Supplemental Data: Kinesthetic information disambiguates visual motion signals

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Supplemental Results

Data analysis

We modeled subjects' judgments of motion direction as resulting from a mixture of strategies - on some trials subjects reported a weighted average of the grating normal direction and the hand movement direction and on other trials they reported the motion direction associated with one of several features in the stimulus. For trials with circular apertures, this was simply the grating normal direction. For trials with square apertures this could have been the direction of one or another of the terminators along the edges of the aperture (± 45° from the grating normal direction) or the grating normal direction itself. The model assumed that the distribution of responses on trials in which the subjects used a specified strategy was a wrapped Cauchy distribution $WC(\bar{r},\varphi)$, where $\bar{r}$ represents the median reported angle and φ represents the quartile of the distribution. This distribution is given by

$$WC(r \mid \bar{r},\varphi) = \frac{1}{2\pi}\frac{1-\varphi^2}{1+\varphi^2-2\varphi\cos\{r-\bar{r}\}} \tag{1}$$

Since we assumed that subjects could use any one of a set of strategies, our model for the distribution of subjects' judgments was a weighted sum of wrapped Cauchy distributions – one for each strategy employed by the subject

$$p(r|h,v) = \sum_{i=1}^{n}\pi_i WC(\bar{r}_i(h,v),\varphi_i),$$

where r is the reported motion direction, h represents the hand movement direction, v represents the grating normal direction, i indexes the different strategies that a subject could use to make their judgment and π_i is the probability that the subject uses a given strategy on a trial. The hand movement angle h was given by the slope of a least-squares regression line fitted to the recorded cube positions. A trial was discarded if the root of the mean squared error of the fitted line was greater than 3 mm. The mean and standard deviation of the percentage of discarded trials of all 16 subjects were 29.6% and 20.2%.

The median reported direction for each strategy is a function of the hand movement and grating normal directions, h and v. We modeled four possible strategies that subjects could use – They could report the grating normal direction ($\bar{r}(h,v) = v$), the motion direction of terminators along the aperture boundary 45° clockwise from the grating normal direction ($\bar{r}(h,v) = v - 45$) (for square aperture stimuli), the motion direction of terminators along the orthogonal boundary ($\bar{r}(h,v) = v + 45$) (for square aperture stimuli) or a direction between the hand movement and grating normal directions. To specify this direction, we applied a generalized linear model to subjects' motion direction judgments. Let $\mathbf{h} = e^{ih}$ and $\mathbf{v} = e^{iv}$ be unit length complex numbers representing the hand movement angle h and the grating normal angle v. The mean of the associated wrapped Cauchy distribution was given by $\bar{r} = \arg[w\mathbf{h} + (1-w)\mathbf{v}]$. The reported angle was on the line defined by the two points $\mathbf{h}$ and $\mathbf{v}$, with the coefficient w measuring how close the reported direction was to the hand movement direction.

Considering that any individual subject could employ any combination of the strategies described above, we fit subjects' data using each of the 15 (2^4-1) models generated by considering all possible combinations of strategies. For each subject, we selected the best model with AIC scores. For no subject was a model containing more than two strategies ever chosen as the best fitting model. Fig. S1A and Fig. S1B show 7 of the 8 subjects' reported motion directions in Experiment 1 as a function of the hand movement direction in trials with circular apertures (Fig. S1A) and square apertures (Fig. S1B). The remaining subject exhibited very high variance in the motion judgments, as occasionally happens with naïve subjects, and the data were not included in analysis. The icon on the top left corner in each plot shows the selected model with AIC scores. All seven subjects in the circular aperture condition appeared to use a strategy in which judgments were a weighted average of hand movement and grating normal direction. Subjects in the square aperture condition showed much more variability in the combinations of strategies used. Fig. S1C shows the influence of the kinesthetic signal from the hand movement on subjects' judgments for the component strategy that integrates kinesthetic and grating normal directions signals (the weight, *w*, in the weighted average). We set this to zero for the one subject (Subject 5) whose data were best fit by a model in which the grating normal strategy was the only one used.

Fig. S2 shows the results in Experiment 2. The influence of kinesthetic information of 7 subjects is close to 0, indicating the motion judgment was dominated by the visual signal. Subject 16's perceptual reports were quite different from the other seven subjects in that experiment and showed strong modulation from the hand movement. We suspect that his choice of hand movement directions, which mostly were concentrated around four distinct directions (Fig. S2C), might have maintained the kinesthetic modulation, which would otherwise be weakened by the delay. A similar concern applies to Subject 15 and Subject 3 in Experiment 1 (Fig. S1D), but the other subjects distributed their hand movements more broadly over the range of possible motions in Experiment 1.

