Abstract

With accurate fixation (or image stabilization), moving gratings are detected if their spatiotemporal frequency lies within the window of visibility. Yet, stimuli beyond these limits can be detected in unrestrained vision by executing saccades, whether they are along, against or orthogonal to the direction of motion of the grating. Improved detection with saccades in the direction of the stimulus motion is understandable because those saccades lower the retinal velocity of the grating, thus bringing it into the window of visibility. But this effect is not expected with saccades against or orthogonal to the direction of motion of the grating. We investigated this anomaly and found that the improved detection of fast-moving gratings with saccades in any direction occurs only when the stimuli are displayed on a sampled device such as a CRT; if the stimuli are presented in a continuous device, improved detection only occurs when the saccades are in the direction of the stimulus motion. Although the anomaly is indeed an artifact produced by sampled displays, the fact that saccades aid detection at all must imply that saccadic suppression is not complete. We present theoretical evidence that saccadic suppression may not be an active mechanism: passive properties of a visual system may in some conditions impair detection during saccades (hence giving the impression of active suppression) and, at the same time, improve detection in other cases (hence giving the impression of active enhancement).

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Fast-moving gratings presented on a CRT (a temporally sampled display) are not detectable under steady fixation.

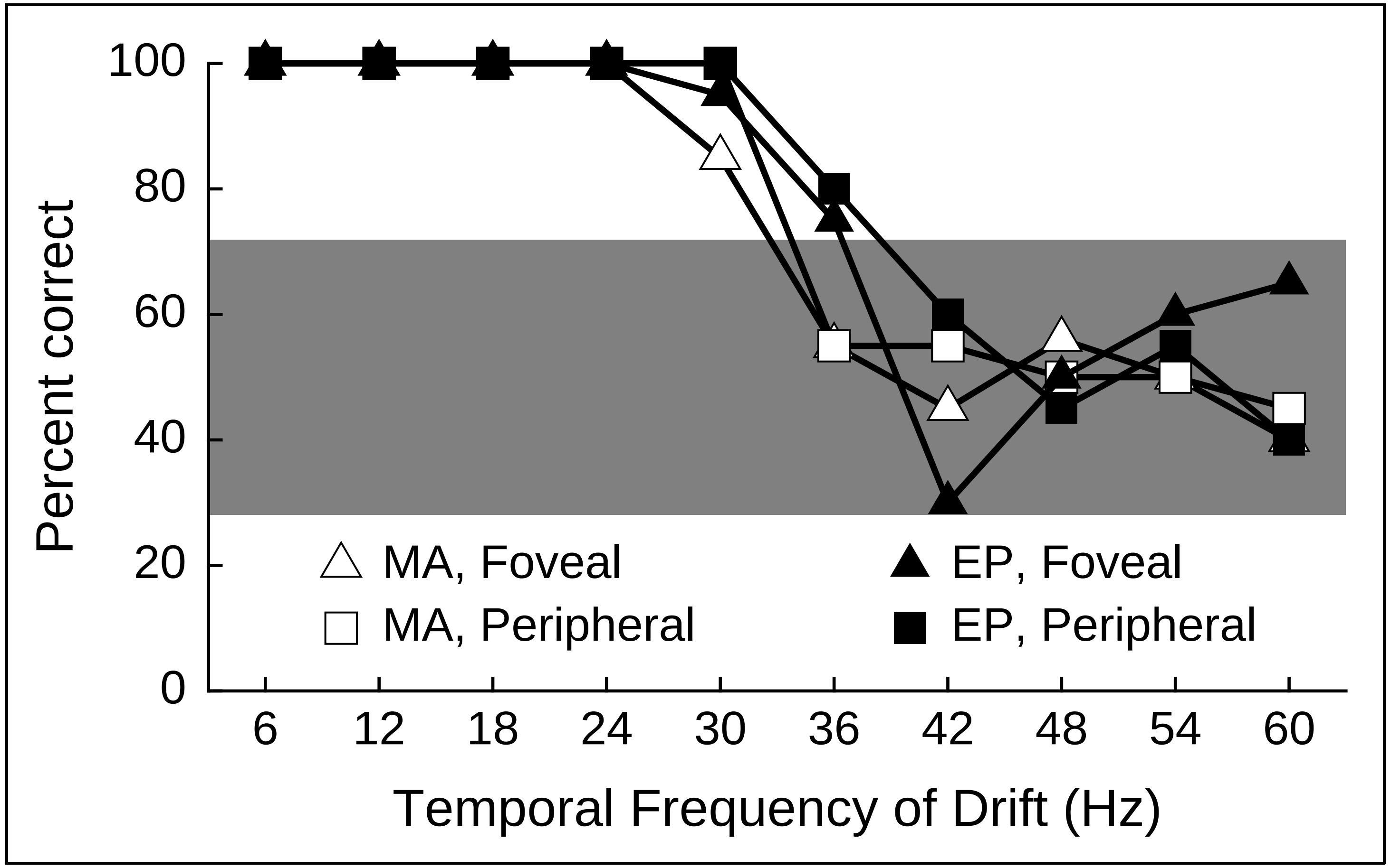


Figure 1.
Results of a 2AFC detection task where one of the intervals displayed a drifting grating and the other displayed a uniform gray field.

Drifting gratings can be detected both foveally and peripherally if their speed is such that temporal frequency is below about 30 Hz, but they cannot be detected at higher temporal frequencies.

The shaded area represents percent values that do not differ significantly from the chance level of 50% at $\alpha = 0.05$.

This is a well-known fact reflecting the temporal-frequency cutoff of the visual system: drifting gratings whose temporal frequency exceeds the limits of the window of visibility cannot be seen (Robson, 1966; Watson, Ahumada and Farrell, 1986).

