**Supplementary Information**

# A key role of orientation in the coding of visual motion direction

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## S1. Oriented streak signals in visual motion stimuli.

In the present study, we used motion clouds to test whether the observed effect of motion axis orientation is due to motion streak signals that are inherent in the random dot motion stimulus. Thus, it is important to confirm that the motion clouds, unlike the dot motion, do not have the motion streak signals. To this end, we first temporally integrated the image frames of the motion stimuli over 100 ms and linearly normalized the pixel intensities in the integrated images to the 0–1 range. The streak signal of the normalized image was then quantified using oriented filters whose responses were squared and combined over spatial location. The filters were Gabor patches with 90° phase shift (i.e., bar detector; **Fig. S1b**). The size of the filter was twice the length of the oriented streak, and spatial frequency was the inverse of half the length of the oriented streak. This way of designing the filter was based on previous findings demonstrating that the motion streak of a moving dot depends on both the speed and size of the dot (**Fig. S1a**). Previous work has shown that the critical speed for a moving dot to produce an effective motion streak is 1 dot width per 100 ms (Geisler, 1999). Any motion stimuli moving slower than the critical speed only produce edges without streak signals when integrated over time, which would not affect the motion perception (Geisler, 1999). To control for any local orientation signals arising from edges without streak signals, the responses of bar detector filters were then normalized by responses of another set of oriented filters with equal size (edge detector; **Fig. S1c**). These filters were designed such that it has sinusoidal curve at the center with its phase set to zero and its spatial frequency set to be equal to that of the bar detector, but the positive and negative peaks of the sinusoidal curve extend to the end of the filter. We performed this procedure with 100 random dot motion stimuli and 100 motion clouds for each motion direction ranging from 0 to 165° in steps of 15° (i.e., a total of 2,400 stimuli). Orientation of the filters were always vertical. Lastly, we normalized the outputs of this procedure for each stimulus type and shifted them such that the output for stimuli moving in the horizontal direction is centered on zero. We refer to this final outcome as a motion streak index. Positive motion streak index for stimuli moving in the direction parallel to the preferred orientation of the filter would indicate that the stimuli would produce an effective motion streak.
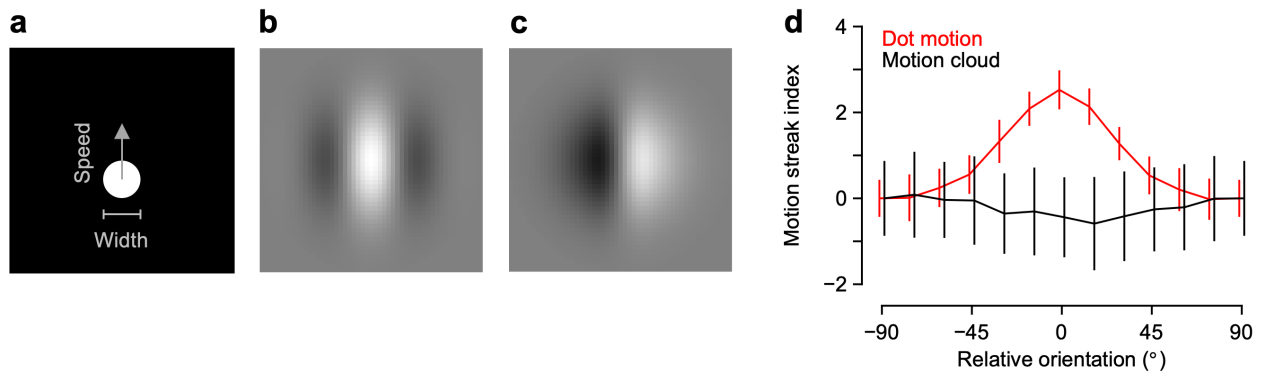


**Fig. S1** Oriented streak signals in the motion stimuli. (**a**) Schematic illustration of a moving dot. (**b**) Bar detector. (**c**) Edge detector. (**d**) Motion streak index for dot motion and motion cloud. Here, the motion streak index was computed using images integrated over 100 ms and oriented filters sensitive to dot size of 4 pixels. Motion streak index of the random dot motion showed a sharp peak at the motion orientation, indicating strong spatial signals of the stimuli, while those of the motion clouds remained relatively constant regardless of the orientation. Error bars represent the standard deviation.

