Action for perception: evidence that ongoing eye movements constrain visual perception

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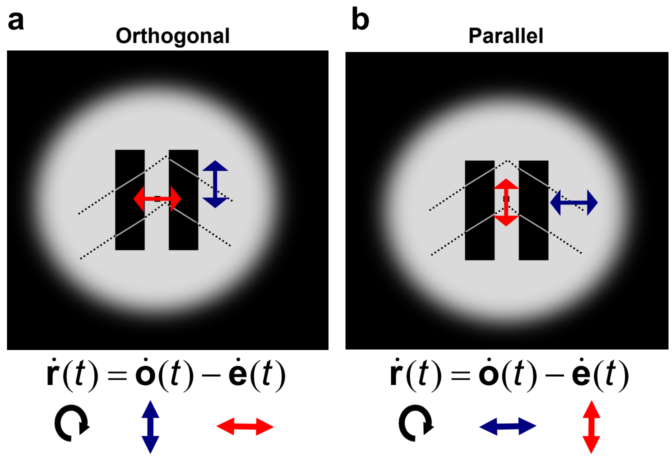
Supplementary Information

Our results from **Figures 1-5** of the main text suggest that eye movement information increases perceptual coherence. Before proceeding to the next set of experiments, we wished to first explore a possible hypothesis about how such an increase happens. Specifically, we hypothesized that eye movement direction may exhibit differential benefits to perceptual coherence depending on how effectively this direction could be used to resolve the ambiguity of the retinal motions associated with the visible segments of the perceived shape. For example, with the chevron stimulus of **Figure 1** of the main text, the use of vertical apertures means that only the vertical component of this stimulus' visible retinal motions is unambiguous[1-6]. It is therefore possible that tracking improves coherence through constraining the ambiguous (horizontal) component.

We started out with the chevron stimulus of **Figure 1** of the main text but now introduced tracking that either involved sinusoidal pursuit (of the fixation spot and occluder) in a direction orthogonal to the orientation of the apertures or one involving sinusoidal pursuit parallel to them. The chevron also translated sinusoidally in a direction perpendicular to the direction of motion of the occluder and fixation spot, subject to the constraint that **equation 1** of the main text yielded $\dot{\mathbf{r}}(t)$ like in fixation (**Supplementary Fig. 1**). At trial end, subjects, who performed two sessions of this experiment, reported on the (subjective) perceived coherence of the stimulus. All other experimental details were identical to those of our original experiment (**Fig. 1**) in the main text.

Eye movement analysis in this experiment was identical to that used for **Figures 1-5** of the main text. However, we now compared the retinal slip of the chevron, as well as the eye position delays during pursuit, in each of the tracking conditions to fixation individually. Just like for **Figures 1-5**, the same conclusion that retinal stimulation was matched as much as possible in orthogonal and parallel tracking to that during fixation was made[*]. As for the observed effects on subjective experience of coherence,

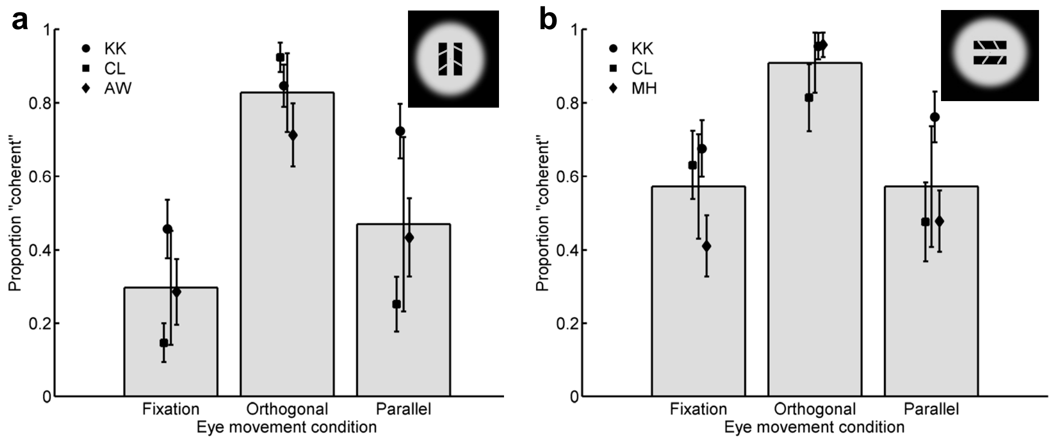
[*] We determined the *P*-value of the eye movement factor in a two-way ANOVA (factors: trial type and time) of our measured retinal slips. Average *P*-values for horizontal and vertical slips across subjects in all supplementary experiments were: 0.66 +/− 0.27 s.d. and 0.53 +/− 0.27 s.d. We also computed the mean radial amplitude of the chevron's retinal slip for each trial in a session. The distribution of this value during tracking trials was compared to that during fixation trials (average % of tracking trials falling within the range of variability of fixation trials across subjects in all experiments in this note: 93% +/− 6% s.d.). Finally, there was minimal phase lag in tracking (average across subjects: 35 ms +/− 20 ms s.d.).



