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# The flash grab effect

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ABSTRACT

When an object moves back and forth, its trajectory appears significantly shorter than it actually is. The object appears to stop and reverse well before its actual reversal point, as if there is some averaging of location within a window of about 100 ms (Sinico et al., 2009). Surprisingly, if a bar is flashed at the physical end point of the trajectory, right on top of the object, just as it reverses direction, the flash is also shifted – grabbed by the object – and is seen at the perceived endpoint of the trajectory rather than the physical endpoint. This can shift the perceived location of the flash by as much as 2 or 3 times its physical size and by up to several degrees of visual angle. We first show that the position shift of the flash is generated by the trajectory shortening, as the same shift is seen with or without the flash. The flash itself is only grabbed if it is presented within a small spatiotemporal attraction zone around the physical end point of the trajectory. Any flash falling in that zone is pulled toward the perceived endpoint. The effect scales linearly with speed, up to a maximum, and is independent of the contrast of the moving stimulus once it is above 5%. Finally, we demonstrate that this position shift requires attention. These results reveal a new "flash grab" effect in the family of motion-induced position shifts. Although it most resembles the flash drag effect, it differs from this in the following ways: (1) it has a different temporal profile, (2) it requires attention, (3) it is about 10 times larger.



## 1. Introduction

It has been shown many times that the position of a moving object appears to be shifted in the direction of its motion. Mackay (1961) first observed this effect when moving a glowing vacuum tube while illuminating it occasionally with a stroboscope. The tube's position when illuminated by the flash appeared to lag behind its position along its continuous motion path, so that it was seen to be in two places at once. Nijhawan (1994) followed with a number of striking demonstrations showing that when one stimulus was flashed adjacent to a moving bar, the flashed stimulus appeared to lag behind the moving one. Several other studies showed a variety of related effects: the flash drag when a flash is presented adjacent to a moving texture (Whitney & Cavanagh, 2000a, 2000b); the flash jump, where a moving object undergoes a transient change in size or color and the change is seen further along the trajectory (Cai & Schlag, 2001); the motion-induced position shift where a stationary patch containing moving texture appears to be shifted in the direction of the internal motion (Anstis, 1989; De Valois & De Valois, 1991; Ramachandran & Anstis, 1990). All of these observations were preceded by the Fröhlich effect (Fröhlich, 1923) where the initial position of a moving object seems shifted along its trajectory. These effects have been reviewed by Whitney (2002) and by Eagleman and Sejnowski (2007).

We now add a new effect to this family of motion-induced position shifts that we call the flash grab effect. It has two components. The first generates the position shift and is specific to the end points of a motion trajectory when a texture or an object undergoes repeated back-and-forth motions. As described by Sinico et al. (2009), the apparent extent of a repeating motion trajectory appears shorter than it really is. The end points where the motion reverses are shifted toward each other by a substantial amount, as much as 30% of the trajectory length. Second, we now show that if a flash is presented at the location where the motion reverses and at the time of the reversal, it is not seen at that location but is grabbed to the perceived location of the reversal. The motion-induced shift is independent of the presence of the flash: the trajectory shortening is the same whether or not the flash is presented. The flash serves to make the position shift distinctive and easy to judge. The movie in Fig. 1 gives a demonstration of the effect.

What does this effect add to the large set of previous demonstrations of motion-induced position shifts? It is of course closely related to the flash drag effect seen for a flash presented adjacent to a moving texture rather than on it (Whitney & Cavanagh, 2000a, 2000b). We will show that the flash grab is 10× bigger than

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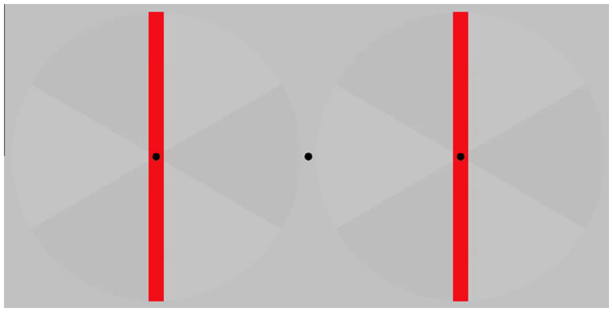

**Fig. 1.** The flash grab. The sectored disks rotate back and forth and on each reversal of direction, a pair of vertical colored lines appear briefly. Although the lines are vertical and parallel, they may appear tilted in (red) and then out (green) at each subsequent appearance. A movie (click here) shows these effects, and the contrast of the moving texture ramps up and down to show that the lines are vertical and parallel. Fixate the central dot for best effect. Click here for all the movies related to the article. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the flash drag and differs from it both in timing and in the involvement of attention. Moreover, there are substantial practical benefits to be gained from using the flash grab stimulus. The effect is very large and robust and so is a useful paradigm for exploring motion-induced position shifts. The transposition of the flash from its physical location to the perceived location of the motion end-point, often a distance of 2 or 3 times the size of the flash, offers a new paradigm for studying the perception of location. Clearly, perceived location of a stimulus cannot be determined by its retinal location alone.

We start by demonstrating the effect of trajectory shortening and then showing that the position shift seen with a flash or a moving mark has the same magnitude. This establishes that the position shift is entirely due to the trajectory shortening effect seen when an object or a texture undergoes motion reversals. We also report a classroom test of the effect with 132 participants, showing a robust position shift despite the different viewing distances and viewing angles and the small number of observations per subject.

We then show that the flash, in order to be grabbed, needs to be presented on the moving surface, not off it, near the internal edges of the moving texture, not between them, and at the time of the motion reversals, as opposed to before or after. Deviations from these conditions produce a sharp decrease in the perceived shift of the flash. The sharp tuning of the effect around the time of the motion reversal is quite different from the broad temporal tuning seen for the flash drag effect (Whitney & Cavanagh, 2000a).

We next show that the effect scales linearly with the speed of the moving texture, up to a maximum, that it has a constant value once the contrast of the texture is more than about 5%, that it depends on the spatial frequency of the moving texture, and that it is created by the motion that follows the flash, not the motion that precedes the flash.

Finally, we test whether spatial attention is required for the effect to be seen. Here we show that trajectories appear shorter only when they are individually attended. If a set of several asynchronous trajectories is attended as a group, they are seen as a dynamic motion texture that fully fills the space between the physical reversal points, with no shortening observed. This dependence on attention is unlike the flash drag, which can be seen even when attention cannot track the motion trajectories (Fukiage, Whitney, & Murakami, 2011; Whitney & Cavanagh, 2000a).

Across these different experiments, we find quite similar effects independent of major modifications of the experimental displays. We use different contrasts and structure of the moving texture; we vary the shape and size of the flash, the speed of the texture and the eccentricity of the flash. To report their location judgments, the observers set the perceived location of the flashes to either vertical or horizontal or in some cases two sets of flashes are presented with illusory position shifts in opposite directions, and subjects adjust the flash locations until they appear aligned. In some cases the flashes and the reversal points of the underlying texture are moved together to maintain their relative locations while in others the reversal points of the texture remain fixed and only the flash locations are moved. The motion-induced displacement remains strong across all these variations and we test the influence of several of them in a number of the experiments.

The results show these two effects: a repeating motion trajectory is seen shorter than it actual length; a flash near the end point of the motion is strongly attracted to that end point. We offer no mechanistic explanation for the trajectory shortening, although it can be described (Sinico et al., 2009) as an effect of location averaging (but not simply blur). It may be a process of predictive position extrapolation (reviewed in Nijhawan & Khurana, 2010). We will show that it only occurs for an individually attended trajectory, unattended trajectories show no shortening. This result will constrain models of the underlying process and differentiate this effect from the flash drag effect that is seen for trajectories that cannot be tracked with attention (Fukiage, Whitney, & Murakami, 2011; Whitney & Cavanagh, 2000a). We also have no mechanistic explanation of the flash grab, the displacement of the perceived location of the flash by up to several degrees of visual angle (dva). Whatever its cause, it serves as a very useful marker for measuring the position shift caused by trajectory shortening. It appears that the flash is grabbed best when it seems to belong to the moving stimulus – when its transient is synchronous with the strong transient of the motion reversal.

## 2. Experiment 1a: Trajectory shortening and its effect on a superimposed flash

Sinico et al. (2009) demonstrated that a single dot travelling back and forth was seen to cover a shorter extent than its physical trajectory. Here we change their procedure to make the trajectory a circular one and, in addition to the green marks that move along the trajectory, we also test a moving texture, albeit a simple sectored ring with one light sector and one dark sector (Fig. 2). We test the texture without the marks, with the marks, or with the marks only flashing at the trajectory endpoint.

### 2.1. Method

#### 2.1.1. Participants

The observers were 3 males and 4 females, all right handed, average age of 29; 6 were naïve and one an experienced psychophysical observer. All had normal or corrected-to-normal visual acuity and normal color vision.

