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

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Abstract

A plaid is the superposition of two sinewave gratings that move independently in different directions, with different speeds and contrasts. Five themes: 1. The components of velocity, direction and speed, are computed separately in early stages of motion processing; the focus here is exclusively on direction. 2. Procedure demonstration: When most stimuli occur in a restricted range of directions, the perception of direction is distorted, therefore motion stimuli must occur in random directions, 0-360deg . 3a. There are three different early motion computations: When only first-order system is stimulated (temporal frequencies =10Hz 2 Ss, 15Hz 1 S), over the entire range of visible contrasts, the contrast ratio of the two plaid components completely determines perceived direction. (b) Each component sine wave is represented as a vector: direction (perpendicular to the sinewave stripes), and length (a factor ρ representing the relative effectiveness of that temporal frequency times contrast to a power $\beta \approx 2$). Perceived direction is determined by contrast-strength vector summation, velocity is irrelevant. (c) Once the β and ρ for a subject have been determined for a particular set of plaids, all with the same component angle, the same parameters predict 97% of the variance of new data with plaids composed of a full range of possible angles. 4. For slow (1&2Hz equal-high-contrast plaids, exclusively third-order motion is perceived –movement in the direction of rigid translation (pattern direction, intersection of constraints). At intermediate contrast ratios and temporal frequencies a combination of 1st & 3rd order motion is perceived. (Second-order motion is irrelevant for these plaids). 5. A purely theoretical, zero-estimated-parameter theory that embodies the above principles, captures the essence of the full range of the data for same-temporal-frequency plaids.

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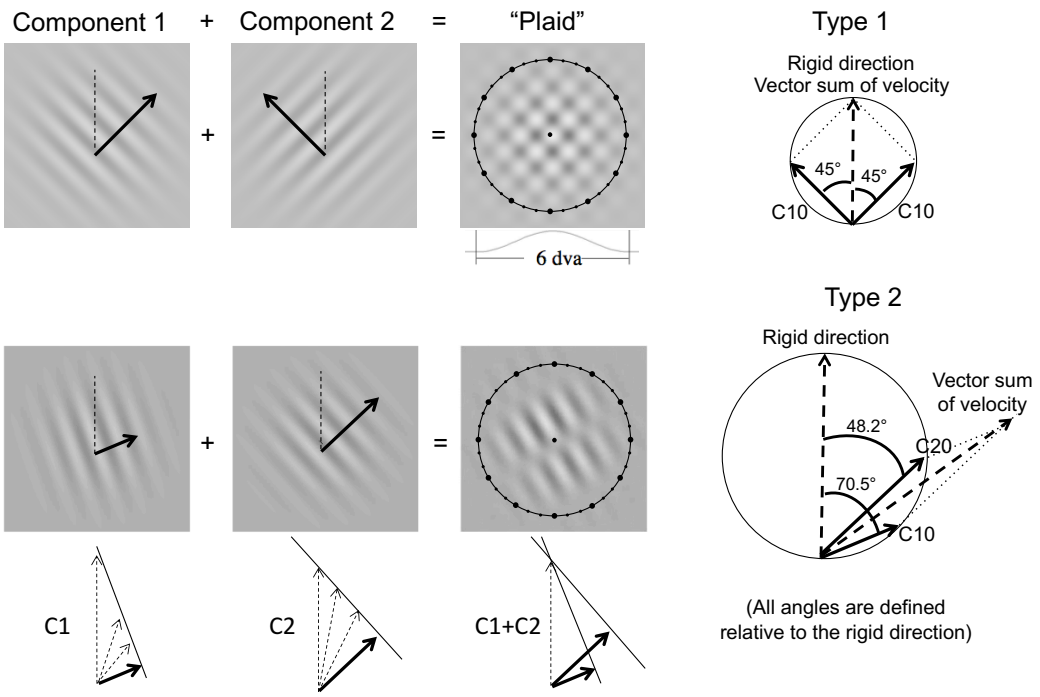

