure 2b). This may suggest that the responsible mechanism, for these stimuli, has a tuning function that peaks at 0.3 deg. However, because the data were collected at a fixed frame rate of 60 Hz, one cannot determine whether the responsible mechanism is tuned to speed or spatial displacement. In experiment 2, perceived numerosity was measured for many spatial displacements at three additional frame rates of 20, 40, and 80 Hz. If the putative motion mechanism is speed-tuned, then one would predict that the peak reduction in persistence would shift to larger step sizes for slower frame rates and to smaller step sizes for faster frame rates. The peak would not shift if the mechanism were limited by spatial displacement.

3.2.1 *Results and discussion.* Figure 3 shows the difference in perceived numerosity between the fixed-trajectory and random-walk condition as a function of step size for the three frame rates, 20, 40, and 80 Hz, for both observers. Each point is the average of four threshold estimates. These data were collected with a stimulus duration of six frames and a directional bandwidth of 360°. Data from experiment 1, collected at a frame rate of 60 Hz, are also replotted as a thick solid line for comparison. For both observers, there is a common trend: the tuning functions peak at a step size of about 0.3 deg or 0.4 deg and show similar falloff regardless of frame rate. This shows that the reduction in the duration of visible persistence with fixed-trajectory motion is governed solely by step size, measured in degrees of visual angle, and not by speed.

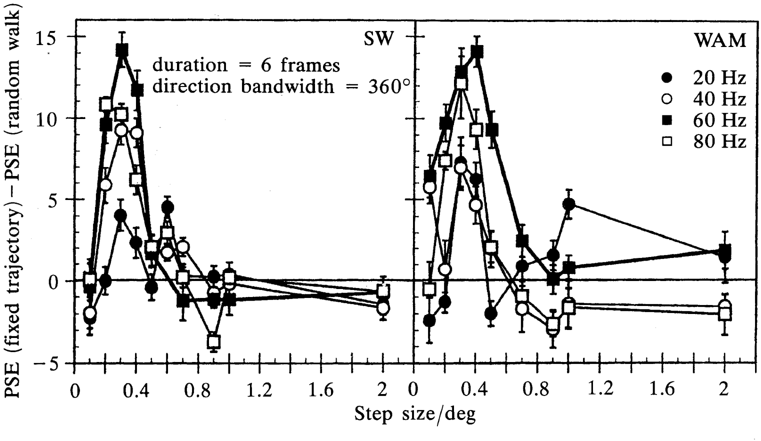

Figure 3. The difference between the fixed-trajectory and random-walk conditions shown for four presentation rates as a function of step size. The 60 Hz data are replotted from figure 2b. Points near zero indicate no difference between the two conditions. Although plotting rate affects the magnitude of the differences in duration of visible persistence obtained in the two motion conditions, the position of the peak and the falloff of the functions are virutally the same across frame rates. This pattern of results indicates that the reduced persistence of dots moving in fixed trajectories is affected only by the step size, not by frame rate. To wit, there is no indication of a shift in the peak that would imply speed tuning. Again, the two observers show good quantitative agreement in the magnitude and range of the effect.

3.3 *Experiment 3: Duration*

Experiments 1 and 2 showed that fixed-trajectory motion yielded shorter persistence than random-walk motion. One should expect that this attribute of fixed-trajectory motion should not be manifest until the putative motion mechanism responsible for modulating persistence is adequately stimulated. To pursue this line of reasoning, I measured how persistence is affected by the duration of the stimuli. Experiment 3 was designed to find out at what point in the display sequence a motion path is interpreted by the visual system to be of the fixed-trajectory type. Physically, the two motion types are separable after only three frames (two displacements). Does the visual system react immediately to the physical characteristics of the stimuli, thus showing the shorter persistence typical of fixed-trajectory motion after only two displacements, or is there some time-consuming processing that must take place before the duration of persistence is modulated? In addition, previous research on persistence with stimuli moving on fixed trajectories has shown that persistence first increases and then decreases as the duration is lengthened (eg Burr 1980; Di Lollo and Hogben 1985). Experiment 3 also provides a test whether such a pattern of persistence reduction occurs when all the elements of the display are not moving in the same direction.