Yet, executing saccades during the presentation period makes fast-moving gratings visible, regardless of the direction of the saccade relative to the direction of motion of the stimulus. Subjects report seeing a flash of a stationary grating with high contrast.

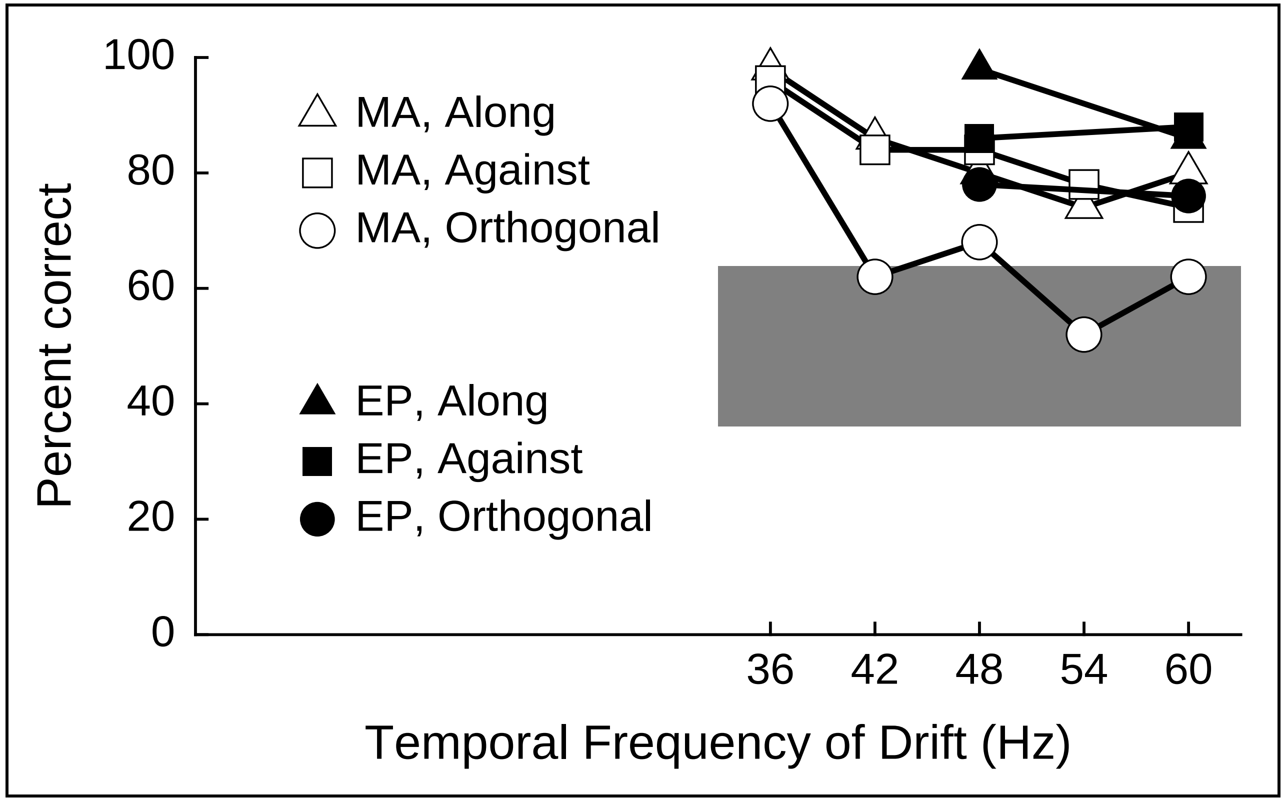


Figure 2.
Results of an experiment similar to that in Fig. 1, except that subjects executed a rightward saccade at the middle of the presentation. Since the stimulus could drift to the right, to the left, or upwards, these saccades could be along, against or orthogonal to the direction of motion of the grating.

These fast-moving stimuli could not be detected under fixation (Fig. 1), but they are easily detected when the eyes move.

The shaded area represents percent values that do not differ significantly from the chance level of 50% at $\alpha = 0.05$.

Saccades affect the **retinal** velocity of the stimulus. For saccades along the direction of stimulus motion, retinal velocity is reduced and the stimulus is brought into the window of visibility. But why is the stimulus detected when the saccades are against or orthogonal to the direction of motion of the stimulus? Similar results have been reported by Deubel, Elsner and Hauske (1987), and we will show that they are an artifact caused by the sampled operation of CRT displays.

When fast-moving gratings are presented on a continuous display, executing saccades only brings into visibility stimuli whose direction of motion coincides with that of the saccade.