Supplementary Figure 1 Exploring differential effects of eye movement direction relative to retinal motion direction. (**a**) When the chevron moved up and down in a sinusoidal fashion and the occluder/fixation spot moved right and left, the same retinal input as in fixation – circular motion of the chevron around the fixation spot – was achieved but only with a horizontal (orthogonal) eye movement. (**b**) Similar to **a** but the circular motion of the chevron in retinal coordinates was caused by a vertical eye movement (parallel) associated with horizontal chevron motion. For both conditions (**a** and **b**), we verified that subjects tracked the fixation spot and therefore experienced similar retinal input to fixation (similar to analysis in **Fig. 2** of the main text). $\dot{\mathbf{r}}(t)$ is retinal slip of the chevron, $\dot{\mathbf{e}}(t)$ is eye velocity, and $\dot{\mathbf{o}}(t)$ is chevron velocity.

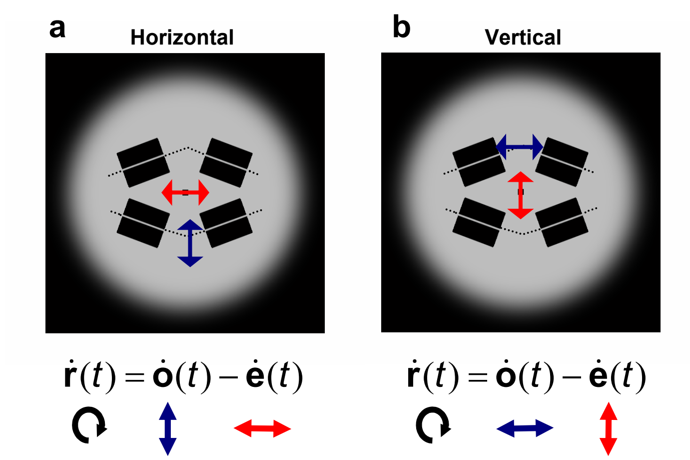
Supplementary Figure 2a summarizes our findings. As can be seen, horizontal tracking had a much greater benefit to coherence than vertical tracking. In fact, perceptual coherence in vertical tracking was not always different from fixation. For each of our subjects, we confirmed that these observations held by performing a χ^2 test to refute the null hypothesis that perceptual coherence was identical in all of fixation, horizontal tracking, and vertical tracking ($P < 0.05$). We then made pair-wise comparisons by computing 95% confidence intervals for the probability of perceptual coherence in each eye movement condition as shown in **Supplementary Figure 2a**.

The above results suggest that when subjects moved their eyes orthogonal to the apertures in the display, they experienced the greatest coherence. Alternatively, these results could simply reflect a benefit to perceptual coherence of tracking along a horizontal axis. To disambiguate this issue, we repeated this same experiment but after transposing all of our stimuli by 90^o clockwise. With horizontal apertures, the ambiguous motion was now produced by the vertical component of the chevron edge motions (since the apertures became horizontal). We again required horizontal or vertical tracking, but this time vertical tracking was equivalent to orthogonal tracking relative to the apertures. As in the original version of this experiment (**Supplementary Fig. 2a**), we were able to refute the null hypothesis that perceptual coherence was identical in all three eye movement conditions for each of our subjects (χ^2 test, $P < 0.05$). In addition, we observed that perceptual coherence was highest when subjects moved their eyes orthogonal to the apertures in the display, even though this now entailed vertical pursuit (**Supplementary Fig. 2b**).



Supplementary Figure 2 Subjective experience of coherence was highest for orthogonal tracking. (**a**) Results from the experiment illustrated in **Supplementary Figure 1**. The orthogonal condition involved horizontal tracking, and the parallel condition involved vertical tracking. The proportion of trials in which subjects experienced coherence was greatest in the orthogonal condition. (**b**) When the stimuli were transposed such that the apertures were horizontal, the orthogonal tracking condition again resulted in the greatest coherence even though it now entailed a vertical eye movement. Data from individual subjects are shown with individual symbols and their own 95% confidence intervals. Bars showing the means and s.d. of the individual subject means are also shown for easy visualization.