#### 2.1.2. Apparatus

The experiments were run on Apple Macintosh G4 computers with custom software written in C using the Vision Shell Graphics Libraries (Comtois, 2003). Displays were presented in a dimly lit room on CRT monitors with 85 Hz refresh rate and resolution of $800 \times 600$ pixels. Adjustments were made with a computer mouse. A chin rest was used to maintain viewing distance of 57 cm.

#### 2.1.3. Stimuli

The screen was filled with a uniform, mid-gray background. A small, black fixation dot was at the screen center and, when present, a single cycle of a rotating annular square wave (sectored ring) wrapped around a ring of 10 dva outer radius and 7.5 dva inner

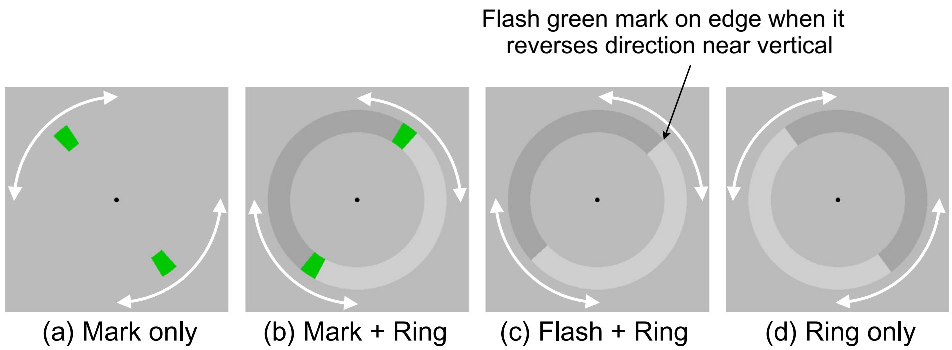


**Fig. 2.** The stimuli rotated back and forth through 90° so that the green marks or sector edges in the ring aligned alternately with horizontal then vertical. The subject rotated the stimulus so that at one end of its travel, the edges or marks appeared to align with vertical. The four stimuli can be seen as movies here. In the Flash + Ring stimulus, the green marks only appeared when the sector edges reached the end of travel near vertical. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

radius (see Fig. 2) centered on the fixation point. The square wave had 25% contrast for the three conditions when it was present. The ring rotated 135° (degrees of rotation) every second (20.6 dva/s) and reversed direction every 660 ms (covering 90°, one half cycle, in that time). At each reversal, the motion stopped for 47 ms (4 frames at 85 Hz). Green marks were used to indicate the edges of the square wave that were to be set to vertical. Each mark was a 11.25° radial segment extending across the width of the ring, 2.5 dva, and was 1.7 dva wide at its midpoint. One mark was centered at each of the light–dark edges of the square wave. There were four variants used to indicate the location on the ring that the observers adjusted to vertical. First, the green marks were present alone, rotating back and forth through 90° with the square wave ring set to 0% contrast (Fig. 2a). Second, the green marks rotated back and forth along with the square wave (Fig. 2b). Third, the square wave ring rotated back and forth and at each second reversal (Fig. 2c) the marks were flashed on for 47 ms. Finally, the ring rotated back and forth and no markers were presented (Fig. 2d).

*2.1.4. Procedure*

On each trial, one of the four types of stimuli (in random order) was presented rocking back and forth. The location of the marks at motion reversal (or square wave edges in the absence of a marker) initially had a random orientation in the range of ±45° of rotation around vertical on each trial. On half the trials, the motion of the marks was clockwise toward the reversal point that was near vertical then counterclockwise away, and on the other half, it was counterclockwise toward vertical and then clockwise away. Using the computer mouse, the observers adjusted the reversal point (or flashes when present) to align vertically with fixation as the ring and/or marks continued to rock back and forth. They had unlimited time to make the setting. When they were satisfied with their setting, they pressed the space bar and the computer beeped to indicate the beginning of the next trial. The four different stimuli were tested 16 times each.

*2.2. Results*

Fig. 3 shows the results averaged across the seven subjects. The apparent location of the marks or the edges of the square wave in the ring at the reversal point was shifted by about the same amount (15° rotation) in the direction of rotation that followed the reversal, whether it was the marks alone, the marks and the ring, marked with flashes, or just the ring. The conclusion is clear: the perceived location of the reversal point was shifted by the same amount, no matter how it was marked. The trajectory was

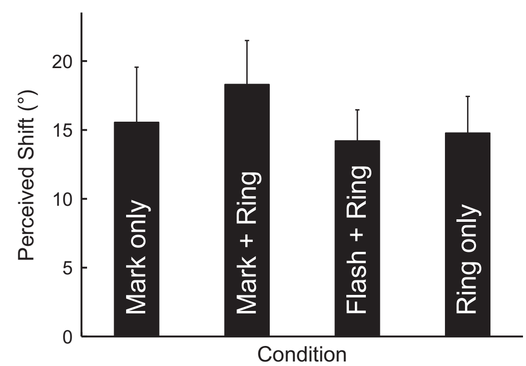


**Fig. 3.** Trajectory shortening vs. flash grab effect. Amount of rotation required for the reversal point to appear aligned with vertical. Vertical bars are +1 SEM. In all cases the stimuli had to be rotated by around 15° in order for the reversal point to appear aligned with vertical. This was true for the isolated mark, for the mark and the ring moving together and for the sectored ring alone. Importantly, the setting was similar for the flash that appeared only at the reversal point. This flash was grabbed to the same position as the shortened endpoint of the motion trajectory.

shortened by 15° out of 90° of travel on the one end that was measured. It was undoubtedly shortened by the same amount at the otherwise identical other end (at horizontal). This means the 90° trajectory was seen as only covering about 60° of arc. This 33% shortening is in the range reported for linear trajectories by Sinico et al. (2009).

The similarity of results across the conditions shows that the trajectory shortening is the basic effect (as measured in the marks only and ring only conditions) and the strength of the displacement is not changed when flashes appear at the reversal point. However, we are most interested in this flash case because although the flash was never in motion itself, it was pulled to the displaced end point (Fig. 4). This is what we call the flash grab effect. The flashed marker does not contribute to the position shift created by the underlying motion but, importantly, it allows us to easily visualize the displacement – especially if the moving texture is complex. For example, in the experiment here, in the conditions without the flashed marker, we had to simplify the moving stimulus to have only one set of edges or marks in the vicinity of vertical reference direction throughout the trial, otherwise observers would not have known which edges or marks to judge. Having a flash to mark the intended alignment point removes these constraints, and as we show here, entails no loss of the size of the effect. It allows us to present the flash when the point of interest approaches vertical, even if there are several otherwise identical points (a multiple cycle grating), or if the texture is random, as

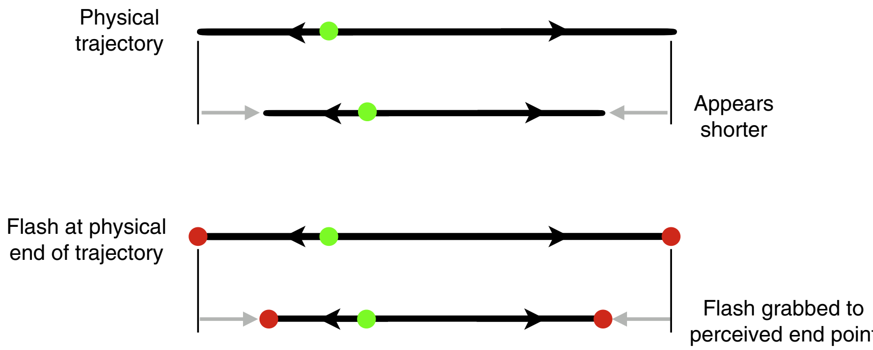


**Fig. 4.** A repeating trajectory is seen to cover a shorter extent than its physical length (Sinico et al., 2009). Our results show that if a flash is presented at the trajectory end point at the moment the motion reverses, it is seen at the same location as the perceived endpoint of the motion. This is the flash grab. The trajectories are shown as linear here for convenience; in our experiment they were circular.

we have previously shown (Kosovicheva et al., 2012; Tse et al., 2011).

## 3. Experiment 1b: Classroom test of the flash grab effect

In our first experiment, the perceived shift was large and robust across a variety of methods of marking the end point of the motion. To demonstrate the strength of the effect and ease of measurement, this next experiment was conducted in a classroom with 132 undergraduates in computer science at UCSD, who were given only a few minutes of instruction. The rocking sectored display (Fig. 5) was different from the displays of the first experiment in a number of ways, none of which turned out be important, as we will show in subsequent experiments. The results here show that the effect is easily measured with simple methods on many observers simultaneously. The differences in display size and viewing angle did not reduce the strength of the measured effect.