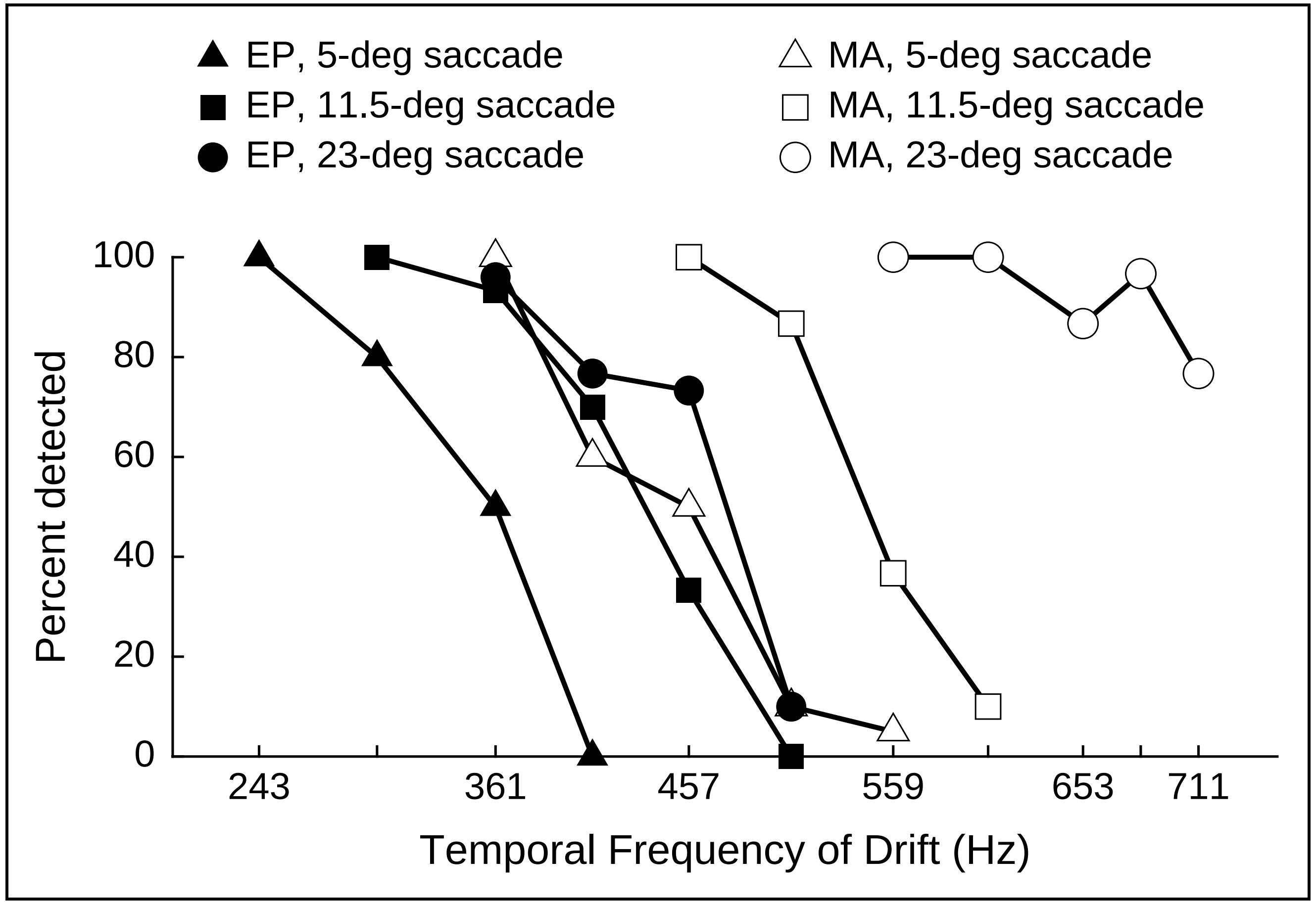


Figure 3.
Results of a yes-no task where subjects executed saccades while a square-wave grating printout mounted on a wheel was spinning indefinitely.

Stimuli whose temporal frequency is much higher than the temporal-frequency cutoff of the visual system can easily be detected, as long as the velocity of the saccade (which increases with saccade amplitude) is high enough to bring the **retinal** stimulus within the temporal-frequency limits of the window of visibility.

All data are for saccades **along** the direction of motion of the stimulus; with saccades against the direction of the stimulus, detection did not occur ever.

Saccades along the direction of stimulus motion in continuous displays help detection of the stimuli; saccades against do not aid detection. The stimulus is also seen as a stationary flash.

In informal observations we determined that the stimulus was not detected under fixation (neither foveally nor peripherally), and that orthogonal saccades do not make the stimulus visible either.

If the continuous display is illuminated only with a stroboscope, the results resemble those obtained with the sampled display: fast-moving stimuli are seen with saccades either along or against the direction of motion of the stimuli.