3.3.1 *Results and discussion.* Data for two observers are plotted in figure 4a. Duration values (lower axis) and number of frames (upper axis) appear on the graph. These data were collected with a frame rate of 60 Hz, a step size of 0.3 deg and a directional bandwidth of 360°. There are four points worth noting. First, at very short durations—one and two frames—the two motion conditions yield similar levels of performance. This similarity arises because the displays are identical: the random-walk and fixed-trajectory algorithms produce identical stimuli at one and two frames (at one frame there is no movement and at two frames every dot has moved only once in its randomly chosen direction). Note also that at a duration of one frame (16.7 ms), observers make essentially veridical judgments about dot number. This shows that observers are able to make accurate judgments about perceived dot number and that such accuracy is not due to counting since one cannot count 50 elements in 17 ms. Second, notice that in the random-walk condition, after about 100 ms the rate of decrease in PSEs with duration slows dramatically—persistence has essentially reached asymptote by 100 ms. This is in good agreement with the results of previous research (eg Burr 1980; Coltheart 1980; Farrell 1984). The third and most important point is that at a duration of three frames (50 ms)—the minimum number of frames required to define a trajectory—the random-walk and fixed-trajectory curves separate and remain apart over the rest of the range of durations, with persistence lasting longer in the random-walk condition.

The shorter duration of visible persistence associated with fixed-trajectory motion can be seen clearly in figure 4b which shows the differences between the two motion conditions for each observer. Again, positive values mean that more dots were needed (less persistence) in fixed-trajectory motion than in random-walk motion to match the number of static dots. These data show that as soon as a trajectory is defined (three frames) stimulus persistence begins to be reduced in the fixed-trajectory condition compared with the random-walk condition. Again, the only difference between the random-walk and fixed-trajectory conditions is the directional consistency of movement of an individual dot over time. Thus, the reduction in persistence observed in the fixed-trajectory condition must be due to a mechanism that responds selectively to motion that is directionally consistent over time. Finally, notice that in the fixed-trajectory condition persistence for observer SW appears to rise (PSE decreases) and then fall (PSE increases) as duration increases up to about 100 ms.

Persistence for observer WAM simply seems to fall as duration is increased beyond about 100 ms. Thus, although the present data do not replicate the findings of Burr (1980) and Hogben and Di Lollo (1985) of a rise and fall in persistence with increasing duration in detail, there is a suggestive trend evident in data from both subjects. Differences in the experimental procedures may be responsible for this difference in persistence with changes in duration. For example, in the studies of Burr, and Hogben and Di Lollo a 200 Hz frame rate was used and the length of smear produced by moving dots was compared to a stationary line of adjustable length presented at the fixation point. In those experiments, observers needed to attend only to the local area around the fixation point in order to make their judgments of the length of smear. In the experiments reported here, observers judged the perceived numerosity of dots presented over the entire display; judgments based on local density or luminance would be more variable than those obtained (see discussion of experiment 1). Thus

