Supplementary Information:

“Weaker signals induce more precise temporal-integration”

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Supplementary Information

Questionnaire after the main experiment

After the main experiment, I had a short questionnaire to ask the participants for their opinion about the task and stimulus. In addition, I orally communicated with all participants and asked about the experiment itself. As a result, all participant did not report that they saw two motion directions except that two participants reported that motions seems to be rotating in some trials.

Experiment for the threshold of local-motion coherence ratio

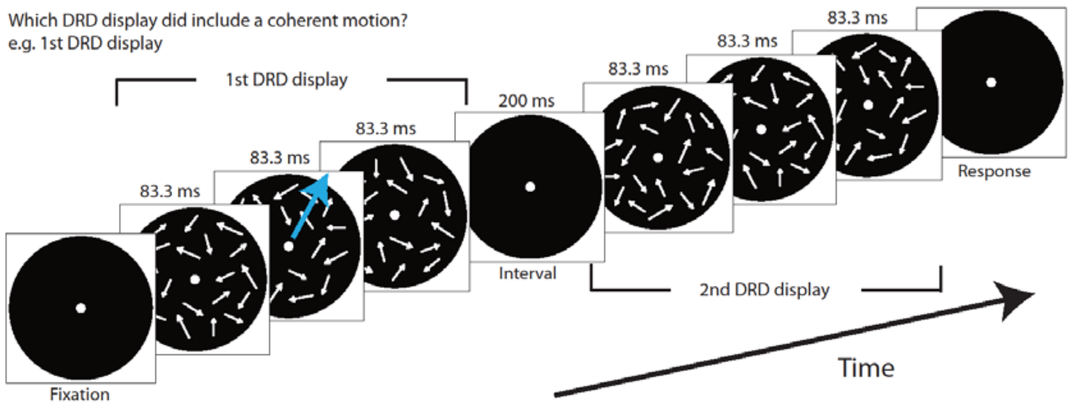

Figure. 1 Design of local-motion threshold experiment without mouse.
Arrows represent motion vectors. The coherent ratios were varied from trial to trial. One coherent motion (blue arrow) was shown between the mask stimuli (0% coherent motions display) in one of two DRD displays. After DRD displays disappeared, the participants reported which DRD display included a coherent motion by pressing a button on a the standard QWERTY keyboard, 1 or 2.

Experiment for the motor error of mouse cursor driven

To test the motor error of mouse driven cursor in the series of psychophysical experiment, I asked some of participants who did the main series of psychophysical experiment to do the extra threshold experiment of local-motion, in which the participants reported the perceived motion direction by rotating a line with a mouse (**Supplementary Information Figure 2**). On each trial the coherence ratio was selected randomly to be 10, 22, 34, 46, or 70%. In a complete experiment, each coherence condition was repeated 80 times, so that a total number of trials was 400. The order of presentation of these conditions was randomly determined for each participant. No accuracy feedback was given to the participants.

To examine how much their responses had motor error in this psychophysical experiment, I calculated how far their responses at 70% coherence ratio condition in the local-motion threshold experiment WITH a mouse were away from the presented direction, because it is assumed that the participants confidently noticed the motion direction at 70% coherence ratio (The accuracy at 70% ratio condition in the local-motion threshold experiment WITHOUT a mouse was significantly above threshold, 85.5 ± 3.6%). The results showed that the motor error at 70% coherence ratio condition with mouse was 5.3 degrees (n = 7), therefore I determined 5 degrees as the motor error of controlling mouse in the series of experiments.

In addition, in order to test the validity of the motor error value, I compared the sigma values of the probability distributions in the local-motion threshold experiment with mouse (the raw data) with the ones determined by 5 degree. On top of that, I compared the sigma values of the probability distributions of the direction in the local-motion threshold experiment with mouse (the raw data) with the ones of the probability distributions in the motion integration experiment (the raw data) only from 10% to 34 % coherences (where the participants successfully made integration according to the results of the model comparison). I found that there are no significant differences between them in both cases. That is to say, the participants' response between a single display and several displays in this study are very similar when assuming the motor error as 5 degree. So, I think that determining 5 degree is not exactly the value of the motor error but quite similar to the value in both cases of estimating the motion direction of single display and estimating the integrated directions of several displays in this experiment.

