Chapter 73

Two-Stroke Apparent Motion

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The Effect

One hundred years ago, the Gestalt psychologist Max Wertheimer published the first detailed study of the apparent visual movement seen when two adjacent lights are flashed sequentially (see Kolers, 1972). Apparent movement can be created by presenting any two identical pictures successively, with the second shifted slightly in position relative to the first. Figure 73-1a shows a very simple example: a bright bar on a dark background is plotted in cross-section, displacing to the right from frame 1 (F1) to frame 2 (F2; solid arrow). The displacement evokes a perception of apparent motion to the right (dashed arrow). Stop-frame animation is based on this well-established technique.

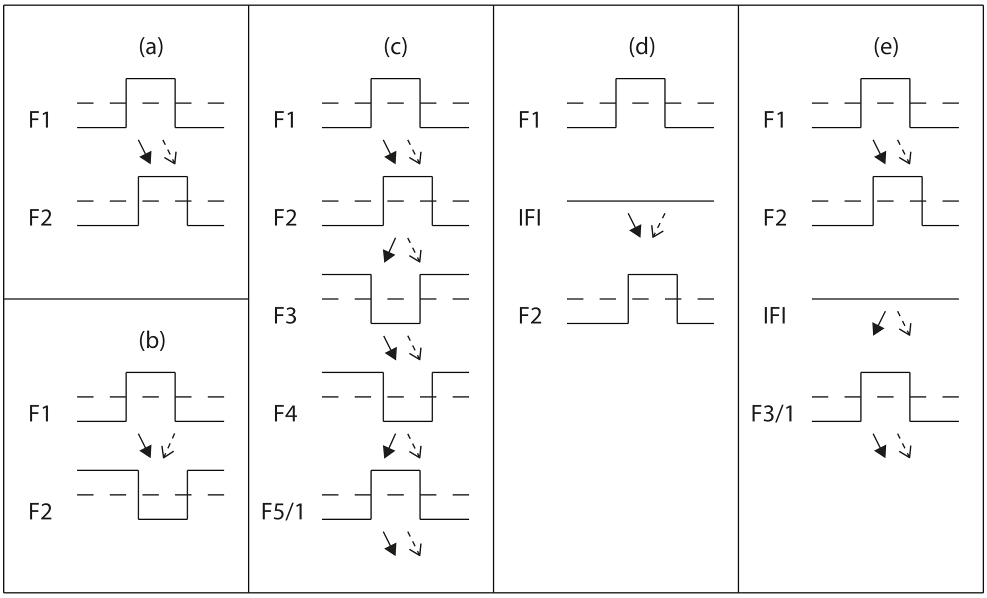

Figure 73-1.
Frame sequences to create simple motion illusions. (a) When a bright bar displaces to the right (solid arrow) from frame 1 (F1) to frame 2 (F2), apparent motion is seen to the right (dashed arrow). (b) When a bright bar displaces to the right and reverses in contrast, apparent motion is seen to the left. (c) A four-stroke cycle in which rightward displacements preserve contrast and leftward displacements reverse contrast. Frame 5 is identical to frame 1 (F5/1) so the sequence repeats, creating an impression of consistent rightward motion. (d) IFI reversal in which two-frame rightward displacement of a bright bar is interrupted by a brief uniform interstimulus interval (IFI). Apparent movement is seen to the left. (e) A two-stroke display containing a bar that displaces to the right from frame 1 to frame 2. Then, after a brief uniform interstimulus interval (IFI), frame 1 reappears (F3/1) and the cycle repeats. The bar appears to move consistently to the right.

Anstis (1970) reported the surprising observation that if the second picture is the photographic negative of the first, then the apparent direction of movement generated by the two-frame sequence is reversed; rightward spatial displacements are seen as leftward apparent motion and vice versa. Figure 73-1b shows a rightward shifting bright bar that reverses contrast in frame 2; apparent motion is now leftward. Anstis called this effect “reversed phi.” Anstis and Rogers (1975) found that small luminance edge displacements of about 0.17 arc degree gave the strongest "reversed phi" effect. Anstis and Rogers (1986) later created apparently continuous unidirectional apparent motion by repetitively cycling through four animation frames containing alternation between forward phi and reversed phi sequences. A simple instance of this four-stroke cycle is shown in Figure 73-1c. Transitions F1–F2 and F3–F4 produce forward phi, and transitions F2–F3 and F4–F5/1 produce reverse phi. Four-stroke apparent motion sequences generate strong motion aftereffects (MAEs) following prolonged inspection (subsequently viewed stationary patterns appear to move in the opposite direction).