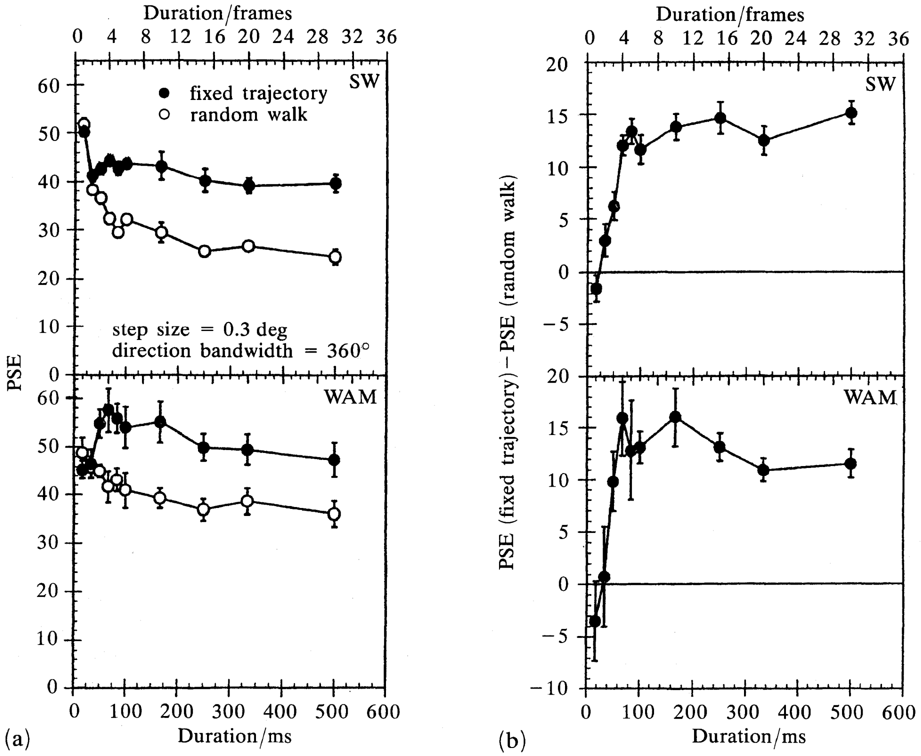

Figure 4. (a) PSE as a function of duration. Smaller PSEs correspond to longer persistence. Each point is the average of six threshold estimates; error bars represent ±one standard error. Two sets of data are plotted for each observer, one for each of the two movement conditions. For durations shorter than 50 ms (three frames), the type of motion has no effect on the perceived number of dots. Once the duration reaches 50 ms the two curves diverge. The fixed-trajectory data remain constant at the value reached at 50 ms while the random-walk data continue to decrease until about 100 ms. Thus, in the fixed-trajectory condition, motion mechanisms are stimulated adequately after only three frames. Once stimulated, the mechanisms act to reduce persistence to a constant short value so that moving objects are seen without blur. Without the stimulation of motion mechanisms, image persistence is known to be about 100 ms. (b) The difference between the two curves in (a) plotted as a function of duration. Again, positive values mean that the fixed-trajectory condition produced shorter persistence than the random-walk condition. Points near zero indicate no difference between the two conditions. This plot shows more clearly the temporal course of reduction in the duration of visible persistence as the duration of fixed-trajectory motion is increased. Asymptote is reached at about 100 ms.

the difference in the experimental task may be responsible for the slight difference in the way persistence changes with the duration of the stimulus in the present experiment compared with the results of Burr (1980) and Hogben and Di Lollo (1985).

3.4 *Experiment 4: Directional bandwidth*

The previous experiments showed how persistence depends on step size (spatial proximity) and duration. In those studies all stimuli were assigned their directions of movement from a distribution containing all 360°. The theoretical conviction in the present work is that the difference in persistence observed between the random-walk and fixed-trajectory motion conditions is due to fixed-trajectory motion activating a motion mechanism that is not activated by random-walk motion. If this hypothesis is correct, the hypothetical motion mechanism should have some directional tuning just as motion-sensitive cortical cells do (eg Movshon et al 1985). Thus, as the range of possible directions of movement is reduced, performance in the random-walk condition should begin to approach that of the fixed-trajectory condition. The directional bandwidth at which performance in the random-walk and fixed-trajectory conditions becomes equal can be considered as an estimate of the directional tuning of the putative motion mechanism.

An addition question may be asked by manipulating the direction distribution bandwidth: at what spatial scale does the hypothetical motion mechanism responsible for reducing persistence operate? The importance of the directional consistency of local motions to persistence is evidenced by the measurable difference between persistence in the random-walk and fixed-trajectory conditions found in the previous experiments where the distribution bandwidth was 360°. But does the reduction of persistence rely strictly on the directional consistency of local motions or do the directional characteristics of the entire display play a role? Because dots in the fixed-trajectory condition move only in a single direction, increasing the directional bandwidth will change only the number of different trajectory directions present in a single display. The pattern of performance of the fixed-trajectory condition should reveal how the large-scale directional characteristics of the display affect duration of visible persistence.