The display the students saw, presented on a large video projection screen at the front of the class, had 3 cycles of a square wave (see Fig. 5) and large colored disks that were flashed at each reversal, once in green when the ring reversed to counterclockwise, and once in red when it reversed to clockwise. This stimulus makes the red and green flashes shift in opposite direction, so that the apparent angle between the red and green is twice the shift of each. The rotation of the ring was 240°/s with reversals every 0.5 s, giving 120° of travel between reversals, with a 50 ms pause in the motion at the reversal (3 frames at 60 Hz). We estimate that the annulus subtended between 3 and 10 dva for students at the back and front of the room. The same light–dark edges always arrived at the top and bottom locations for each reversal. Nine versions of the movie were prepared with physical offsets between the red and green reversals disks ranging from −10° to +70° (at +60°, the red would be +30° clockwise and the green −30° counterclockwise). Each version was presented once in a random order. The students pressed one button on a clicker to indicate whether they saw red left of green and another to indicate green left of red. Their responses crossed 50%, the point of subjective equality, at 45.7 ± 6.1° between the red and green disks, indicating about 23° of shift in opposite directions at each of the two reversals. Note that as the angles between the red and green disks increased, they changed their amount of overlap with the light–dark edges at the moment they were flashed (as these edges were always at the same locations at the moment of the reversal). We will see in the next experiment that this might have reduce the strength of the effect that we measured here, although given the large size of the disks, they were never far from the nearest light–dark edge.

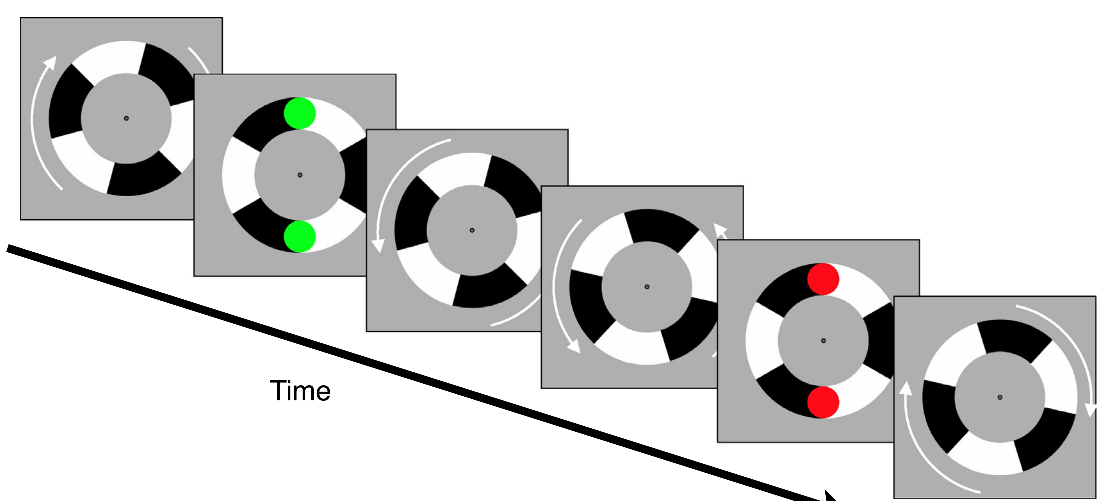


**Fig. 5.** The ring oscillated back and forth through 120° so that the sector edges aligned with vertical at each reversal. Green disks were flashed at one reversal and red at the next. Since the motions had opposite directions at the two reversals, the green and red disks appeared to be shifted away from each other in opposite directions. Seven versions of the movie were presented, each with a different physical offset between the red and green disks (they are shown aligned here and in the movie). 132 students in an computer science class at UCSD reported whether red was to the left of green for each of the offsets to generate the data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Whatever the effect of the disk to edge alignment, a strong effect was reported, doubled in amplitude (as it was in the original demonstration of Fig. 1) by presenting a flash at both reversals where the two flashes are necessarily shifted in opposite directions. This shows, as did Fig. 1, that the superimposed flash lets us estimate the trajectory shortening effect in a variety of circumstances, using flashes of different shapes and motion of different contrasts.

## 4. Experiment 2: Position and timing requirements for flash grabbing

The first experiment showed that using a flash to mark the trajectory end point gives the same position shift as is seen for the motion trajectory itself. The flash is grabbed by the trajectory end point and appears to have been presented at the same location as the perceived end point. In this experiment, we test how selective this flash grab is to the positioning of the flash relative to the moving edges in the rotating ring and to the timing relative to the point of motion reversal. The procedures in the three conditions differ substantially but the results suggest that to be grabbed maximally, the flash has to be on the moving texture, on or near a moving feature of that texture, at the time of the motion reversal.

### *4.1. Method*

#### *4.1.1. Participants*

*4.1.1.1. On-vs.-off-the-ring.* The observers were 5 males, all right-handed, average age of 30, 4 were naïve and one an experienced psychophysical observer. All had normal or corrected-to-normal visual acuity and normal color vision.

*4.1.1.2. On-vs.-off-the-reversal.* The observers were 3 males and 1 female, all right handed, average age of 26, 3 were naïve and one an experienced psychophysical observer. All had normal or corrected-to-normal visual acuity and normal color vision.

*4.1.1.3. Synchrony.* The observers were 3 right-handed males and 1 left handed female, average age of 27, all were experienced psychophysical observers. All had normal or corrected-to-normal visual acuity and normal color vision.

#### *4.1.2. Apparatus*

The equipment was identical to that of Experiment 1a.

#### *4.1.3. Stimuli*

*4.1.3.1. On-vs.-off-the-ring.* The screen was filled with a uniform, mid-gray background. A small, black fixation dot was at the screen center and a 4 cycle square wave (8 sectors) filled an annulus of 12 dva outer radius and 8 dva inner radius (see Fig. 6a) centered on the fixation point. The square wave had 100% contrast. The ring rotated 270° every second (47 dva/s) and reversed direction every 660 ms (covering 180°, two cycles of the square wave, in that time). Light–dark edges aligned horizontally with fixation on each reversal at which point the motion stopped for 47 ms. During that pause, two large disks, each 4 dva across, were flashed on opposite sides of the ring at locations adjusted by the observer. They alternated between red and green on each reversal. The disks were centered at one of nine eccentricities from fixation, in equal steps of 2 dva, from 2 dva to 18 dva. At 10 dva eccentricity the disk fell exactly within the rotating ring.

*4.1.3.2. On-vs.-off-the-reversal.* Similar except that two cycles of a rotating annular square wave (sectored ring) filled an annulus of 10 dva outer radius and 7.5 dva inner radius (see Fig. 6b) centered on the fixation point. The square wave had 25% contrast and rotated 135° every second and reversed direction every 660 ms (covering 90°, one half cycle of the square wave, in that time). At each reversal, the motion stopped for 47 ms and during that pause, a pair of green markers was presented. Observers rotated the ring and marker location with it until the two flashes appeared aligned with vertical. The markers were radial segments, 11.25° wide, spanning the width of the ring, 2.5 dva, and 1.7 dva wide at their midpoint. The location of the markers relative to the light–dark edges was varied over nine locations from 90° of spatial phase counterclockwise from the light–dark edge (midway in the square wave sector) to 90° of spatial phase clockwise of the light–dark edge (−90, −40, −20, −10, 0, 10, 20, 40, 90). At each relative location between the flash and the light–dark edge, the ring was oriented so that the flash would occur at vertical at motion reversal when the observer made a 0° adjustment (no rotation either way). When the observer rotated the green marker locations to set perceptual vertical, the ring rotated as well maintaining the relative spatial offsets of markers and light–dark edges.

*4.1.3.3. Synchrony.* Similar to the on-vs.-off-the-reversal condition except that the motion did not pause at each reversal, but switched directions immediately. The markers appeared for 47 ms (4 refresh frames of the monitor) and were always aligned to the mean location of the light–dark edge during the marker's appearance. The timing of the marker appearance was varied from 330 ms before to 330 ms after the reversal. At each relative timing between the flash and the reversal, the ring was oriented so that the flash would occur at vertical when the observer made a 0° adjustment. When the observer rotated the green marker locations to set perceptual vertical, the ring rotated as well maintaining the relative timing of marker appearance and reversals.

#### *4.1.4. Procedure*

*4.1.4.1. On-vs.-off-the-ring.* On each trial the disks were presented at one of the nine eccentricities (in random order) as the ring rocked back and forth. The red disks alternated with the green disks at each reversal so that the directions of motion at the reversals were opposite for the red and green disks, ensuring that their shifts, if any, were opposing directions. The orientation of the ring at the reversal points was constant throughout with a light–dark edge on both sides aligned along horizontal through fixation. The locations of the red and green flashes were always symmetrically placed above and below horizontal and were superimposed at horizontal for a veridical setting. The positions of the disks were set initially to a random orientation in the range of ±30° around horizontal (in opposite directions for red vs. green) on each trial. Using the computer mouse, the observers adjusted the angle between the red and green disks as the ring rocked back and forth until the red and green disks appeared to exactly overlap. They had unlimited time to make the setting. When they were satisfied with their setting, they pressed the space bar and the computer beeped to indicate the beginning of the next trial. The nine different eccentricities were tested 5 times each for each observer.