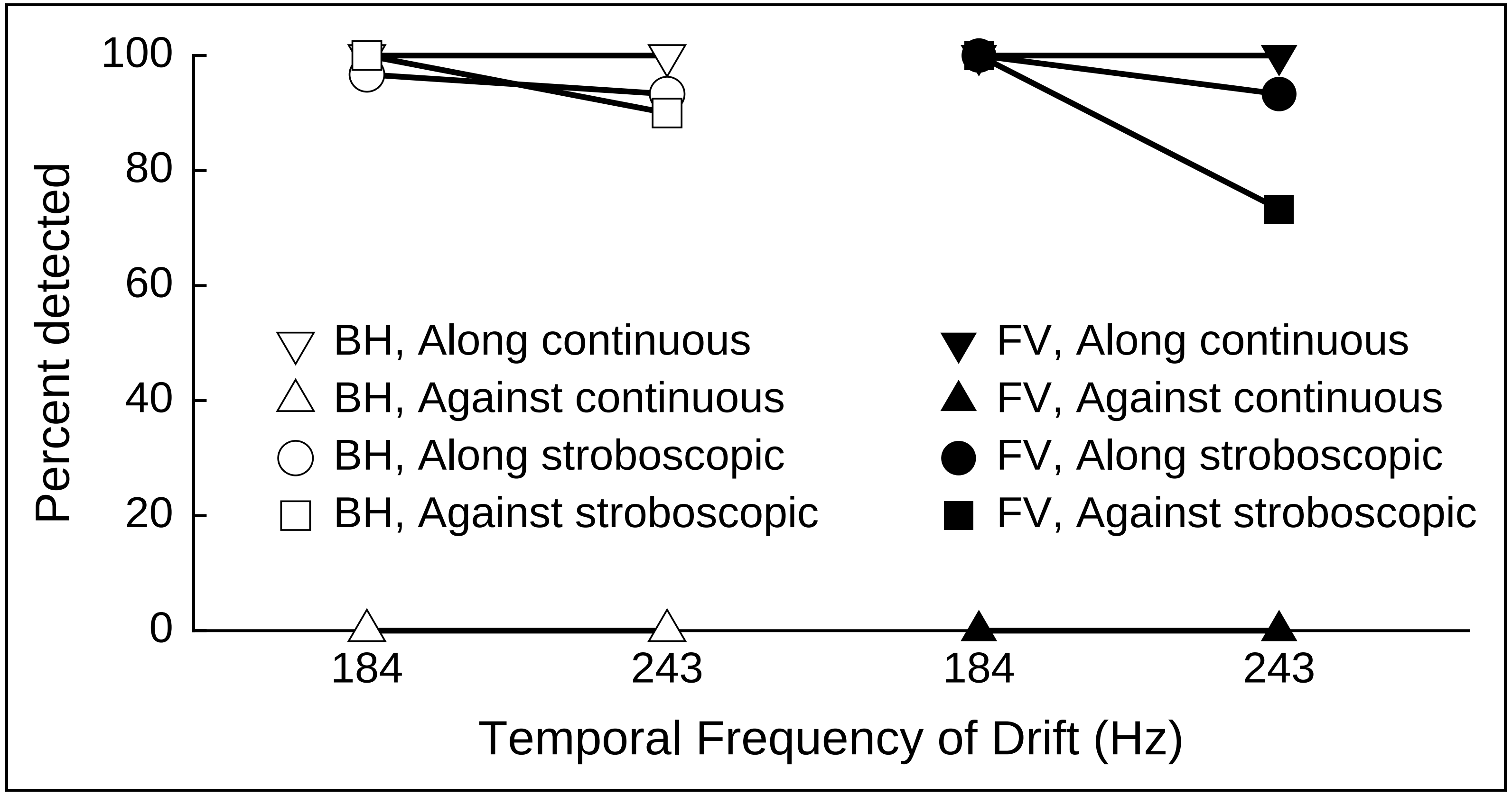


Figure 4.
Results of an experiment similar to that in Fig. 3, except that the spinning wheel was illuminated either with a continuous light source or with a stroboscope running at 333.33 Hz. In the former case, stimuli are only detected with saccades along the direction of motion of the stimulus; in the latter, the stimulus is detected with saccades either along or against the direction of the stimulus.

All saccades spanned 23 deg.

Stroboscopic illumination of a continuous display turns it into a sampled display, and the detection of fast-moving gratings through saccades has the same characteristics as found with a sampled display.

Saccades make the stimulus visible, appearing as a short-duration flash with a contrast that looks close to the actual contrast of a snapshot of the stimulus. How is this apparent "saccadic enhancement" compatible with "saccadic suppression"?

- Saccadic suppression has been used to explain the lower sensitivity to sinusoidal gratings during saccades, as compared to sensitivity to the same stimuli under fixation. This lower sensitivity occurs for low-frequency (Burr, Holt, Johnstone and Ross, 1982; Burr, Morrone and Ross, 1994) and high-frequency gratings (Ridder and Tomlinson, 1997).

- The above studies have used very short presentations: 20 ms in Burr, Holt, Johnstone and Ross (1982); 17 ms in Burr, Morrone and Ross (1994); or 16.67 ms in Ridder and Tomlinson (1997). Thus, sensitivity measures without saccades result from a single (foveal) retinal area collecting the full energy of the stimulus; conversely, sensitivity measures with saccades result from the integrated operation of a diverse set of peripheral and foveal areas each collecting a small portion of the energy of the stimulus. In this latter condition, a reduced sensitivity should be expected on grounds of retinal inhomogeneity and the spread of stimulus energy over a substantial number of receptors (recall Bloch's law). None of the above studies has controlled these factors or proved that the reduction in sensitivity is not caused by them. Unless these passive factors are ruled out, there is no conclusive evidence for an active process of saccadic suppression.

- Our experiments confirm the observations of Deubel, Elsner and Hauske (1987) and Kelly (1972, 1990) to the effect that invisible fast-moving gratings become visible during saccades, and they appear as a momentary flash of a motionless version of the stimulus at its actual contrast. That the stimulus is seen during the saccade indicates that saccadic suppression is not operating.

- We next show that passive processes explain the detectability of high-contrast stimuli during saccades.

Passive processes explain the results obtained with the sampled display, without any active saccadic suppression or enhancement.

