1 General Methods

1.1 Observers

Observers were one of the authors (P.B.M.) and SOME NUMBER OF naïve observers. All had normal or corrected-to-normal vision. All subjects provided informed written consent, and all procedures involved were approved by the Institutional Review Board at the University of Washington.

1.2 Equipment

Stimuli were presented on a flat CRT video monitor (ViewSonic PF790). Its resolution was set to 800 by 600 pixels over a display area of 35.5×25.8cm and it used a 120Hz refresh rate. Experiments were programmed in MATLAB using the Psychtoolbox (Brainard, 1997) and Eyelink toolbox extensions (Cornelissen et al., 2002), along with custom OpenGL code. All guns were fixed at the same voltage to show grayscale stimuli. The monitor was calibrated using a Tektronix model-number photometer. A midpoint gray background of 0.13cd/m^2 was chosen to lie at the midpoint between minimum (0.13cd/m^2) and maximum (61cd/m^2) luminances. A hardware lookup table with 10-bit resolution was used to linearize the display response.

Subjects sat behind a blackout curtain so that ambient illumination was mostly due to the monitor and viewed the screen binocularly using a chin and forehead rest with the eyes 60cm from the screen. Eye position was monitored using a video-based eye tracker (EyeLink 1000; SR Research) using a sample rate of 1000 Hz. Subjects gave responses by turning a knob (PowerMate; Griffin Technologies) with their preferred hand in the direction of the perceived motion.

1.3 Stimuli

Stimuli were designed to allow us to independently manipulate higher-order, position-based motion, and first-order motion energy. We did this by independently controlling the motion of the envelope and the carrier of oriented motion stimuli. This stimuli used are shown in figure Figure 1. The stimuli consisted of a number of repeatedly [??] presented, identically moving elements arranged into a circle at centered on the fixation point figure Figure 1. The elements were presented 5 times, each offset by regular space (Δx) and time (Δt) intervals figure Figure 1. Along the direction of motion, the luminance distribution of an element was given by a Cauchy filter function (Klein and Levi, 1985) At right angles to the direction of motion the elements were windowed by a Gaussian envelope with standard deviation $w/2$, while the temporal onset and offset of each element was a Gaussian with standard deviation equation $d/2$. An equation describing the luminance profile of a single envelope, centered at $(x, y, t) = (0, 0, 0)$ with the direction of motion along x is:

$$L(x, y, t) = \cos^n(\tan^{-1}(fx/n))\cos(n \cdot \tan^{-1}(fx/n) + \omega t)e^{-(t/2d)^2-(y/2w)^2}$$