Figure 1: The Type 1 and Type 2 plaid stimuli and their components used in these experiments. Top row: Type 1 Plaid. Top left: A single frame (snapshot) of Component 1, a 1 cycle per degree (cpd) sinewave with 30% contrast modulation around the mean background level that moves upward to the right within a Gaussian window ($\sigma = 2.0$ degrees of visual angle). The temporal frequency was 10.6 Hz resulting in a speed of (10.6 Hz)/(1 cpd)=10.6 deg/sec. Component 2 moves upward to the left with the same parameters as Component 1. "Plaid" is the algebraic sum of Components 1 and 2. The moving plaid appears within a circle of 6 deg diameter with a central fixation spot intended to control fixation, vergence, and accommodation. The ticks on the circle help the trained subjects to indicate the direction of perceived movement in degrees (0,...,359). The rigid (aka pattern, intersection of constraints) direction is represented by the dashed arrow in Type 1 diagram. The rigid direction was randomly varied from trial to trial between 0,...,359 deg. The labels C10 and C20, respectively, indicate Components with temporal frequencies of of 10.6 Hz and 21.2 Hz, respectively. Middle row: Type 2 plaid. The Components' arrows represent velocity (direction-and-speed). Bottom row. (C1,C2) The vectors indicate the range of velocities consistent with each of the Type 2 components. (C1+C2) The geometric construction of possible velocities consistent with each component (the intersection of constraints) shows that one, and only one, pair of component velocities is consistent with a rigid translation of the plaid pattern. See text for details.

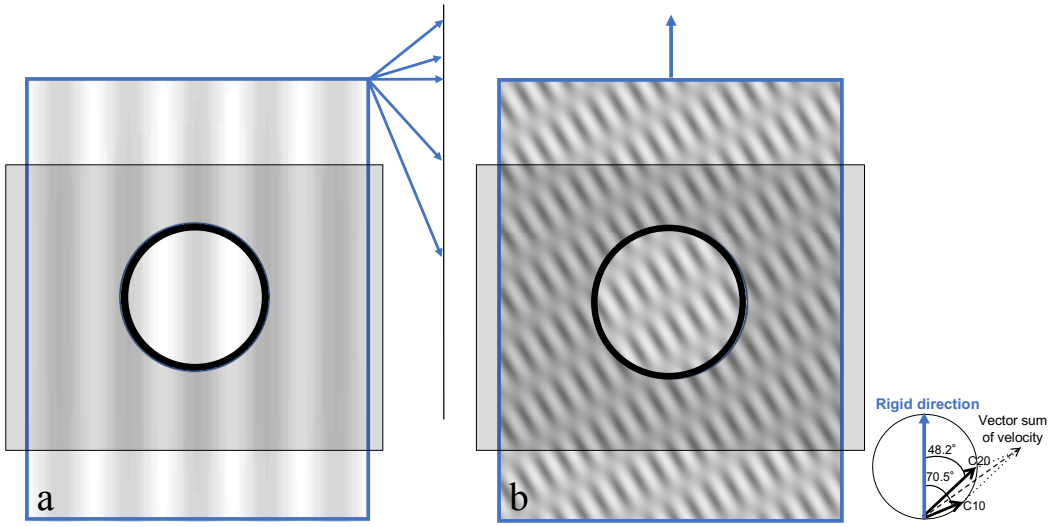

Figure 2: Rigid motion direction defined: All motions of sinewave gratings and of plaids (pairs of sinewave gratings) can be produced by viewing a moving snapshot of the grating or plaid through an aperture. (a) A sinewave grating. The arrows indicate velocities (directions and speeds) of motions of the rectangular picture that would produce identical image sequences within the circular aperture. Therefore, the physical direction of motion of a sinewave grating is inherently ambiguous. (b) The Type 2 plaid used in the experiments. When the two moving sinewave grating components of a plaid are nonparallel, there is a unique direction and velocity of the snapshot of the plaid (the rigid direction) that within the window reproduces exactly the two different velocities of the component gratings. The black arrows in the insert show the velocities of the plaid component sine waves; the dotted arrows show the rigid direction and and the vector-sum-of velocities direction. Although a brief view of a moving plaid is logically sufficient to define the rigid direction, i.e., the direction in which the snapshot of the plaid is moving, the rigid direction usually is not the perceived direction of motion.

