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1 Experiment 2

In Section ??we saw that the perceived direction of motion becomes more sensitive to carrier motion when spacing is large. Equivalently, we could describe the results of Section ?? as being that observers were more sensitive to carrier strength when the number of elements on the screen is large. The relevant term in the model described in Section ?? is $\beta_S \frac{C}{S}$, which could be wriutten equivalently as $\beta_N CN$ with N being the number of elements in the scene. We sketched an interpretation in Figure ?? on page ?? in which this term is described as being summed over a window surrounding one attentively tracked element. However as far as the data from Section ?? is concerned, this window of summation could be any size, from an interaction directly between an element and its neighbor to a summation over the entire visual field. We therefore wished to determine how global the summation of carrier motion was.

A parallel concern is that we describe the decline in sensitivity to envelope motion, described by the term $\beta_{\Delta x}(S)$, as being due to the number of elements in the stimulus. Equivalently, we could have parameterized it in terms of the number of elements on screen, in which case we would be talking about a decline in sensitivity with increasing numbers of elements. Therefore we wish to distinguish these two possibilities.

Similarly, our model in Section ?? characterized the response to carrier strength as being proportional to the product of the carrier direction content with the element density (i.e. the inverse of the spacing); in ??. This factor can be interpreted as a summation of the carrier strength of elements in some region, indicated by the red circle in Figure ?? on page ??. This raises the question of how large that region is. In particular, we wonder if the region of summation is of a similar size as the "critical distance" controlled by the parameter S_C in our model.

Our model also included terms controlling a repulsive effect. This effect did not appear to depend on the density it may either reflect a sort of normalized average of the motion energy across the visual field, or the influence of the carrier motion of an isolated element on itself. where am I going with this>:

Therefore we wished to know whether the loss of ability to track changes in position (i.e. envelope motion) could be better explained as a function of element spacing or of element number. Our approach to both of these questions was to modify the stimulus to cover only a portion of the scene, so that spacing and number can be varied independently. The necessarily involves varying the *extent* of the stimulus, which is the area in the visual scene spanned by all moving objects. We measure this as a distance along the circle at constant eccentricity on which elements are located. Any two of these variables (spacing, number, and extent) determine the third, so to some extent our choice in favoring one pair of these variables over another is arbitrary, but we hope to choose the description that makes the most parsimonious account of the data.

1.1 Methods

- Show stimulus design; covarying element number and density
- Mention flankers, which are not counted as moving elements
- Show demo movie, numbers linked to stimulus space
- Mention how displacement and direction content is chosen, based on data from Experiment 1, in an ad-hoc manner. Illustrate with comparisons of Exp 1 and Exp 2 data from illustrative subjects (NJ, PBM)
- We also test in alternate hemifields blockwise (but this is less important.)
- SUBTLE BUT IMPORTANT POINT: It's the slope of the lines that matters most, not their height or the change in height with element number (which is explained away as full-field sum of motion-energy). Whether the lines collapse together plotted against spacing, as PBM, or collapse plotted versus number, as NJ, doesn't actually matter. What matters is that In particular, it's that the slope does not change with element number, that distinguishes this model from e.g. one in which element number causes collapse due to failure of attentive tracking or whatever. Work through why the model predicts this.

The task was identical to that in Section **??**; The stimulus was fixed at degrees eccentricity. The stimulus consisted of a number of moving elements, identically specified to those in Section **??** but instead of being evenly distributed around a circle, the elements were distributed in a limited area on either the left or right wide of the display. We varied both the spacing and the number of elements used; accordingly, the total spatial extent of the stimulus varied from trial to trial. The values of spacing and element count we used are shown in Figure Figure 3 on page 5. This stimulus set was constructed so that each value of element spacing was tested using more than one value for the element count, and vice versa. We chose a set of stimuli that were symmetrically arranged in number and density, spanning a similar range for both variables (covering a factor of NaN in element number and a factor of 2.78 in element spacing.)

