0.1 Experiment 1

1 Model-based results and/or discussion

1.1 Lack of pooling across large distances

Still under construction – please skip to section 1.4

We motivated the description of our model by considering that the observer attends a single element of the display; other elements were taken to be ignored as best the observer is able, though they reveal their influence via crowding or induced motion depending on distance. However, in our task the stimulus is composed of identical, identically moving elements. Therefore in principle, it is not necessary that a subject isolate any particular element to arrive at a veridical perception of envelope motion; any element will do the same job. This raises the possibility that an observer might pool multiple envelope position signals in order to improve sensitivity to envelope displacement. If that is the case than the sensitivity to displacement (i.e. the slope of the psychometric function of displacement) should increase with the number of elements on the display, as long as targets remain widely separated enough to avoid crowding.

To assess the presence or absence of pooling at large distances we compared subjects' sensitivities to envelope displacement as element number varied, for the subset of data where there were 6 or fewer elements on the display. We measured sensitivity by fitting a logistic regression model,

$$\Pr\left(\text{clockwise} \mid \Delta x, C, n\right) = \text{logit}(\beta_n \Delta_x + k_{C,n})$$

where the slope of the psychometric function is modeled by β_n and a separate intercept is used for each value of direction content and. We then asked whether a single coefficient β was sufficient, or whether the model fit was improved by letting separate values of β_n apply to each number of displayed elements.

Values of β obtained by this procedure are plotted ...., using one symbol for each subject. We do not find that the number of visible elements significantly affects the

To further check whether there was any sign of pooling, we performed a one-way ANOVA on the fitted values of β_n where. For __ subject did was any significant effect of element number; we interpret this as indicating there is not a significant amount of envelope position signals between elements.

1.2 With shorter distances between elements, sensitivity to envelope motion declines.

1.3 At shorter distances, carrier motion summates, causing an increase in sensitivity to carrier motion.

One feature of our model, as illustrated in figure is that . We again motivate this model feature by allowing the model

1.4 At longer distances, carrier motion repels direction judgments

An interesting feature of our model is the component M_I which we describe as due to a very long range or global average of motion energy. This is the component that describes the extent to which carrier motion biases observers' judgements when elements are widely spaced. An example is shown in 1. At narrow spacings (the upper subplots of the graph) we see that the effect of changing local direction content is to bias subjects toward perceiving the motion in the same direction as the added direction content. So, clockwise direction contents, indicated in the figure by warmer colors, cause a leftward shift in the psychometric functions, and vice versa. However, at wider spacings, shown in the lower subplots, this effect reverses. Thus assimilation of first-order motion under crowded conditions is a summation, but when elements are widely spaced apart, there is a repulsion. (We discuss the extent to which this effect applies to all subjects in the next section.) We feel this is similar to some phenomena that have been called "induced motion" (Reinhardt-Rutland, 1988), in which a distant or full-field motion biases the perceived motion of an individual target. While our particular stimulus, with identical targets, does not inherently distinguish the "inducer" from the "induced," we can apply our previous insight about the lack of pooling of position information; if the task is performed by attending or tracking single elements, then any attended or tracked elements may be subject to motion induced by the remainder of the display.

1.5 The induced motion effect is nonlinear in carrier direction content and insensitive to element number

There are two characteristics of this induced motion that deserve comment. The first is that the degree of repulsion appears to be a nonlinear function of direction content. Another is that the strength of repulsion seems to be determined by the average direction content of the elements, rather than a sum over the motion energy content of all elements – in other words changing the number of elements does not appear to change the magnitude of the repulsion. Both these features were captured in described in Section **??** using the function $M_I(C)$; here we elaborate and discuss the support for those characteristics.

