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The wagon wheel illusion in movies and reality

(perception/vision/time/stroboscopic presentation/rotation)

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ABSTRACT **Wheels turning in the movies or in other forms of stroboscopic presentation often appear to be rotating backward. Remarkably, a similar illusion is also seen in continuous light. The occurrence of this perception in the absence of intermittent illumination suggests that we normally see motion, as in movies, by processing a series of visual episodes.**

Most moviegoers have probably noticed the apparent backward rotation of a wheel attached to a vehicle that is clearly moving forward (the stagecoach in a western, for example). This phenomenon—the wagon wheel illusion (1–6)—arises from a discrepancy between the rate at which movies are filmed and the speed of wheel rotation, as explained in Fig. 1. We were stimulated to think further about this illusion and its interpretation when we noticed that the apparent backward rotation of wheels can also be seen in continuous light. Automobile wheel covers, airplane propellers, jet engine fans, and other radially patterned objects rotating in daylight provide opportunities to observe this phenomenon. Indeed, an ordinary record player in daylight offers an especially simple means by which anyone can explore this illusion: paper disks the size of an LP with spokes or other radial patterns readily elicit the perception of reversed rotation when accelerated to 33–78 rpm. As we could find no analysis of these surprising observations, we have explored their basis and significance for human vision.

MATERIALS AND METHODS

To understand why we see this illusion that, in movies, video, or stroboscopic light, depends on the sequential presentation of discrete scenes, we constructed an apparatus consisting of an aluminum disk 40 cm in diameter mounted on the shaft of a dc motor, the speed of which was controlled by a computer. The rate of rotation was determined by monitoring the applied voltage, which was in turn calibrated to the actual speed of rotation measured with a stroboscope. A variety of wheel designs could be mounted interchangeably on the disk by means of adhesive backing. Because of the inherent periodicity of video images, it was important to carry out these experiments with such apparatus rather than computer-generated patterns. The rotating disks were illuminated with two 34-W sealed-beam headlights powered by a highly filtered dc in an otherwise dark room. It should be noted that all the effects we describe were equally evident in sunlight, ruling out artifact associated with the dc power source.

RESULTS

The illusion of reversed rotation was apparent in both scotopic and photopic conditions with each of a variety of wheels we examined. These included patterns in which the spokes were wedges instead of radial lines, in which the edges of the spokes were blurred, and in which isolated elements at the same radial distance were used. In addition to ourselves, 11 of 12 naive observers saw the illusion when tested. The perception of reversed rotation invariably gave way to the reappearance of the spokes turning in the direction of actual rotation; the whole sequence lasted up to several seconds. This cycle repeated itself as the velocity of rotation continued to increase until the disk was spinning too fast to discern the stimulus elements. If the velocity of rotation was kept constant over a broad range (see below), the illusion of reversals continued to alternate indefinitely with the perception of orthograde rotation. The other aspect of the wagon wheel illusion—the perception of a number of spokes greater than the actual number (Fig. 1)—was also evident in continuous light. Thus, supernumerary spokes (or other radial elements) that could not be distinguished from the real ones were readily evident under these conditions. All these phenomena were equally apparent using one or both eyes and could be seen whether the wheel was fixated centrally or observed with peripheral vision.

To explore the possibility that changes in the position of the eyes produce the illusion, we monitored eye movements while subjects observed reversed rotation of wheels (or drums; see below) with an infrared tracking system that allowed detection of movements as small as half a degree of visual arc (model 210; Applied Science Laboratories, Waltham, MA). No discernible eye movements occurred as subjects perceived reversed rotations with an assortment of stimulus patterns. We also examined the rotation of an entoptic image generally referred to as Haidinger's brushes (7, 8). This phenomenon, which occurs when polarized light interacts with the pigment of the macula, generates an image about 3–4° in extent and shaped roughly like a propeller. If the polarizer is rotated, the image rotates at the same speed. Each of five subjects saw reversed rotation of Haidinger's brushes at rates of revolution approximately the same as those that create the illusion of reversal with rotating wheels. Since such images are entoptic, these observations support our conclusion that overt eye movements are unlikely to play a significant role in the generation of apparent backward rotation. Taken together, these results appear to rule out any but an extremely small and subtle variety of eye movements as an explanation. These control observations should not, however, be taken to imply that the central circuitry for eye movements plays no part in the illusion. Indeed, the bizarre perception of object movement upon attempted eye movements during oculomotor paralysis raises the intriguing possibility that such circuitry may be pertinent (9, 10).

