Figure 1. A simulation of the dynamic field theory performing one spatial recall trial. In each panel, location is across the x-axis, activation on the y-axis, and time on the z-axis. The model consists of seven layers: (A) a perceptual field in an egocentric reference frame; (B) a system that transforms locations from egocentric to an object-centered frame; (C) a perceptual field in the object-centered reference frame; (D) a long-term memory field associated with this perceptual field; (E) a shared layer of (inhibitory) interneurons; (F) a spatial working memory field in the object-centered reference frame; (G) a long-term memory field associated with the spatial working memory field. Green arrows show excitatory connections between layers, and red arrows show inhibitory connections between layers. Brackets describe the behavioral functions of subsets of the layers. See text for additional details.
Figure 2. The “spaceship” table used in our laboratory. Two dots mark the midline symmetry axis, which corresponds to 180° in the model, with 90° to the right and 270° to the left. A sample triangular “spaceship” target is shown at 220°.
Figure 3. Two mathematical functions that govern neural interactions in the DFT. (A) A local excitation/lateral inhibition function where neurons that code for similar locations excite one another (positive activation) while neurons that code for dissimilar locations inhibit one another. (B) A sigmoidal function that determines which neurons participate in interaction: highly active neurons contribute fully to interaction (weighted by 1), while inactive neurons do not participate (weighted by 0).
Figure 4. The dynamics of the DFT yield qualitatively different attractor states. The simulation in the left column shows the self-sustaining “on” state. The target (T) is presented at 220° in an input field (A), which leads to a peak of activation in the SWM field (B), which is sustained during the memory delay (see oval) via locally excitatory and laterally inhibitory interactions with the inhibitory field (C). Because the system is close to the transition between the “on” and “off” states with this parameter setting, the simulation in the right column shows a spontaneous bifurcation to the “off” state during the memory delay (see oval in (E)) with the same parameters and input (see (D)). In each panel, location is across the x-axis, activation on the y-axis, and time on the z-axis. Arrows indicate excitatory (green) and inhibitory (red) connections among layers.
Figure 5. Reference frame calibration and re-alignment in the DFT. On the first trial (left column), activation from the reference frame (R) is originally presented at 180° in the egocentric perceptual field (A). Across eye movements (indicated by arrows in (A)) the reference frame and target inputs (T; presented 40° from the reference) shift; this shift in the egocentric frame is corrected (B) to bring the reference frame input into 180° in the object-centered perceptual field (C). The continued activation of the object-centered reference frame leaves a trace in long-term memory (D). The second trial (right column) begins with a resting level boost (h-boost in (G)), which creates a peak in the object-centered field (G) due to input from long-term memory (H). After a brief interval when the shift mechanism is off (F), reference input in the egocentric perceptual field (E) is re-aligned (F) with the reference from the previous trial. Axes and arrows are as in Figure 4.
Figure 6. Spatial working memory within a stable reference frame. The perceptual field (A) maintains the reference frame (R) throughout the trial, leaving an inhibitory trace in (B). The target (T), presented at 220°, forms a self-sustaining peak in SWM (C); this peak drifts away from 180° (see “drift” in (C)) over delay due to the inhibition associated with the reference frame. In contrast, when the target is presented at 180° (right column), activation from the reference frame in the perceptual field (D) aligns with the target peak in SWM (F); this peak does not drift over delay (see (F)). Rather the peak is stabilized by excitatory input (green arrow) from the perceptual field (D). Axes and arrows are as in Figure 4.
Figure 7. Integration of short-term and long-term spatial memories in the DFT. On the first trial (left column), the perceptual field (A) maintains the reference frame (R) throughout the trial. Activation from both the target (T) and the reference leave traces in the associated long-term memory field (B). The target, presented at 240°, forms a self-sustaining peak in SWM (C), which drifts away from midline over delay. The peak in SWM leaves a trace of activation in the associated long-term memory field (D). By the third trial (right column), the repeated activation from the reference frame in the perceptual field (E) has left a robust memory for the reference in long-term memory (F). The target, presented at 220°, still drifts away from midline in SWM (G), but now long-term memory (H) shows traces of three target locations—an experience-dependent spatial category. Axes and arrows are as in Figure 4.
Figure 8. Position discrimination in the DFT. In the left column, two stimuli (S1 & S2) are presented at 180° in quick succession (A). S1 leads to a trough of inhibition (B) and a peak in SWM (C). When S2 is presented in the same location, activation is maintained in SWM (C), leading to a same peak, and suppressed in the perceptual field (A). In the right column, the stimuli are presented in different locations (D). Because S2 falls outside of the inhibited region in the perceptual field (D) created by the peak in SWM (F), S2 builds a different peak in the perceptual field (D) which suppresses activation in SWM (F). Axes and arrows are as in Figure 4.
Figure 9. Illustration of the spatial precision hypothesis. Early in development (black line) interaction is broad and primarily excitatory. Later in development (light grey line) excitation is narrower and stronger with stronger lateral inhibition. Intermediate lines show the hypothesized gradual nature of this change over development.
Figure 10. Developmental change in geometric bias in the DFT. When the target (T) is presented at 220° (A), the ‘child’ model (left column) forms a broad, self-sustaining peak in SWM (C) due to broader and weaker neural interactions early in development. During the delay, the reference input does not create a sustained reference peak in the perceptual field (A). Consequently, the peak in SWM is attracted toward midline (C) due to excitatory input (green arrow) from the perceptual field (A). The right column shows a simulation of the ‘adult’ model drifting away from 180° (F) for comparison (see left column of Figure 6). Axes and arrows are as in Figure 4.