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 \((x_{t,H},y_{t,H})\) and \((x_{t,V},y_{t,V})\) and (for the flanker) as \((x_{f,H},y_{f,H})\) and \((x_{f,V},y_{f,V})\). For an interference zone with width \(\sigma_x\) 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

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

and for side-flankers they are:

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

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

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

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:

\[
\begin{align*}
    x_{\text{colinear}} &= w_{\text{colinear}} (x_{t,V} + N(0,\sigma_{\text{noise}})) + (1 - w_{\text{colinear}}) (x_{t,V} + N(0,\sigma_{\text{noise}})) \\
    y_{\text{colinear}} &= w_{\text{colinear}} (y_{t,H} + N(0,\sigma_{\text{noise}})) + (1 - w_{\text{colinear}}) (y_{t,H} + N(0,\sigma_{\text{noise}}))
\end{align*}
\]

\[
\begin{align*}
    x_{\text{parallel}} &= w_{\text{parallel}} (y_{t,V} + N(0,\sigma_{\text{noise}})) + (1 - w_{\text{parallel}}) (y_{t,V} + N(0,\sigma_{\text{noise}})) \\
    y_{\text{parallel}} &= w_{\text{parallel}} (x_{t,H} + N(0,\sigma_{\text{noise}})) + (1 - w_{\text{parallel}}) (x_{t,H} + N(0,\sigma_{\text{noise}}))
\end{align*}
\]
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:

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

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

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.