As expected, the motion streak index for dot motion showed a sharp peak when orientation of the motion axis is aligned with orientation of the filter, indicating strong motion streak signals in the stimuli (**Fig. S1d**). By contrast, motion streak index for motion clouds remained non-positive for all orientations, which reflects the lack of predominant spatial signals oriented in the motion axis orientation. For each stimulus type, we computed the probability of choosing the true motion direction (i.e., vertical) among all 12 possible motion directions using only the motion streak index. We performed this procedure 100 times, randomly paring stimuli with different motion directions. The probability of being correct was significantly greater than chance for dot motion (mean ± s.d.: 63.98 ± 2.91%) and no better than chance for motion clouds (4.95 ± 1.63%), when we integrated

the image frames over 100 ms and used oriented filters sensitive to dot size of 4 pixels (**Fig. S1d**). We observed consistent results using all spatial frequencies of filters corresponding to all possible length of motion streak (which is bounded by the stimulus speed) as well as all temporal integration window sizes up to 500 ms.

## S2. Examining the distribution of response errors.

Current study demonstrates the importance of non-directional orientation signals in the coding of visual motion direction. An alternative explanation is that participants sometimes misperceived the motion direction by 180°. This type of motion misperception has been observed in several studies (Bae & Luck, 2022; Glasser & Tadin, 2013; Kwon et al., 2015). To examine this possibility, we analyzed the distribution of response errors (**Fig. S2**). Results showed that in our experiments participants did not show any significant misperceptions of motion direction. One subject in the random dot motion experiment had 198 trials (out of 1,635 trials) with response error within $180 \pm 30°$, another in the motion cloud experiment had 27 trials, and all the others had $\leq 6$ trials. All these trials with opposite direction estimates fell into the criterion of outliers (i.e., response error more than 2.5 s.d. away from the mean response error) and were excluded from main analysis. Crucially, we excluded not only outlier trials but also trials after those outlier trials, eliminating any immediate effects of those misperceived trials.
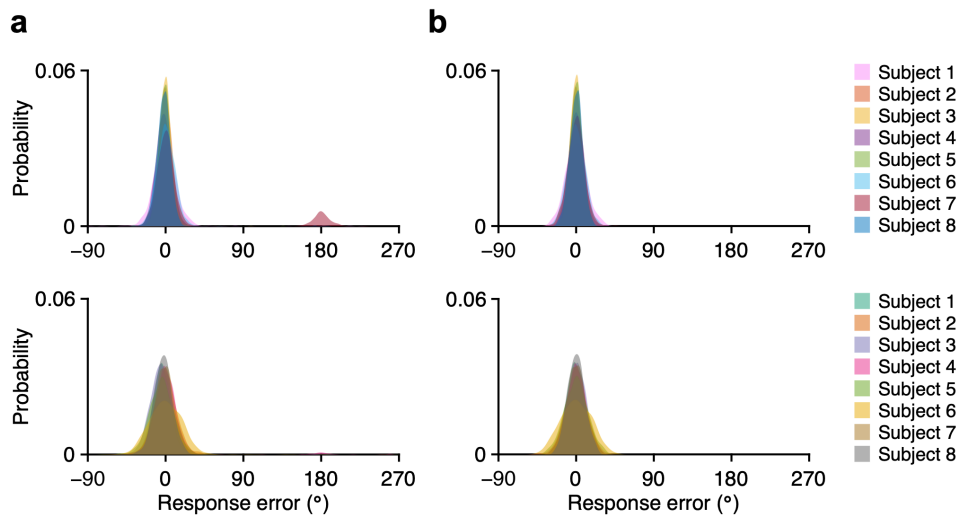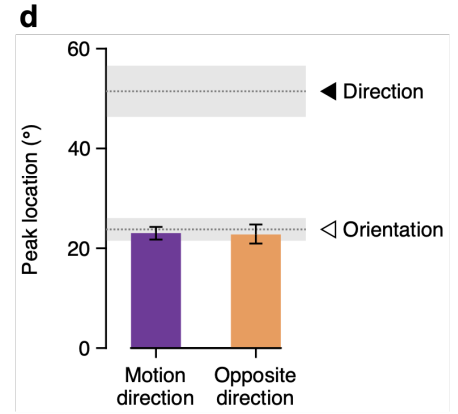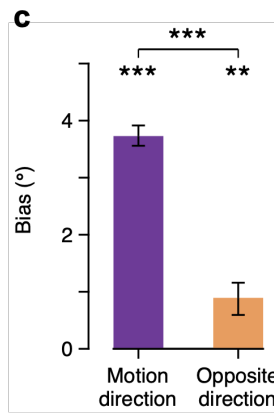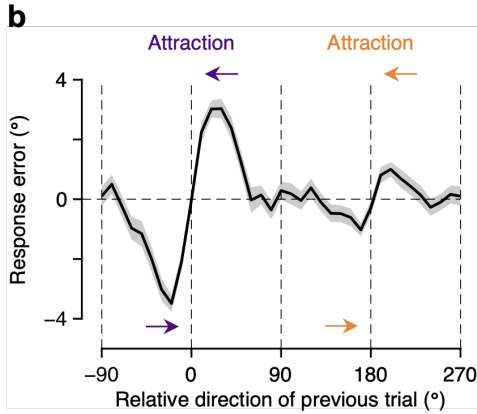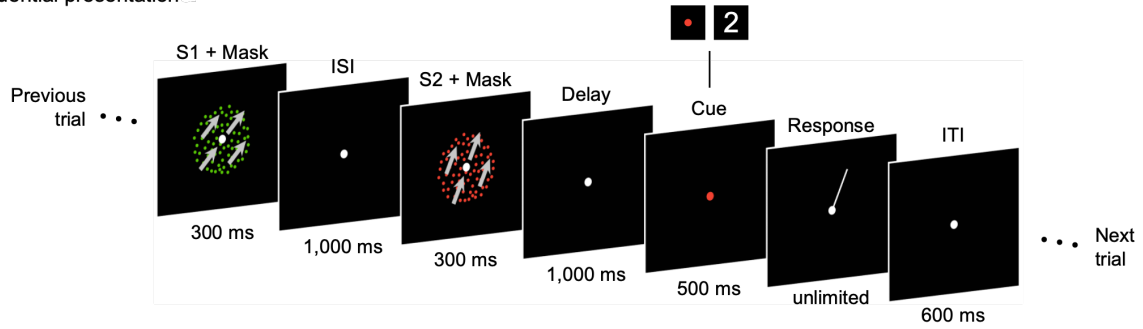