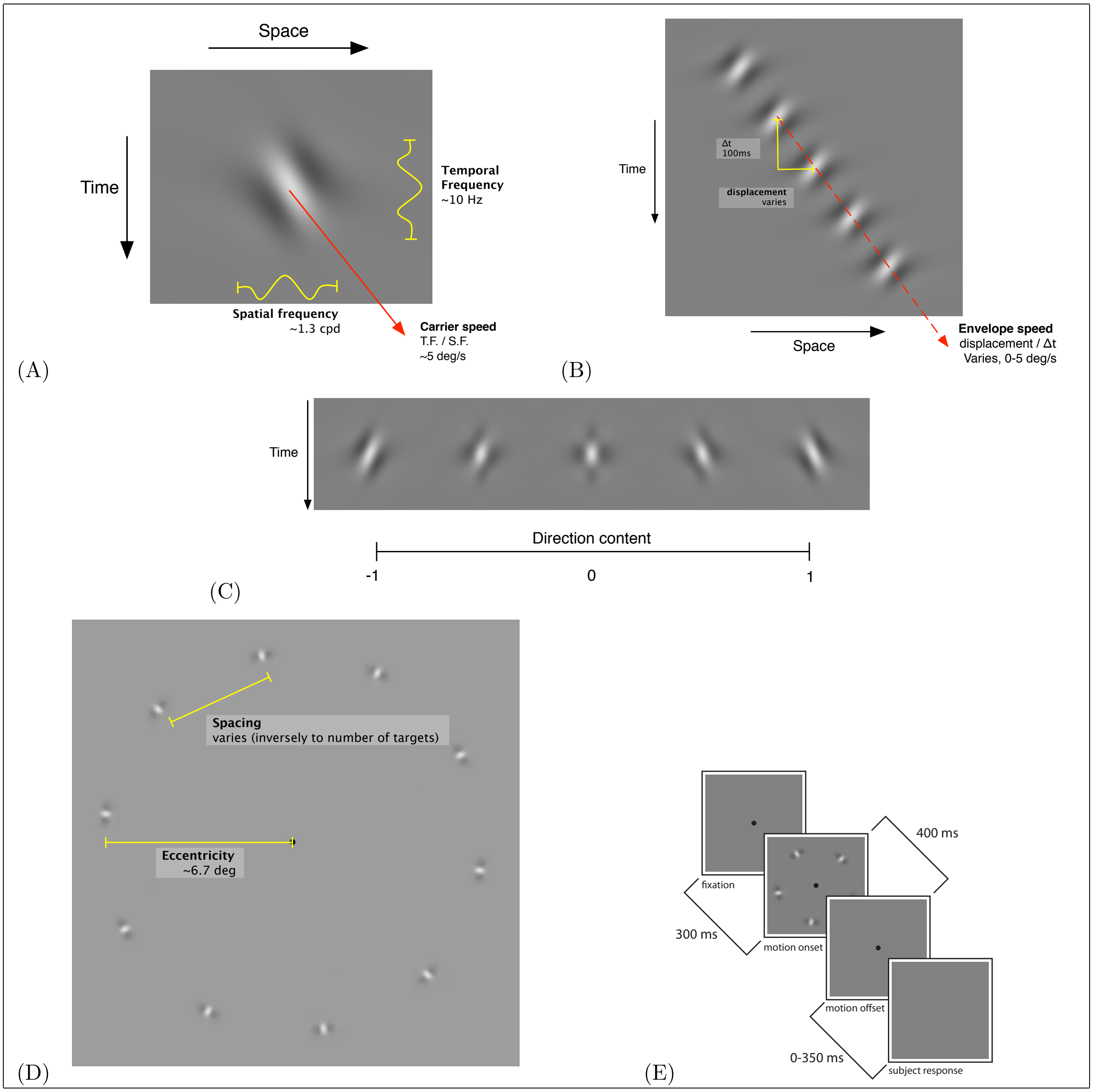

Figure 1: Construction of motion-direction stimuli. (A) A single motion element, shown in a space-time diagram. Space is shown across the horizontal axis, and time is shown running down the vertical axis. Elements are Gabor-like with a moving carrier (visible as the tilt in this diagram) and a fixed envelope. The same motion elements are used for all experiments in this paper. (B) Motion elements were constructed of several motion pulses, offset at regular intervals in space and time. "Displacement" refers to the spatial displacement of the Gabor-like elements at each step. The interval between steps was always 100ms. (C) We varied the directional content of the motion elements by mixing two carriers in opposite directions. A direction content of 0 is counterphase flicker, with equal energy along both directions of carrier motion. A direction content of 1 uses only the clockwise carrier. The total luminance contrast of counterclockwise and clockwise carriers was fixed at 50%. (D) Stimuli comprised several motion elements arranged around a circle, with the directions of carrier and envelope motion along its circumference. (E) Illustration of task. Subjects viewed motion stimuli such as in Figure 2.

Figure 2: Example stimuli. For these experiments, identically scaled stimuli were shown at 6.67 degrees eccentricity.

Here ω controls the temporal frequency, f the spatial frequency, temporal profile of each envelope was Gaussian, with standard deviation ; at the moment of maximum contrast the carrier was always in cosine phase figure Figure 1. The motion elements were with peak spatial frequency .