We found it necessary to include two stationary flanking elements, indicated in Figure Figure 1 on page 3. These served to hide the displacement of the moving elements at either end of the display, which would otherwise be easier to discern lacking a crowding flanker on one side. The flanking elements had zero envelope movement and null carrier direction (i.e. their carriers flickered in counterphase.) The flanking elements were positioned so that they were between $0.5°$ and $1°$ away from the adjacent moving element at its closest approach; this allowed that there was not a conspicuous gap opening or closing

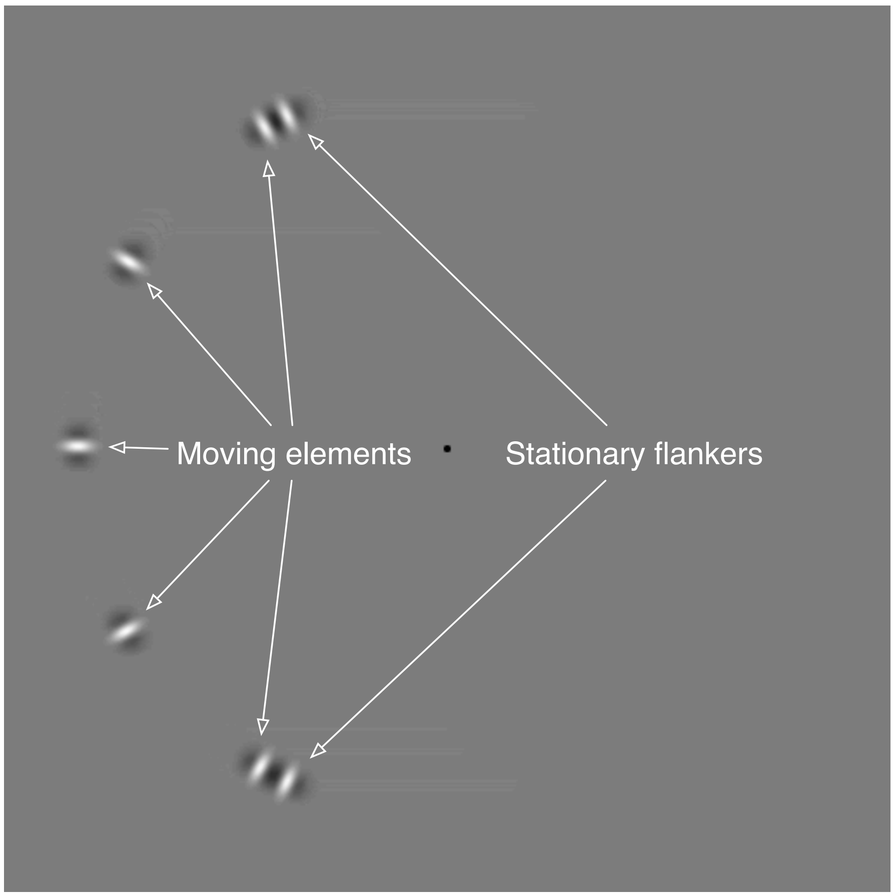

Figure 1: Example frame from a partial-circle stimulus. A number of moving elements are present on one side of the display. Two additional flanking elements are added, which always have carrier strength of 0 (i.e. they flicker in counterphase.) The flanking elements are positioned $0.5, 1^\circ$ away from the nearest moving elements at their closest approach.