In the 1990s several papers reported another curious visual effect seen in two-frame apparent motion displays: interframe interval (IFI) reversal. When the two frames of the animation are separated by a brief IFI that contains a blank field, the apparent direction of the sequence reverses (Shioiri & Cavanagh, 1990; Strout, Pantle, & Mills, 1994; Takeuchi & De Valois, 1997). So a rightward spatial displacement from the first frame to the second appears as a leftward movement when a brief blank field separates the two frames, as illustrated in Figure 73-1d. Reversals of apparent direction only occur over a narrow range of IFIs lasting around 30 to 50 msec. Mather (2006) exploited IFI reversal to create a new illusion of apparently continuous motion called two-stroke apparent motion. The sequence involves only two pattern frames, one spatially displaced relative to the other, which alternate repetitively. Every second pattern frame is followed by a brief blank field (a simple example is shown in Fig. 73-1e). Displacements that are not interrupted by the IFI yield apparent motion in the same direction as the spatial displacement (e.g., frame transition F1–F2 in Fig. 73-1e). Displacements separated by the IFI yield apparent motion in the direction opposite to the spatial displacement (e.g., frame transition F2–F3/1 in Fig. 73-1e, where F3 is identical to F1). The repeating sequence thus appears to move only in one direction (unidirectionally), because forward displacements are seen as forward motion, while backward displacements are apparently reversed and also seen as forward motion. Shifting the IFI so that it follows the first pattern frame rather than the second reverses the direction of the apparent motion seen in the sequence without altering the contents of the two pattern frames themselves. As in the case of four-stroke apparent motion, prolonged exposure to two-stroke apparent motion leads to a strong MAE.

Two-stroke apparent motion is so robust that it can be created relatively easily using any pair of pictures containing spatial displacements, such as two adjacent frames from a video. One of the two frame transitions in the repeating cycle should include an IFI lasting about 30 msec (two display refreshes on a 60 Hz monitor) and containing a blank field set to approximately match the mean luminance of the pattern frames.

Relevance of Two-Stroke Motion for Vision Research

On a practical level, the two-stroke motion effect allows one to create dynamic images that appear to move consistently in one direction from the bare minimum of displacement information—namely, just two animation frames. Two-stroke motion is counterintuitive and theoretically challenging: How can the addition of a blank interval to a back-and-forth animation sequence create an impression of continuous forward movement when the blank interval itself contains no useful information? The illusion can be used as a tool to probe the neural computations underlying motion perception. The adequacy of theoretical models of the process can be tested by comparing their output to data on two-stroke motion obtained from psychophysical experiments. The next section summarizes some of the critical stimulus parameters for obtaining two-stroke apparent motion, and the final section considers the detailed implications of the effect for theoretical models.

Important Parameters in Two-Stroke Motion

Mather and Challinor (2009) used MAE duration following adaptation to two-stroke motion as an index of the strength of the illusion. They found that the illusion was strongest when IFI duration fell between 30 and 70 msec and when the luminance of the blank IFI matched the mean luminance of the pattern frames. These results mirror those obtained for IFI-reversal motion, indicating a common origin. Motion processing is known to change significantly at low light levels (e.g., Gegenfurtner, Mayser, & Sharpe, 2000), so if two-stroke motion depends on these processes, it should be sensitive to changes in light level. Challinor and Mather (2010) investigated the effect of varying the mean luminance of the entire pattern. MAEs following exposure to two-stroke motion were measured in bright conditions (the mean luminance of both the pattern frames and the IFI was 46 cd/sq.m^2) and in dim conditions (mean luminance 0.23 cd/m^2). Lower mean luminance appeared to slow down the response of the motion system, stretching out the time dependence of the two-stroke effect in a way that is consistent with other effects of low luminance levels on motion perception: in bright conditions (solid lines in Fig. 73-2, top), MAEs were maximal at IFIs of around 60 msec, while in dim conditions (solid lines in Fig. 73-2, bottom), the peak in MAE duration occurred at IFIs of around 167 msec.

