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. verbiage about subject compensation, experiment protocol approval, etc.

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 x by y cm and it used a 120 Hz 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 50% gray background was chosen to lie at the midpoint between mimimum () and maximum () luminances, which were in turn measured as patches against the gray background. 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 60 cm 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.

1.3 Stimuli

Stimuli were designed to provide independent 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 sitmuli. 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:

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

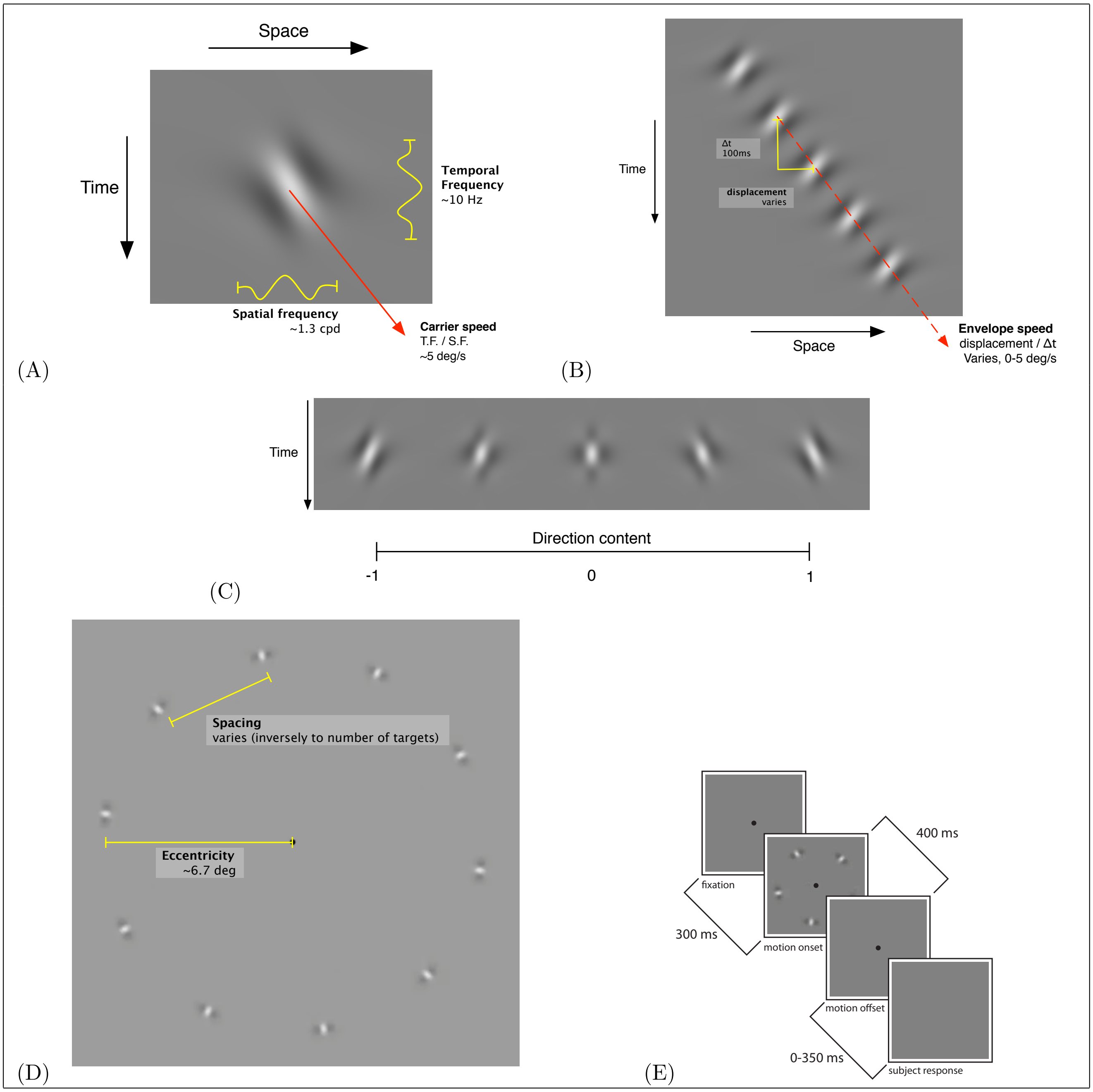

Figure 1: Construction of motion-direction stimuli. (A) A single motion element, shown in a space-time diagram. Space is shown across the horizontal axis, and time is shown running down the vertical axis. Elements are Gabor-like with a moving carrier (visible as the tilt in this diagram) and a fixed envelope. The same motion elements are used for all experiments in this report. (B) Motion elements were constructed of several motion pulses, offset at regular intervals in space and time. "Envelope displacement" refers to the spatial dimension of the step. The temporal dimension was fixed at 100 ms for these experiments. (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 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 and indicated the apparent direction of motion within 500-900 ms from stimulus onset.

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.