A variety of additional illusions, most of which have been described previously, were also apparent with rotating wheels (11–16). Color illusions usually referred to as the Benham wheel effect, the Cornsweet illusion (the appearance of areal differences in luminance), and the waterfall illusion (an after-image of slower counterrotation) could all be seen. Moreover,

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Abbreviation: rps, revolutions per second.
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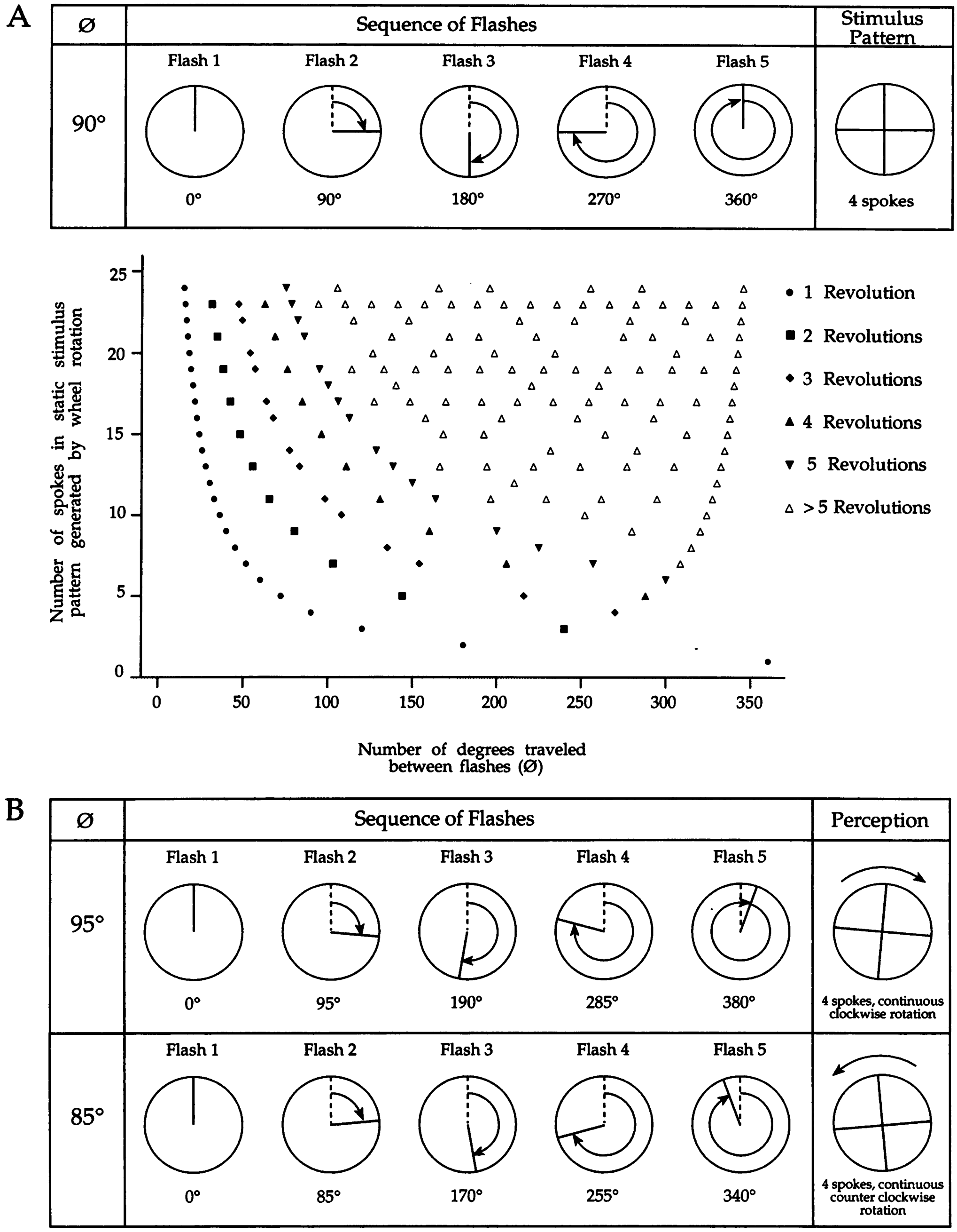