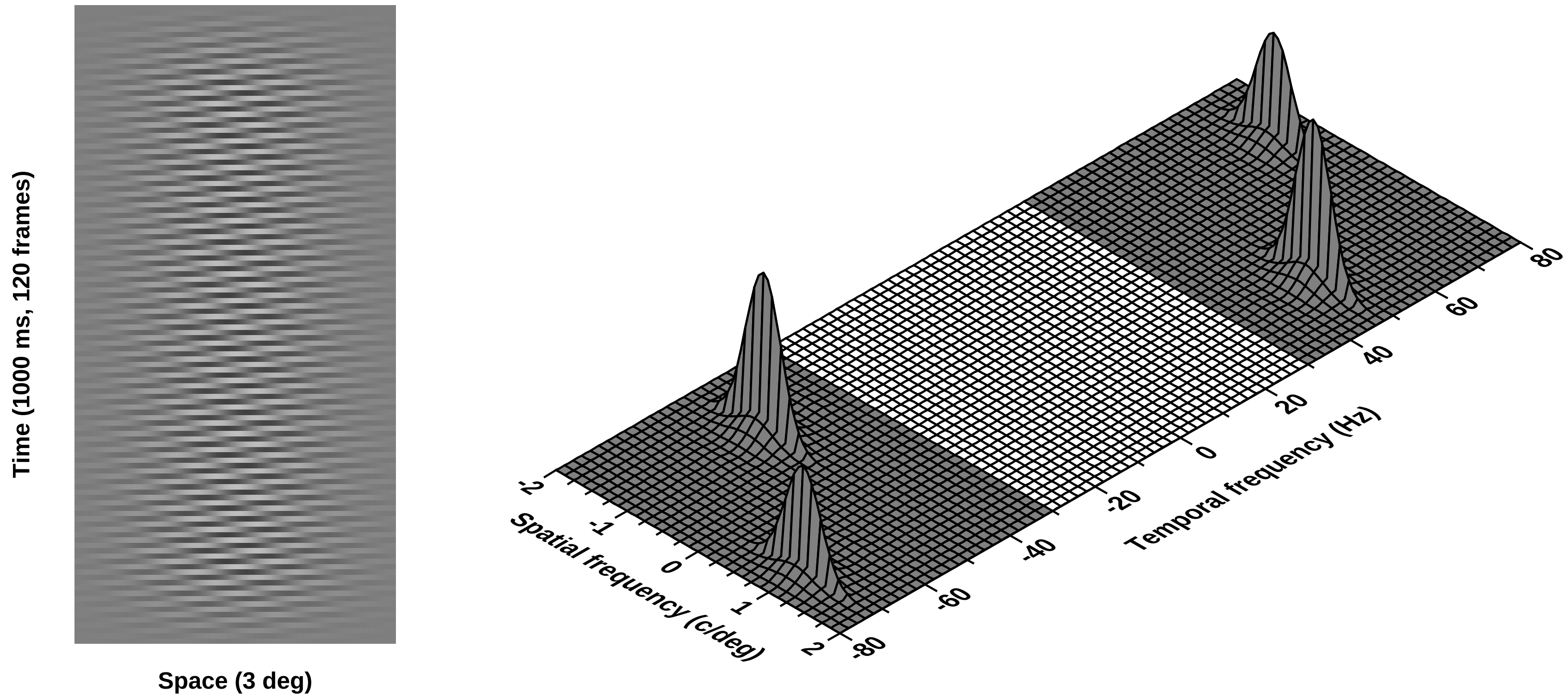


Figure 5. A fast-moving grating under fixation is not perceived because it lies outside the limits of the window of visibility. A space-time plot of the stimulus is on the left, where time runs from bottom to top and space is the horizontal dimension. This is one of the stimuli used in the experiment of Fig. 1, with the same temporal contrast envelope, duration and frame rate. The spatiotemporal-frequency spectrum (on the right) has a blob at a spatial frequency of 1 c/deg and a temporal frequency of 48 Hz, plus a symmetric blob at −1 c/deg and −48 Hz. The two other smaller blobs at ±72 Hz are replicas produced by the sample-and-hold operation of CRTs (see García-Pérez and Peli, 1999). The region **outside** the window of visibility (bounded within ±30 Hz) is shaded in gray.

With fixation, fast-moving gratings are not visible because of the lowpass nature of the visual system.