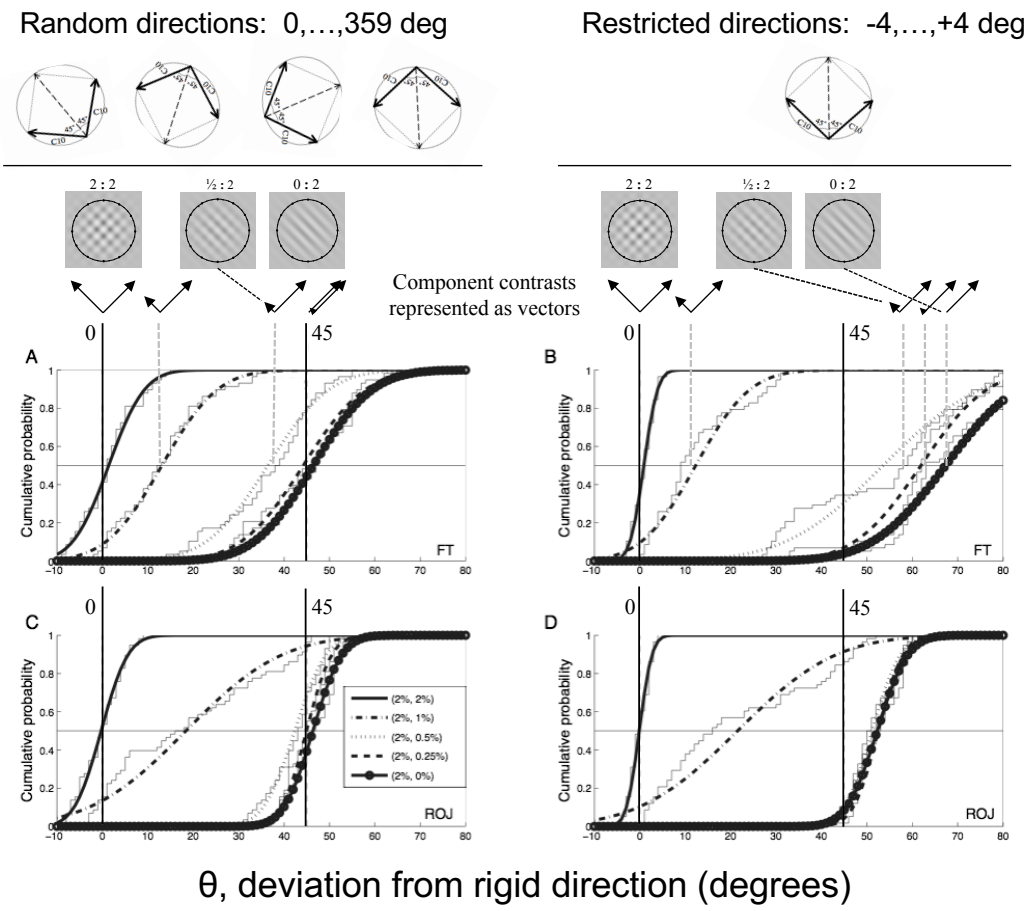

Figure 4: Experiment 1. Cumulative histograms of the judged directions of plaids in which the direction of rigid motion varies randomly between (0, 359) deg or between (-4, +4) deg. Thumbnail images represent 3 of the 5 combinations of component contrasts. The illustrated contrasts, about 30%, are much higher than the presented contrasts (max = 2%). Below the thumbnail stimulus images, the contrasts of the components are represented as vectors: Vector direction represents component direction, vector length represents component contrast. The numbers 0, 45 and the corresponding vertical lines represent the only two stimuli whose physical directions and judged directions are expected to coincide within measurement error, as they indeed do in the (0,359) deg but not in (-4,+4) deg paradigm. (A) (B): Data from subject FT. (C) (D): Data from subject ROJ. In each panel, the abscissa indicates the direction of motion θ relative to the rigid direction; the ordinate indicates the cumulative probability that a judged direction is greater than θ. Jagged curves indicate raw data, smooth curves indicate Gaussian fits. The five curves–some overlap completely–represent the five contrast ratios of the stimulus components. All directions are relative to the rigid direction, which is represented here as vertical, upwards. See text for details. Single-component plaid directions (pure sine waves) are judged correctly for the (0, 359) deg conditions (A and C) but incorrectly for restricted directions (-4, +4) deg conditions (B and D). For contrast ratios of 8 or greater, the lower contrast component is ignored.