FIG. 1. The wagon wheel illusion generated by intermittent (stroboscopic) light. (*A Upper*) Wheel with a single spoke rotating at a constant speed. At any particular speed of rotation and frequency of illumination, the number of degrees (θ) each spoke turns in the interval between flashes is given by

$$\theta = 360 \cdot \frac{v}{f}, \quad [1]$$

where f is the frequency of the intermittent light pulse, and v is the angular velocity of the wheel in revolutions per second (rps). The apparent number of spokes (n) can be calculated by the relationship

$$n = \frac{360}{\theta} \cdot r, \quad [2]$$

where r is the number of revolutions the wheel must turn before the illuminated spoke is once again at its starting point. In this example, the interflash interval is such that the spoke travels 90° between flashes. Thus, the stimulus pattern presented to an observer is a static wheel with four spokes. (*A Lower*) Stimulus patterns predicted by Eqs. **1** and **2** for a wheel with a single spoke for values of θ from 0° to 360° (only patterns of up to 24 spokes are illustrated; an infinite number is possible). For a wheel with multiple spokes Eq. **2** becomes

$$n = \frac{s \cdot 360}{\theta} \cdot r, \quad [3]$$

where s is the number of actual spokes. (*B*) The illusion of rotary motion occurs if the number of degrees a wheel turns during the interval between flashes does not allow the spoke (or spokes) to occupy an identical set of positions in the series of illuminated scenes. The apparent motion will be in the direction of actual rotation (clockwise in the figure) if the number of degrees turned in each interval generates procession (example θ = 95°); the apparent motion will be in the opposite direction if this value generates precession (example θ = 85°). Although the latter perception conventionally defines the wagon wheel illusion, a series of gradual transitions between equally illusory clockwise and counterclockwise rotation are seen as a wheel accelerates or decelerates. In short—and contrary to what is often stated about the wagon wheel illusion in movies (e.g., refs. 1 and 6)—a wheel rotating more slowly than the movie camera frame rate (or faster for that matter) can, when projected, produce a stimulus that is perceived as static, in clockwise rotation, or counterclockwise rotation, depending upon its geometry and the number of degrees the wheel turns between successive frames.

at very low speeds of rotation (on the order of 0.1 rps), another phenomenon was evident, best described as a stuttering appearance of each spoke (or other radial element), which could also give the impression of stalled or even reversed rotation for brief periods. To minimize or eliminate this variety of potentially confounding phenomena seen with rotating wheels, further analysis was carried out using drums turning in the horizontal plane (Fig. 2). This style of presentation reduced the stimulus pattern to a series of elements moving linearly, whose frequency crossing the point of fixation could be varied by changing the speed of rotation. The illusion of reversed direction of motion was equally well seen in this configuration (or turning in the vertical plane), indicating that the effect in continuous light does not depend on a circular geometry or rotary motion per se.

By measuring the velocity of drums with different numbers of stimulus elements, we could determine the frequency of element presentation at which the illusion of reversed rotation is first seen (Fig. 2 and Table 1). When the moving stimuli passed the point of fixation at frequencies less than a characteristic value for each interspot angle, all five observers tested perceived the stimulus elements moving in the direction of actual rotation. When the frequency of presentation exceeded these values, however, all subjects perceived the illusion of reversed rotation alternating with intervals of perceived orthograde motion. As the frequency of stimulus element presentation continued to increase, these alternations persisted until the velocity of the stimulus elements became too great to