*4.1.4.2. On-vs.-off-the-reversal.* At each motion reversal, the markers were presented at one of the nine offsets from the light–dark edge (selected in random order across trials), as the ring continued rocking back and forth. The location of the markers initially had a random orientation in the range of ±45° around vertical on each trial. On half the trials, the motion of the markers was clockwise toward the reversal point that was near vertical then counterclockwise away, and on the other half, it was counterclockwise toward vertical and then clockwise away. Using the computer mouse, the observers adjusted the perceived location of the top and bottom flashed markers to align vertically with fixation. When they were

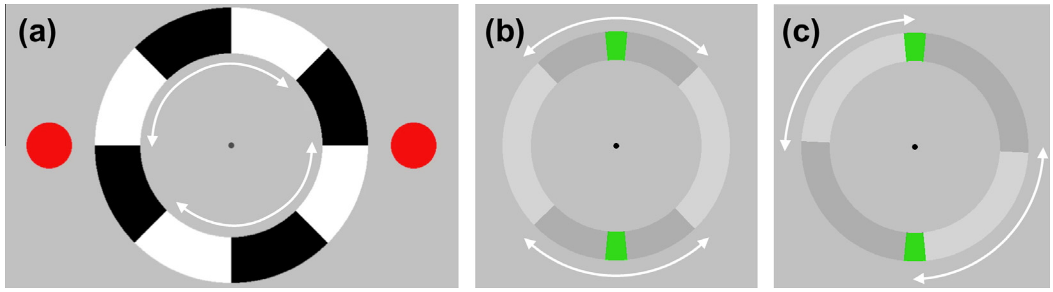


**Fig. 6.** (a) On-vs.-off-the-ring stimulus. Colored disks were flashed at each motion reversal alternating between red and green and so that they were displaced in opposite directions. Observers adjusted the relative locations of the red and green flashes until they appeared to fall at the same location. The disks were presented at one of nine different eccentricities from well outside to well inside the moving ring. (b) On-vs.-off-the-reversal stimulus. The green flashes were presented at different locations relative to the sector edge (here midway between, 90° phase), but always appeared at the moment of the motion reversal. Observers rotated the whole stimulus until the green flashes appeared aligned vertically. (c) Synchrony stimulus. The green flashes were presented at different times relative to the moment of motion reversal, but always aligned with the sector edge. Observers rotated the whole stimulus until the green flashes appeared aligned vertically. Click here to see the movies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

satisfied with their setting, they pressed the space bar and the computer beeped to indicate the beginning of the next trial. The nine different offsets of the markers from the light–dark edge tested 8 times each.

*4.1.4.3. Synchrony.* Procedure was the same as for the on-vs.-off-the-reversal condition with the following exceptions. At each motion reversal, the markers were presented at one of the nine timings relative to the motion reversal (selected in random order across trials), as the ring continued rocking back and forth. The nine different timings of the markers relative to the motion reversal were tested 10 times each.

### 4.2. Results

The results show that to be grabbed maximally, the flash has to be on the moving texture, on or near a moving feature within that texture, at the time of the motion reversal. In the first condition where the flashed disks were moved off the moving ring, the perceived shift dropped dramatically (Fig. 7). However, the effect was still present when the disks no longer overlapped the ring, at a level comparable with that reported in flash drag experiments (e.g., Whitney & Cavanagh, 2000a, 2000b) where flashes are placed adjacent to but not on the moving texture.

The second condition kept the flashes on the ring but moved them relative to the moving contrast edge. The perceived locations of the flashes were displaced most when they were near the contrast edge (Fig. 8). Specifically, the central three data points in Fig. 8 are for flashes that fall within ±10° spatial phase of the contrast edge. Since the square wave had 2 cycles around the annulus, this is ±5° of rotation. equivalent to ±0.75 dva. The flashes were 1.7 dva wide and so within this range of the central three points of Fig. 8, the flashes physically overlapped the edge. When the flashes fell in the middle of the sector, equally distant from the

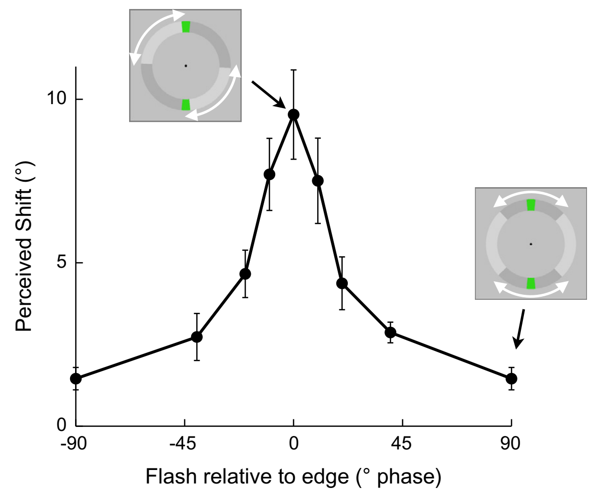


**Fig. 8.** Effect of flash distance from the sector edge in the moving ring. The flash occurs at the time of the motion reversal. The largest effect is seen when the flash is located on the sector edge. The vertical bars show ±1 SEM.

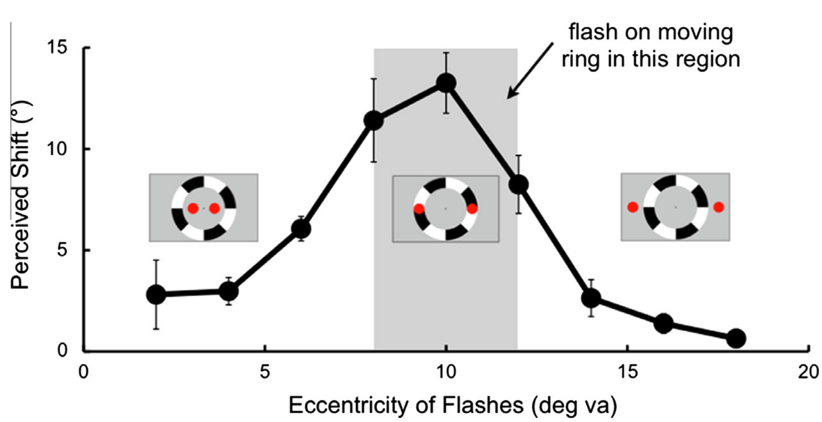


**Fig. 7.** Effect of flash distance relative to the moving ring. Large shifts are seen when the disk is in or half on the ring but these effects drop quickly with the disks off the ring. The vertical bars show ±1 SEM.

two adjacent contrast edges (about 7 dva on each side), the effect dropped to about 1/8th its maximum.

This result suggested that a cross, flashed on a rotating 6-sectored pattern, could demonstrate this difference in a single percept (Fig. 9). The cross has one arm aligned with a contrast edge and the other arm falling in the featureless center of a sector so the displacement of the two arms should be maximally different – unless, right angles are detected prior to the motion-induced displacement and resist distortion. In fact, they do not and the "Wonky Cross" demonstration movie shows that they are perceived as substantially different from right angles.

Finally, in the third condition, the flashes were again on the moving ring and always aligned with the contrast edge. However, their timing relative to the moment of motion reversal was varied (Fig. 10). The displacement effect is strongest when the flash occurs at the moment of reversal. When it occurred earlier or later, the effect dropped to quite small values. Clearly, there is a large effect that extends 200 ms before and after the reversal. This fairly symmetrical effect contrasts to the asymmetrical and longer lasting effect seen for the flash drag stimulus (e.g., Whitney & Cavanagh, 2000a). With their stimulus, the effect also began about 200–300 ms before the reversal, reaching a maximum at the time of the reversal, but then remained at that level for 2 s. Roach and McGraw (2009) found the flash drag effect was maximum at the time of a motion onset and decreased within a second to about half of its maximum, maintaining that level for as long as 5 s.