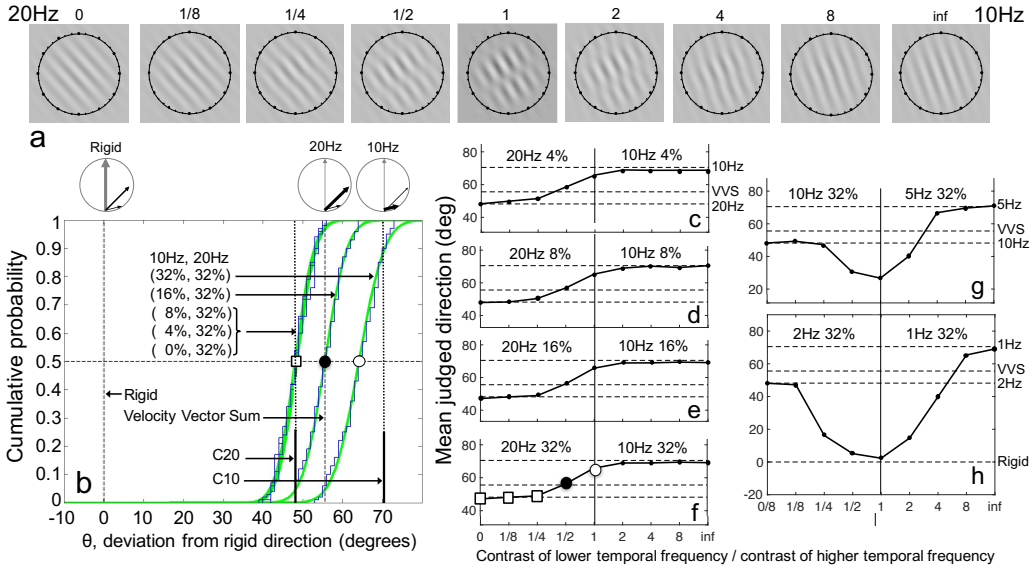

Figure 5: Stimuli and results for one subject in Experiment 2: Judged direction of randomly oriented Type 2 plaids as a function of the contrasts and temporal frequencies of the components. (a) The 32% contrast set of 9 stimuli and the contrast ratios: (lower temporal frequency)/(higher temporal frequency). (b) Cumulative histograms of direction judgments for plaids with five different component contrast ratios. Abscissa: Judged direction θ relative to the rigid direction. The angles of the two component gratings (48.2 deg, 21.2 Hz; 70.5 deg, 10.6 Hz) and the rigid direction (0.0 deg) are represented as dark arrows in the diagrammatic thumbnails above vertical dotted lines that extend to the abscissa. Ordinate: Cumulative probability that the judged direction of motion is greater than θ. Three cumulative Gaussian curves overlie the five data sets. Data for plaids with contrast ratios 0/32, 4/32, and 8/32 are all equivalent and are all fit by the same Gaussian curve. The Point of Subject Equality (PSE) is taken as the angle where the cumulative probability is 0.5 which, for the smallest three contrast ratios, corresponds almost exactly to the direction of the 20.2 Hz grating (indicated as C20). The PSEs are indicated by different symbols, and are again represented in panel (f). (c-h) Each panel exhibits motion direction judgments for 9 plaids of different contrast ratios. All plaids in a panel have the same pair of component temporal frequencies and same maximum contrast. The temporal frequency that owns the maximum contrast in each half of the graph is indicated. VVS is the direction of Velocity Vector Summation of the plaid components; Rigid is the direction of rigid translation; both are independent of the contrast ratio. Whereas the temporal frequencies in panels c-f are 10 and 20 Hz (pure first-order stimuli), plaids with equal-contrast components of 1 and 2 Hz stimulate pure third-order motion precisely in the rigid direction.