**Fig. S2** Response error distribution in the random dot motion experiment (*top*) and the motion cloud experiment (*bottom*). (**a**) Response error distribution for individual subjects. (**b**) Response error distribution after outlier correction and mean centering.
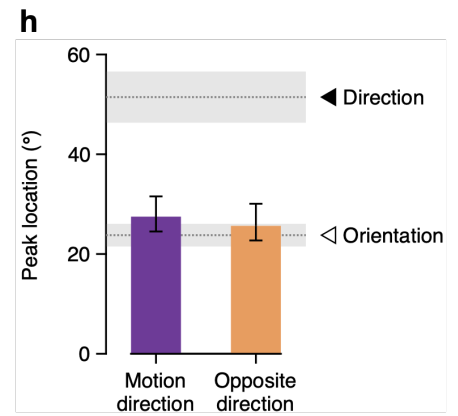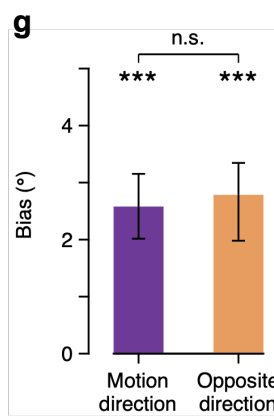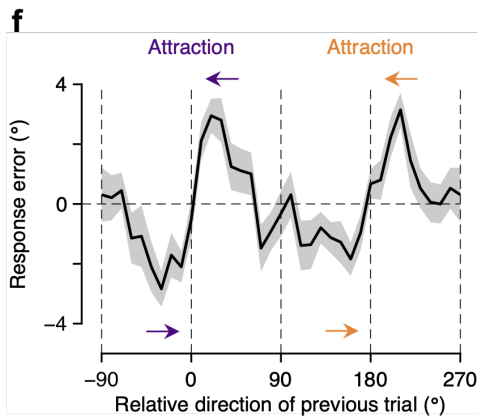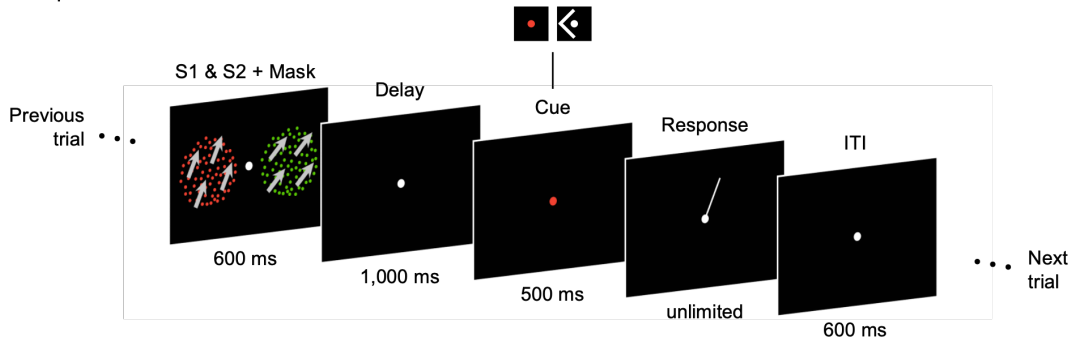
## S3. Generalization of the current results to a qualitatively different experimental paradigm: a secondary analysis of Fischer et al. (2020).