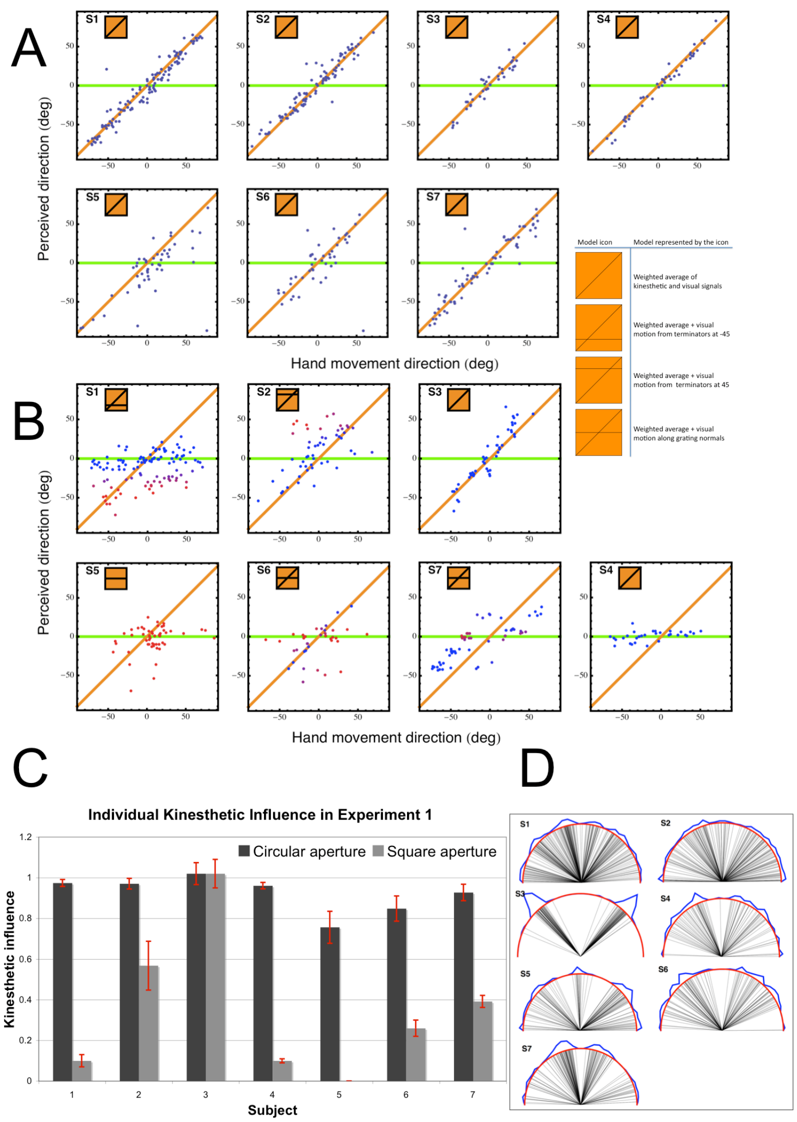

Figure S1. Results of individual subjects in Experiment 1. (A-B) Subject's perceived motion directions as a function of hand movement direction in the trials with circular apertures (A) and square apertures (B). The angles are normalized with regard to the grating normal directions—zero degrees would correspond to a perceived motion direction perpendicular to the gratings. The icon on the top-left corner shows the selected model of each subject. (C) Kinesthetic influence of the trials with circular and square apertures, respectively, in Experiment 1. Error-bars are 1-SE. (D) Histograms of subjects' hand movement directions in Experiment 1. Each radial line represents the direction in one trial.