To control the amount of motion energy in each element we combined two elements with opposite directions of motion, with varying amounts of relative contrast figure Figure 1. We define the DIRECTION CONTENT $C = \frac{C_{CW} - C_{CCW}}{C_{CW} + C_{CCW}}$ where C_{CW} and C_{CCW} denote the contrasts of clockwise and counterclockwise components. Thus C has a range of $[-1, 1]$ and a value of 0 indicates a counterphase flicker with equal parts clockwise and counterclockwise motion energy. The total luminance contrast $C_{CW} + C_{CCW} = 0.5$ for the experiments reported here.

The examples in Figure 2 have the following settings, the same as used in **??**: For all trials, $\Delta t = 100$ms, $\omega = 120$Hz, . Most experiments use stimuli at $6.67°$ eccentricity, where stuff about spatial parameters. When eccentricity was varied, these three parameters were scaled proportionately.

Talk more about this example movie. May need to redo it with reference to “direction content” rather than “congruent/incongruent”

1.4 Methods

1.4.1 Task

The timecourse of a trial is illustrated in figure Figure 1. A fixation point was presented. The computer then waited for the observer to fixate. 250 ms after detecting fixation, the motion stimulus was shown for 500 ms (the initial location, then 4 steps of displacement at 100ms intervals) After the motion stimulus concluded, observers indicated the direction of perceived motion by turning a knob within a response window that lasted 500-900 ms from stimulus onset. If an observer blinked or broke fixation before the offset of the motion stimulus, the trial was aborted and reshuffled into the stimulus set, to be repeated later in the session. Response latency was defined as the elapsed time between motion onset and the knob being turned. If the response latency was more than or less than, observers received visual feedback that their response was either too fast or too slow, and the trial was reshuffled into the stimulus set to be repeated later in the session. An audio click was played each time subjects gave a response; this seemed to help subjects establish a consistent rhythm through the experiment. No feedback was given as to the correctness of observers' responses, only whether they had responded within the time window. Observers were instructed to report the apparent direction of motion, and told that there were no correct answers. In some conditions observers reported seeing conflicting directions of motion. In those cases observers were instructed to report whichever direction of motion appeared more salient.

Observers performed the task in sessions that lasted a maximum of 1 hour, divided into 4 to 6 blocks, and were prompted to take a break between blocks. Subjects could also rest at any point by simply delaying fixation. At the beginning of each block, the eye tracking system was automatically recalibrated by asking the subject to make saccades to a sequence of targets at randomly chosen locations on the screen.

1.4.2 Staircase procedure

To measure the sensitivity of observers to envelope motion, we collected psychometric functions measuring the proportion of clockwise responses as a function of the envelope displacement, Δx. For each psychometric function we used two interleaved staircases, one 2-up-1-down and the other 2-down-1-up, to bracket the particular displacement at which subjects were equivocal about perceived direction (PSE). In a typical session, 6-8 such staircases were collected concurrently, with each staircase operating independently and trials from all staircases being randomly interleaved. Example data from this procedure is shown in figure Figure 3, with Δx plotted on the abscissa and the proportion of "clockwise" responses on the ordinate. In these graphs we scale the area of the data points to be proportionate to the number of trials collected at that displacement. Thus, the smaller a data point, the further it may acceptably lie from the model fit; some data drawn using the smallest dots may represent a single trial.