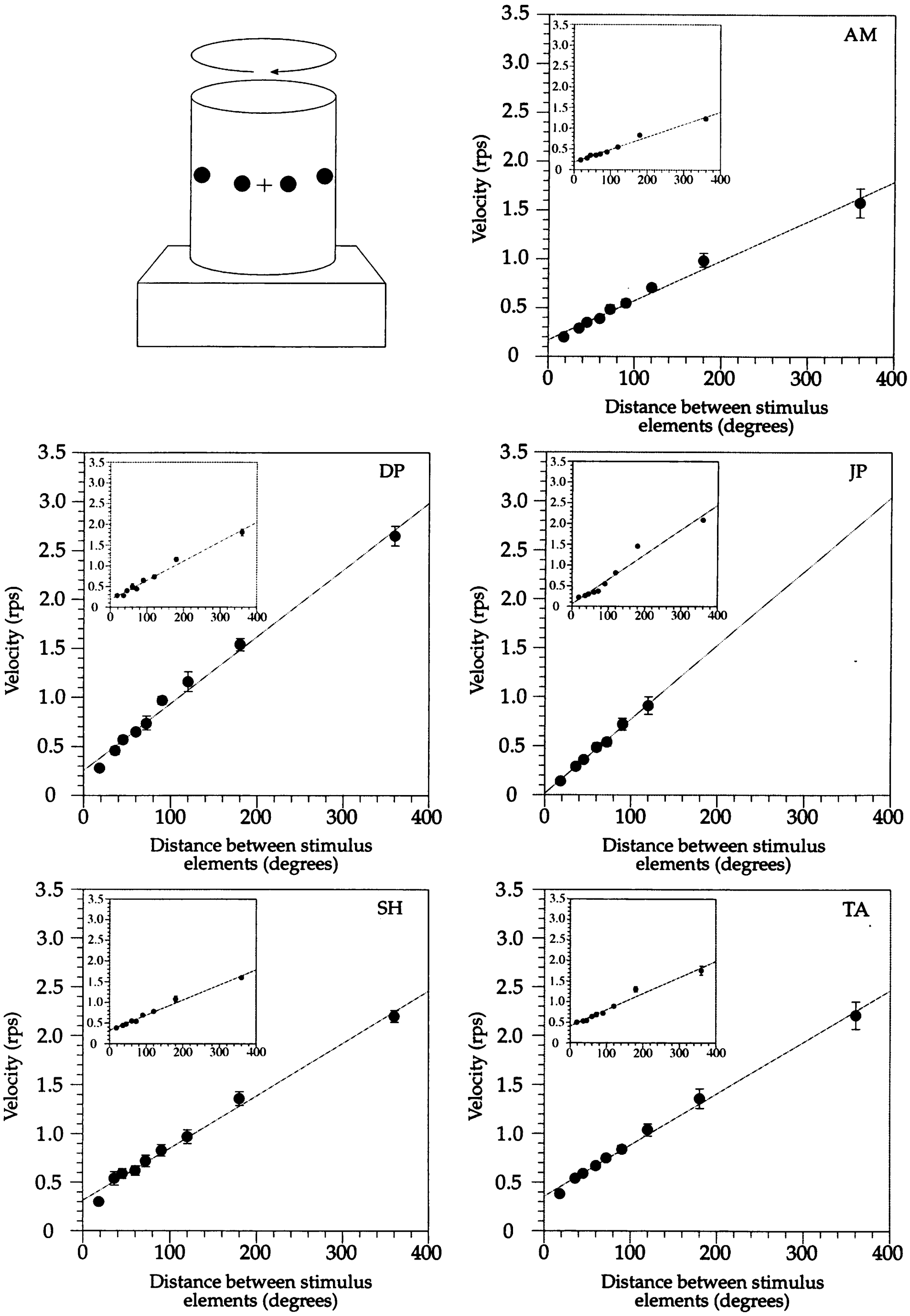

FIG. 2. The wagon wheel illusion in continuous light. A white drum 27 cm in diameter decorated with 1 to 20 equally spaced elements (black spots 38 mm in diameter) was accelerated from 0.1 rps at 0.05 revolutions per sec^2 (diagram at upper left). Graphs indicate the velocity of drum rotation at which observers first perceived apparent reversal of direction for linearly accelerating stimulus patterns presented in continuous illumination. Observers viewed the drum from a distance of 1 m while fixating on a 5-mm red dot projected by a laser beam (+ in the diagram); the rotational velocity at which they first saw directional reversal was indicated by pressing a key. Each point represents the average of five sets of 10 trials each (bars indicate standard errors). For observer JP the spots were already blurred at the expected reversal speed for drums with one or two spots; therefore, these data are not shown. When the stimulus elements pass the point of fixation at a set of characteristic frequencies for each subject (see Table 1), apparent backward movement is perceived. (*Insets*) Performance of each subject when smaller drums (9 cm in diameter) with proportionally smaller spots (13 mm) were substituted for the larger drums. The similar performances with different sized drums indicate that the most important parameter determining the illusion is the frequency of element presentation.