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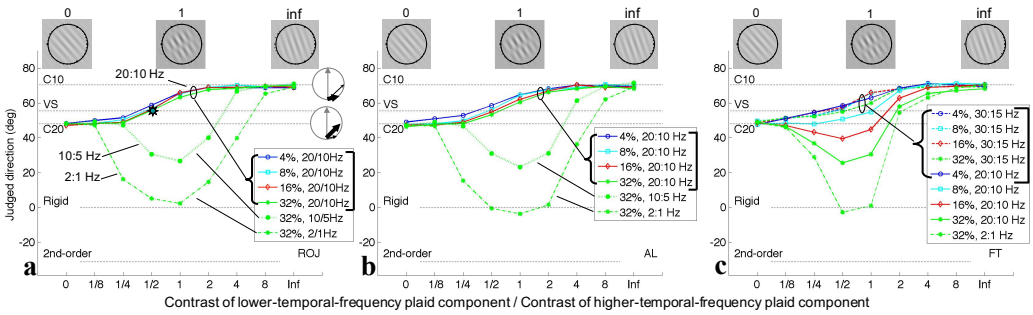

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Figure 6: Judged directions of randomly oriented Type 2 plaids as a function of the contrast ratio and temporal frequencies of the components, data for 3 subjects. The three thumbnail images above each panel illustrate the two pure sinewave stimuli and the plaid with equal-contrast components. The parameters of each condition, maximum contrast, temporal frequencies of the components, are indicated directly in the panels. The. horizontal lines labeled C10, C20 represent the directions of these components in 10,20 Hz plaids, and the directions of the slower, faster component for plaids composed of other temporal frequencies. VS is the direction of the velocity Vector Sum of the plaid components; Rigid is the direction of rigid translation; Second-order is the direction of the strongest Second-order motion component; none of these depends on relative contrast, all are indicated as horizontal lines. At temporal frequencies sufficient high to bypass the third-order system (20Hz,10Hz panels a,b; 30Hz,15 Hz panel C), the judged directions of the four stimulus sets of different contrasts lie on top of each other within measurement error. The judged direction of pure first-order plaid motion depends only on the contrast ratio of the components and is independent of the absolute values of the contrasts over the full range of contrasts. Lower temporal frequencies admit contributions of third-order motion processing (in the direction of rigid translation) to judged motion direction See text for details.