3.4.1 *Results and discussion.* In figure 5a, PSEs are plotted as a function of directional bandwidth for the two observers. A bandwidth of zero indicates that all dots moved in the same direction. These data were collected at a step size of 0.3 deg and at a duration of 100 ms (six frames). There are two points of note. First, random-walk and fixed-trajectory motion produce similar performance for bandwidths up to about 90°. For bandwidths larger than 90°, random-walk motion produces smaller PSEs (longer persistence) than fixed-trajectory motion. This effect is seen more clearly in figure 5b which shows the difference between the curves in figure 5a for both observers. The data show no systematic departure from zero (random-walk and fixed-trajectory conditions produce similar performance) until the bandwidth becomes larger than 90°. This suggests that the directional tuning of the motion mechanism responsible for reducing persistence is about 90°. Second, PSEs for the fixed-trajectory condition do not change monotonically with bandwidth; the PSEs of observer SW show essentially no change with increasing bandwidth while the more variable PSEs of observer WAM first decrease and then increase. These data suggest that the large-scale directional characteristics of the display are not affecting stimulus persistance; rather, the reduction of visible persistence is controlled only by the directional consistency of the individual moving dots.

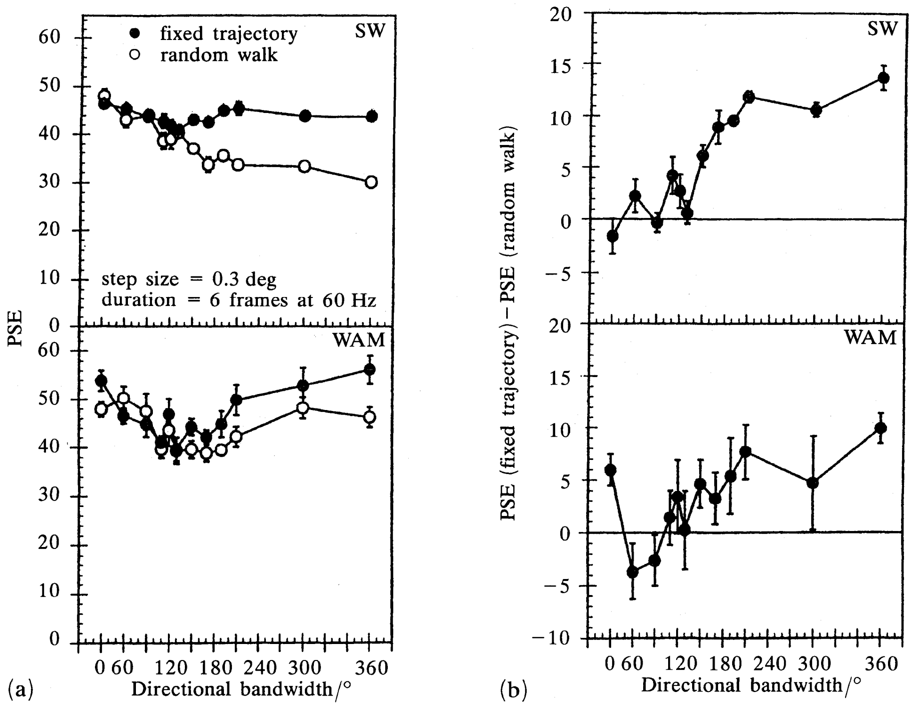

Figure 5. (a) PSE as a function of directional bandwidth. Smaller PSEs correspond to longer persistence. Each point is the average of six threshold estimates. Error bars represent ± one standard error. Two sets of data are plotted for each observer, one for each of the two movement conditions. PSEs for the two motion conditions are similar until the directional bandwidth becomes larger than about 90°. This effect is clearly seen for observer SW and is somewhat less clear for observer WAM. This effect is seen more clearly in (b) where the difference between the two curves in (a) is plotted as a function of directional bandwidth. Despite the greater variability in data from observer WAM, it is clear that for both observers fixed-trajectory motion reduces persistence more than random-walk motion for directional bandwidths greater than 90°.

