Supplemental materials

Details of the PAPA model

Stimuli are defined by the x and y-coordinates of their horizontal and vertical bars, denoted (for the target) as \((x_{tH},y_{tV})\) and \((x_{tV},y_{tV})\) and (for the flanker) as \((x_{fH},y_{fH})\) and \((x_{fV},y_{fV})\). For an interference zone with width \(\sigma_a\) and length \(\sigma_y\) (free parameters #1 and #2) we compute a pair of distance measures between the locations of the near-collinear and parallel bars. For end-flankers these are

\[
d_{\text{colinear}} = d(x_{t,V},y_{t,V},x_{t,V},y_{t,V}) \quad \text{and} \quad d_{\text{parallel}} = d(x_{t,H},y_{t,H},x_{t,H},y_{t,H})
\]

and for side-flankers they are:

\[
d_{\text{colinear}} = d(y_{t,H},x_{t,H},y_{f,H},x_{f,H}) \quad \text{and} \quad d_{\text{parallel}} = d(y_{t,V},x_{t,V},y_{f,V},x_{f,V})
\]

where \(d()\) is a two-dimensional Gaussian weighted measure of distance:

\[
d(a_1,b_1,a_2,b_2) = \exp\left(\frac{(a_1 - a_2)^2}{2\sigma_x^2}\right) \exp\left(\frac{(b_1 - b_2)^2}{2\sigma_y^2}\right)
\]

From these measures we compute, on a trial-by-trial basis, the magnitude of crowding, independently for collinear and parallel features, e.g.:

\[
w_{\text{colinear}} = \begin{cases} w_{\text{average}} (1 - d_{\text{colinear}}) & U(0,1) < w_{\text{prob}} (1 - d_{\text{colinear}}) \\ 0 & \text{otherwise} \end{cases}
\]

where \(U(0,1)\) is a uniform random variable in the interval (0,1), \(w_{\text{peak}}\) is a free parameter (#4) that – in combination with the distance measure - weights the probability that crowding will occur \(w_{\text{average}}\) is a free parameter (#3) modulating the strength of the interference zone on the magnitude of crowding. Having computed the weighting parameters \(w_{\text{colinear}}\) and \(w_{\text{parallel}}\) for the influence of the flanker, we compute the predicted position of the critical features within the crowded target using a standard weighted average. For end-flankers these are:

\[
x_{\text{colinear}} = w_{\text{colinear}}(x_{t,V} + N(0,\sigma_{\text{noise}})) + (1 - w_{\text{colinear}})(x_{t,V} + N(0,\sigma_{\text{noise}}))
\]

\[
y_{\text{parallel}} = w_{\text{parallel}}(y_{t,H} + N(0,\sigma_{\text{noise}})) + (1 - w_{\text{parallel}})(y_{t,H} + N(0,\sigma_{\text{noise}}))
\]
where \( N(0,\sigma_{\text{noise}}) \) refers to a normal deviate with zero-mean and standard \( \sigma_{\text{noise}} \) which sets the level of additive noise applied to the encoding of bar-position (free parameter \#5). Note that when \( w_{\text{colinear}} \) falls to zero, these expressions return the original target-bar locations (corrupted only by additive noise). For a side-flanker predicted bar-locations are:

\[
x_{\text{parallel}} = w_{\text{parallel}} (x_{f,V} + N(0,\sigma_{\text{noise}})) + (1 - w_{\text{colinear}}) (x_{t,V} + N(0,\sigma_{\text{noise}}))
\]

\[
y_{\text{colinear}} = w_{\text{colinear}} (y_{f,H} + N(0,\sigma_{\text{noise}})) + (1 - w_{\text{colinear}}) (y_{t,H} + N(0,\sigma_{\text{noise}}))
\]

Finally, in order to generate a predicted response from these position measures we determine the quadrant that their resulting angle (the arctangent of the \( y \) and \( x \) values) falls into and classify the result as an upwards, rightwards, leftwards or downwards facing 'T' accordingly.