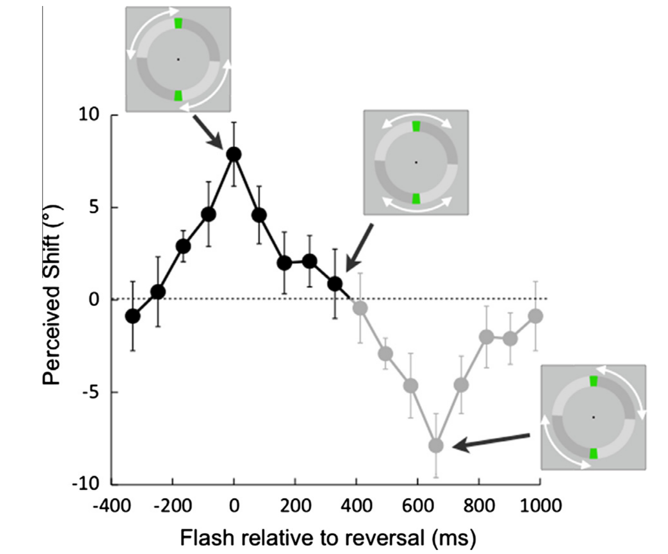


**Fig. 10.** Effect of timing of flash relative to moment of motion reversal. The flash always occurs at the sector edge when it is near vertical. The largest effect is seen when the flash occurs at the time of the reversal, one at the 0 ms origin and one 660 ms later. Data are combined over the two directions of reversals so the data points on the left are duplicated on the right, grayed-out and flipped in sign. Vertical bars show ±1 SEM.

## 5. Experiment 3: Effects of contrast, speed, spatial frequency, and temporal order

The previous experiments showed that a flash can be grabbed to the perceived end point of a trajectory, making the measurement of the position shift of the motion end point quite straightforward. The flash is optimally grabbed if it occurs right on top of a distinctive feature of the moving texture, at the moment the motion reverses direction. In the experiments here, we test how the effects of speed, contrast, and spatial frequency on the strength of the position shift and also whether it is the motion that follows the reversal (and the flash) or the motion that precedes it that causes the trajectory shortening that the flash measures.

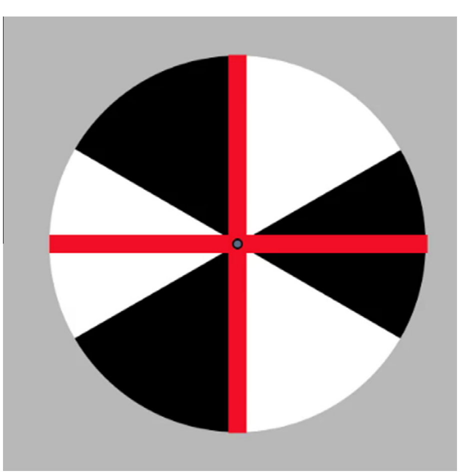

**Fig. 9.** Demonstration of difference of shift for a flash at the sector's edge (vertical red bar) vs. in the middle of the sector (horizontal red bar). Click here to see the movie. The red cross alternates with a green cross that will be dragged the opposite direction. If right angles have a privileged status, the flashed cross may resist the different strengths of shift for its vertical and horizontal segments and remain a right-angled cross. The demonstration shows otherwise. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 5.1. Method

#### 5.1.1. Participants

*5.1.1.1. Contrast, speed, spatial frequency (square wave).* The observers were 4 females and 3 males, all right handed, average age of 30, all were naïve except one experienced psychophysical observer. All had normal or corrected-to-normal visual acuity and normal color vision.

*5.1.1.2. Spatial frequency (sine wave).* The observers were 3 males and 2 females, all right handed, average age of 26, 4 were naïve and one an experienced psychophysical observer. All had normal or corrected-to-normal visual acuity and normal color vision.

*5.1.1.3. Temporal order.* The observers were 3 males and 1 female, all right handed, average age of 26, 3 were naïve and one an experienced psychophysical observer. All had normal or corrected-to-normal visual acuity and normal color vision.

#### 5.1.2. Apparatus

The equipment was identical to that of Experiment 1a.

#### 5.1.3. Stimuli

*5.1.3.1. Contrast, speed, spatial frequency (square and sine wave).* Everything was identical to the stimuli of the on-vs.-off-the reversal condition of the last experiment with the following exceptions. The markers were always flashed aligned with the light–dark edge during the 47 ms pause at motion reversal. In the Contrast condition, the texture had 2 cycles and moved at 135° of rotation per second, covering 90° in the 660 ms between each reversal. Contrast of the texture took on one of seven values, randomly chosen on each trial from these levels: 0%, 2.5%, 5%, 10%, 20%, 40%, 80%. In the Speed condition, contrast was fixed at 25% and the speed took one of eight values on each trial randomly chosen from these values: 33.75, 67.5, 101.25, 135, 202.5, 270, 405, and 540°/s. The interval between reversals was again fixed at 660 ms for all speeds. In the Spatial frequency condition, the texture always had 25% contrast and had either a sine wave or a square wave profile. The markers were always aligned with a light–dark transition and the speed was always 135° rotation per second (90° of travel between reversals). The number of cycles in the radial grating took one of five values: 2, 4, 8, 16, or 32 randomly on each trial.

*5.1.3.2. Temporal order.* Similar to the conditions above with 2 - cycles of a square wave a with 25% contrast, moving at 135° of rotation per second with the following exceptions. The motion was presented for 660 ms alternating with 660 ms of blank (no texture, no flashes). Within the 660 ms of motion, a single direction reversal with a 47 ms motion pause occurred at one of eight moments equally spaced from 0 and 660 ms. The marker was presented at the reversal. If the reversal occurred at 0 ms, then the first frames presented the marker and the texture (not moving) followed by 660 ms of motion in one direction. If the reversal occurred at, for example, 200 ms then 200 ms of motion in one direction was seen, followed by the green marks and a static texture for 47 ms, followed by 440 ms of motion in the opposite direction and then 660 ms of blank. If the reversal occurred at 660 ms, then 660 ms of one direction of motion was seen followed by 47 ms of the green marks and the static texture, then 660 ms of blank.

### 5.1.4. Procedure

*5.1.4.1. All conditions.* The same as for the on-vs.-off-the-reversals condition of the previous experiment.

## 5.2. Results

### 5.2.1. Contrast

The size of the perceived shift increased with the contrast of the moving texture but this saturated very quickly, around 5% contrast (Fig. 11a). The contrast invariance of the effect beyond 5% is similar to the properties of the magnocellular pathway (Derrington & Lennie, 1984; Snippe, 1998) where responses saturate at 3–5% contrast.

### 5.2.2. Speed

The size of the position shift increases with speed up to about 270° of rotation a second, 0.75 revolutions per second, and saturated beyond that point (Fig. 11b). The interval between reversals was always 660 ms so at higher speeds the texture edges covered larger distances. We do not know if the saturation in perceived shift represents a limit in the trajectory-shortening process or perhaps a limit to the temporal resolution of the monitor. These higher speeds produce the impression of multiple trailing images at our monitor refresh rate of 85 Hz and this degraded motion percept may be responsible for the limit we see here.

### 5.2.3. Spatial frequency

The size of the position shift decreases slowly with increasing spatial frequency for the square wave texture (Fig. 12). With 2 cycles per rotation, the lowest frequency we tested, the green marks are flashed on top of the 25% contrast light–dark edge, spaced 90° of arc away from the next edge. As the spatial frequency increases, the marker is always on top of a light dark edge of 25% contrast but now other edges are closer so in one sense, each edge becomes overall less salient. It is just one of many. The result for the sine wave texture is very different. There is little if any effect at the lowest spatial frequency and then it rises to meet the curve for the square wave texture at around 16 cycles per rotation. ANOVAs showed a significant linear decrease in perceived shift with spatial frequency for the square wave texture ($p < 0.01$), but a significant linear increase for the sine wave texture ($p < 0.0001$).

This result suggests that it is not the overall contrast that counts in producing the position shift, but the contrast step localized at or near the flash. The low frequency sine wave presents only a gradual contrast gradient at its midpoint whereas the square wave presents the same contrast step at the flash location at all frequencies. The higher frequency sine waves have a steeper contrast step in the immediate vicinity of the flash and at the 8.75 dva mean eccentricity of the ring, the higher frequency sine and square wave

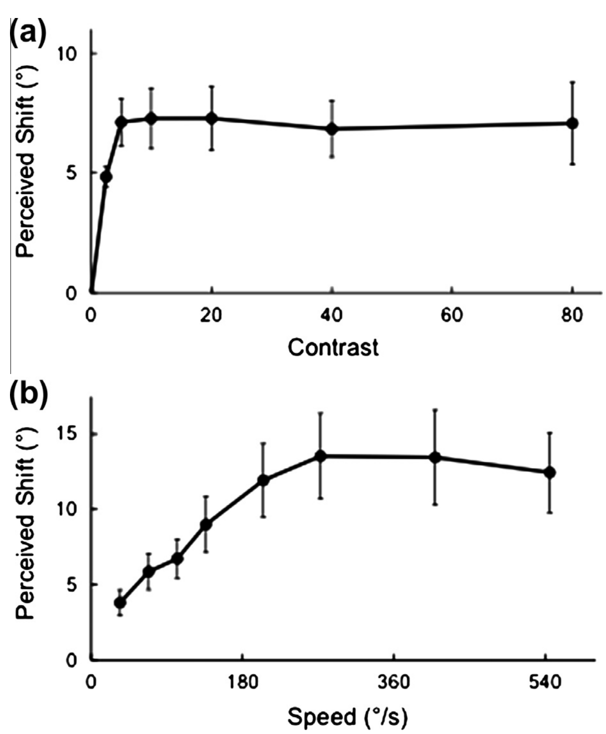


**Fig. 11.** (a) Rotation of rings and flash locations required to perceive the green flashes as aligned to vertical plotted as a function of the contrast of the light and dark sectored ring. (b) Rotation required as a function of speed of the rings (in degrees of rotation per second). Vertical bars show ±1 SEM.