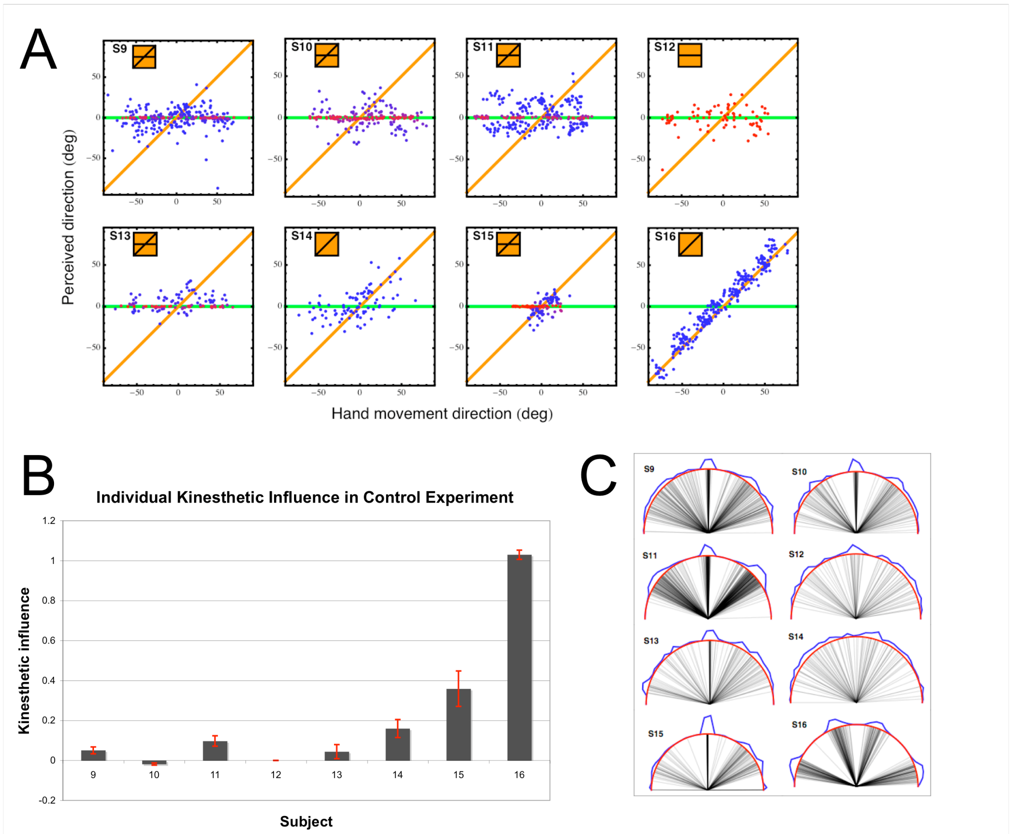

Figure S2. Results of individual subjects in Experiment 2. (A) Subject's perceived motion directions as a function of hand movement direction. (B) Kinesthetic influence in Experiment 2. Error-bars are 1-SE. (C) Histograms of subjects' hand movement directions in Experiment 2.

Supplemental Experimental Procedures

Apparatus and display

All experiments were performed with a calibrated virtual display system (Fig. 1A). Subjects held a 1-inch wide and 0.5-inch thick metal cube with their thumb and index finger and moved it on a fronto-parallel tabletop. Square-wave grating patterns (0.5 cycles/degree) were rendered on a CRT screen (resolution 1280x1024 and refresh rate 120 Hz) and viewed through a mirror so that the grating patterns appeared in a virtual plane that co-aligned with the top of the cube. The orientation of the gratings was randomly chosen from (0,40,80,120,160) degrees in each trial.

Subjects viewed the stimuli binocularly with CrystalEye LCD shutter glasses (RealD, CA). A 12-degree aperture was rendered such that it appeared on the plane 10 mm above the grating pattern. The aperture plane was textured with random dots (0.2 degrees in diameter with density 2 dots/degree.) The gratings and the random dots were drawn in red to take advantage of the fast decay time of the red phosphor of the CRT display. The luminance of the bright stripes was 15.1 cd/m^2 and that of the dark stripes was less then 0.002 cd/m^2. The luminance of the dots was 7.91 cd/m^2. The cube was tracked by an Optotrak 3020 system (Northern Digital Inc., ON, Canada) and its positions were recorded at 120 Hz, which enabled us to update the position of the grating pattern in real time and therefore render the pattern with the same velocity as the hand. We used predictive filtering (Kalman filter on the 3-D position, velocity and acceleration of the cube) to compensate for the 8 ms delay between the computer graphics and the real-time hand movement information from the tracker.

Subjects could not see their hands and the cube during the experiment. The hand movement was physically confined to a 12-degree circle on the table (using a cardboard cutout) in agreement with the visual aperture. This was to ensure spatial congruency of the hand and the visual pattern.

Subjects

Sixteen subjects participated the study, eight in each experiment. All subjects were students of the University of Rochester and naive for the purpose of the experiments. All subjects had corrected vision and had a 5 or higher score of the Randot (Precision Vision, IL) stereo test. All provided informed consent in accordance with the guidelines from the University of Rochester Research Subjects Review Board.

General Procedure

Subjects finished two one-hour sessions in two days. Each session contained 3 or 4 blocks, depending on how fast subjects performed the task. The first block of the first session was treated as a training block and the data were not used for analysis.

At the beginning of each trial, subjects were shown a coordinate system with two quadrants shaded and were asked to choose a random direction within the quadrants to move the block, including the horizontal and vertical axes. Subjects were instructed to choose different directions for each trial. The shaded quadrants were chosen to avoid movement directions parallel to the grating, which would create little visual motion. A trial started when a subject aligned a white dot, which coincided with the center of the top face of the hand-held cube, with the center of the coordinate system. The grating-aperture stimulus then appeared and subjects moved the cube along the chosen direction back and forth for 3500 ms. The gratings were rendered to move at the same velocity (direction and speed) as the hand movement. At the end of the trial, subjects reported the perceived motion direction of the grating pattern by turning a double arrow on the screen with a mouse wheel. A double arrow was used because an angle x and $x+180^{\circ}$ both identified the same direction, the consequence of the back and forth movement.

Four of the eight subjects in Experiment 1 were asked to fixate on a cross (0.4 degrees) at the center of the aperture.

To enhance the causal connection between the visual and hand motion, we randomly inserted unambiguous baseline trials, which had random square dots overlaid on the gratings. A quarter of all trials in each block were baseline trials. All subjects reported seeing the motion along the hand movement directions, which were consistent with the visual motion directions, in baseline trials.