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Brief communication

Two-stroke: A new illusion of visual motion based on the time course of neural responses in the human visual system

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Abstract

A sequence of static images presented in rapid succession can create a powerful impression of visual movement, a fact exploited by the visual media (television and cinema) and by animators. A new illusion of movement called "two-stroke" is described, in which repeated presentation of a two-frame pattern displacement can create an impression of continuous forward motion, without the inclusion of any additional pattern displacements. The illusion can be explained by a biphasic temporal impulse response that modifies the stimulus delivered to motion energy sensors. It offers a basis for further research on temporal and motion responses in the visual system as well as a tool for animators and graphic artists to create consistent apparent movement from minimal external stimulation.

Keywords: Motion perception; Illusion; Apparent motion; Motion detection

1. Two-stroke motion

The apparent motion seen in sequences of static images is mediated by specialised neural circuits in the visual cortex (Adelson & Bergen, 1985; van Santen & Sperling, 1985; Watson & Ahumada, 1985). A minimal motion sequence requires two frames containing a pattern displacement from the first frame to the second. A single 'one-shot' presentation of the two frames leads to the appearance of forward motion. If the two frames are presented continuously in alternation, then observers perceive a repeating cycle of forward and backward motion. Fig. 1A shows two pattern frames (rows 1 and 2) containing a simple shape that displaces rightward from the first frame to the second to create apparent oscillation (arrows) during repeated presentation. However, if a brief pause or inter-stimulus interval (ISI) is added after the second frame (Fig. 1B), observers perceive continuous rightward movement of the shape when the frames are presented in a repeating cycle. If the ISI is placed between the first frame and the second instead (Fig. 1C), observers perceive continuous leftward movement. This illusion has been demonstrated to large numbers of naïve observers[1], and can be viewed in Supplementary videos. Supplementary video 1 shows a sequence corresponding to Fig. 1A; Supplementary video 2 shows a sequence corresponding to Fig. 1B. Online Flash movies are available at www.lifesci.susx.ac.uk/Home/George_Mather/TwoStrokeFlash.htm.

Fixation at the centre of the illusion display for a short time (about 15 s) is sufficient to build up an after-effect of apparent movement in the opposite direction when the animation is stopped. To view this effect in online materials, use the media control to stop video 1; then fixate at the centre of video 2 for 15 s while it is running; finally transfer gaze to the centre of video 1. A motion after-effect should be seen. Such motion after-effects are strong evidence for

[1] The illusion was presented to international vision scientists at the European Conference on Visual Perception, La Coruna, Spain, August 2005. It was voted one of the top three new illusions in the inaugural International Illusion of the Year competition during the meeting.

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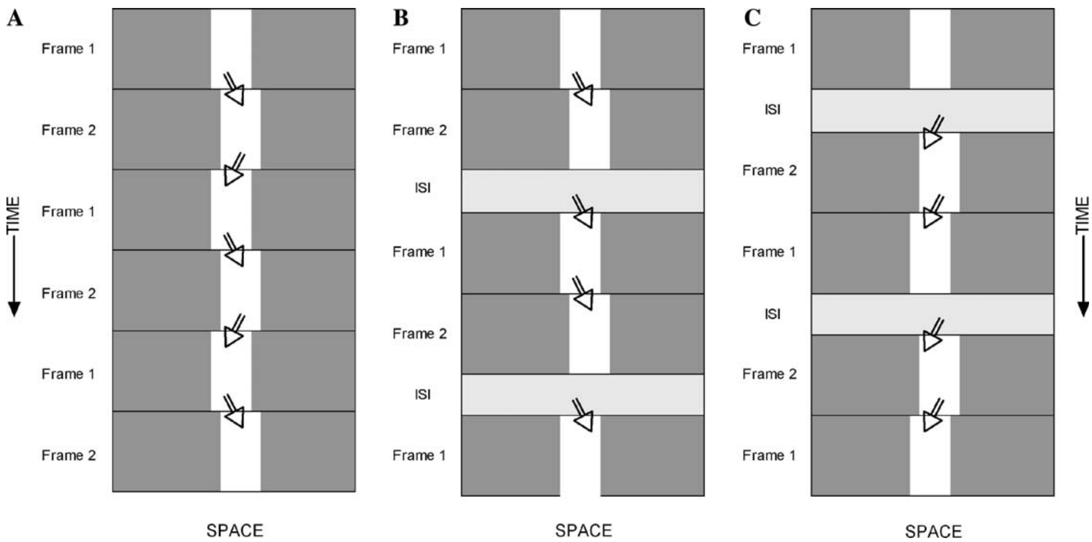