Figure 2: Example stimuli for Experiment 2. In this movie, the elements are shown in the left hemifield; in the experiment, stimuli alternated hemifieldsin trial blocks. Two stationary flankers with no carrier carrier motion (i.e. counterphase flicker_ are present in all stimuli. Stimuli numbered 1 and 2 have identical numbers of targets, with large, then small spacing. Stimuli 3 and 4 show targets with identical spacing, with fewer and then more targets. The numbers correspond to stimuli marked with a number in Figure Figure 3 on page 5

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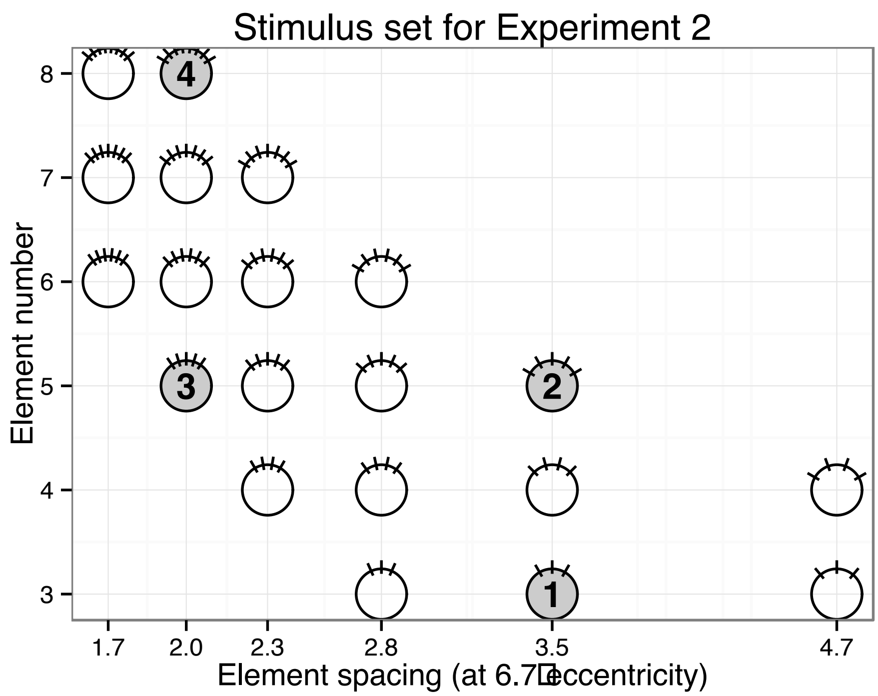

Figure 3: The combinations of element spacing and element number used in this experiment. Tick marks on symbols indicate variations in spacing and number (which are also shown on the X axis.) Numbers reference the stimuli demonstrated in Figure 2.

between the flanker and moving elements as the moving elements underwent envelope displacement. The flankers spanned an angle that was at least 56° and no more than 165° (in terms of the angle formed by two segments each connecting one of the outermost moving elements to the fixation point. The movie shown in Figure 2 demonstrates the stimuli with flanking elements, for the four configurations indicated with numbers in Figure 3.

The particular values of direction content and envelope motion were chosen for each subject based on preliminary findings of Experiment 1. We selected stimuli with the goal of finding a setting where both envelope and carrier motion mechanisms would be sensitive to changes in spacing and/or number. Figure 5 shows the choice of stimulus for one observer, with reference to the model fit shown as a heatmap as in Figure **??** on page **??**. Some subjects were tested using more than one value of envelope displacement and/or carrier strength, but results were qualitatively similar between the configurations tested, so we show them here averaged (while our model still accounts for the particular values used.)

Since the strength of crowding is typically not uniform across the visual field and varies between hemifields [1], we tested stimuli positioned in the left and right visual fields. Each session used an equal number of stimuli positioned in the left and right hemifields, with the position alternating in blocks of 100 to 200 trials. In preliminary experiments we found that having the stimulus appear randomly between trials was detrimental to observer's performance as they could not anticipate where to direct their attention for the brief stimulus.