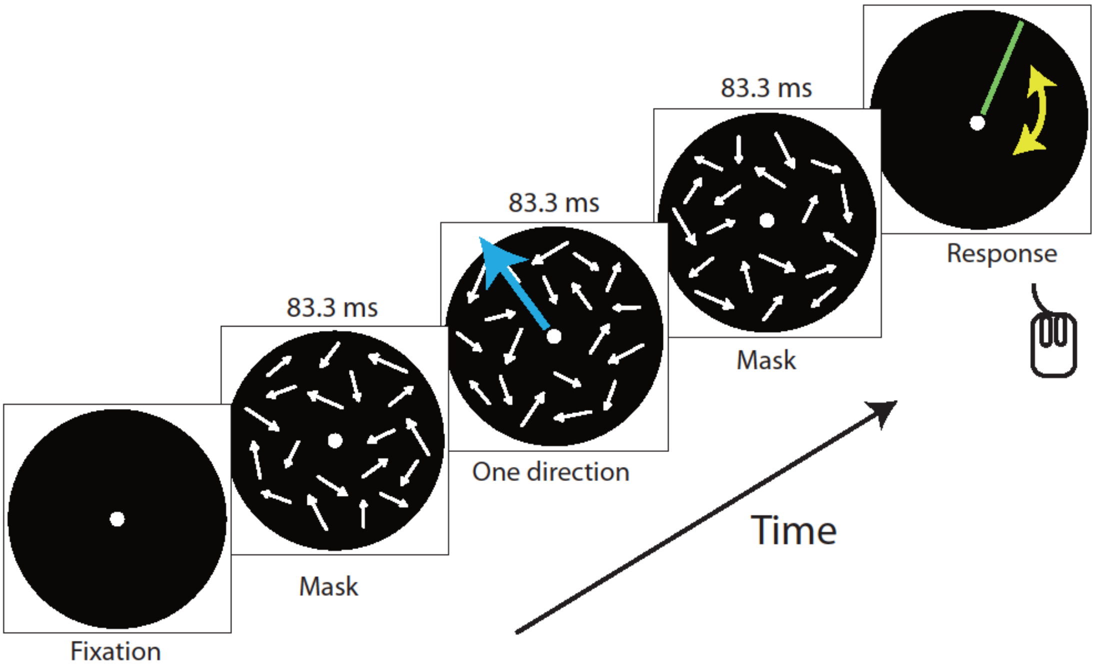

Figure. 2 Design of local-motion threshold experiment with mouse .
Arrows represent motion vectors. The coherent ratios were varied from trial to trial. One coherent motion (blue arrow) was shown between the mask stimuli (0% coherent motions display). After DRD displays disappeared, the participants reported the perceived motion direction by rotating a line with a mouse. By comparing the performance without mouse and the one with mouse, I found the motor error value in this condition.

Supplementary Information of local-motion experiment with mouse

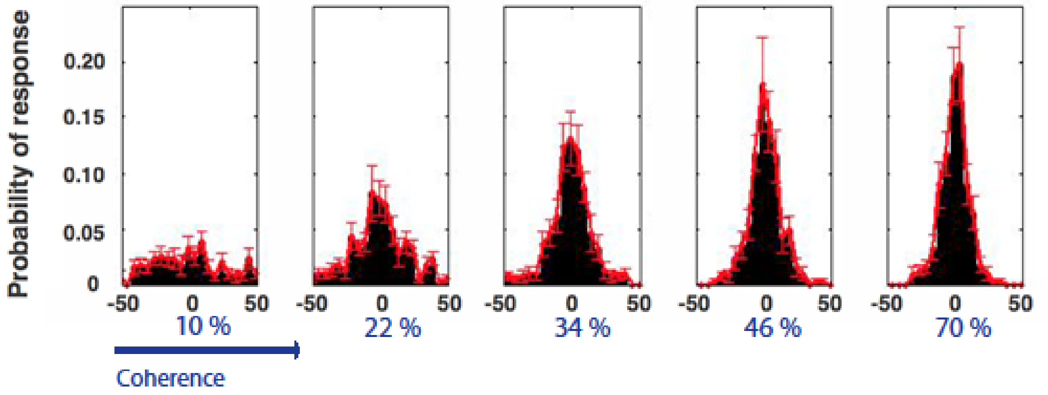

Figure. 3 Mean probability distribution of local-motion perception with mouse
Mean probability distribution of response (n=13, only between -50° to +50°). '0' in the scale of relative direction indicates the direction of coherent motions. Red lines represent the data points of the histogram (The bin size is 5 degrees) of the mean probability of response. Vertical error bars, ± 1 SEM. The result was obviously different from the result of motion integration experiment (Figure 2a in the main manuscript).