We first address the nonlinearity of the induced motion as a function of direction content. In the example data for subject JB, shown in Figure 1, this nonlinearity is visible at high spacings (e.g. the second-to-bottom subplot of the figure) as a "clustering" of data into basically two groups of clockwise and counterclockwise direction content, despite a fivefold range of the actual magnitudes of the direction contents tested. Moreover, for these two in some cases a stronger direction content actually seems to lead to weaker bias than a moderate direction content, as

We illustrate the presence of this nonlinearity by comparing three nested models. In the null case, we consider the model without any contribution of induced motion, that is, $M_I = 0$. but otherwise identical to the full model

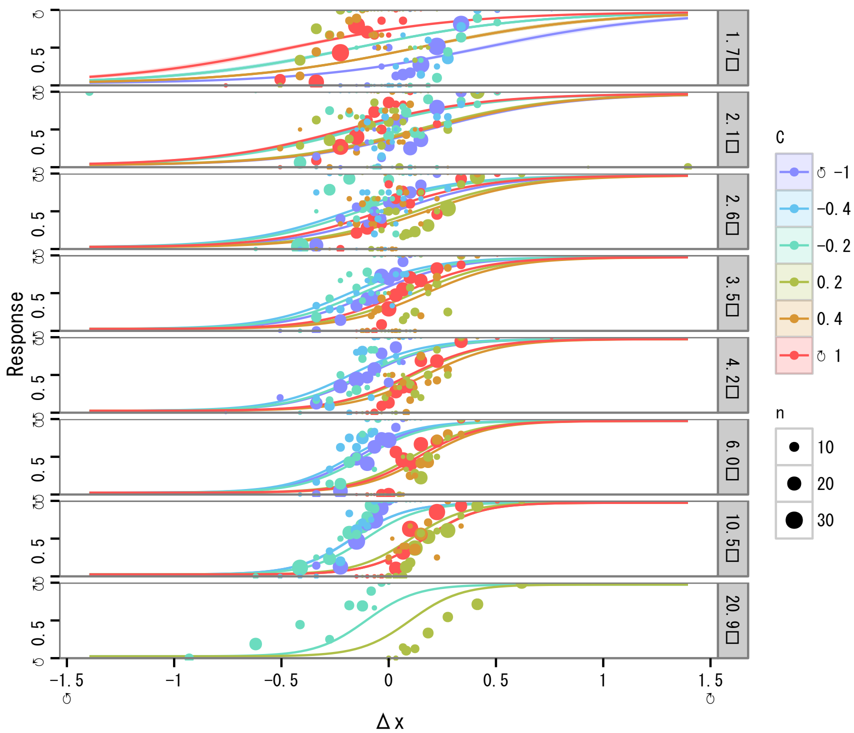

Figure 1: As element spacing changes, assimilation becomes repulsion. Here example data from observer JB is shown. JB was tested with a variety of carrier direction contents and spacings (one magnitude of direction content per session). Here, each subplot contains data from a single spacing, and the direction content is indicated by the color (with warm colors indicating clockwise carrier motion and cool colors indicating counterclockwise.) In each subplot the vertical axis measures the proportion of responses "clockwise" to a given stimulus, while the size of each point indicates the number of trials collected for that stimulus. Curved lines show model fits to this data. Notably, observe that the effect of direction content reverses as spacing changes; as small spacings JB is biased to respond in the direction of carrier motion (in the graph, warm colors are displaced to the right of cool,) while at large spacings the opposite bias occurs. Other subjects also show spacing dependent reversals, as discussed in 1.4.

described above in **??**. The second model we consider is one in which the strength of induced motion is linearly related to the direction content of the stimulus; $M_I = \beta_I C$. For this model, we found that 8 out of 10 subjects showed a significant ($p < .05$; likelihood ratio test using a χ^2 distribution with 1 degree of freedom) improvement to the model fit by adding the linear parameter. However, we additionally suspected that the induced motion effect was nonlinearly related to the direction content of the stimulus, as Murakami and Shimojo (1993) had observed that the strength of induced motion was non-monotonically related to the contrast of the inducer for some subjects. Therefore we also considered a model in which there was a second-order, odd-symmetric component to the induced motion signal; $M_I = \beta_{I_a} C + \beta_{I_b} C\,|C|$. As compared to the linear model, we found that for all 10 subjects, the fit was significantly improved by adding the second-order component, the largest p-value being $p = 2.4 \times 10^{-7}$ for subject CJ.