1.2 Results

Of the observers who had previously participated in **??**, 8 participated in Experiment 2. An example of the data collected is shown in Figure 4. Each plot shows the rate at which subjects responded "clockwise" to a stimulus at a particular value of spacing and of element number, with the spacing values organized along the x-axis and the y-values organized along the y-axis. At first glance the response patterns of these two observers appear very different. NJ's response probability changes little with element spacing, while being greatly affected by changes in element number. PBM, on the other hand, appears to change his response probability along with changes in spacing, while being little affected by changes in element number. However, there are also common patterns. There does not appear to be any interaction between spacing and slope; the lines traced out by changing spacing at a smaller number of elements parallel the lines traced out by changing spacing at a larger number of elements, although the two lines may be offset with respect to each other.

At first glance it would appear that these two observers are using different rules to perform the task. However, interpreting these patterns of behavior in detail requires correlating them with the measurements from **??**; since the earlier experiment suggested more than one mechanism that could contribute to an observer's perceived direction of motion, what appear to be different patterns of response may be a result of differing strengths of contribution of each respective

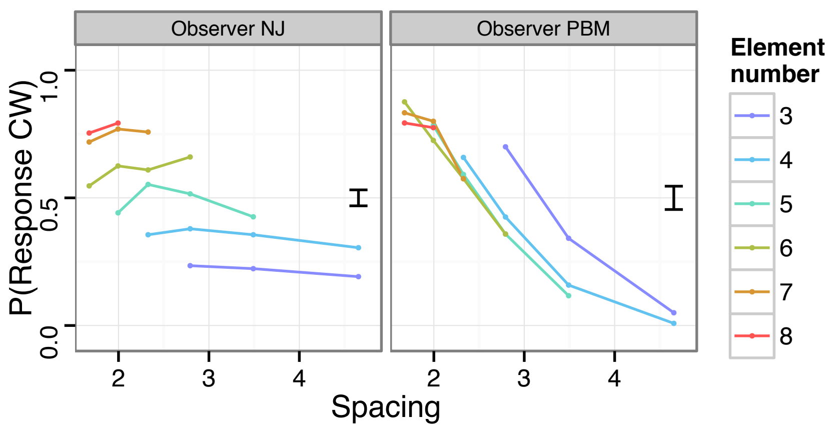

Figure 4: An example of the measurements performed in Experiment 1.We show data for two observers. We plot the proportion of responses clockwise as a function of the spacing between elements, connecting lines for each element. Lines show how observers' proportion of responses clockwise varied as a function of element spacing, with other parameters (envelope displacement, carrier strength and element number) held constant. Colors indicate different numbers of elements on the display. Error bars show the standard error for each data point (same for all points.)

mechanism.

We tried to see whether these patterns are captured by the existing model. Our model predicts that there will be a progressive change in sensitivity to envelope motion as a function of spacing (or number) and there will be a change in sensitivity to carrier motion based on changes in the number or elements (or their spacing). Thus, as spacing or number changes, the response rate will progressively change, as either envelope or carrier motion makes a larger contribution, despite the envelope motion and carrier strength remaining the same for all stimuli. So we expect to see the same gross features as in Figure 4, i.e. some consistent relationship of response rate to changes in spacing and another consistent relationship of response rate to changes in density, but we must make some assumptions about the envelope- or carrier- motion mechanisms to see if they agree with our data.

1.2.1 Agreement with predictions of Section ??

We asked how well the results from Experiment 2 could have been predicted by the model discussed in **??** and fit to data taken from **??**. There are different possible ways to obtain predictions based on the full circle stimuli used in **??**, depending on how we interpret the coefficients β_{Δ_x} and β_S. We can interpret the change in displacement sensitivity $\beta_{\Delta x}$ as being a function of the local spacing between elements or due to the global number of elements; we can interpret the sensitivity to carrier strength β_S as being controlled by a local summation (i.e., adding up carrier motion over small regions of space) or a global summation (i.e. adding up carrier motion over a small region of space, or adding up over a large region). Thus we have four scenarios to compare: envelope local/carrier local, envelope local/carrier global, envelope global/carrier local, and envelope global/carrier global.