We tested whether the observed orientation effect generalizes to other visual motion estimation paradigms. Fischer et al. (2020) used more complex experimental paradigms involving multiple features and multiple stimuli. Specifically, they presented two random dot motion stimuli to subjects either sequentially (**Fig. S3a**) or simultaneously (**Fig. S3e**) on each trial. After a short delay, subjects were asked to report the perceived motion direction of dots with a specific color or at a specific serial/spatial position within the trial. The results revealed a significant attractive bias only toward the target stimulus on the previous trial (i.e., stimulus that was cued for report on the previous trial), but not toward the non-target stimulus on the previous trial. For more details, see Fischer et al. (2020).

**Fig. S3** Further validation of key results based on a re-analysis of publicly available data from Fischer et al. (2020). (**a**) Sequential presentation paradigm. On each trial, two motion stimuli were presented sequentially, and then one of them was cued for report (i.e., target). The task was to report the perceived direction of target motion. (**b–d**) Experimental results for sequential presentation. Data are analyzed in the same way as shown in **Figures 2** and **3**. (**e**) Simultaneous presentation paradigm. The task was same as in **a**, except that two motion stimuli were presented simultaneously. (**f–h**) Experimental results for simultaneous presentation. Shaded regions represent s.e.m., and error bars represent 68% credible intervals.

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While both sequential and simultaneous presentation paradigms differ significantly from ours, the simultaneous paradigm can be seen as more comparable with ours in that the sequence across trials consists of previous target, previous response, current target, and current response. In contrast, the sequential presentation paradigm is considerably different from ours in that a non-target stimulus (or two) is always embedded among the sequence of previous target, previous response, current target, and current response. Because details of experiments within certain presentation paradigm only differed in context feature that served as a cue to identify the target stimulus, we grouped experiments according to sequential versus simultaneous paradigms to increase the statistical power and re-analyzed the serial dependence on the previous target to test whether there are attractive biases toward the opposite direction of the previous target motion direction as well.