Additionally, while the signs of β_I in the linear model are mixed, in the second-order model, every subject with the exception of CJ has a negative value of β_{I_a} and a positive value of β_{I_c}, indicating that small imbalances of motion energy at wide target spacings usually lead to repulsion, but that the repulsion is proportionately weaker, or even reverses, with stronger direction content.

Figure 2 illustrates the difference between linear and second-order models. There we show model projections for stimuli with no envelope displacement, at a fixed value of 10° element spacing, for varying values of direction content. We show fitted curves for the linear and second-order models, as well as data points corresponding to a complete model (in which the induced motion is allowed to take on a different strength for each value of C tested.) As mentioned above, for all subjects except CJ, the slope of the linear component is is negative, indicating a repulsive induced motion effect; for the same subjects the coefficient of the second-order component is positive, indicating that the repulsion proportionately weakens, or in some cases reverses, when direction content approaches $|C| = 1.0$.

The other salient feature of induced motion is that it does not appear to depend on the number of elements, even at wide spacings. To show this, we consider the subset of data with spacings greater than 6 degrees

2 Experiment 2 number versus density.

References

Murakami, I. and Shimojo, S. (1993). Motion capture changes to induced motion at higher luminance contrasts, smaller eccentricities, and larger inducer sizes. *Vision Res*, 33(15):2091–107.

Reinhardt-Rutland, A. H. (1988). Induced movement in the visual modality: an overview. *Psychol Bull*, 103(1):57–71.

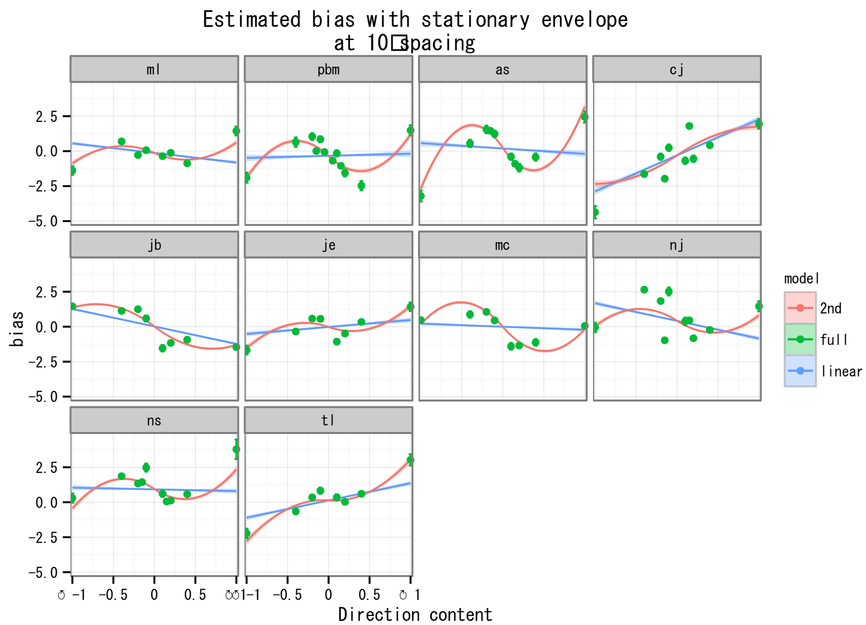

Figure 2: Effects of induced motion at wide spacing. Here we show, for each subject, modeled biases at a nominal 10° spacing with varying levels of direction content. Predictions from two models are shown one where response bias is linearly related to direction content, and one where a second-order, odd-symmetric component is added. For comparison, points with error bars show a full model, where bias is allowed to take on a separate value for each direction content tested. The second order model obtains a better fit (see section 1.5.) Under this model, all but one subject shows a negative slope of the curve where direction content crosses zero, indicating a repulsive effect for weak direction content, while the second order coefficient weakens or reverses this effect for stronger direction contents.