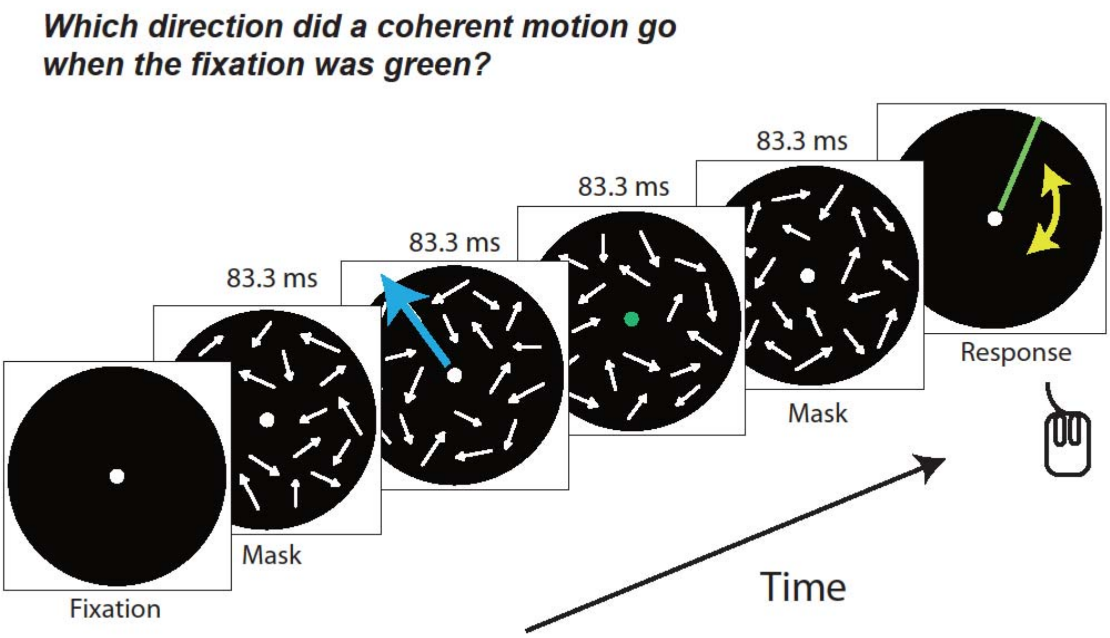

Figure. 4 Design of MAE experiment (MAE test condition).
Arrows represent motion vectors. To test whether or not the participants appropriately reported the perceived motion direction when the fixation was green, in the half of trials, MAE inducer (blue arrow) was shown before the fixation turned to be green (0% coherent motions display) (MAE test condition). In the other half, after MAE inducer was presented, the other directional coherent motions was randomly chosen and presented when the fixation was green (control condition). After DRD displays disappeared, the participants

reported a perceived direction at the time when the fixation was green. The coherent ratios were varied from trial to trial.

