SUPPLEMENTARY MATERIAL

(The video section is edited for Sperling's web page)

Theory of the Perceived Motion Direction of Equal-Spatial-Frequency Plaid Stimuli

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Specifications of the video demonstrations

Five video files to demonstrate the phenomenon described in the paper are available for direct viewing or download. All files are .mov files that can be opened in viewers like Acrobat, browsers like Safari, or by programs like Apple QuickTime. Videos 1-4 demonstrate compositions of Type 1 and Type 2 plaids at high and low temporal frequencies. Video 5 demonstrates different perceived directions of motion as the plaid component contrast ratio varies.

For correct display of these videos, a monitor with a refresh rate $\geq$ 60Hz is required. To view these videos directly on your own computer without internet, download this zip file that contains a DEMOs directory with five .mov files plus, for convenience, a PDF copy of this article. The contrast of each component sine wave of the Videos 1-4 is 30% on our monitor but is undetermined on other monitors; Video 5 has nominal contrast of 3%.

1. Type1_fast_cmb.mov

This video is a combination movie (cmb.mov) of three concurrent motion stimuli demonstrating the composition of a Type 1 plaid. The temporal frequency is 10Hz when played on a monitor running at 60 Hz refresh rate. [The display temporal frequency of the plaid is (monitor refresh rate)/6.]

The video contains three concurrent motion stimuli. The leftmost is a 10Hz, single sinusoidal grating moving at 45° up to the left. The middle is a 10Hz, single sinusoidal grating moving at 45° up to the right. Superimposing (algebraically adding) the left and the middle results in a 10Hz, Type 1 plaid on the right. Explicit link to movie: http://www.cogsci.uci.edu/~whipl/staff/sperling/DEMOs/Type1_fast_cmb.mov

2. Type1_slow_cmb.mov

This video is same as Type1_slow_cmb.mov except that it is a 1 Hz, Type 1 plaid, when played on a 60Hz monitor.

3. Type2_fast_cmb.mov

This video demonstrates the composition of a 7.5:15 Hz Type 2 plaid when played on a monitor running at 60 Hz refresh rate. [15 Hz is the fastest temporal frequency possible for accurate displays on 60 Hz monitor. The display temporal frequency of the plaid is (monitor refresh rate)/4.]

This video contains three concurrent motion stimuli. The leftmost is a 7.5 Hz, single sinusoidal grating moving at 70.5° relative to vertical and up to the right. The middle is a 15 Hz, single sinusoidal grating moving at 48.2° relative to vertical and up to the right. Superimposing (algebraically adding) the left and the middle results in the 7.5:15 Hz, Type 2 plaid on the right. The experiments used 10:20 Hz but 15 Hz is the highest frequency that can be accurately produced on a 60 Hz monitor.

4. Type2_slow_cmb.mov

This video is same as Type2_fast_cmb.mov except that sinusoidal components are 1 and 2Hz, instead of 10 and 20Hz, the primary frequencies used in the main experiment.

5. five_plaids_low.mov

This video contains five Type 1 plaids, all composed of low-contrast sinusoidal gratings running at 15 Hz. From left to right, the nominal percent-contrasts of the two component gratings are: 3:0, 3:1, 3:3, 1:3, 0:3. The contrast of the plaid components is 3% on our monitor but is unknown on other monitors. Low contrasts were used because higher contrast stimuli could be perceived as a "barber poles illusions" which would indicate activation of more complex motion process (e.g., Sun, Chubb, & Sperling, 2014, 2015). Although Type 2 plaids were used in the Experiment 2 and 3 to establish the theory for the first-order system, these Type 1 plaids were used in Experiment 1 because the 90° angle between the two single components offers a much wider range of perceived directions than the 22° angle between the Type 2 plaid components.

Sun, P., Chubb, C., & Sperling, G. (2014). A moving-barber-pole illusion. *Journal of Vision, 14(5):1,* 1-27.

Sun, P., Chubb, C., & Sperling, G. (2015). Two mechanisms that determine the Barber-Pole Illusion. *Vision Research, 111A,* 43-54.