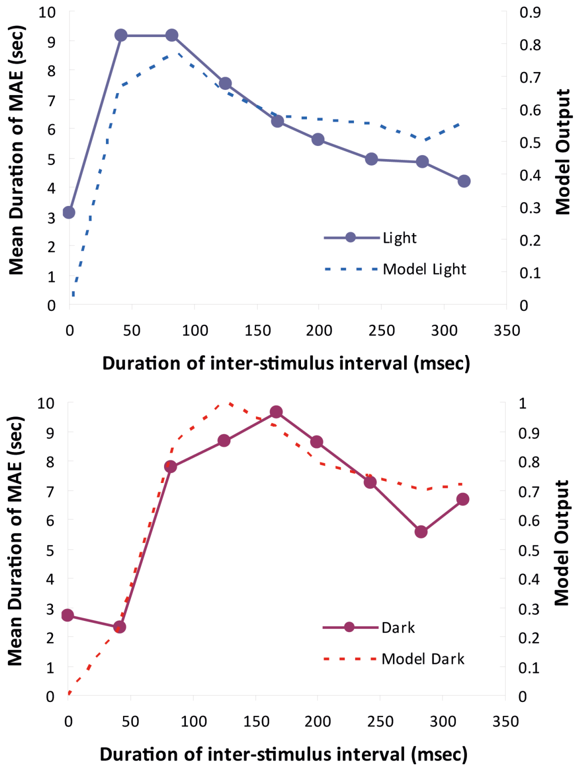

Figure 73-2.

Solid lines: Results of experiments to measure the duration of the MAE following adaptation to two-stroke motion, as a function of interframe interval (horizontal axis) and mean light level. Data in the top graph were obtained at a mean luminance of 46 cd/m^2; data in the bottom graph were obtained at a mean luminance of 0.23 cd/m^2. Broken lines: Output of a computational model of early motion detection (Adelson & Bergen, 1985), with temporal filter parameters set to the best-fitting values. (Data are replotted from Challinor & Mather, 2010.)

Discussion of Theories

As Anstis and Rogers (1986) noted, Fourier theory offers a simple, informal account of reversed-phi and four-stroke motion. According to Fourier theory, any visual stimulus can be considered the sum of a set of sinusoidal grating components each having a specific spatial frequency, contrast, and spatial phase (position). When a photographic image is reversed in contrast, each frequency component in its Fourier spectrum reverses in contrast (dark bars become bright and vice versa). Contrast reversal of a sine wave is equivalent to a shift in its spatial phase of 180°, or half a cycle. So if the wave displaces, say, to the right by +90° and simultaneously reverses in contrast, the resulting displacement corresponds to a total rightward shift of +270° or equivalently a leftward shift of –90°. Assuming that the direction of perceived motion is governed by the direction of shortest displacement, a rightward displacement accompanied by contrast reversal should appear to be a leftward displacement; hence contrast reversal would lead to reversed-phi and four-stroke apparent motion. Anstis and Rogers (1986) did not specify the process that computes motion direction from phase shifts in Fourier components, arguing that almost any model that successfully detects real motion will sense motion in their stimuli.

The fact that stroke-based motion illusions elicit strong MAEs indicates that they stimulate the specialized neural motion sensors that are universally believed to underlie the MAE (see Mather, Pavan, Campana, & Casco, 2009). Adelson and Bergen (1985) proposed a detailed computational model of motion detection based on spatiotemporal energy (Fourier spatial frequency components that change phase over time). They showed that the output of their model offers a good account of reverse-phi effects (though Bours, Kroes, & Lankheet, 2007, presented a different theoretical perspective on reversed phi). The spatiotemporal energy model has since become the dominant model of early motion detection in the human visual system, supported by both psychophysical and physiological data (see Emerson, Bergen, & Adelson, 1992; Georgeson & Scott-Samuel, 1999).