We performed the same data analysis as with our data and plotted the results in **Figure S3**. As reported by the original study, there was a significant attractive bias toward the motion direction of previous target in both paradigms (sequential presentation: 3.66°, [3.29 4.11], $p < 0.001$; simultaneous presentation: 2.58°, [1.48 3.70], $p < 0.001$). For the attractive bias toward the opposite direction of the previous target, we found that the results can be differentiated by the presentation conditions. When the motion stimuli were presented sequentially (**Fig. S3b**), there was a significant attractive bias toward the opposite direction of the previous target (0.86°, [0.26 1.51], $p = 0.007$), albeit the magnitude of bias was significantly smaller than the bias to the direction of previous target (difference: −2.83, [−3.44 −2.18], $p < 0.001$; **Fig. S3c**), suggesting a reduced role of motion axis orientation possibly due to a non-target stimulus embedded among the sequence of events from the previous target to the current target (see **S4** for an additional analysis on the sequential paradigm). On the other hand, when the motion stimuli were presented simultaneously (**Fig. S3f**), we found a significant attractive bias toward the opposite direction of the previous target (2.79°, [1.32 4.02], $p < 0.001$) whose magnitude is statistically comparable with that of the bias to the previous target (difference: 0.06°, [−1.26 1.44], $p = 0.908$, $BF_{10} = 0.235$; **Fig. S3g**).

Peak locations of the attraction profiles provide an additional support for the role of orientation information (**Fig. S3d** and **S3h**). Across both presentation conditions, the peak locations for motion direction (sequential presentation: 23.01°, [20.69 25.75]; simultaneous presentation: 27.49°, [21.62 35.07]) and for opposite direction (sequential presentation: 22.52°, [18.40 26.82]; simultaneous presentation: 25.65°, [19.60 34.10]) were comparable to each other (differences: sequential presentation: −0.20°, [−4.27 2.79], $p = 0.707$, $BF_{10} = 0.472$; simultaneous presentation: −0.69°, [−9.08 5.33], $p = 0.654$, $BF_{10} = 0.560$). Furthermore, both of them were more consistent with the peak location for orientation estimation tasks (motion direction: both $p$s > 0.182; opposite direction: both $p$s > 0.431) than for direction estimation tasks (motion direction: both $p$s < 0.001; opposite direction: both $p$s < 0.001), all in line with our findings. Taken together, these results suggest that subjects still incorporated the orientation information of the motion stimuli, even though they had to form representations of multiple features of multiple stimuli within each trial.

## S4. Sequential effects of non-directional orientation when not having reported the preceding motion direction.

Using the sequential presentation paradigm data by Fischer et al. (2020), we examined the effect of the preceding non-target motion stimulus (i.e., stimulus that was not cued for report) on the following target motion stimulus within each trial (**Fig. S4a**). The angular difference between non-target and target motion direction was uniformly distributed across all available range, except 0 and 180°. We pooled trials on which the second stimulus was the target (**Fig. S4a**) and analyzed response error as a function of angular difference between two sequentially presented motion stimuli (**Fig. S4b**). As expected from earlier studies (Fritsche et al., 2017; Pascucci et al., 2019; but see Fischer & Whitney, 2014; Manassi et al., 2018), we observed a significant repulsive bias in subjects' estimation error when it is conditioned on the previously seen, but not reported, motion stimulus. Importantly, the perceived direction of motion following un-reported motion were not only