Protocol and parameter details for Experiment 1.

Low-contrast Type 1 symmetrical plaids were presented to subjects in two types of sessions: moving in unrestricted random directions (0, 359) deg and restricted directions (-4, +4) deg. Each plaid consisted of two sinewave components, with equal or unequal contrasts. Each component had a spatial frequency of 1.0 cpd and a temporal frequency of 10.6 Hz. Five contrast-ratios were used, with the higher contrast fixed at 2%. Each pair of unequal contrasts was used in two mirror-opposite plaids. The direction of rigid motion is arbitrarily designated as zero degrees. If we use C1 to indicate the plaid component moving counterclockwise from rigid direction, and C2 clockwise, then the two mirrored plaids can be represented by (C1, C2) and (C2, C1). Results from (C2, C1) are pooled with results from (C1, C2) after flipping the former around zero degrees.

Experiment 4.

The section contains the details to support the conclusions reported in the text.

Method

Stimuli. Type 2 plaids were used: 10 and 20 Hz components, both 1 cpd with an angle of 22.3 deg between them (as in Experiment 2). The component with the higher contrast had a contrast of 32%. The ratios of the lower contrast component to the higher contrast component were: 1, 1/2, 1/4, 1/8 and 0. This aspect of the design is similar to that of Experiments 1 and 2 (e.g., see Figs. 3, 11).

Procedure. There were two conditions: motion, and static (Fig. 11). The motion condition was identical to the same conditions in Experiment 2. The stimulus was displayed for 200 msec in a random orientation 0-359 deg, and the subject made a judgment of motion direction 0,...,359 deg, as before. The static condition was similar to the motion condition except in two respects: Only one ”static” snapshot of the plaid was shown for 200 msec. In the static condition, the subjects' task was to judge the orientation of the main axis of the static plaid, i.e., of the gray lines separating the high-contrast alternating bars or of the orientation of the bars themselves (Fig. 11). The orientation response range was 0,...,180 deg.

In order to compare results of orientation judgment with that of motion-direction judgment, the orientation perpendicular to that of subjects' judgment was used to display the results of the orientation judgment.

Two subjects who had participated in Experiment 2 also participated in Experiment 4.

Results

Figure 12 shows the data (both motion judgments and orientation judgments) for the two subjects. Both subjects show similar patterns of judged orientation. For subjects ROJ and FR, respectively, the PSE for (32%, 32%) component contrasts are 60.1 and 58.2 deg, very close to the second-order orientation of 58.3 deg. For all other contrast ratios, the lower

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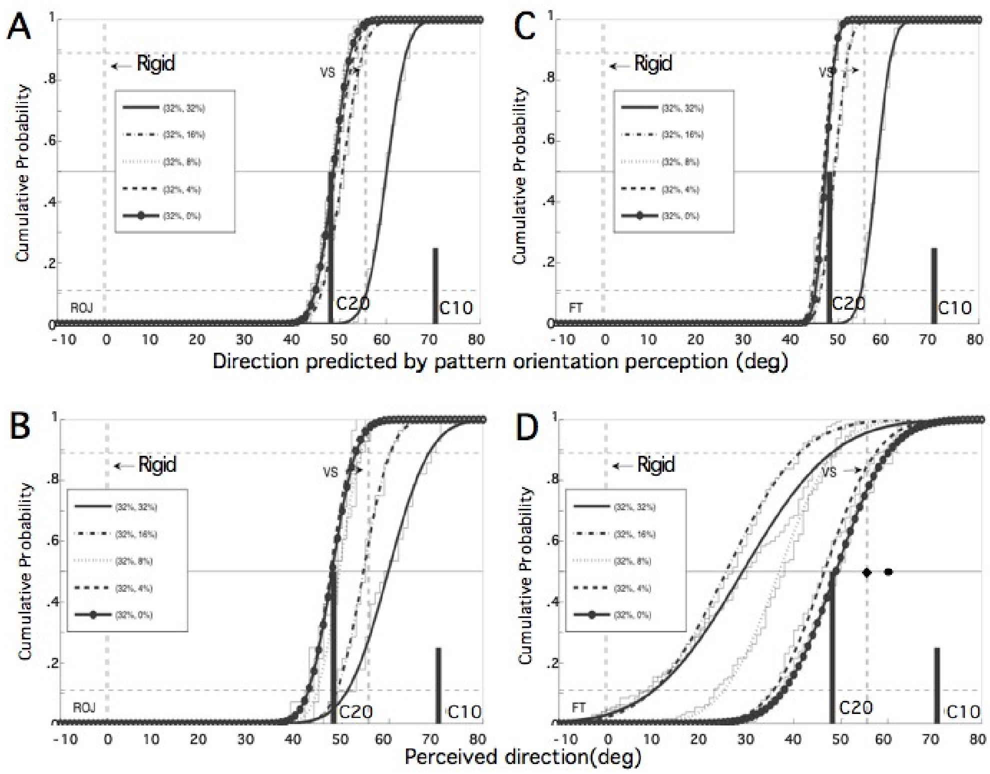