To go one step further in exploring our hypothesis, we repeated the above experiment one more time but with a stimulus consisting of a diamond with oblique apertures (see **Fig. 5c** of the main text). In one session each, subjects viewed the conditions of **Supplementary Figure 3** in addition to basic fixation and again made a subjective report on the perceptual coherence of the diamond. Eye and object speed were matched to give retinal motion identical to that in **Figure 5c,d** of the main text. The behavioral results we

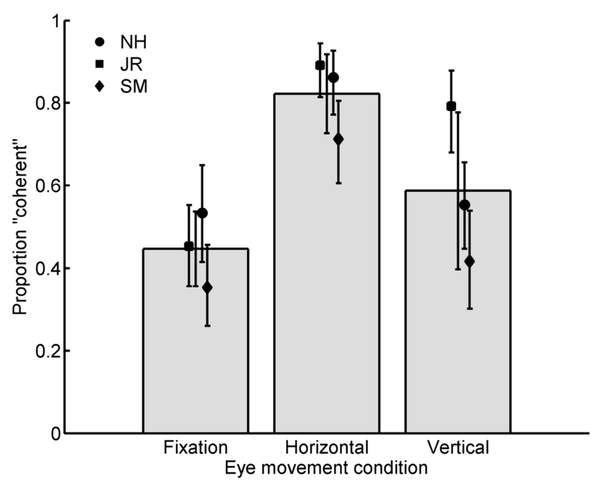


$$\dot{\mathbf{r}}(t) = \dot{\mathbf{o}}(t) - \dot{\mathbf{e}}(t) \qquad \dot{\mathbf{r}}(t) = \dot{\mathbf{o}}(t) - \dot{\mathbf{e}}(t)$$

Supplementary Figure 3 Exploring differential effects of eye movement direction relative to retinal motion direction with a different shape. We again compared fixation to two tracking conditions (**a** and **b**). However, now, the stimulus consisted of a diamond that was partially occluded with oblique apertures. The apertures were such that line terminators for the visible diamond segments moved identically in retinal coordinates to the orthogonal component of these segments' motions. $\dot{\mathbf{r}}(t)$ is retinal slip of the diamond, $\dot{\mathbf{e}}(t)$ is eye velocity, and $\dot{\mathbf{o}}(t)$ is diamond velocity.

observed were very similar to those obtained with the chevron above: for each subject, the probability of reporting perceptual coherence differed with the different eye movement conditions (χ^2 test, $P < 0.05$); moreover, horizontal tracking promoted perceptual coherence the most, although one subject also showed a significant increase over fixation for vertical tracking as well (**Supplementary Fig. 4**).

Although this result might seem expected from the chevron results, we felt that it was important to obtain it explicitly because the diamond stimulus that we chose uniquely dissociates aperture shape effects from visible line motion effects. Specifically, with any stimulus involving a line moving through an aperture, there exist two sources of motion signals: the motion orthogonal to the line (with ambiguous 2-D components), and the motion of the terminators of the line at the junctions with the aperture[1-6]. With the chevron stimulus, these two sources compete, and the latter unambiguous one wins in fixation. This might suggest that eye movement direction gives differential benefits to perceptual coherence because it interacts with only this latter source of retinal motion. Our diamond stimulus, on the other hand, was designed such that the retinal terminator motion was identical to the orthogonal component of line motion. Therefore, the differential benefits to perceptual coherence that we have observed with this stimulus are just as likely to have occurred because of influences on the ambiguous orthogonal line motion. In addition, the benefits are expected to depend on whether the horizontal or vertical component of the line motion is more ambiguous: with shallow lines (as we have done), the horizontal component of true edge motion is more ambiguous than the vertical component. Therefore, horizontal tracking results in a greater benefit. We expect that



Supplementary Figure 4 Subjective experience of coherence was highest for horizontal tracking with the diamond stimulus of **Supplementary Figure 3**. With oblique apertures, the only retinal motion signals available for the visible line segments of the diamond are those that are orthogonal to the line orientations. Because these line segments were of shallow slope, the horizontal components of their true motions were more ambiguous than the vertical components. Eye movements seem to have preferentially constrained these more ambiguous components. The main text shows results with steep line segments, where vertical eye movements resulted in higher coherence. Each individual subject data is shown with 95% confidence intervals. Bars showing the means and s.d. of individual subject means are also shown for easy visualization.

vertical tracking should result in greater benefit with steep lines (where the vertical component of true edge motion is more ambiguous than the horizontal one). We have performed this latter experiment *objectively* in the main text.

To summarize, we found that the subjective experience of coherence for both the chevron and diamond improves during tracking *even when the shape is not stationary in the world*. We also found that this improvement is greatest when the eye movement direction is along the more ambiguous component of the true direction of motion of the shape – whether this ambiguous component is due to occlusion (only motion orthogonal to the visible lines is accessible) or due to the presence of a stronger unambiguous cue (line terminator motion). These results encouraged us to fully explore these phenomena using more objective methods in **Figures 6-8** in the main text. These experiments were designed in a very similar fashion to the experiments above *specifically* to allow us to cross-validate our objective and subjective report results. In addition, we used the diamond stimulus with oblique apertures in those experiments instead of the chevron because it allowed us to avoid retinal line terminator motion as a possible cue for motion integration.

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