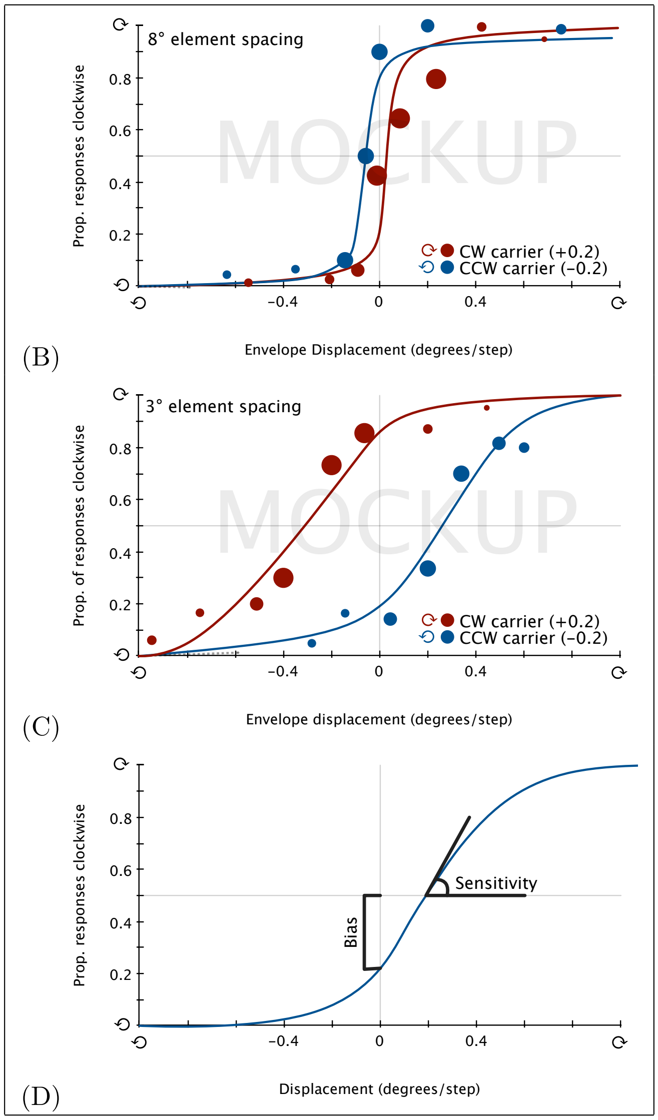

Figure 3: Example measurements from subject FAKE. (B) Psychometric functions taken at a wide element spacing. We measured the proportion of subjects' responses clockwise, as a function of the envelope displacement for different conditions of carrier content. Curves show model fits (as discussed below) to FAKE's data . For the blue dots, carrier motion is biased to the left, and for the red dots, carrier motion is biased to the right. Note that a leftward shift of the psychometric function reflects that the observer respond "clockwise" more often, so this observer sees more counterclockwise motion when clockwise content is added to the carrier; that is, there is repulsion. (C) Example data taken at narrow target spacing. The slopes of the psychometric functions are shallower and the effect of carrier motion is stronger. Now the bias is in the direction of the carrier motion; there is assimilation. (D) To summarize each psychometric function we characterize each psychometric function in terms of sensitivity and bias, here indicated on an example psychometric function.

1.4.3 Data folding

Presuming that observers do not show a particular bias toward either clockwise or counterclockwise directions, we can consider 'flipped' versions of the experiment as equivalent, and can average data together after flipping the signs of carrier direction content, envelope displacement, and the observer's response. That is, we assume that the probability of an observer responding "clockwise" given direction content C and displacement Δx equals their probability of responding "counterclockwise" given direction content $-C$ and displacement $-\Delta x$, and count these two circumstances as the same.

Note that the sStaircase procedures were run using "folding." So, a staircase that used a C of 0.2 would actually pseudorandomly present either clockwise (0.2) or counterclockwise (-0.2) motion on a given trial.

1.5 Experiment 1

The demonstrations in**??** and **??** seem to suggest that the perceived reversal of motion direction is a function not only of eccentricity viewing but of an interaction between multiple moving elements. We explored this spatial interaction by examining the interactions between local and global motion as a function of both the distance between elements and the amount of carrier direction content. Data were collected under two conditions, in the first the carrier direction content C was fixed across the entire session and the spacing between elements was varied. In the second condition we used two fixed values for spacing and varied direction content over four values (0.1, 0.2, 0.4 and 1.0), thus collecting eight psychometric functions.

1.6 Experiment 2 (number versus density)

1.7 Experiment 3 (effect of eccentricity)

References

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Klein, S. A. and Levi, D. M. (1985). Hyperacuity thresholds of 1 sec: theoretical predictions and empirical validation. *J Opt Soc Am A*, 2(7):1170–1190.