Sensitivity to rapid temporal change is an essential characteristic of motion sensors, allowing them to respond to high velocities of movement across the retina. In order to achieve this sensitivity, the temporal response of motion sensors to a brief flash of light (known as the temporal impulse response [TIR]) is thought to contain two phases, a positive phase and a negative phase, as illustrated in Figure 73-3. In a two-frame display such as that shown in Figure 73-1a, with each frame typically lasting 30 to 40 msec with no IFI, the sensor's biphasic TIR drives down sensor response to the first frame in time for the appearance of the second frame, so the sensor can detect each frame separately and therefore encode the direction of motion.

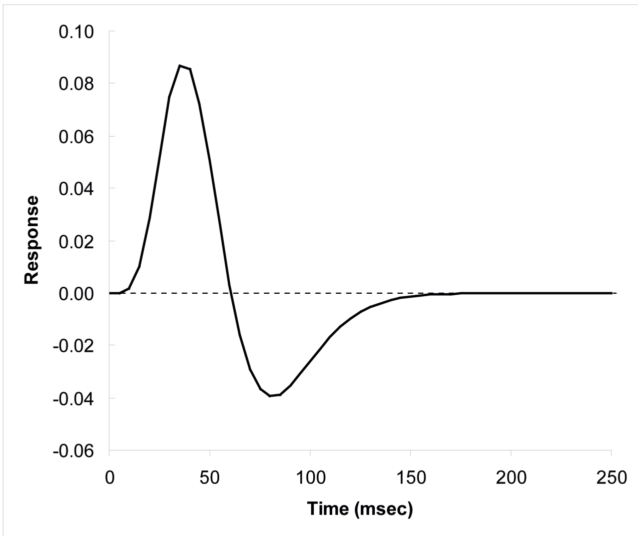

Figure 73-3
A biphasic TIR of the kind used in models of temporal vision and motion detection. The response to a brief flash of light at time zero reaches a positive peak within about 50 msec after the onset of the bright flash, and a negative peak within about 100 msec after the flash.

Informally, the biphasic TIR in Figure 73-3 can explain two-stroke motion as follows. During the IFI the visual response to the first frame of the stimulus sequence enters its negative phase, and as a result the neural representation of the first frame reverses in contrast. Motion sensors then combine the contrast-reversed internal representation of the first frame with the initially positive-contrast representation of the second frame. The contrast-reversed internal representation shifts the spatial phase of all frequency components and thus reverses the signalled direction. Whereas in the case of four-stroke motion contrast reversal is physically applied to the stimulus before presentation, in two-stroke motion the contrast reversal occurs inside the visual system, as a consequence of the biphasic TIR of motion sensors.

To formally test this explanation of two-stroke motion, Mather and Challinor (2010) and Challinor and Mather (2010) implemented Adelson and Bergen's (1985) spatiotemporal energy model and applied it to the two-stroke stimulus. The model was found to provide a very good account of two-stroke motion, provided that the parameters of its TIR filters were selected appropriately. The dashed lines in Figure 73-2 show the output of the model as a function of IFI, superimposed on data from MAE experiments using the same IFIs. In bright conditions, the best-fitting TIR filters had a center temporal frequency of between 4 Hz and 6 Hz, and in dim conditions they had a center temporal frequency of 2 to 4 Hz.