Figure 1: A comparison of orientation judgments in snapshots of Type 2 plaids with motion direction judgments for the same plaids with components now moving at 20 and 10 Hz. (A,C) Two subjects' data from orientation judgment task. The directions perpendicular to subjects' original orientation judgments are shown, because they would correspond to subjects' motion direction response if a strategy of using the orientation of plaid pattern as a clue to infer motion direction were used. The contrast of 20 Hz component was 32%, the contrast of the 10 Hz component was varied as indicated. Except for the equal contrast components (32%, 32%), orientation judgments were entirely or almost entirely determined by the higher-contrast component. (B,D) Motion direction judgments. (C) Subject ROJ's motion judgments differ from orientation judgments primarily for component gratings with a 2:1 contrast ratio. (D) Subject FT's motion direction judgments with 20 and 10 Hz components, as in Experiment 2, deviate strongly towards the rigid direction and no longer lie between the component vectors. The two dots on in right middle of Panel D represent FT's data from Experiment 2 with components of 30 and 15 Hz at contrasts, from left-to-right, of (32%, 16%) and (32%, 32%).

contrast grating is virtually ignored, and the judged orientation is that of the 32% contrast grating. This is significantly different from the second-order orientation which is independent of contrast ratio.

Subject ROJ's motion data Fig. 12B are generally similar to the orientation data Fig. 12A. For contrast ratios of 4:1 and greater, the higher-contrast grating dominates: it determines both the perceived orientation and the perceived motion direction. When the components are of equal contrast, the PSE for perceived motion direction is 63.3 deg, which differs slightly but significantly from the perceived orientation of 60.1 deg. The big difference between perceived orientation and motion direction occurs for gratings of 2:1 contrast ratio. The lower contrast component is ignored in orientation judgements but exerts a very significant impact on motion direction.

Subject FT's motion data, which lie almost entirely outside of the angle between the two components, are strongly deviated towards the rigid direction; the motion judgments are completely different from the orientation judgments. A similar data pattern was observed for this subject in Experiment 2 and interpreted as showing a residual influence of third-order motion even at these high temporal frequencies. In Experiment 2, with components of 30 and 15 Hz, this subject show the same data pattern as did the other subjects at 20 and 10 Hz. Two points of the Experiment 2 motion judgments are plotted in Fig. 12D. These points are quite similar to the equivalent points for the other subject. Again, the big difference between the very high temporal frequency motion judgments and the orientation judgments occurs when the plaid components have a 2:1 contrast ratio.

It was noted above that orientation judgments cannot be the main contributer to motion-direction judgments because orientation is independent of component temporal frequency. This is illustrated in Fig. 12C and 12D, where motion direction judgments change tremendously as temporal frequency changes even as orientation remains invariant. At the highest temporal frequencies, when only the first-order motion system is activated, the perceived motion and perceived orientation differ greatly as a function of the contrast of the plaid components. The independence of perceived static pattern orientation and motion temporal frequency, and the difference between perceived pattern orientation and perceived motion direction as a function of component contrast ratio suggest a minimal role for perceived pattern orientation in judgments of plaid motion direction.