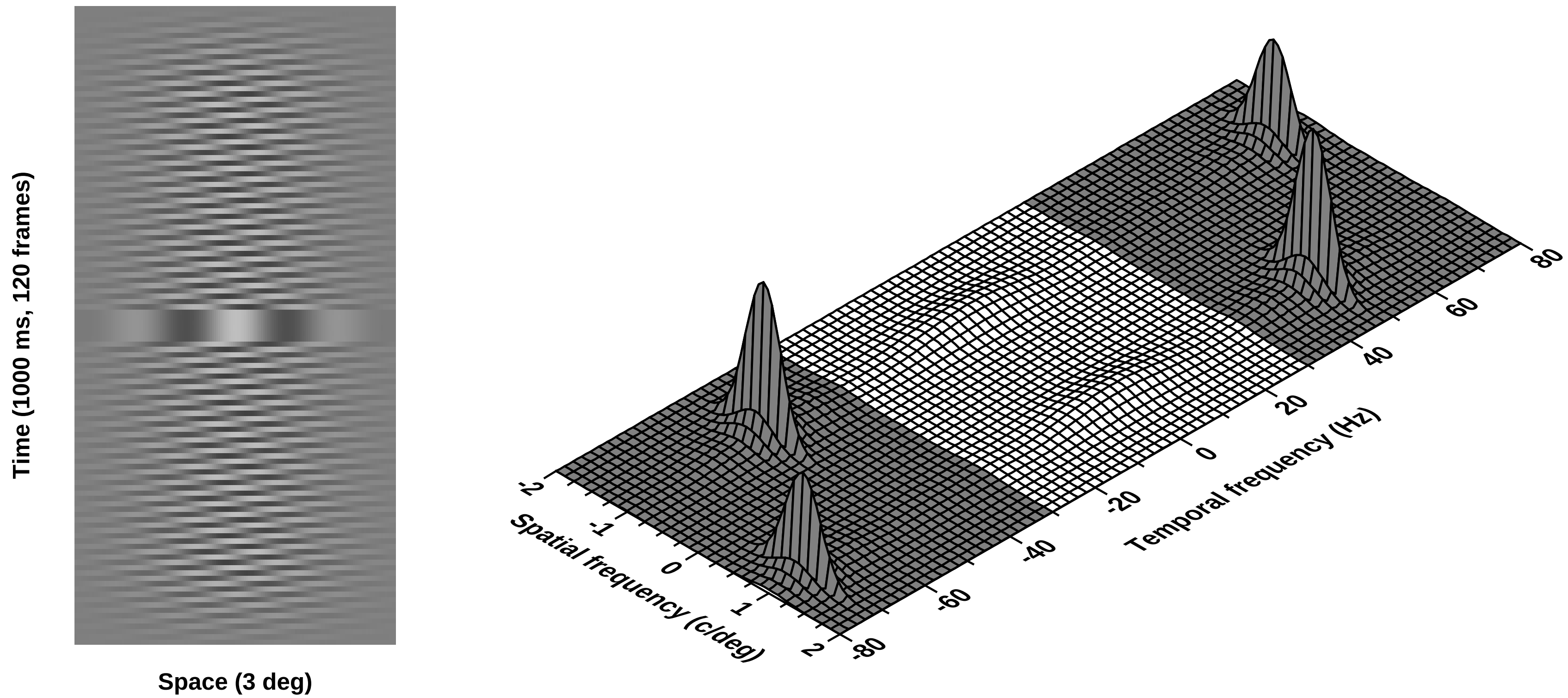


Figure 6. The same fast-moving grating of Fig. 5, but with a 50-ms saccade in the middle of the presentation duration whose speed and direction matches that of the stimulus. The saccade has been idealized by assuming a constant speed from beginning to end (as in Morrone, Ross and Burr, 1997); the net effect will not be very different for other more realistic trajectories (see Harwood, Mezey and Harris, 1999). Changes in the retinal location of the projection of the stimulus have not been represented in the space-time plot on the left. The spatiotemporal-frequency spectrum on the right has additional blobs within the window of visibility.

With a saccade along the direction of motion of the stimulus and with a velocity that matches the nominal velocity of the grating, this fast-moving grating remains stationary on the retina for a short time (6 frames here, or 50 ms). As compared to the same grating viewed under fixation, the saccade introduces energy into the window of visibility, thus making the grating detectable.

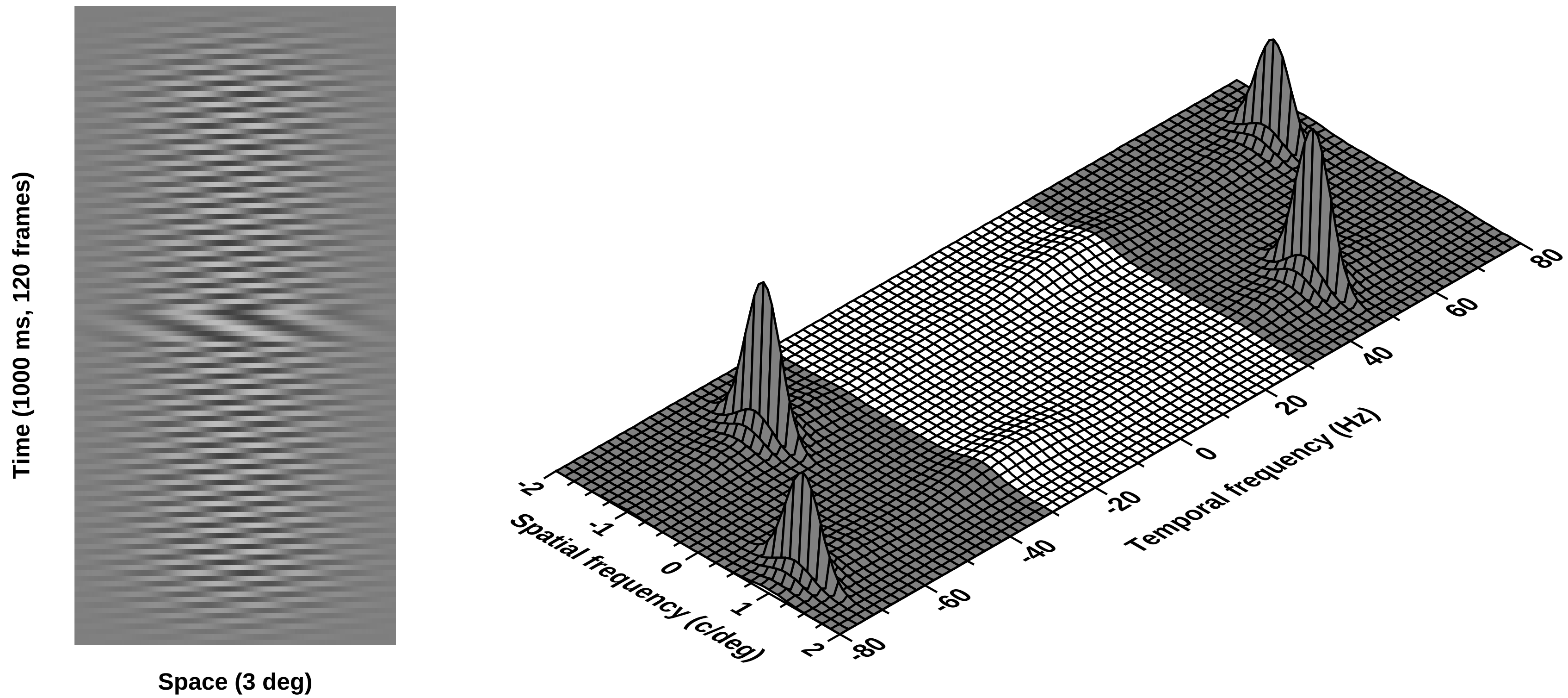


Figure 7. The same fast-moving grating of Fig. 5, but with a saccade in the middle of the presentation duration whose speed matches that of the stimulus but goes in the opposite direction. The saccade has been idealized as in Fig. 6. The spatiotemporal-frequency spectrum also has additional blobs within the window of visibility, but in this case they come from the replicas introduced by the sample-and-hold operation of the display.

