1 Model details and motivation

A schematic explanation of our model is shown in figure 1. Conceptually the model combines three signals to produce decisions about motion direction: M_s is a sum of first order motion energy inside a relatively restricted region (shown by the smaller dashed circle), $\bar{\Delta_x}$ is an estimate of the change of position of a tracked target, within the same restricted regionM_I is a repulsion due to first order motion signals integrated across a wider region of space (shown by the larger dashed-dotted circle).

For M_S, we begin by assuming that the strength of the local motion signal is linear with respect to carrier direction content C. However, as spacing decreases and there are more elements within the summation region, we expect signals from to sum, so that the local motion signal is proportional this carrier motion signal to become stronger, as follows.

$$M_S = \frac{C}{S}$$

For dX, we assume that envelope motion is computed by taking two successive noisy estimates of the position of a given element. The strength of the envelope motion estimate therefore has uncertainty directly proportional to the uncertainty, of the successive position estimates. The sensitivity to displacements, β_{Δ_x} will be inversely proportional to this uncertainty. We assume that as flanking elements come closer to the tracked element, they will interfere with the visual system can select a single tracked element, so the sensitivity to changes in position will collapse. We model this by making $\beta_{\Delta_x}(S)$ a sigmoid function of the spacing between elements (figure 1): :

$$\beta_{\Delta_x}(S) = \beta_0 \left(2 - \frac{2}{1 + e^{-\frac{S_C}{S}}} \right)$$

This function results in sensitivity that approaches β_0 at large spacings and approaches zero at small spacings, as plotted in the lower graph of figure 1. β_0 is the sensitivity to envelope displacement for uncrowded targets; S_C describes the distance over which spatial interference between targets takes place. S_C has a natural interpretation as the spacing at which the threshold for discriminating a feature (in this case envelope motion) doubles, which is often used as an empirical definition of the "critical distance" in crowding. As can be seen from this function, our model assumes that sensitivity to envelope motion approaches an asymptote above Sc, and therefore does not change as a function of the number of targets, once the targets are sufficiently far apart.

In other words, decreasing the spacing between elements has opposite effects on the strengths of the carrier and the envelope motion. For the carrier motion estimate, cramming more elements into the summation region increases the strength of the carrier motion signal, which is a simple summation of local motion within that region. For the envelope motion estimate, cramming more elements into the summation region makes it difficult to estimate the position

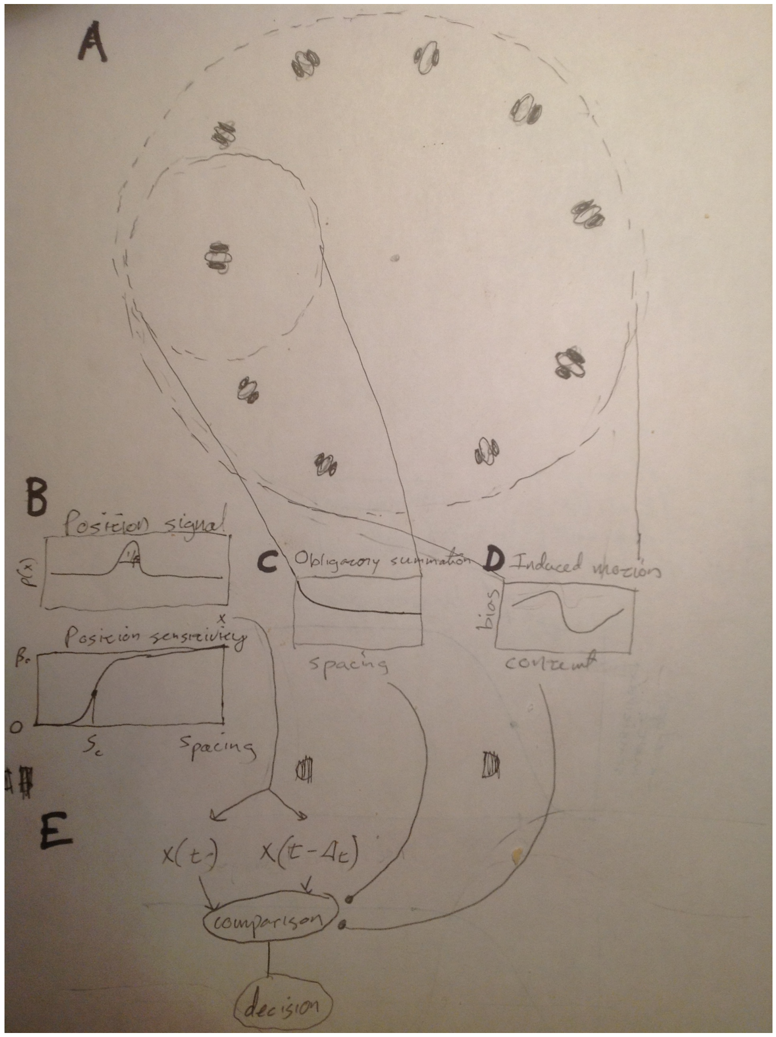

Figure 1: Schematic of motion model. (A) A typical motion stimulus is shown. The dotted circle indicates a local summation region . (C) Envelope motion is estimated by taking two successive noisy estimates of the position of a given element. Due to “crowding” the uncertainty in position $1/\beta(S)$ increases as a function of the flanker spacing S EQ here. The form of $\beta(S)$ is an sigmoid, as plotted, in Panel XX. Its parameters are β_0, reflecting the sensitivity in position of an uncrowded target, and S_C, which is the distance at which discrimination thresholds for envelope motion double. (B) The carrier motion estimate is a simple summation of the local motion energy within the summation region. This signal is inversely proportional to the element spacing . (D) Motion repulsion is assumed to be proportional to the global integration of carrier motion outside the region of interest. The strength of this signal is an odd-symmetric function of direction content. (E) The decision rule is modeled as a single logistic cumulative distribution function combining these three estimates of motion.

of any individual element, and thereby weakens the signal. Thus, decreasing the spacing results in carrier motion having a stronger influence on the final percept.

One addition to this basic model is required to account for the effect of first order motion signals outside our small summation region. The third component M_I is an "induced motion" effect, whereby the perceived direction of motion of an attended target is also influenced by the motion of the full display. The influence of this process is generally repulsive; carrier motion outside the integration field biases observers towards perceiving the motion of individual elements as being in the opposite direction. We modeled this using a function defined as:

$$M_I = n \cdot f_R(C)$$

where n is the number of targets outside the receptive field, and f is an odd-symmetric function of direction content which uses up a parameter R; I haven't quite worked out the best parameterization yet.. Note that in the case of section §**??**(basic experiment) we can treat n as just being inversely proportional to s, but in section §**??**number/density experiment) we vary these quantities independently.

We then combined these three types of motion information with a simple decision rule;

$$\Pr\left(\text{clockwise} \mid \Delta x, C, s, n\right) = \text{logit}(\beta(S)\Delta_x + \beta_S M_S + \beta_I M_I + c)$$

where $\text{logit}(r) = \left(1 + e^{-r}\right)^{-1}$ is the standard logistic cumulative distribution function. The free parameters of the model are β_0, S_C, β_S, β_I, and R. We only use c as necessary account for an overall clockwise or counterclockwise bias; for subjects with no such bias we use $c = 0$.