Supplementary Information of MAE experiment

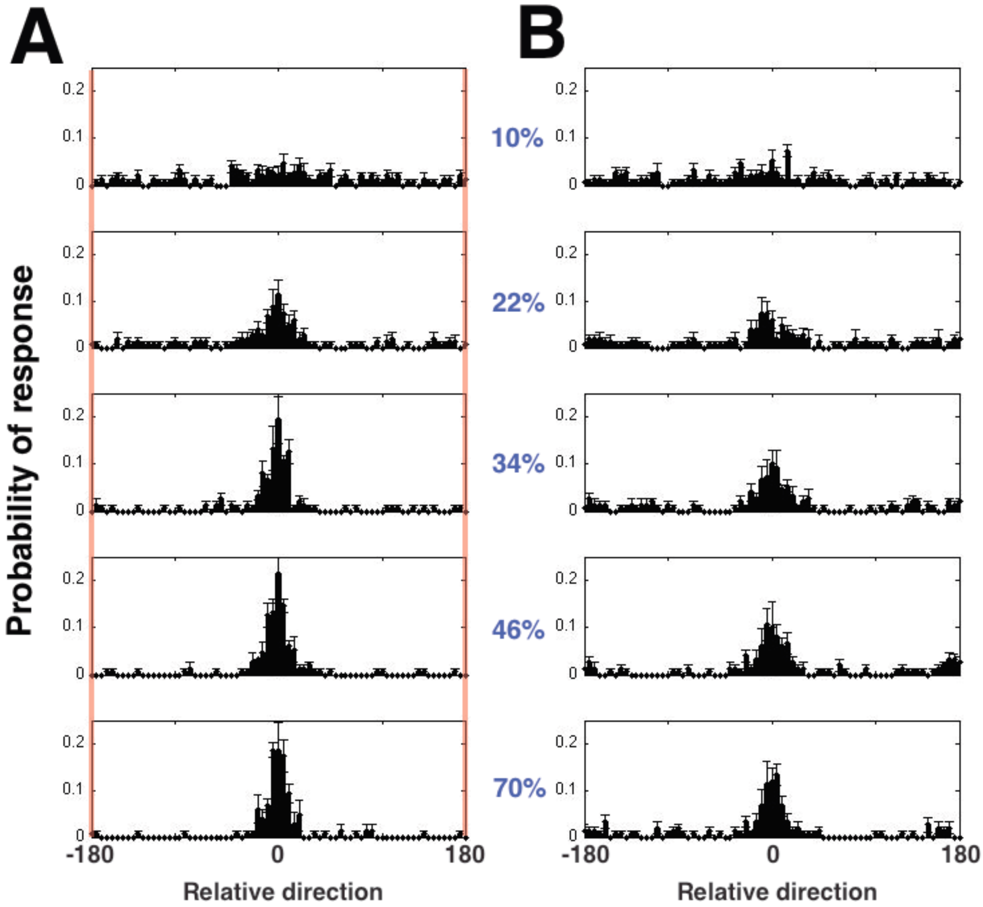

Figure. 5 Mean probability distribution of perceived direction in MAE experiment. Mean probability distribution of response (n=6). **(A)** MAE test condition. '0' in the scale of relative direction indicates the inducer direction. If significant MAE was observed, the probability of response at 180 (or -180) degrees in the relative direction (red lines) would be significantly higher or equivalent of that at 0 degree. However, such result was not obtained in this condition **(B)** Control condition (To test whether or not the participants appropriately reported the perceived motion direction when the fixation was green.). '0' in the scale of relative direction indicates the direction of coherent motion presented at the time when the fixation was green. If the participants could not report the perceived direction when the fixation turned to be green (e.g. they just reported the perceived direction right before when the fixation turned to be green, or they reported the global motion direction that combined the direction when the fixation was green, with the inducer direction.), the results showed something significantly different from the results of other local-motion threshold experiment, such as Figure 3 in Supplementary Information. However, such result was not obtained here.

Integration and non-integration models compared

The behavioral results provided the evidence that participants are more likely to respond as if the motion directions were integrated into a single, the averaged direction when motion coherence was below psychophysical threshold. To confirm this quantitatively I constructed and compared two models: the motion integration model which assumes that motion integration occurs and the non-integration model which assumes that no motion integration occurs and instead that participants reports the first or second motion direction as a perceived direction. I examined which model is more likely to describe the behavioral results (Figure. 2a in the main manuscript) at each coherence ratio.

Motion integration model

The motion integration model assumes that participants either randomly guess or respond with an estimate of the central tendency of the two motion directions (Zhang & Luck, 2008). I include a random guess component because the model fits were significantly improved by including this parameter for both the motion integration and non-integration models. A probability distribution of guess responses is assumed to be uniform (responses were independent of the central direction). I assume that the remaining response in non-guess trials would be normally distributed. Therefore, the non-guess trials were modeled as a normal distribution along a circular dimension (von Mises distribution) with parameters for the standard deviation (how accurate participants were at judging the average motion) and for the mean (whether participants' responses were biased towards the first or second motion direction). Therefore, the probability distribution of the modeled responses consists of a weighted mixture of a uniform and a circular normal distribution. A weighting parameter was defined as a rate of guesses. Thus, the motion integration model had three parameters.