If the saccade goes against the direction of motion of the stimulus with the same speed as before, the velocity of the fast-moving grating gets aliased upon projection on the retina for the duration of the saccade. As compared to the same grating viewed under fixation, the saccade also introduces energy into the window of visibility, thus making the grating detectable. Saccades of other velocities will have different effects on the aliased retinal velocity, but the grating will still be detectable in most cases.

Passive processes explain the results obtained with the continuous display.

- Let $f(x,y,t) = \exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right]\cos\left[2\pi\rho_0(x-\upsilon_0 t)\right]$ be the drifting Gabor patch (with spatial spreads σ_x and σ_y), with a carrier of frequency ρ_0 and velocity υ_0, in retinal units (ie, c/deg and deg/sec, respectively), given a convenient origin of coordinates.

- Assume that the stimulus is present for unlimited time so we can leave aside the temporal window of presentation. Assume also that velocity is such that temporal frequency is beyond the limits of the window of visibility (ie, $\rho_0 \upsilon_0$ » 30 Hz).

- An idealized saccade (ie, of constant velocity υ_s throughout) will effectively change the retinal velocity of the stimulus (from υ_0 to $\upsilon_1 = \upsilon_0 - \upsilon_s$) throughout the duration of the saccade. This change occurs during a window τ sec in duration.

- The retinal stimulus (disregarding the shift in retinal position) becomes $f(x,y,t) = \exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right]\cos\left[2\pi\rho_0(x-\upsilon_0 t)\right]\left[1-\Pi_\tau(t)\right] + \exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right]\cos\left[2\pi\rho_0(x-\upsilon_1 t)\right]\Pi_\tau(t)$, where Π_τ is a rectangle function of width τ. The stimulus has velocity υ_0 outside the interval defined by Π_τ and velocity υ_1 within the interval defined by Π_τ.

- The stimulus has energy at the original spatiotemporal frequency [ie, at $(\rho_0, \rho_0 \upsilon_0)$ in the frequency domain], which will not lead to detection. But it also has some energy at the velocity introduced by the saccade [ie, at $(\rho_0, \rho_0 \upsilon_1)$]. For saccades against the direction of stimulus motion, $\rho_0 \upsilon_1$ is further away from the limits of the window of visibility, and these saccades do not make the stimulus visible. For saccades along the direction of stimulus motion, $\rho_0 \upsilon_1$ may be within the window of visibility depending on the relative magnitudes of υ_0 and υ_s, in agreement with our experimental results (see Fig. 3).

Conclusions

- Gratings drifting at a speed beyond the limits of the window of visibility cannot be perceived under steady fixation, but saccades along the direction of stimulus motion bring them into the window of visibility and, thus, make them visible.

- If the stimulus is presented on a sampled display, saccades against the direction of motion of the stimulus also make the stimulus detectable, but this is only an artifact of the sample-and-hold operation of these displays. If the stimulus is displayed on a continuous device, these opposite-direction saccades do not make the fast-moving grating visible.

- On a sampled display, orthogonal saccades also make fast-moving stimuli detectable. With our upward-moving horizontal grating and horizontal saccades, this result must have been caused by a vertical component in horizontal eye movements.

- That the stimulus is seen specifically during the saccade must mean that saccadic suppression is not a truly active process taking place whenever a saccade occurs. The decrease in sensitivity that is observed when saccades occur during the detection of near-threshold stimuli might simply reflect Bloch's law: a result of receptor pooling and the spread of stimulus energy across a diverse set of retinal locations in the saccade trials as compared to the fixation trials.