repelled away from the preceding motion direction (−2.10°, [−2.97 −1.19], $p < 0.001$) but also from its opposite direction (−3.24°, [−4.77 −1.88]; **Fig. S4c**). This bias away from the opposite direction was even larger in magnitude than the bias away from the motion direction (difference: −1.18°, [−2.44 −0.08], $p = 0.035$), presumably because the peak location for the opposite direction was also larger than that for the motion direction (motion direction: 45.83°, [40.67 52.13]; opposite direction: 63.41°, [54.49 77.70]; difference: 16.90°, [8.90 30.69], $p < 0.001$; **Fig. S4d**). We did not compare the peak locations to those from prior serial dependence studies because these are the peaks of the repulsion profiles, not attraction.
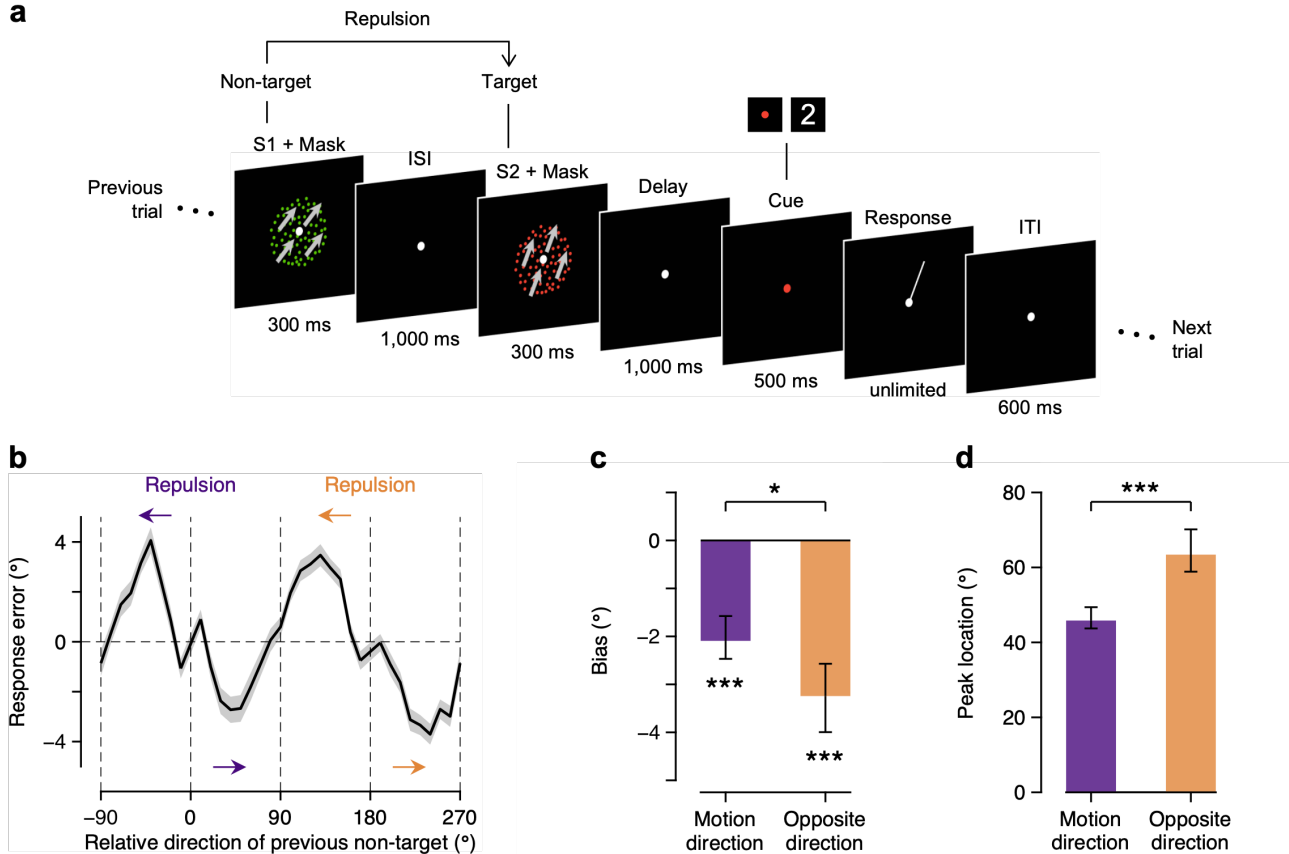


**Fig. S4** A role of non-directional orientation in representing motion in a task that does not require a report of the preceding motion direction. (**a**) An example trial used in the analysis. The task was same as in **Figure S3a**. We pooled trials on which the non-target motion stimulus was presented first, followed by the target motion stimulus. (**b**) Data shows repulsive biases away from the orientation of the previous non-target motion. Response error on the current trial (defined as the reported target motion direction minus the correct target motion direction) is plotted as a function of relative direction of the previous non-target (defined as the previous non-target motion direction minus the current target motion direction). Subjects' responses were not only repelled away from the previous non-target motion direction (0° on the abscissa; purple arrows) but also to the opposite direction of the previous non-target motion direction (180° on the abscissa; orange arrows), resulting in a periodic pattern. (**c**) Magnitudes of repulsive biases in perceived target motion direction away from the previous non-target motion direction and from the opposite direction of the previous non-target motion direction. (**d**) Peak locations of the repulsion profiles. Note that unlike the serial dependence analysis, we did not compare the peak locations with those from prior serial dependence studies, since the present peaks reflect the repulsion profiles. Shaded regions represent s.e.m., and error bars represent 68% credible intervals. Data adapted from Fischer et al. (2020).

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