4 General discussion

Previous research has shown strong evidence for a 'non-motion' mechanism that modulates visible persistence based on spatiotemporal proximity (eg Di Lollo and Hogben 1987). Results from experiment 1 for the random-walk condition confirm that spatial proximity has a strong influence on persistence, independent of coherence of motion (see figure 2). Di Lollo and Hogben (1987) provide a good discussion of inhibitory interactions which could be the basis of such a mechanism. In the same vein, Farrell et al (1990) present a simple gain-control model which modulates the amplitude of the temporal response produced by a stimulus based on the spatiotemporal proximity of adjacent stimuli. However, the present data show unambiguously that displays of random dots with fixed spatial and temporal parameters can exhibit different amounts of visible persistence depending upon the directional consistency of individual dot displacements. Models that predicate the suppression of persistence only upon the spatiotemporal parameters of stimuli cannot account for these findings. There must exist an additional mechanism of persistence modulation within the motion perception system.

What are the characteristics of the motion-dependent suppression of persistence? The present data shed some light on this question. It is clear from experiment 1 that to stimulate the putative motion mechanism, dot displacements must be less than 0.5 deg. This displacement limit is likely set by early motion detecting units.

However, this displacement limit does not reflect the spatial extent of the motion mechanism that modulates persistence, because the motion-dependent modulation of persistence is not evident until three frames (two displacements) of the stimulus have been shown (see figure 5). Thus the motion mechanism that modulates persistence is extended in space (spanning at least 1 deg) combining the input from many early motion detectors. In addition, experiment 2 showed that the motion mechanism that reduces persistence is tuned to spatial parameters and not to speed.

Burr et al (1986) suggested that motion mechanisms extending over space and time could account for many motion phenomena such as reverse phi motion and spatiotemporal interpolation. They also hypothesized that such mechanisms could remove the blur from moving images by cooperative interactions among many mechanisms with different spatiotemporal profiles. However, it is unclear what predictions their model would make for the present stimuli since the model is not completely specified. For example, how many mechanisms there are and how they interact with each other is important. Experiment 4 shows that the number of different directions present on the screen does not seem to affect the reduction in persistence in a systematic way. So persistence is reduced when dots move in fixed trajectories whether or not the paths of individual dots cross the paths of other dots (see figure 5). This suggests that the motion mechanism responsible for reducing persistence must be relatively local, responding to each dot independently. It is unclear whether the model of Burr et al (1986) could accommodate this requirement.

Given that there is an effect of motion on visible persistence, what more can we learn of the putative motion mechanism from the present experiments? One interesting piece of information comes from experiment 4. This experiment showed that there is little change in the persistence of the fixed-trajectory condition for bandwidths ranging from 1° to 90°. At first glance, this seems to suggest that the directional tuning of the mechanism responsible for reducing persistence is about 90°. This measure of the directional tuning for a motion mechanism is larger than the 30° to 45° suggested by other researchers (van Doorn and Koenderink 1983; Welch and McKee 1985; Watamaniuk et al 1989). This discrepancy, however, can be accounted for by noting that, although the full bandwidth of the rectangular direction distributions used in the present experiments measured 90°, the average change in direction for any given dot would be only 45°. Thus the directional tuning according to experiment 4 is about 45° (ie the persistence-reducing mechanism tolerates up to a 45° change in direction from one frame to the next). This adjusted value agrees well with previous measures of the directional tuning of motion mechanisms.

5 Conclusion

The present experiments provide clear evidence that there is a motion-dependent effect on the reduction of visible persistence. When individual dots move in a consistent direction, visible persistence is reduced more than when dots change direction randomly in each frame. The reduction in visible persistence due to motion is in addition to the reduction due to spatial proximity. This suggests that there are at least two mechanisms responsible for the reduction of persistence: a motion mechanism that when adequately stimulated reduces persistence to sharpen the moving image, and a motion-independent mechanism that modulates the persistence of dots that are presented in close spatial and temporal proximity.

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