Apparatus

Experiments with a CRT display

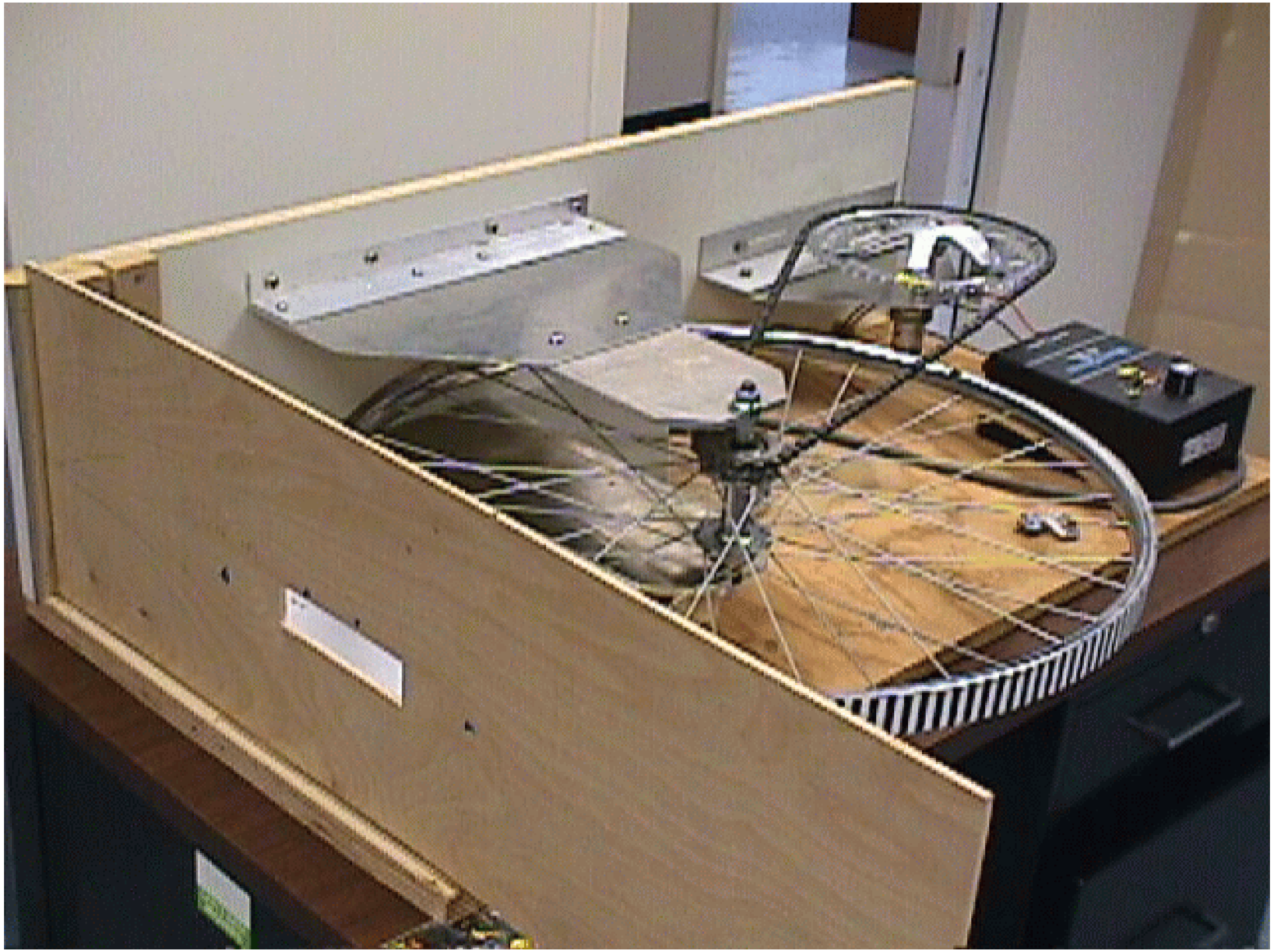
Stimuli were Gabor patches with a static gaussian aperture and a drifting carrier. The carrier was a 1-c/deg sinusoid whose velocity could be varied up to 60 deg/s, corresponding to a temporal frequency of 60 Hz, and its orientation was vertical (in the experiment of Fig. 1) or both horizontal and vertical (in the experiment of Fig. 2). The circular gaussian aperture had a space constant of 0.65 deg, yielding a half-amplitude spatial-frequency bandwidth of 0.86 octaves. The 1000-ms window of stimulus presentation was trapezoidal (125-ms linearly ramped onsets and offsets, bracketing a 750-ms 50%-contrast presentation period). The half-amplitude temporal-frequency bandwidth of all stimuli was 1.55 Hz.

Stimuli were created within 150×150-pixel arrays, and there were 45.3 pixels per cycle of the carrier. The array was displayed on an EIZO FlexScan FX·E7 21" monitor driven at 120 Hz. The monitor was linearized by gamma correction. Mean luminance was 34 cd/m^2. All experimental events were under control by a PC equipped with VisionWorks™ (Vision Research Graphics Inc., Durham, NH) hardware and software.

Experiments with a continuous display

The apparatus (pictured next) consisted of a bicycle wheel whose circumference presented a locally flat surface 174 cm around and 3 cm wide. Rotation of the wheel was achieved by a DC motor which could render speeds between 50 and 245 rpm. A square wave grating of 1 c/cm was laser printed at a resolution of 600 dots-per-inch, and these printouts were suitably mounted around the surface of the wheel.

The apparatus was hidden from the observer’s view by a cardboard with an opening 11.5×3 cm. Drawn on the cardboard were three pairs of marks separated by 5, 11.5 and 23 cm (centered on the cardboard opening) that served as guides for subjects to execute horizontal saccades. Viewing distance was 57 cm (spatial frequency was thus 1 c/deg), and rotation of the wheel at 1 rpm (i.e., at a linear velocity of 2.9 cm/s) produces an almost flat stimulus moving at a retinal velocity of 2.9 deg/s (and, then, a 2.9-Hz temporal frequency of drift).



Method

Experiments with a CRT display

Natural pupils and accommodation were used, and viewing was binocular from a distance of 1 m. A small dot (luminance: 41 cd/m^2; radius: 0.1 deg) graphically overlaid on the screen served as a fixation aid in the experiment of Fig. 1 (which required fixation either on or off the location where gratings were to be presented). In the experiment of Fig. 2 (which required saccades), two dots (11.3 deg apart) were used to mark the origin and endpoint of the horizontal saccades, and they were near the edges of the monitor whereas the stimulus appeared in its center.

A two-alternative forced-choice (2AFC) detection task was used in combination with the method of constant stimuli. In the experiment of Fig. 1 (requiring fixation), temporal 2AFC trials consisted of two 1000-ms intervals (each signalled by a tone of different pitch over the entire duration of the interval) separated by 250 ms. The stimulus appeared in one of the intervals (at random on each trial) and the next trial did not start until the subject had responded. There were 20 trials per condition.

In the experiment of Fig. 2 (requiring saccades), the same temporal 2AFC trials were used. Each trial started while the subject was fixating on the single visible fixation mark (on the left of the display). This mark disappeared at the midpoint of the presentation interval, and the mark on the right then appeared which directed the subject to execute a saccade. The next trial did not start until the subject had responded. There were 50 trials per condition.

Experiments with a continuous display

A yes-no detection task was used in combination with the method of constant stimuli. On each trial, the wheel was set in motion in a random direction, the subject was asked to fixate one of the marks around the viewing aperture, and then the window was uncovered. Stimulus presentation time was unlimited. Subjects executed saccades across fixation marks, pausing briefly before reversing direction. The subject's task was to indicate which saccade direction made the stimulus visible. Since this experiment was not automated, the experimenter judged how many trials were necessary per condition, but the usual number was 30.

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