These four sets of predictions are shown in Figure 5. In this figure the shaded ribbons with dotted lines plot response rates predicted almost entirely from the data taken from Section **??** with little input from Experiment 2 (on;y the overall proportion clockwise is ajdusted to match); these predictions are plotted as shaded ribbons on top of the actual data we took. Four rows show predictions over four assumptions (global or local summation of carrier motion; global or local change in envelope motion sensitivity); two columns correspond to models that were fit to two example observers. The entire set is shown in the appendix in **??**.

When carrier motion or envelope motion is interpreted as "global" (i.e. acting over a large field) we have extrapolated from **??**'s model stimuli by assuming that the global summation happens over one hemifield. That is, the displacement sensitivity is interpreted as a function of the number of elements that fall in one hemifield, and the carrier motion sensitivity similarly. On the other hand, when carrier or envelope motion is interpreted as "local" the carrier and displacement sensitivity is interpreted with reference to the fits obtained from Section **??**, ad a function of spacing without regard top the extent of the stimulus. Different assumptions about the size of the regions of spatial interaction lead to somewhat

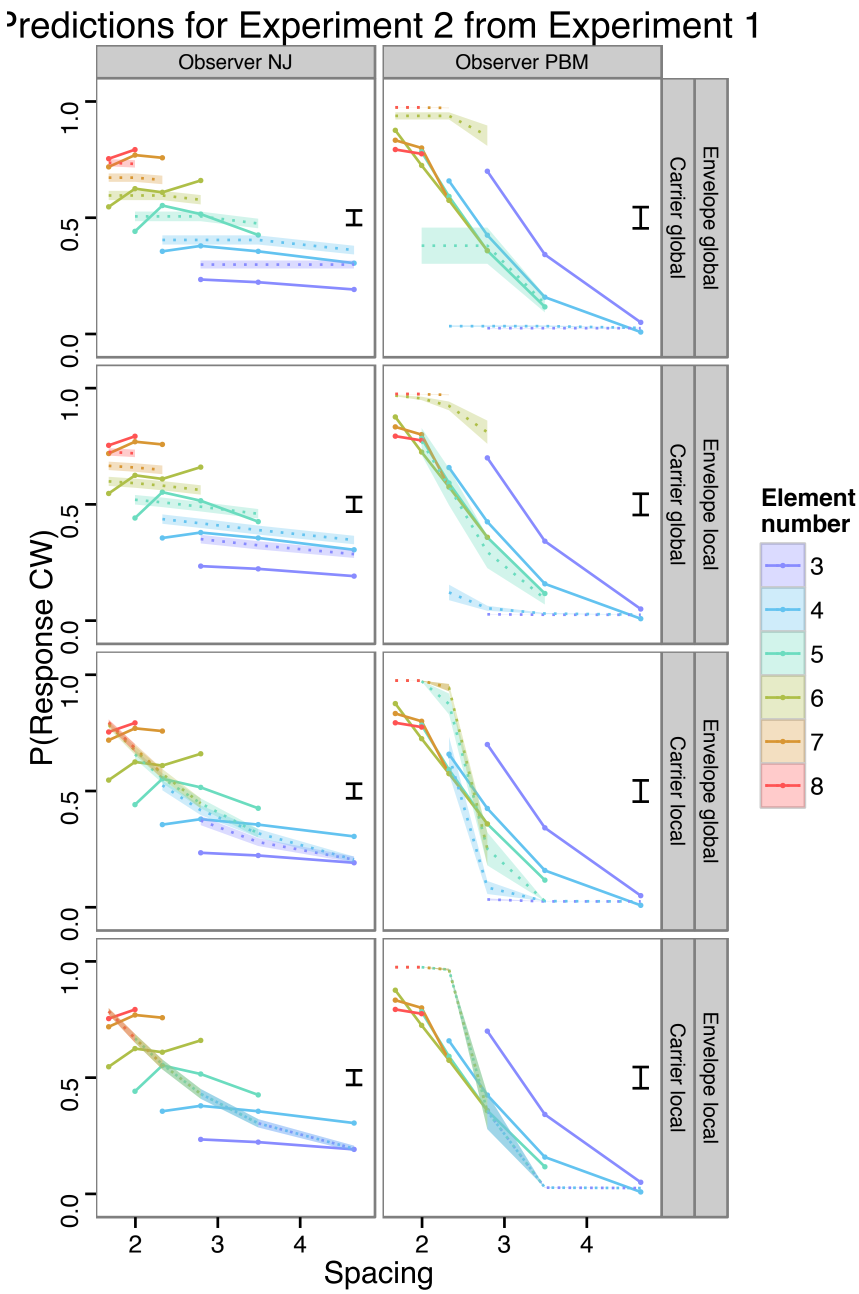

Figure 5: Alternate predictions for Experiment 2. Data for two observers are shown one in each column. The data in the four columns shows four predictions for the same observer, constructed using only data from Experiment 1.

different results, but do not change the qualitative agreement or disagreement with the data. We do note that in the raw data there is little appearance of saturating behavior as a function of the extent of the stimulus; adding another element or changing the spacing seems to have the same relative effect for larger stimuli as for smaller, so we conclude that effective regions of both envelope and carrier motion are either larger or smaller than all the extents tested. That is, if the size of a effective region for either carrier or envelope motion fell in the range of extents tested, we would see a "bend" in the lines plotted in these figures, rather than a consistent slope . We will address the question of how large the spatial interaction regions might be subsequently.

