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Wagon-wheel illusion under steady illumination: real or illusory?

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Abstract. Wheels turning in the movies sometimes appear to rotate backwards. This is called the wagon-wheel illusion (WWI). The mechanism of this illusion is based on the intermittent nature of light in films and other stroboscopic presentations, which renders them as a series of snapshots rather than a continuous visual data stream. However, there have been claims that this illusion is seen even in continuous light, which would suggest that the visual system itself may sample a continuous visual data stream. We examined the rate of this putative sampling and its variations across individuals while in different psychological states. We obtained two results: (i) WWI occurred in stroboscopic lights as expected, (ii) WWI was never reported by our subjects under continuous lights, such as sunlight and lamps with DC power source. Thus, WWI cannot be taken as evidence for discreteness of conscious visual perception.

1 Introduction

Wagon-wheel illusion (WWI) is the misperception of the direction of rotation of a wheel in stroboscopic light, for example in movies. It has been suggested that it is due to the loss of information between two successive frames and the reverse matching that this creates at the appropriate speeds of motion and frames (Palmer 1999; figure 1). This illusion has also been reported to occur in continuous light, such as sunlight and electric lamps with DC power source, by Purves et al (1996). These authors reported the occurrence of this illusion over a range of 33 – 78 rev min^{-1}—which is equal to 0.55 – 1.3 rev s^{-1}—and have suggested that their findings imply that the human visual system processes sequential episodes of information at frequencies of 2 – 20 Hz rather than as a continuous temporal stream. Purves et al tried to relate their result to the phenomenon that has elsewhere been described as "perceptual intermittency" (Allport 1968). We investigated the psychophysical determinants of this illusion and their potential roles in the measurement of the frequency of such sampling episodes across individuals. The initial step of our study was to replicate WWI in continuous light as described by Purves et al (1996).

2 Materials, methods, and subjects

We had two disks made of hard plastic with diameters of 40 cm and 11 cm. These disks were white in colour and black rectangular labels could be radially attached to their surface to serve as the spokes of wheels. In addition, we constructed two drums with diameters of 27 cm and 16 cm, again white in colour, with black circular labels that could be attached around their trunk like a belt (figure 2). The diameter of these black circles was 38 mm for the larger drum and 22.5 mm for the smaller one. These disks and drums were mounted on the shaft of a DC motor, the speed of which was controlled with an electronic circuit designed for this purpose. In addition, another speed-measurement circuit was used to determine the speed of rotation by monitoring the applied voltage so that the speed of rotation would be double-checked. We used drums rotating in the horizontal plane, as described by Purves et al (1996), to eliminate other illusions that may

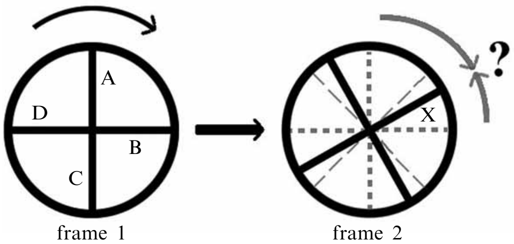

Figure 1. The figure shows two successive frames of a movie. Seeing these frames allows one to solve the 'correspondence problem'—whether spoke A or spoke B, in frame 1, corresponds to spoke X, in frame 2. Since the most potent factor in solving the correspondence problem is proximity (Palmer 1999), the obvious answer is: "spoke B". Then the perceived direction of rotation is opposite to the veridical direction. In this example we used a 4-spoke wheel. This strategy for solving the correspondence problem is what has elsewhere been called the Nearest Neighbour Rule (Finlay et al 1984). The WWI occurs when the angle of rotation between the two successive frames exceeds 45° (thin lines in frame 2). Generally speaking, it occurs when a wheel with n spokes rotates $360/2n$ degrees ($1/2n$ revolutions, which is half the angular distance between 2 adjacent spokes of the wheel) during the interval between two successive snapshots. This interval equals to $1/f$; where f is the frequency of information sampling (such as the frequency of the stroboscopic light). So the critical rotation speed in which the illusion would be perceived is equal to $1/2n$ divided by $1/f$ (the displacement divided by the elapsed time), which would be $f/2n$ rev s^{-1}.

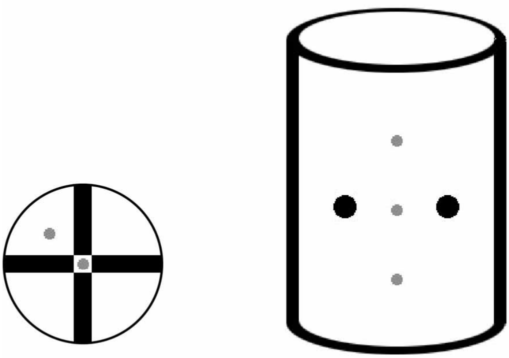

Figure 2. A 4-spoke disk and a drum with 4 circular elements. The gray dots show the alternative locations for the fixation point.

have been perceived in a presentation with rotating disks, such as the Benham illusion and the Cornsweet illusion. 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 of the drum. As Purves et al have stated, the illusion of reversed direction of motion would be seen equally well in both configurations.

We chose 40 cm, 27 cm, and 38 mm for the diameters of different parts of our apparatus in order to strictly reproduce the conditions described by Purves et al and then added the other three parameters (ie 11 cm, 16 cm, and 22.5 mm, respectively) to test their statement that the illusion would also be perceived with smaller disks and drums.

We mounted either of the two disks, or the two drums, on the shaft of the motor and showed them to the subjects at different rotating speeds. A different number of spokes on the disks or on the circular elements of the drums were tried under different lighting conditions: (i) fluorescent light with domestic 50 Hz AC power source, (ii) two 12 V, 21 W light bulbs connected serially to a DC power source, and (iii) sunlight.