see them clearly, at which point reversals were no longer evident (Table 1). Thus, the illusion of reversed rotation in continuous light is first observed at frequencies of 2–3 Hz and continues to be elicited at frequencies up to at least 20 Hz.

To confirm the salience of the frequency of element presentation in the generation of the illusion, we constructed a set of smaller drums that could be compared with the larger versions. The perception of the first illusory reversal for smaller drums with the same number of stimulus elements on their circumferences occurred at rates of rotation similar to those observed for the larger drums (Fig. 2 *Insets*). This finding accords with the perception of the wagon wheel illusion generated by rotating disks in continuous light. The different parts of a spoke rotate at different linear velocities, yet the

Table 1. Frequency of stimulus element presentation at which the illusion of reversed rotation was perceived in continuous light with different numbers of stimulus elements on the drum circumference (see Fig. 2)

Subject	Drum diameter	Distance between stimulus elements, degrees																	
		360		180		120		90		72		60		45		36		18	
		Frequency of stimulus element presentation for first reversal																	
AM	Large	1.6		2.0		2.1		2.2		2.5		2.4		2.8		2.9		4.1	
	Small		1.2		1.7		1.7		1.7		1.9		2.1		2.8		2.8		4.9
DP	Large	2.6		3.1		3.5		3.9		3.7		3.9		4.6		4.6		5.6	
	Small		1.8		2.3		2.2		2.6		2.2		3.0		3.2		2.8		5.7
JP	Large	—		—		2.7		2.9		2.7		2.9		2.9		2.9		2.8	
	Small		2.1		2.9		2.4		2.2		1.8		2.1		2.4		2.6		4.5
SH	Large	2.2		2.7		2.9		3.3		3.6		3.7		4.7		5.4		6.0	
	Small		1.6		2.2		2.3		2.7		2.7		3.3		3.9		4.4		7.5
TA	Large	2.2		2.7		3.1		3.4		3.8		4.0		4.7		5.4		7.5	
	Small		1.8		2.6		2.7		2.9		3.4		3.8		4.3		5.3		10.1
Average		2.2	1.7	2.6	2.3	2.9	2.3	3.1	2.4	3.2	2.4	3.4	2.8	3.9	3.3	4.2	3.6	5.2	6.5
SEM		0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.3	0.5	0.5	0.8	1
		Frequency of stimulus element presentation for last reversal																	
AM	Large	2.2		3.2		4.1		4.8		5.2		5.1		5.8		6.0		11.8	
	Small		2.2		3.2		4.0		4.5		4.8		5.9		7.7		9.0		16.6
DP	Large	4.2		5.6		7.2		7.8		11.2		11.7		12.6		15.2		24.5	
	Small		3.7		6.1		7.6		9.3		10.5		12.2		12.6		15.5		16.4
JP	Large	—		—		4.8		5.1		5.8		6.2		7.6		10.1		20.9	
	Small		3.3		5.5		6.5		7.3		8.5		9.6		11.4		14.0		24.3
SH	Large	2.7		3.7		4.5		5.2		5.9		6.0		7.3		7.8		10.1	
	Small		2.3		3.1		3.8		4.2		4.6		6.6		6.2		7.8		10.7
TA	Large	3.0		4.5		5.7		6.9		8.2		8.6		9.7		13.4		15.1	
	Small		2.7		4.1		5.3		6.1		7.3		8.1		10.9		12.4		19.4
Average		3.0	2.9	4.2	4.4	5.3	5.4	5.9	6.3	7.3	7.1	7.5	8.5	8.6	9.8	10.5	11.7	16.5	17.5
SEM		0.4	0.2	0.5	0.6	0.5	0.7	0.5	0.9	1.1	1.1	1.1	1.1	1.1	1.2	1.7	1.4	2.7	2.2