There is one deviation from a "pure" prediction from **??**: we have adjusted the average response rates of the predictions shown in Figure 5 to agree with the total number of clockwise responses, with the intention that the phenomena determined by globality or locality (i.e. the slopes of the lines of response rate with respect to spacing , and the change in response rate as a function of element number); can be more directly compared. When modeling the dataset as a whole we find we can discard this adjustment.

In Figure 5 we see the best agreement with the model projections is in the second row, where the response to carrier strength is taken to be global (so that changing the number of elements affects the carrier strength summation) and the change in spacing sensitivity appears to be local (so that adding elements does not change the response; only the distance from an attended element to the nearest flanker does.) This model, compared to the alternatives, manages to capture the slope of the relation between spacing and response rate, even though these two observers had very different slopes. It does not capture the effect of element number on response rate as well. But we tentatively conclude that for the data **??** and section 1 to be consistent with each other, the summation of carrier strength happens over a large region and the "crowding" effect on envelope motion detection happens over a relatively smaller region.

1.2.2 The size of the region of summation

Of the two components in the stimulus, it appears that only the carrier motion one operates over a large region of space. We conclude that the the mechanism sensitive to envelope motion is relatively local, operating on the spatial scale identified as the "critical spacing" between adjacent elements and not being affected by other elements. on the order of the size of the. On the other hand, it appears that the mechanism responsive to the carrier motion operates over a much larger scale. To reconcile the data from both experiments we will add a parameter to our model that corresponds to the actual size of the region of summation.

We start by computing the extent E of the stimulus, where $E = NS$ (where N is the number of elements shown.)

We replace the carrier motion summation term $M_S = \beta_S \frac{C}{S}$ with a term that accounts for a constant width$W$ of the summation region and the variable extent E of the stimulus. If we add the carrier motions coming from one region

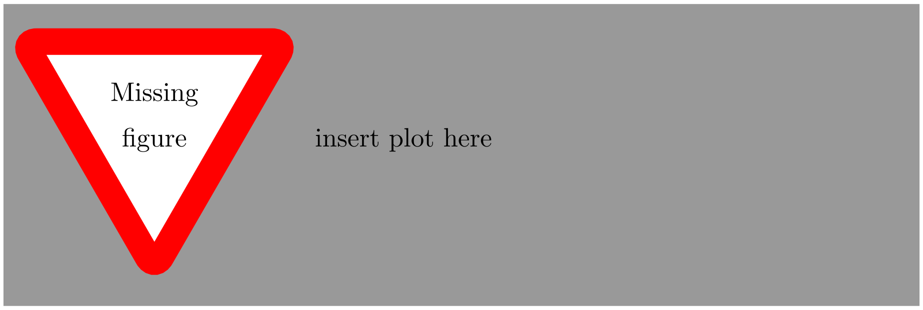

Figure 6: Predictions from a model combiningh the data for two observers. The model here fits values from both **??** and Experiment 2, with an extra parameter added corresponding to the extent of the stimulus.