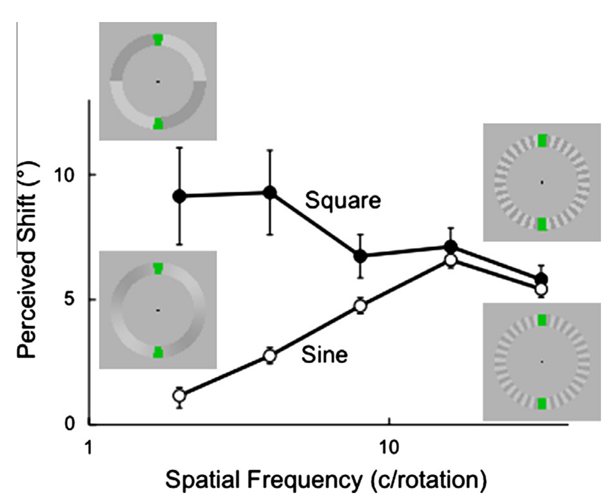


**Fig. 12.** Rotation of rings and flash locations required to perceive the green flashes as aligned to vertical, plotted as a function of the radial spatial frequency of the sectored ring. The filled symbols show the settings for the square wave ring and the outline symbols for the sine wave ring. Vertical bans show ±1 SEM. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

patterns have similar visual appearance. The position shift for the sine wave reaches a maximum at 16 cycles per rotations and at this frequency, the width of the flashes matches one-half cycle of the moving texture.

*5.2.4. Temporal order*

The effect of the timing of the motion reversal relative to the onset of the motion is shown in Fig. 13b. When the flash appears with the onset of the texture, it is equivalent to the classic Fröhlich (1923) where the start point of a moving trajectory appears shifted in the direction of the motion. The difference here is that the location of the start point is marked with a green flash. The result, the leftmost data point on the graph, shows a strong shift seen in the flash itself. This suggests that the shift is created by the motion that follows the onset and the flash. Moreover the displacement of the flash indicates that the loss of the initial portion of the trajectory is not a result of masking or delayed appearance, it is truly a position shift even in this simple case, equivalent to the Fröhlich (1923) effect. The data for progressively delayed flashes and reversals show that additional opposing motion prior to the reversal adds little or nothing, and the shortening of the motion duration following the flash does not decrease the shift effect until there is less than 200 ms following the reversal. The last data point shows that even a full 660 ms of motion *prior* to the flash produces no position shift when it is not followed by motion in the other direction.

The fact that the motion before the flash did not affect its perceived location shows that the illusion is not some form of motion (Mather, Verstraten, & Anstis, 1998), tilt (Schwartz, Hsu, & Dayan, 2007) or figural aftereffect (Kohler & Wallach, 1944; McEwen, 1951). It is also consistent with Whitney and Cavanagh's (2000a) finding that the flash-drag effect is determined by the direction of smooth movement after but not before the flash.

## 6. Experiment 4: Is attention required?

Here we ask whether the trajectory shortening (and the *flash grab* that it generates) is a property of the motion itself or occurs only for attended trajectories. By way of comparison, the *flash drag* (where the flash is presented adjacent to the moving texture rather than on) can be seen without attention (Fukiage, Whitney, & Murakami, 2011; Whitney & Cavanagh, 2000a). The goal of this last experiment is to compare the position shift in the perceived location of a motion reversal for attended motion trajectories vs. unattended trajectories. One problem here is that observers should not be able to report the properties of an unattended stimulus, at least not if it is properly unattended (for instance, owing to inattentional blindness; Mack & Rock, 2000). To overcome this, we presented multiple, parallel trajectories and ask observers to judge the trajectory end points of the entire set (Fig. 14). The trajectories are asynchronous but all trajectory end points are aligned so the whole set appears to fill a region with motion texture or linear optic flow. The boundary of the region, where the trajectories all reverse, is the visible edge of this texture. There are enough closely spaced trajectories to make it difficult to isolate a single dot. The trajectories are not unattended though, they are attended as a group. What is different between this group judgment and the judgment for a single trajectory is the allocation of attention, either to the whole group, or to a single dot.

We then examined whether the presence of several dots somehow influences the position shifts for other reasons like crowding or lateral interference. To do so we colored one dot in the field of several dots and asked observers to make judgments only about that dot while ignoring the others. Finally, we also ran a control with the multiple dots further in the periphery so that the eccentricity of the innermost dot of the group matched that of the single

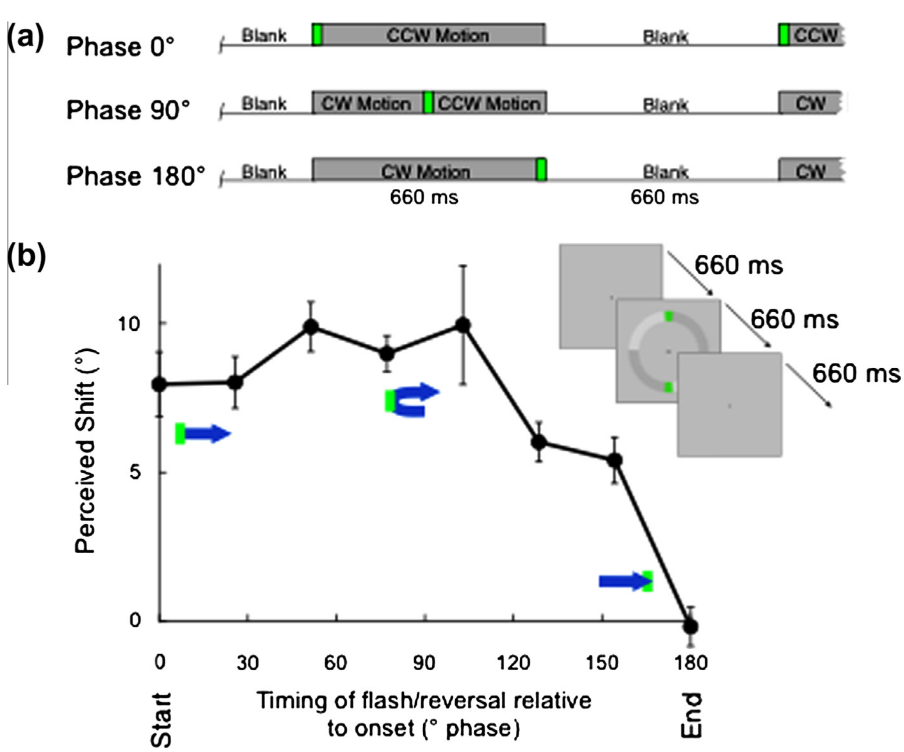


**Fig. 13.** (a) Timing of the temporal order presentations, alternating blank field and rotating ring every 600 ms. Click here to see sample movies. The 0° phase flash appeared for 47 ms at the same time as the ring and then motion continued uninterrupted for 660 ms, followed by a blank field. Between 0° and 180° phase, two directions of motion were presented, one before and the opposite after the reversal with the flash appearing at the moment of the reversal. The 180° phase flash appeared at the end of 660 ms of uninterrupted motion, followed by a blank field. (b) Perceived shifts as a function of temporal order. Vertical bars show ±1 SEM. The shift of the ring required for the top and bottom flashes to appear aligned to vertical is large starting immediately at 0° phase with no preceding motion and then dropping as the amount of motion trailing the flash decreases below about 200 ms (after 120° phase).