Fig. 1. Two-stroke motion. (A) Illustrates standard apparent motion; (B and C) illustrate two-stroke motion. (A) A white rectangle shifts rightward from frame 1 to frame 2. When the two frames are presented repeatedly in alternation, they create an impression of to-and-fro movement (arrows). (B) If a brief blank inter-stimulus interval (ISI) is inserted at the transition between frame 2 and frame 1, the direction of apparent motion during the transition reverses, so that presentation of the whole sequence creates an impression of continuous forward motion (arrows). (C) If the blank ISI is inserted between frame 1 and frame 2, presentation of the whole sequence creates an impression of continuous backward motion (arrows).

unidirectional excitation in neural motion sensors (Mather, Verstraten, & Anstis, 1998).

2. Explanation

The illusion is called "two-stroke" apparent motion because it requires only two pattern frames[2]. Its explanation requires two propositions:

(a) that the biphasic temporal impulse response of the visual system generates a contrast-reversed neural image in the visual system during the blank ISI;
(b) that reversed apparent motion is generated when the contrast-reversed neural image is combined with the initially positive image generated by the next pattern frame.

2.1. Biphasic impulse response

In bright conditions, the visual system's response to a brief flash (impulse) shows an initial positive phase (excitation) followed by a brief negative phase (inhibition). The impulse response plotted in Fig. 2 is based on a standard model derived from a large body of psychophysical data (Watson, 1986). During the brief ISI in two-stroke displays the negative phase of the impulse response generates a contrast-reversed neural image of the preceding frame in the visual system (e.g., frame 2 in Fig. 1B). The contrast-reversed neural image is then combined with the positive response to the following frame at the stage of motion energy detection to generate a motion signal.

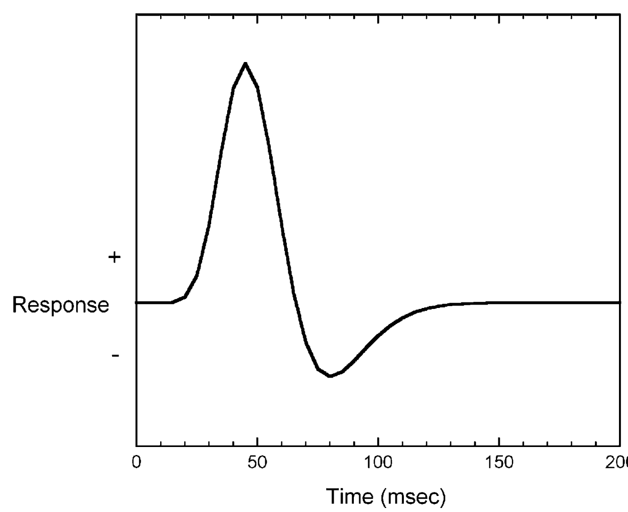

Fig. 2. Temporal impulse response of the visual system. The visual system's response to a brief flash of light at time zero shows an initial positive phase (excitation) followed by a negative phase (inhibition). The curve is based on a model derived from a large body of psychophysical data on flicker detection (Watson, 1986).

2.2. Reversed apparent motion

It is well known that when one frame in a two-frame motion display is contrast-reversed, the perceive motion is also reversed (Anstis & Rogers, 1975). So the transition

[2] It is arguable that the illusion should be called "three-stroke" rather than "two-stroke", since it contains three frames. The "two-stroke" nomenclature was favoured because only two frames contain pattern information; the motion illusion can be generated from any arbitrary pattern displacement provided that just two pattern frames are available.

from a contrast-reversed neural image of frame 2 to the positive neural image generated by frame 1 results in forward apparent motion rather than backward motion. Since both [frame 1 → frame 2] and [frame 2 → ISI → frame 1] transitions create forward apparent motion, the display appears unidirectional.