in space centered on the stimulus.

$$M_S = \beta_S \frac{C}{S} \mathrm{softmin}_\sigma \left(E, W\right)$$

Here $\mathrm{softmin}_\sigma \left(x, y\right) = -\frac{1}{\sigma} \log\left(e^{-\sigma x} + e^{-\sigma y}\right)$ is a function that approximates minimum of its two arguments while remaining smoothly differentiable. The parameter σ is an aid to model fitting which controls the "sharpness" of the approximation to min; as $\sigma \to \infty$, $\mathrm{softmin}\left(x, y\right) \to \min\left(x, y\right)$.

We also considered alternative models including local summation of carrier motion, and a parameterization of˘†e effective size the region of interference for envelope motion, but the present model appeared to fit the data the best.

As an empirical check on the model fit, we cast the parameter E to a discrete factor, with a number of the model to one in which the stimulus extents are grouped into 5 values, and add four linear terms $\beta_{S,i} E \delta_i$ where the $\delta_i$are dummy variables coded with reverse Helmert contrasts; this effectively fits a piecewise linear function of carrier sensitivity depending on stimulus extent. This allows us to capture how much summation there is for each size of the stimulus, and compare to the model parameterization. Results from this procedure are shown in Figure 7; the curved line corresponds to the fitted model parameterized by the field size, while the segmented line with error bars corresponds to the piecewise check. The vertical line corresponds to the size of the integration field that is fit by our model.

With the addition of this single parameter for the size of the summation region, a single model makes a good fit to data from both Experiment 1 and Experiment 2. The predictions from this model for two observers are shown in and hte entire set are shown in the appendix.

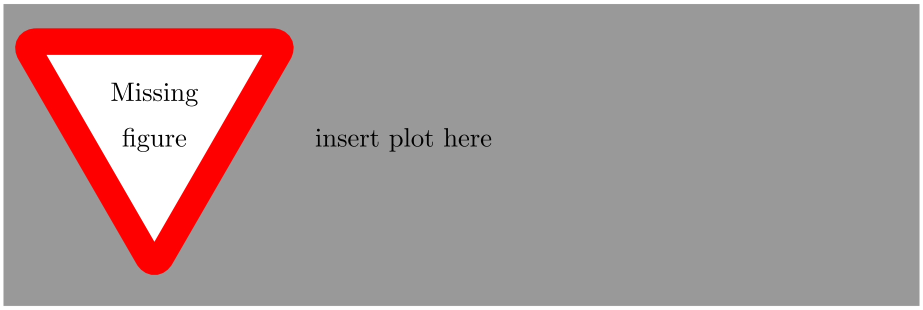

Figure 7: Sensitivity to carrier strength as a function of the stimulus extent E. This is the sum of contributions of the terms $\beta_{I_A} C$ and $\beta_I /$ The first term contributes a constant repulsion effect, causing the sensitivity to weak carrier motion to be negative for most stimuli. while the second adds more energy as the. The "knee" in the fitted curve corresponds to the size of the field over which carrier motion is summated; the vertical line shows this coefficient and the surrounding shaded region its standard error. Two observers are shown here, with the complete set shown in the appendix.

References

[1] Chengzhi Feng, Yi Jiang, and Sheng He. Horizontal and vertical asymmetry in visual spatial crowding effects. *J Vis*, 7(2):13.1–10, 2007.