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

The examples in Figure 2 have the following settings, the same as used in **??**: For all trials, , , and d. For stimuli at 10° eccentricity, spatial frequency, and, and these three parameters were scaled proportionately to eccentricity.

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. After the motion stimulus concluded, observers indicated the direction of perceived motion by turning a knob. 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. There was also a time pressure to the task; 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 direction 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 of at most 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 measured psychometric functions of envelope displacement. The displacement Δx was placed under computer control, with For each psychometric function collected we used two interleaved staircases, one 2up-1down and the other 2down-1up, 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 drawn points in proportion to the number of trials collected at that displacement, to favor a visual weighting toward the values where most data was collected. note in viewing these graphs that the smaller a point, the further it may acceptably lie from the model fit; some values of Δx, drawn using the smallest dots, may only visited by one trial if that value turned out to be far from the PSE; being one

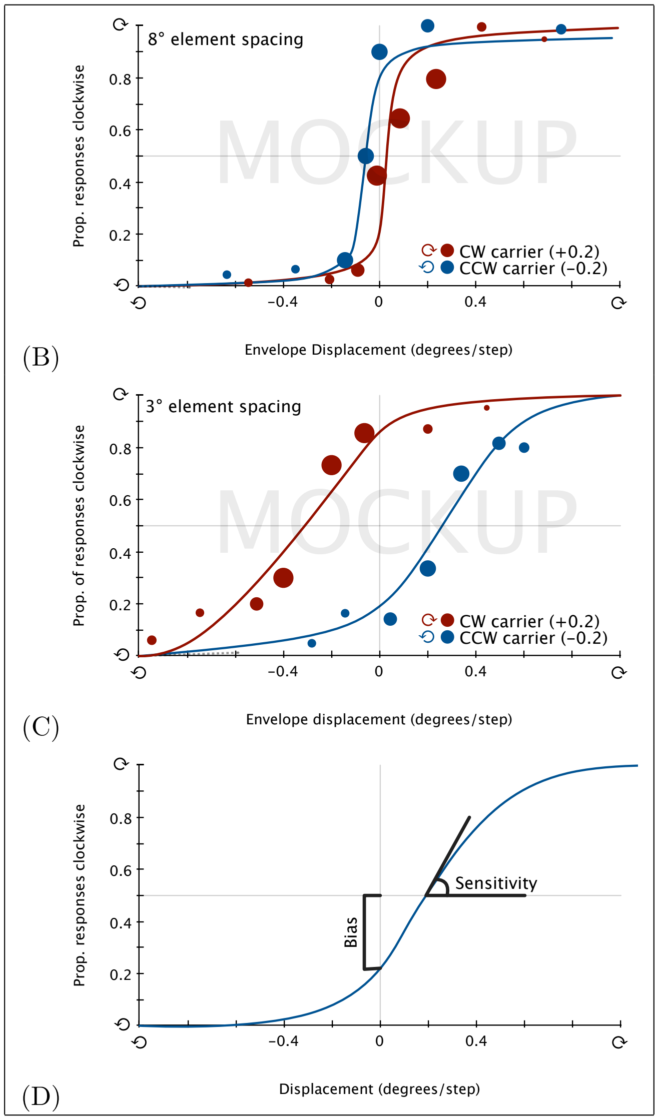

Figure 3: Example measurements from subject FAKE. (B) Psychometric functions taken at a wide element spacing. We measured the proportion of subjects' responses clockwise, as a function of the envelope displacement for different conditions of carrier content. Curves show model fits (as discussed below) 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.

trial these points can only lie at $p = 0$ or $p = 1$.

1.4.3 Data folding

For some questions we will make use of "folded" data. Presuming that observers do not show a particular bias toward either clockwise or counterclockwise directions, we may treat counterclockwise direction content as being equivalent to clockwise direction content with the opposite direction of displacement. 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 staircase procedures were run with folding. So, a staircase that used a C of 0.2 (clockwise) actually used both clockwise and counterclockwise motion in its trials

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 varying the distance between elements that were moving at a constant eccentricity.

1.5.1 Effect of spacing

In these sessions the direction content C was fixed for the entire session (though we randomized whether it was clockwise or counterclockwise.) To characterize the effect of spacing we used several values of spacing, collecting an independent staircase for each one.

1.5.2 Effect of content

In separate sessions we focused on the effect of direction content. We chose two values for spacing, below and above the critical spacing, and ranged direction content over four values (0.1, 0.2, 0.4 and 1.0; both counterclockwise and clockwise), thus collecting eight (folded) psychometric functions.

1.6 Experiment 2 (contrast versus density)

1.7 Experiment 3 (effect of eccentricity)

References

Brainard, D. (1997). The psychophysics toolbox. *Spatial Vision*, 10(4):433–436.

Cornelissen, F. W., Peters, E. M., and Palmer, J. (2002). The eyelink toolbox: eye tracking with matlab and the psychophysics toolbox. *Behav Res Methods Instrum Comput*, 34(4):613–617.

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.