Why does contrast-reversal cause reversed apparent motion? Consider the simple case of a two-frame display containing a sine-wave grating that shifts phase rightwards by 90° from the first frame to the second (or, equivalently, leftwards by −270°). Observers perceive motion in the direction of the shortest phase shift, namely rightwards. When the second frame is reversed in contrast, the resulting grating is identical to one that has been shifted in phase by 180° in either direction. Now the transition from frame 1 to frame 2 involves a total rightward shift of 270° or, equivalently, a leftward shift of −90°. Observers perceive leftwards apparent motion. The effect seems trivial when described in terms of a single sine-wave, because of the equivalence between contrast-reversal and half-cycle phase shifts. More counter-intuitively, the contrast-reversal effect also succeeds in complex, non-periodic displays such as natural images or patterns such as those in Fig. 1. According to Fourier theory these displays can be considered to contain many sinusoidal frequency components. A population of motion energy sensors in the visual system (such as those proposed by Adelson & Bergen, 1985; van Santen & Sperling, 1985; Watson & Ahumada, 1985) decomposes complex patterns into their frequency components in order to sense movement direction. Each of the frequency components detected by these sensors will generate reversed signals in contrast-reversing complex patterns, since all the frequency components reverse in contrast (or, equivalently, shift phase by half a cycle). The illusion consequently relies on the visual system decomposing complex patterns into their frequency components in order to sense movement direction.

3. Discussion

A related motion illusion called "four-stroke" apparent motion (Anstis & Rogers, 1986; Mather, 1991) consists of four pattern frames. The first two frames contain a two-frame motion sequence; the second two frames are contrast-reversed versions of the first two. When the four frames are presented in a repeating cycle observers see continuous forward motion, due to the effect of contrast-reversal on motion sensor responses. The crucial differences between four-stroke and two-stroke motion are that: (a) the new illusion obviously contains half the number of pattern frames; and (b) the contrast-reversal necessary for unidirectional apparent motion is created inside the visual system by the system's temporal response, rather than in the stimulus.

Since the illusion requires only two pattern frames containing a single displacement, it could actually be used to create apparently continuous motion from a single source image. All that is required is a second version of the original image that has been shifted, rotated or expanded. When the original and shifted versions are alternated repeatedly with an appropriate ISI inserted at one of the two frame transitions, observers will perceive continuous translation, rotation or expansion.

It could be argued that the effect of the ISI in two-stroke motion is not to generate a reversed motion signal, but simply to disrupt the normal signal that would be generated by the preceding and succeeding frames. However, several previous studies of direction discrimination in two-frame apparent motion displays reported a large number of response errors when the two frames are separated by a brief blank ISI (Shioiri & Cavanagh, 1990; Strout, Pantle, & Mills, 1994; Takeuchi & De Valois, 1997). The effect is optimal for mid-grey ISIs lasting 20–50 ms, and under peripheral viewing. Computational modelling in these studies confirms that the temporal impulse response of the visual system can explain the effect. The results of these papers actually inspired the creation of two-stroke apparent motion: the effect of the blank ISI is harnessed to create apparently continuous motion from a minimal stimulus containing two pattern frames and a single inter-frame displacement. Informal observations of two-stroke motion to date indicate that black or white ISI fields abolish the effect, as anticipated on the basis of these papers. These issues are presently being investigated in the laboratory.

4. Conclusion

Two-stroke motion is strong evidence for the existence of a biphasic temporal response preceding motion energy analysis. It provides a simple tool to demonstrate and explore the properties of the visual system's temporal impulse response, since it readily generates a measurable motion after-effect. The illusion will also be of interest to animators seeking to generate a consistent impression of motion from the minimum amount of image information (useful in situations where bandwidth is limited).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.visres.2005.12.022.

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