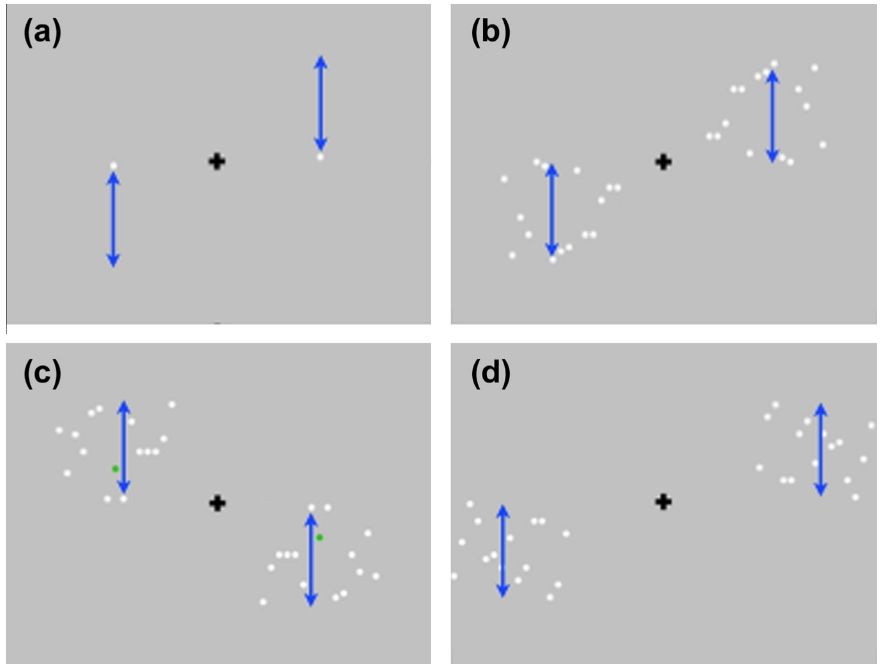


**Fig. 14.** The four stimulus arrays for the endpoint alignment cask. Click here to see sample movies. Dots oscillate up and down on the right and left. Observers adjust the relative vertical positions of the trajectories so the top end of one trajectory is horizontally aligned with the bottom end of the other. (a) A single dot moves up and down on the left and another on the right. (b) A set of 15 dots on the left moves up and down asynchronously between the same top and bottom end points while a second set does the same on the right. Observers adjust the apparent endpoints of the set of trajectories to line up horizontally, top end points on the left and bottom end points on the right. (c) The central dot of the 15 is colored green and observers are asked to adjust the locations of the sets of dots as before but now so that the endpoints of just the two green trajectories line up horizontally. (d) As in (b) but now the sets are moved further out so the nearest dot is at the same eccentricity as the single dot in (a) and the colored dot in (c). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dot when presented alone or presented as the one colored dot among all the others.

### 6.1. Method

#### 6.1.1. Participants

The observers were 2 females and 6 males, all right handed, average age of 39, all were experienced psychophysical observers including one of the authors (P.C.). All had normal or corrected-to-normal visual acuity and normal color vision.

#### 6.1.2. Apparatus

The equipment was identical to that of Experiment 1a.

#### 6.1.3. Stimuli

White dots (0.6 dva diameter) moved vertically and continuously on a gray background covering a trajectory of 10 dva between motion reversals. The speed of the motion was 21.3 dva/s and the duration between each reversal was 470 ms. The single trajectory was presented at 9.5 dva eccentricity on the left and right of fixation (Fig. 14a), one trajectory above and the other below the horizontal line through the fixation so that, during adjustment, the lower end of one trajectory could be aligned horizontally with the upper end of the other. When the dots were presented as a group, 15 dots were presented on the left and 15 on the right, all following parallel, vertical trajectories with the horizontally aligned upper and lower reversal points (Fig. 14b). The dots were spaced by 0.75 dva center to center, and the middle dot of the 15 was at the same eccentricity as the single dot (9.5 dva). All other parameters were the same as for the single dot. The condition of multiple dots with one colored was identical to the multiple dot stimulus except that the central dot was colored green (Fig 14c). Finally, a control stimulus (Fig. 14d) was identical to the multiple dot stimulus except that its inner dot trajectory was at the same eccentricity as the single dot (9.5 dva).

#### 6.1.4. Procedure

On each trial one of the four conditions was presented in random order: single dot, multiple dots, multiple dots one colored, multiple dots eccentric. The observers held fixation on the central mark throughout while adjusting the relative locations of the right and left groups of dots by moving the computer mouse. The positions were adjusted so that the end points of the trajectories, the top reversal on the left, bottom reversal on the right or vice versa, aligned horizontally through the fixation. Half the trials had a dot, or dots, in the upper quadrant on the left and in the lower quadrant on the right. This was reversed for the other half of the trials, alternating randomly. When a single dot or one colored dot among many was present on left and right, the observer aligned the trajectory end points of only that dot. When several dots were presented and all were white, the observer aligned the end points of the entire set on the left with those on the right. When satisfied with their setting, the observer pressed the space bar and the computer beeped to indicate the beginning of the next trial. The four different conditions were tested 12 times each for each observer.

### 6.2. Results

The size of shift required to perceive the end points as aligned is shown in Fig. 15. For the single white dot, a shift of the trajectory end point by 9.83 ± 0.84% of the trajectory length on one side was required for it to appear aligned to the end point on the other side (which was shifted an equal amount in the opposite direction during adjustment). That shortening at one end of the trajectory was most likely paired with a similar shift at the other end, suggesting therefore about a 20% shortening of the linear motion path. This

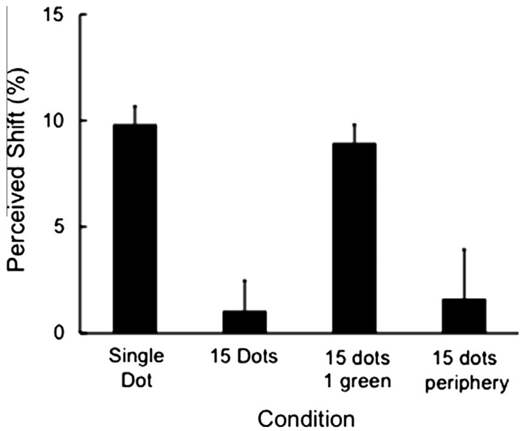


**Fig. 15.** The shifts of the trajectory end points required to make them appear aligned, in percent of trajectory length for the four different conditions. Vertical bars show ±1 SEM. Trajectories were 10 dva in length. The absence of effect for the sets of dots attended as a group shows that the trajectory shortening is not a product of low-level motion. It appears only when the trajectory is attended as an individual motion path.

compares reasonably well with the 33% shortening seen for the circular path in Experiment 1a, mark only condition, suggesting that we have measured the same basic phenomenon despite changes in method and stimuli.

Critically, when adjusting the end points of the 15 dots, this trajectory shortening was not seen as the adjustments were small (1.06 ± 1.42%) and did not differ significantly from 0.

Equally important, the results show that this loss of effect was not due to crowding from the close spacing of the dots. Specifically, when one of the 15 dots was colored and observers made their settings based on its perceived end points alone, the effect returned despite the close spacing of the adjacent dots. The required shift to match end points was now 8.95 ± 0.85%.

Finally, we had a control condition where the multiple dot trajectories started at the same eccentricity as the single dot (9.5 dva) to check that the larger end point shift at 9.5 dva for the single dot (and single colored dot among may) was not an effect of eccentricity. With the multiple dots, the innermost dot was much closer to the fovea and if observers based their setting only on that innermost dot, this eccentricity difference might have accounted for a smaller shift. In fact, however, the setting for the eccentric set of multiple dots was similar to the first set with a small offset 1.62 ± 2.33% that was not significantly different from 0.

These results strongly suggest that the trajectory shortening is a feature only of individually attended trajectories and not of trajectories attended as a group. The shortening (and flash grabbing it supports) therefore appears to be a property of the attentive tracking of the moving stimulus and not of the motion itself.

In contrast, the *flash drag* effect can be seen without attention. Specifically, Whitney and Cavanagh (2000a) showed that there was a significant shift in perceived location for flashes adjacent to a grating moving at even 12 Hz, above the 5–7 Hz maximum rate at which attentive tracking is possible (e.g., Verstraten, Cavanagh, & Labianca, 2000). Fukiage, Whitney, and Murakami (2011) also showed a flash drag effect around random motion reversals. The authors claimed that the motion creating the effect was preattentive because participants were unable to identify the jump direction at the time of the flash. On the other hand, another study (Watanabe, 2005) showed that participants must at least be aware that there is motion: when the visibility of the motion was suppressed with binocular rivalry, there was no flash drag effect on adjacent flashes which were themselves visible binocularly and not suppressed.

## 7. Conclusions

We have documented the large position shift, the flash grab, seen for a flash presented on top of a moving texture if the flash appears at the moment the motion reverses direction and is presented at the location of a clear feature of the moving texture. We also showed that the displacement of the flash is driven by the shortening of the perceived trajectory of the moving texture: the flash is grabbed to the perceived location of the trajectory end point. The flash itself does not contribute to the motion-induced position shift but only serves as a convenient marker to measure the trajectory shortening effect.

The strength of the effect and the ease of measuring it with the end point flash were demonstrated in a class room version where 132 observers gave a quick evaluation that showed an effect similar in size to what we measured under more controlled conditions.