Fifteen subjects (twelve males and three females, aged 22 – 50 years, with educational backgrounds varying from absolutely illiterate to PhD) volunteered to participate in the two experiments we conducted.

2.1 *Experiment 1*
In experiment 1, which was conducted under the 50 Hz fluorescent light, we mounted the disks on the motor and changed the rotation speed in a range from 700 to 800 rev min^{-1}, or 1400 to 1600 rev min^{-1} with 4-spoke or 2-spoke disks, respectively (see discussion why we chose these speed ranges). We increased and decreased the speed in steps of 5 rev min^{-1} and instructed the subjects to tell us when the direction of rotation changed (which we took for passing the 'critical speed' at which WWI occurs).

2.2 *Experiment 2*
Experiment 2 was conducted under sunlight with 2-spoke, 4-spoke, and 8-spoke disks and with drums that had 4, 8, and 16 identical circular elements attached to them. In this experiment we changed the rotation speed from 30 to 90 rev min^{-1} and back, covering the range reported by Purves et al (ie 33 – 78 rev min^{-1}). This range differs greatly from the range of speeds in experiment 1 (700 – 1600 rev min^{-1}); we obtained these lower speeds from the same motor by using an appropriate gearbox. The remaining steps were the same as in experiment 1.

Both experiments were conducted with different fixation-point conditions:
(1) on the centre of the disk, or on the centre of the drum in the belt zone;
(2) on the midway point between the disk centre and its outer border, or on the midway point between the central belt on the drum and the higher or lower border;
(3) no fixation point (figure 2).
An ordinary laser-beam pointer was used to project a red dot on our apparatus (as used by Purves et al 1996).

3 Results
3.1 *Experiment 1*
In experiment 1, with intermittent fluorescent lighting, all subjects reported the critical speed (where the apparent direction reversed) as 750 rev min^{-1} (12.5 rev s^{-1}) and 1500 rev min^{-1} (25 rev s^{-1}) for 4-spoke and 2-spoke disks, respectively. At this critical speed subjects reported that they could not discriminate the rotation direction and their only perception consisted of a number of clearly detectable stationary 'phantom' spokes. The phenomenon of perceiving supernumerary spokes, which is a well-defined aspect of WWI, was clearly observed in this condition. Minimal increase or decrease in the speed caused the supernumerary phantom spokes to appear to rotate in opposite directions.

3.2 *Experiment 2*
In experiment 2, none of our subjects reported a reversal in the rotation direction. They also did not report the phenomenon of perceiving supernumerary spokes. Conducting the experiment under the two DC light bulbs in an otherwise dark room yielded the same result as under sunlight. Thus, all our subjects failed to perceive WWI under the conditions described earlier by Purves et al, while being able to perceive it in conventional stroboscopic light.

Changing the sizes of the disks and drums or applying different conditions for the fixation point did not result in any change in the results in either of the two experiments.

4 Discussion and conclusion
The results of our first experiment are as expected from prior calculations. Notice that the 50 Hz AC power source would turn the fluorescent lamp on and off 100 times per second, because there is one on – off period during the positive half-period of the sine wave and its following zero crossing, and another on – off period during the negative half-period and its successive zero crossing. If we now substitute 100 for the variable f

and the numbers 4 or 2 for the variable n in the formula $f/2n$ (see figure 1), then the results would be 12.5 rev s^{-1} and 25 rev s^{-1}, respectively. This coherence between calculated and empirical values shows that our minds are able to process information presented at the rate of 100 Hz without losing any of those 100 frames presented during 1 s.

Purves et al (1996) reported WWI in continuous light at rotation speeds of 0.55 – 1.3 rev s^{-1}, which should be taken as the outcome of the $f/2n$ formula. They used disks (drums) with 1 – 20 spokes (elements): so n would be 1 – 20 in the formula. Notice that the greater the number of spokes (elements) the lower the critical speed for WWI. So, 0.55 rev s^{-1} is the critical speed when 20 spokes (elements) are used and 1.3 rev s^{-1} is the critical speed when just 1 spoke (element) is used (as noted by Purves et al). Therefore, the proper value for f in the equation $f/2n =$ critical speed, to hold both sides consistent, would be some value between 2 and 20 or a little bit more. This is the rate at which Purves et al proposed that our visual system samples the stream of visual data.

It appears to us that the results reported by Purves et al, which have recently been used as some evidence for discreteness of our conscious perception in some articles (Crick and Koch 2003; VanRullen and Koch 2003), are not replicable. Our second experiment showed that WWI does not occur under steady illumination, and our first experiment showed that it is not possible to explain WWI by assuming a sampling rate for the visual system. Purves et al have hypothesised that the visual system samples what it sees. They have proposed a sampling rate within the range of 2 – 20 Hz for the visual system. If we assume that different subjects are going to perceive a rotating wagon wheel under 100 Hz intermittent light (just as we have done in experiment 1), 100 snapshots of the wagon wheel would be presented to their visual system during 1 s. If we accept the hypothesis of a range of sampling rates between 2 and 20 Hz for the visual system, then we would expect that each of the subjects would sample a different number of the 100 snapshots and would perceive WWI under intermittent light at various critical speeds; none of such reported speeds, equal to the critical speed, was obtained from the calculation. Our first experiment was not in agreement with this assumption. We observed that all of our subjects reported the same critical speed obtained by calculation; thus the phenomenon of WWI and its critical speed does not depend on the psychophysical properties of the visual system, but the effect is purely physical.

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