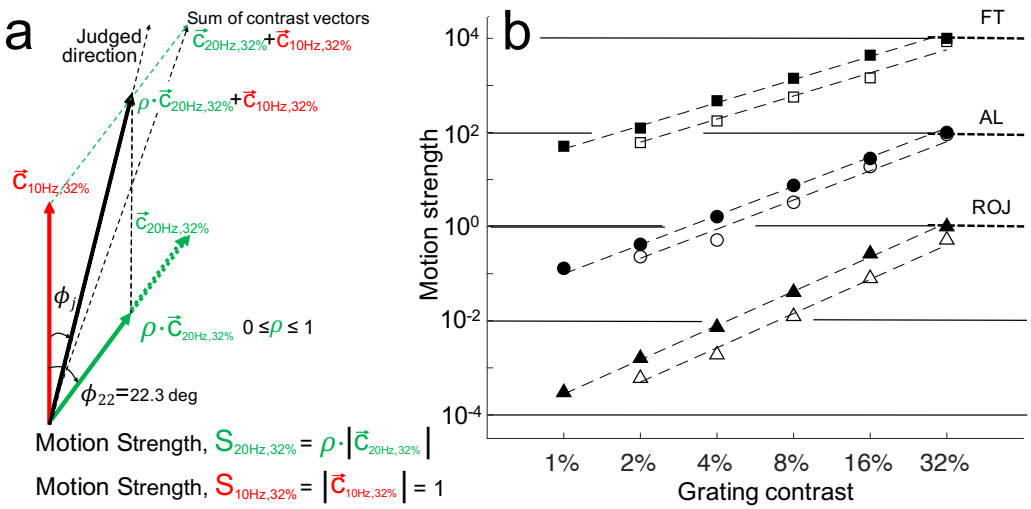

Figure 7: The vector-sum-of-motion-strengths model and the result: Motion strength is a power function of stimulus contrast. (a) Estimating the relativer motion strength S of the two components of a plaid from the plaid's judged direction. Plaid components are represented as vectors that have a direction equal to the direction of the component sinewave and a length proportional to its contrast. Both plaid components have a spatial frequency of 1 cpd and a contrast of 32%. Component 1, $C_{10,32}$, has a temporal frequency of 10 Hz and moves directly upward; Component 2, $C_{20,32}$, has a temporal frequency of 20 Hz and moves at an angle of ϕ_{22}=22.3 deg relative to component 1 (as in the Experiment 2). If the components were of equal strength $|C_{32,10}| = |C_{32,20}|$, then the vector sum $|C_{32,10}| + |C_{32,20}|$ would lie on a direction $\phi_{22}/2$ exactly between the two components. However, the judged direction $\phi_j < \phi_{22}/2$. The geometric construction in (a) shows that, if the contrast of the 20 Hz component were reduced by a factor ρ, $\rho < 1$, the vector sum $C_{10,32}$ $+\rho C_{20,32}$ would indeed match the judged direction. Component 2, $C_{32,20)}$, is a vector, its motion-strength $S_{32,20}$=$\rho|C_{20,32}|$ is a scalar. The strength of the strongest stimulus in the experiment $|C_{10,32}|$ is arbitrarily defined as 1.0. The geometric construction enables estimation of the relative strength ρ of any two components, and the estimation of the absolute strength strength of component 2 whenever the absolute strength of component 1 is known. (b) Motion strengths of the Type 2 plaid stimuli of Experiment 2 derived from motion-direction judgments by the vector-sum-of-motion-strengths model (a) . The ordinate represents the strengths of the grating components for subject ROJ. For clarity, motion strengths are translated upward by two log_{10} units for subject AL and four log_{10} units for subject FT. Filled dots indicate 10 Hz gratings (subjects ROJ, AL), 15 Hz (FT); Unfilled dots indicate 20 Hz gratings (subjects ROJ, AL), 30 Hz (FT); The straight lines are least squares best fits to the data, they are constrained to have the same slope for all data from a subject; they account for 99% of the variance, and they represent power laws with exponents of approximately 2 (see text for details). Only plaid components with estimated motion strengths that differed significantly from zero-strength are shown and incorporated into the data fits.