Although the timing and positioning of the flash were critical for obtaining the maximum effect, the measurements were robust to several other variations: the shape of the flash, type of trajectory, the texture contrast, and the measurement procedure itself. The effect was strongest if the moving texture had sharp edges (square vs. sine) that were widely spaced and the effect scaled with the speed of the texture. If we average the size of the optimal effect across all the speeds that were tested we find that the displacement is equivalent to about 70 ms of travel of the moving texture. This compares with a wide variety of equivalent delays for the flash lag effect (e.g. Oğmen et al., 2004) where the overall effect may also include a delay between registering the flash and sampling the position of the moving stimulus. Our stimulus does not have this extra delay component as observers respond only to the flash itself, whenever and wherever they see it. It is a measure of a pure displacement effect and on average, the observers are reporting the location of a unique feature whose perceived displacement from its actual location is equivalent to 70 ms travel of the target.

Critically, Experiment 3 (temporal order condition) showed that it is the motion after the flash, following the reversal that determines the amount of perceived shift. If the flash and motion appear together, a large shift is seen, equivalent to the Fröhlich (1923) effect. This is not just a delay in seeing the motion or masking of the initial segment of the motion (see Eagleman & Sejnowski, 2007). The mark present at motion onset is shifted in the direction of the following motion and clearly visible. So it represents a spatial compression and translation of the initial segment of motion. Nothing is masked. If the motion is underway briefly before the flash and reversal, the effect stays strong until there is less than 200 ms of motion present following the reversal, then the effect drops away. If the motion stops and the flash appears at the same time, with no subsequent motion in the opposite direction, there is no effect. This pattern of results clearly identifies the motion following the reversal as the source of the trajectory shortening revealed by the flash.

Finally, Experiment 4 showed that the trajectory shortening occurs only for individual trajectories, suggesting that it is a property of the attentional processing of the motion, possibly to optimize action toward the target. It might be the case that attention cannot keep up with the rapid direction reversal at the end points and so provides an average location over some time window. Note that this must be an average computed on position values and not on image values because the perceived trajectory does not show the 20–30% blurring of location along the motion path that this would produce. Note also that if this attention-mediated averaging occurs, it requires that the perceived location is itself constructed by this attentional process as no shortening, or location averaging, is seen for the trajectories that are not individually attended. Clearly, whatever the process, it is capable of generating conscious percepts of dots (Experiment 4) and flashes (Experiments 1 to 3) that are relatively clear but quite distant from their actual retinal location. No image blur can do this.

We have characterized the properties, but not the source, of the trajectory shortening and the requirements for a flash to be grabbed to the perceived endpoint of the trajectory. We showed that the flash does not contribute to the position shift, but that it does serves to make it easily visible and measurable. The displacement of the flash was greatest when it was aligned in time and location with the physical trajectory endpoint. Nevertheless, there was a shift in the perceived position of the flash that remained at about 1/10th the maximum even when it was presented off the moving texture rather than on it (e.g., as in the flash drag stimulus, Durant & Johnston, 2004; Whitney & Cavanagh, 2000a; Roach & McGraw, 2009; Shim & Cavanagh, 2005; Whitney, 2006), or at the midpoint of the trajectory rather than at the reversal point, or out of alignment with the local contrast edges in the moving trajectory, rather than in alignment.

Our new *flash grab* effect uses a stimulus similar to the well established *flash drag* effect – with the sole exception that our flash is superimposed on the moving texture rather than adjacent to it. So we must ask whether the flash grab is a qualitatively different phenomenon or just a stronger version of the flash drag effect. Based on the data we have so far, we argue that it is qualitatively different. First, its time course is different and, second, attention appears to be required for the flash grab (as tested with the trajectory shortening) but not for the flash drag.

The time course of the *flash grab* is narrowly and symmetrically tuned around the motion reversal (Fig. 10). We attributed the temporal tuning to the binding between the flash and the motion. This binding is strongest when the reversal and the flash are simultaneous. In contrast, the *flash drag* shows a strong and continuing effect up to several seconds after the motion reversal (Whitney & Cavanagh, 2000a) or onset (Roach & McGraw, 2009). The flash grab and flash drag effects also differ in the role of attention. Specifically, the flash grab effect requires attention (Fig. 15) whereas the flash drag can be seen with or without attention. In particular, the flash drag is seen with attentive tracking (Shim & Cavanagh, 2005) and transformational apparent motion (Whitney, 2006) where there is no low-level motion signal. It is also seen for motion that cannot be tracked attentively either because it is too fast (Whitney & Cavanagh, 2000a) or because it is reversing too rapidly and unpredictably (Fukiage, Whitney, & Murakami, 2011).

Why is the flash attracted toward the local, moving feature when it reverses direction? We believe that the strength of this attraction is an indication that the flash is interpreted as part of the moving texture. Specifically, the flash is an isolated transient and the motion reversal is the only isolated transient in the otherwise smooth motion profile of the texture background. This "synchronicity" (Bregman, 1990) or "common fate" (Wallach & O'Connell, 1953) between the flash and the motion reversal transients is a strong clue that the two events belong together. In this case, we assume that the flash is taken as part of the motion and undergoes the motion-based shift in position that is applied to the moving texture throughout its trajectory. This motion-based shift likely occurs throughout the motion trajectory, although reversing direction near the endpoint. The flash is only significantly displaced at the endpoints because that is where it groups best with the motion.

If the flash grab is due to the grouping of the flash with the moving stimulus, then this is also a possible explanation of the difference between the *flash lag* effect, where a flash lags behind an adjacent moving stimulus, and the *flash grab* where it is pulled along with the motion. In typical test of the flash lag, the flash is presented beside the moving stimulus and would not be strongly grouped with it, so not shifted in position itself. It then serves as a reference to reveal the shift in the apparent position of the adjacent moving stimulus. We note two points here. First, the flash is in fact shifted slightly in the direction of motion (Eagleman & Sejnowski, 2007; Shi & Nijhawan, 2008; Whitney & Cavanagh, 2000a, 2000b). Also, not all of the flash lag effect is attributed to a shift in perceived location as other factors have been implicated (delay in attending to the motion, Baldo et al., 2002; Moore & Enns, 2004; visual or location persistence, averaging, differential latency, Krekelberg & Lappe, 2000, 2001; Mateeff & Hohnsbein, 1988; Metzger, 1931; Whitney & Murakami, 1998). Interestingly, previous studies have shown that a flash is not grabbed by a moving stimulus even if it is flashed on top of it. For example, a small bar flashed on a larger moving bar (Nihjawan, 1997) or a disk flashed briefly inside a moving ring (Nijhawan, 2002) both appear to lag behind. Part of the reluctance of these flashes to shift with the moving stimulus may be due to timing: they are typically presented in mid trajectory where we also show that the flash is poorly grabbed (Fig. 10). Additional evidence for this point comes from the "flash jump" effect of Cai and Schlag (2001, 2002), who did not superimpose a flash but just changed the color of the moving stimulus.

In these studies (Cai & Schlag, 2001, 2002), the odd colored flash was seen with very large position shifts in the middle positions of a motion trajectory, an effect that we do not find here (Fig. 10). Two factors were probably critical for this effect. First, the moving stimulus itself was changed rather than a different flash imposed on or near it. Second, the motion was a sequence of discrete steps so that the color change was a transient in a series of transient steps. These results suggest that if the flash appears to belong to the motion sequence, it can reveal the position shifts in mid trajectory as well as at the end points.

Overall we have found that when a contrast edge or a dot moves back and forth over a trajectory, that trajectory appears to be shorter than it actually is and that a flash presented at the physical location where the motion reverses, at the time of the reversal, is seen at the perceived trajectory endpoint. This flash grab can displace the perceived location over several degrees of visual angle, a stronger effect than that reported in the many related phenomena. The effect remained strong over many variations of parameters and procedure and was found only for individually attended trajectories.

A number of variables remain to be examined; we will mention just flash size and predictability here. First, we showed that the flash displacement was largest within a small region around the moving contrast edge, but we did not systematically vary the flash size. We assume that the critical factor is the overlap of the flash with the contrast edge at the moment of motion reversal so that the large the flash the further its center can be from the edge. Our indirect evidence for this assumption comes from Experiments 1b and 2 (on-vs.-off-the-ring) where we found strong effects even though the flash centers were often significantly displaced from the moving contrast edge at the moment of the motion reversal. However, the flashed disks in these two experiments (Exp. 2 on-vs.-off-the-reversal) were quite large compared to those in the experiment that explicitly tested flash location (Experiment 2 on-vs.-off-the-reversal). It would be useful to test this assumption in a further study. Second, we had shown that attention to the individual trajectory was critical for the position shift (Experiment 4) and we assume that this may also explain why the displacement effect is stronger for textures with fewer contrast edges (Experiment 3, spatial frequency). Specifically, with fewer edges, attention is more focused on the edge where the flash will appear. This suggests that the effect would decrease if the reversal and the flash occurred at an unpredictable moment or if there were moving several edges and the subject did not know on which edge the flash will occur. Again, it would be useful to test this assumption in a further study.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.visres.2013.07.007.

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