It was noted earlier that IFI-reversal and two-stroke motion are both sensitive to the luminance of the IFI; both motion effects are strong using mean luminance IFIs but weak using bright or dark IFIs (Mather & Challinor, 2009; Shioiri & Cavanagh, 1990). When the spatiotemporal energy model is run with parameters set to the standard values used in the literature, it predicts no effect of IFI luminance. Changes in the parameters of the temporal filter make no difference. However, the model also includes parameters for spatial receptive fields, which take the standard form of a Gabor function (a sinusoid multiplied by a Gaussian) or, equivalently, a difference of Gaussians (DoG) function. Figure 73-4 (top left) shows a cross-section of this standard receptive field alongside its spatial frequency response (top right). Mather and Challinor (2010) reported that a slight change in the spatial receptive field profile, as shown in Figure 73-4 (bottom left and right), is sufficient to predict the obtained effect of IFI luminance on two-stroke motion perception. The relevant change in receptive field profile involves a reduction in the width of the Gabor's Gaussian space constant from 0.6x the period of the Gabor's sinusoid to 0.44x the period (equivalently, the introduction of a slight imbalance of 0.9 between the DoG's excitatory and inhibitory Gaussians). This change introduces a slight DC bias into the spatial filter output, sufficient for the spatial receptive field to respond to changes in IFI luminance. Data from cat and monkey striate cortical receptive fields are consistent with this bias: Ringach (2002) reported that best-fitting Gabors had a Gaussian space constant of between 0.2x and 0.5x the Gabor's sinusoid.

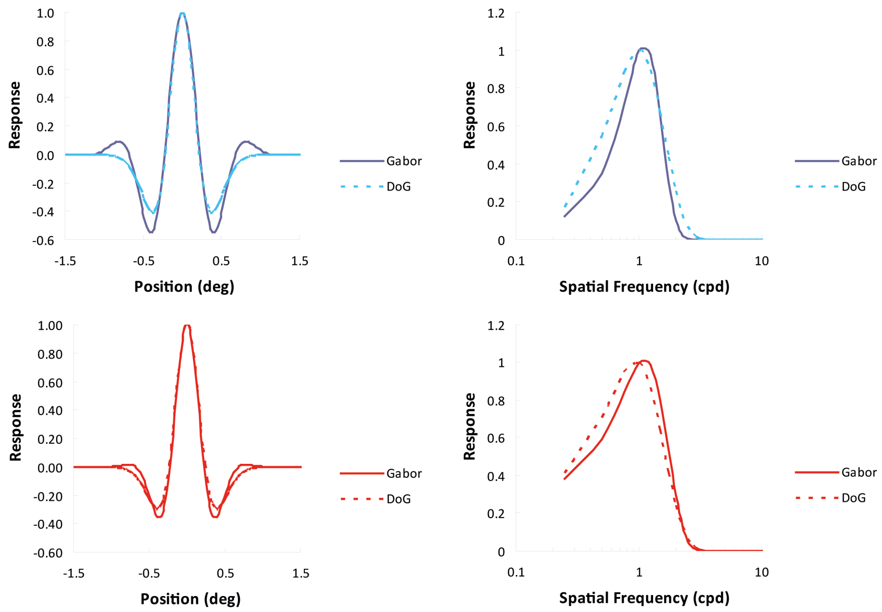

Figure IV.73-4.
Spatial receptive fields used in the motion energy model tested against the two-stroke illusion. Top row: Standard Gabor and equivalent DoG filters used in published accounts of the model. The Gabor has a spatial frequency of 1.1 cpd and Gaussian space constant of 0.55°. The DoG function has an excitatory space constant of 0.25°, inhibitory space constant of 0.4°, and balance of 1.0 (relative area of excitatory and inhibitory Gaussians). Bottom row: Filter profiles required to predict the effect of IFI luminance on two-stroke motion. The bottom Gabor differs from the top Gabor in having a narrower Gaussian space constant of 0.4°, and the bottom DoG differs from the top DoG in having a balance factor of 0.9 (excitation slightly stronger than inhibition).

In summary, two-stroke apparent motion is a robust, vivid impression of unidirectional motion created by alternating just two pattern frames, with a blank IFI at alternate frame transitions. It can be used to probe the properties of the underlying neural processes that encode retinal motion. A computational model of motion detection based on spatiotemporal energy can explain the effect, provided that its parameters are set to give a biphasic temporal response and a slightly imbalanced spatial response.

Author's Note
For demonstrations of stroke-based motion illusions, see
http://www.georgemather.com/MotionDemos/TwostrokeMP4.html

For a detailed description and Matlab© code for Adelson and Bergen's (1985) spatiotemporal energy model of motion detection, see
http://www.georgemather.com/Model.html

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