Frequencies were calculated by dividing the angular velocity in degrees per sec by the number of degrees between the stimulus elements. The frequencies of element presentation required to perceive the first illusory reversal during acceleration from rest were calculated from the data in Fig. 2. The frequencies of element presentation at the last perceived reversal were calculated from an additional three sets of five trials for each subject in which the acceleration of the wheel continued until illusory reversals could no longer be seen.

illusion of reversed rotation involves the entire wheel. Taken together these observations indicate that the frequency of stimulus element presentation—rather than the linear velocity of the elements or the size of the drum—primarily determines the illusion of reversed rotation.

DISCUSSION

Some differences between the illusion in continuous light and that seen in stroboscopic presentation should be noted. First, whereas static spoke patterns are readily seen in stroboscopic illumination by suitable adjustment of the rate of rotation and/or flash frequency (see Fig. 1*A*), static patterns are not observed in continuous light. Second, the illusion of reversed rotation in continuous light appears suddenly rather than gradually. Moreover, the apparent rate of backward rotation in continuous light is faster than the perceived speed in the direction of actual rotation. A third difference is that the perception of both orthograde and retrograde rotation in stroboscopic light represents apparent motion; in continuous light, the motion perceived in the actual direction of rotation is real. A fourth difference is that the perception of supernumerary spokes in continuous light involves the progressive addition of elements; in stroboscopic illumination, supernumerary spokes appear by multiplication of the actual spoke number (see Fig. 1). Finally, whereas stroboscopic conditions can generate a stable perception of reversed rotation, in continuous light the illusion always alternates with the perception of orthograde motion.

Despite these differences, the similarity of the illusions in intermittent and continuous light with respect to apparent backward rotation and supernumerary spokes suggests that they hold some property in common. What might this be? Stroboscopic illumination, movies, or video present a series of discrete scenes that are fundamental to explaining the illusion of reversed rotation and supernumerary spokes (Fig. 1). If the visual system (or at least some component of it) *ordinarily* processed information in sequential episodes, a similar effect could arise in continuous light. Thus, if the actual positions of the spokes or other repeating elements in sequential scenes were such that they precessed, backward rotation would be transiently perceived (for the same reasons that generate the illusion in stroboscopic light—see Fig. 1*B*). Similarly, the illusion of supernumerary spokes in continuous light could be accounted for if the movement of the actual spokes placed them in different positions in each episode. The integration of sequential scenes would then give the impression of a wheel with more spokes than it actually has, as in the case of the stroboscopic illusion. In this conception, the boundary in Fig. 2 between the perception of orthograde motion and the zone in which subjects begin to see reversed rotation represents the point at which the presentation frequency of a given stimulus can no longer be accommodated by the visual sequencing mechanism under the prevailing stimulus conditions.

A variety of circumstantial evidence already offers some support for the idea that visual perception entails processing information as a series of episodes. Saccades normally change the image falling on the retina several times a second (17). Thus, we read by a series of fixations at 3–5 Hz (18) and inspect pictures by fixations at about the same frequency (see ref. 17, p. 176). If the acquisition of a new scene is prevented, however, the perception of detail quickly fades (19, 20). Although most of the literature on this subject implies the disappearance of stabilized retinal images over a few seconds or more, recent results indicate that the perception of a perfectly fixed entoptic image can vanish in a fraction of a second (D. Coppola and D. P., unpublished results; see also ref. 21). These several observations are in keeping with the suggestion raised by the wagon wheel illusion in continuous light—namely, that visual information is normally processed in episodes at frequencies of 2–20 Hz or more, an idea that has sometimes been considered (22–26) but not generally accepted.

CONCLUSION

The illusion of wheels or other radial patterns rotating backward in continuous light, together with the perception of supernumerary spokes, suggests that the human visual system processes sequential episodes of information rather than a continuous temporal flow. In addition to accounting for this remarkable illusion, a strategy of vision that parses the world in this way can explain why movies are so realistic (simply because that is the way we normally see things) and how we detect motion (by comparing the position of the same objects in sequential episodes).

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