Non-integration model

While the motion integration model assumes that participants' reports in non-guess trials follows a single distribution, the non-integration model assumes that participants' reports follows two distributions corresponding to first and second motion directions, respectively. That is, the model assumes that a probability distribution of responses in non-guess trials consists of a mixture of two circular normal distributions with different mean values. For simplicity, I assumed that the two normal distributions had identical standard deviation values (see also Bays, Catalo, & Husain, 2009). Therefore, the probability distribution of the modeled responses consists of a weighted mixture of three distributions—a guess distribution plus the two circular normal distributions. Two weighting parameters were defined. The first weighting parameter represented a rate of guesses. The second weighting parameter represented the likelihood of responding to the first or second motion patch when they were not guessing. Thus, the two weighting parameters describe the likelihood of the three possible respond distributions in the model. Thus, the non-integration model had five parameters. Note that the motion integration model is a special case of the non-integration model. Therefore, for a model comparison I used Akaike's information criterion (AIC; Akaike, 1974) to take the number of parameters in each model into account.

Model estimation and comparison

I determined the model parameters (three parameters for the integration model and five parameters for the non-integration model) for each coherence ratio. To obtain more stable results of model estimation and test statistical significance, all behavioral results from 13 participants were pooled, and I performed a bootstrap resampling analysis (Efron, 1982) consisting of 100 resamples. A dataset for each bootstrap analysis was created by selecting a set of 13 participants, with replacement, from the set of possible participants (a single participant could be selected multiple times) and including the data of that participant for each coherence level. As a result, each detaset included 780 trials in total. The model parameters were determined by maximum likelihood estimation for the dataset. Result of model fitting for each coherence ratio is shown in Supplementary Information Figure. 6.

I evaluated which model is more likely to describe the behavioral results by comparing AIC values obtained from the bootstrap analysis for the 100 resamples at each coherence ratio.

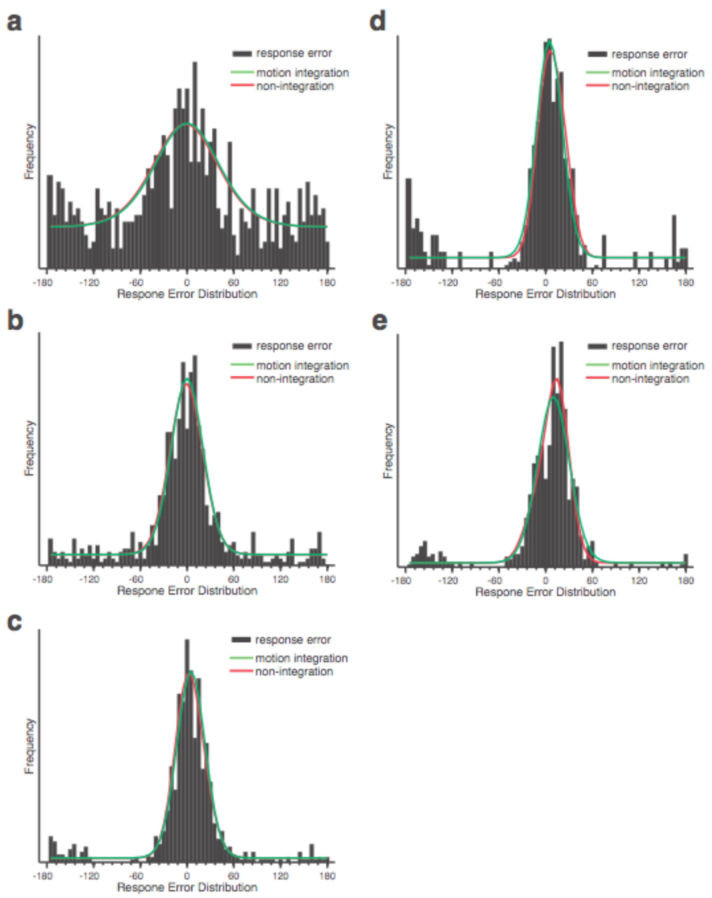

Figure. 6 An example of probability distributions of participants' response and the best fitting probability distributions for the motion integration (green) and non-integration (red) models at the five coherence ratios (10%, 22%, 34%, 46%, and 70%; **a**-**e**, respectively). For this particular resample, the non-integration model only provided the better fit at 70% coherence.

Supplementary Information References

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Bays, P.M., Catalao, R.F.G., and Husain, M. (2009). The precision of visual working memory is set by allocation of a shared resource. *J. Vision 9*, 1-11.

Efron, B. (1982). "The jackknife, the bootstrap, and other resampling plans". *Society of Industrial and Applied Mathematics CBMS-NSF Monographs*, 38.

Zhang, W., and Luck, S. (2008). Discrete fixed-resolution representations in visual working memory. *Nature 453*, 233-235.