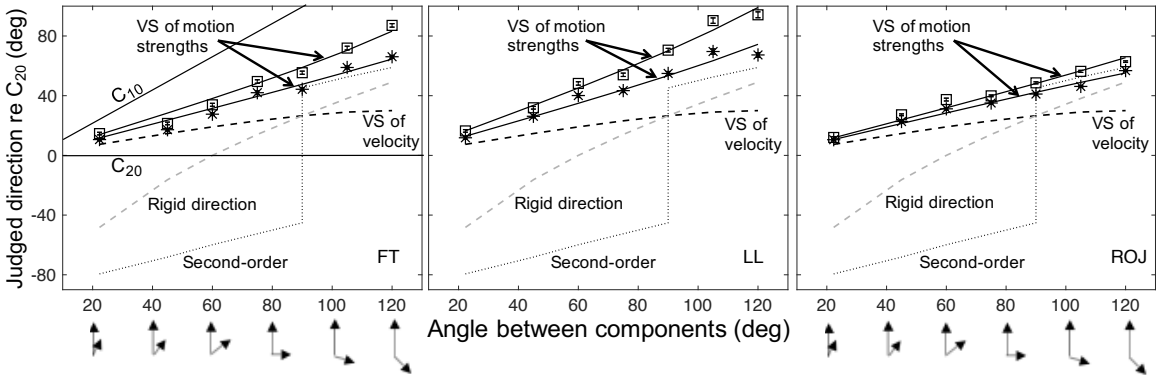

Figure 10: Predicted and perceived directions of randomly oriented plaids as the angle between the component gratings is varied. Each panel represents data points from one subject plus 5 continuous curves representing theoretical predictions of 4 theories. As in Experiment 2, one grating component of the plaid has a temporal frequency of 20 Hz, the other 10 Hz; the contrasts of the data points are: squares (C20,4%; C10,4%), asterisks (C20,4%; C10,2%). The abscissa indicates the angle between the components and illustrates the configuration, the longer vertical arrow is the 20 Hz component. The ordinate indicates the judged motion direction relative to the direction of 20 Hz grating. The two uppermost curves are the a priori predictions of motion direction based on the Vector Sum of the motion strengths of the two plaid component gratings using the relative motion strength ρ from Experiment 2 (for subjects FT and ROJ) and a ρ estimated only from 20 deg data for a new subject LL. The a priori predictions account for over 97% of the variance of the data for both conditions for each subject. Also shown are the predictions for Vector Sum of velocities, Rigid direction, and the direction of Second-order motion. The direction of Second-order motion flips 90 deg as the angle between the gratings changes from 89 to 91 deg; the strength of Second-order motion approaches zero as the angle between the gratings approaches 0 or 180 deg. The direction of rigid motion is undefined for parallel gratings (angle = 0 or 180). The solid straight lines (left panel only) show the directions of the plaid components C_{20}, C_{10}.

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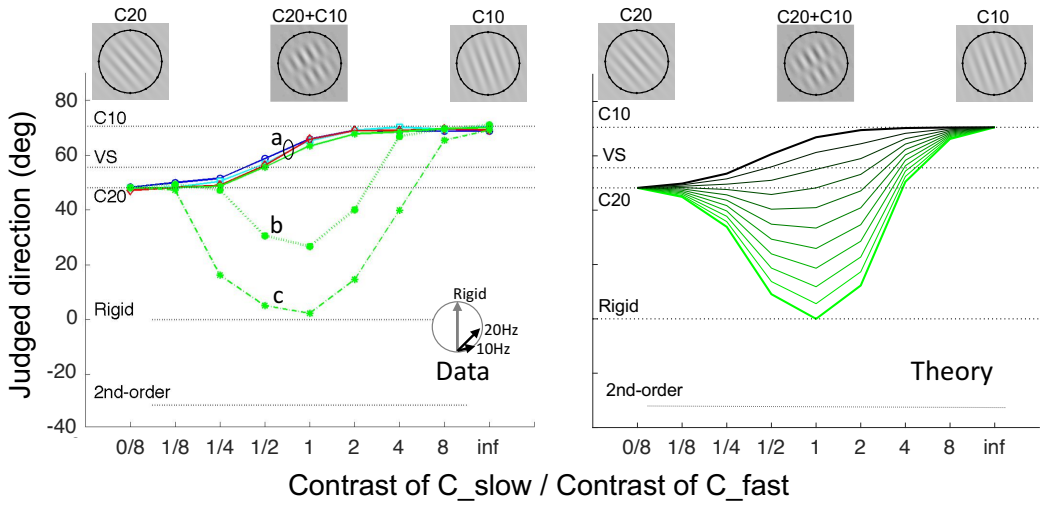

Figure 12: Data and theory for one subject judging the motion direction of Type 2 plaid stimuli as a function of the contrast ratio of the component sinewaves (abscissa) with overall contrast and temporal frequency as the parameters. Data are reproduced from Fig. 6a (above). Ordinates: Data: Judged plaid motion direction relative to the rigid direction; Theory: Predictions of judged motion direction. The horizontal lines labeled C10, C20, represent the angles (relative to rigid direction) of the 10, 20Hz sinewave components. VS represents Vector Sum of their velocities. Second-order represents the direction of second-order motion, The direction of rigid translation was varied randomly from 0, 359 deg; all angles are given relative to the Rigid direction. Component sine waves were 1 cpd; the insert in the Data panel indicates the plaid's rigid direction and the velocity vectors of the two component sinewaves. The curve parameter (a) indicates component frequencies 10Hz+20Hz, and 4 overlapping curves with the contrast of the higher-contrast component = 32, 16, 8, and 4%; the perfect overlap of the four curves means that only the contrast ratio matters. (b,c) indicate higher-component contrast of 32%; component frequencies (b) are 10Hz+5Hz, (c) 2Hz+1Hz. (Theory) Predictions of the one-parameter-alpha-theory as α (the proportion of third-order motion processing versus first-order) varies from 0 (pure first-order motion, top) to 1 (pure third-order motion, bottom).