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SPAM-Ling: A Dynamical Model of Spatial Working Memory and Spatial Language

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Abstract

Spatial language is an ideal domain to examine perceptual-motor and language integration precisely because it is an unambiguous case of these systems coming together. To date, however, researchers in this domain have made little headway in understanding the real-time processes underlying spatial language behaviors. Here, we describe a dynamical systems model—SPAM-Ling—that integrates the real-time processes that underlie spatial working memory and the use of spatial prepositions in a canonical “above” ratings task. Comparisons between empirical data and model simulations demonstrate the effectiveness of this approach. We conclude by highlighting several novel predictions of the model that we are currently testing in our laboratory.

How Do Sensory-Motor and Linguistic Systems Interact?

Understanding how the sensory-motor and linguistic systems interact is a central issue in cognitive science. Spatial language is an ideal domain to explore the relationship between these systems because it brings language and space together. To date, two general approaches to representation speak to this interaction in spatial language (Barsalou, 1999): amodal symbolic systems and perceptual symbol systems.

Amodal symbolic systems presume representational independence between symbolic processes like language and sensory-motor systems (Harnad, 1990). As a result of this strong separation, amodal systems require a transduction process that permits “communication” between these separated systems.

Barsalou’s Perceptual Symbol Systems (1999) approach contrasts with this transduction-based, amodal approach by positing inherently grounded perceptual symbols. These perceptual symbols are “records of neural states that underlie perception” (p.583) and are both in the given sensory modality and capable of replicating the flexible, productive, hierarchical capacities of traditional symbolic systems.

Although both approaches to the interaction of sensory-motor and linguistic systems have received support, there are two critical limits of these proposals. First, they largely rely on descriptive, conceptual accounts of representational

structure. Such descriptive accounts are, of course, critical to theory development, but their potential flexibility makes them difficult to empirically falsify. The second limitation is that both approaches focus on representational structure in the abstract. Spatial language studies have tended to focus on the nature of representational structure rather than the second-to-second processes that give rise to those representations. This can lead to a theoretical impasse because the empirical probes of the underlying representational structures are not strongly grounded in real-time, task-specific performance. We contend that it is critical to understand these real-time processes if we are to make headway on the challenges inherent in integrating “higher” cognitive and sensory-motor systems.

Spatial Language: An Empirical Impasse

Consideration of an ongoing debate within spatial language illustrates the limitations discussed above. To examine the correspondence between linguistic and sensory-motor spatial representations, Hayward and Tarr (1995) conducted a series of experiments comparing linguistic and sensory-motor spatial representations. Based on preposition use, ratings of the applicability of spatial prepositions to visual displays, location memory performance, and same-different discrimination judgments, Hayward and Tarr concluded that linguistic and sensory-motor systems depend on the same representational spatial structure, a result consistent with Barsalou’s PSS approach. In particular, results suggested that people use spatial prototypes aligned with the cardinal axes in the task space.

Subsequent work by Crawford, Regier, & Huttenlocher (2000) probing both linguistic ratings and visual representations of space presented a different picture. For instance, although people rated, that prototypical “Above” was aligned with the vertical axis as in Hayward and Tarr (1995), Crawford et. al. also found evidence of a location memory bias away from the vertical axis in a location memory task when targets appeared to the right and left of this axis. To account for these memory biases away from the vertical axis, Crawford et al. posited that spatial category prototypes lie along the diagonal axes in the task space. Consequently, responses in the memory task are biased toward these prototypes and away from the vertical

axis. This proposal is consistent with the Category Adjustment (CA) model (Huttenlocher et al., 1991). Considered together, the results from Hayward and Tarr and Crawford et al. illustrate the limits of dealing with representation in the abstract: both sets of researchers used similar experimental tasks and reported largely similar findings, yet they draw starkly different conclusions, conclusions that depend critically on abstract definitions of representational structure (in this case, prototypes).

Why might this be the case? We contend that because the real-time processes underlying spatial memory and ratings generation are not specified, it is difficult to make precise predictions about performance across tasks that delineate between the two accounts of spatial language and its relationship to spatial memory. This failure to reach a satisfactory resolution mirrors the larger failure to resolve the modal-amodal conflict. In both cases, the current empirical data fail to delineate the proposed accounts.

Shared Processes in Language and Memory

In attempting to synthesize these competing accounts, we observed a subtle but critical methodological difference between the typical ratings and spatial memory tasks. Unlike the spatial memory task, in which participants generated their response when the target was absent, ratings responses could be generated while the target was visible.

In light of this task difference, the obvious question is whether spatial language might exhibit a performance profile similar to that of spatial memory once this time-dependent methodological difference is taken into account. To the extent that spatial language and spatial memory exhibit similar time-dependent signatures, it would suggest that they rely on a shared set of real-time processes. This would be consistent with the spirit of Barsalou's PSS proposal. If, on the other hand, there are minimal similarities in performance across the memory and ratings tasks even after we take the real-time processing considerations into account, it would suggest that the methodological difference was merely incidental and that spatial language and spatial memory are nonetheless representationally distinct.

To answer this question, we tested whether the processes that create delay-dependent biases in spatial memory might also leave some empirical signature in a spatial language task. The data presented are from a single experiment previously reported. Because they are indicative of the general findings and have been replicated across several variations (e.g. Lipinski et al., 2005), we simply present the general results. All effects discussed are significant ($p < .05$).

Empirical Evidence: General Methods

Participants sat at a large table with a homogeneous surface. A compute mouse was placed on the table directly to the participant's right. A projector underneath the table projected the stimuli onto the table surface. Experimental sessions were conducted in dim lighting in a room with

black curtains covering all external landmarks. A curved border occluded the corners of the table (and therefore the diagonal symmetry axes).

A single referent disc appeared along the vertical axis 30cm in front of the participant and remained visible throughout each presentation trial. At the start of each trial the participant moved a cursor to this disk. A number (100-500) then appeared and participants begin counting backwards by 1s aloud until they made a response. This counting task prevented the verbal encoding of the task. A small, spaceship-shaped target then appeared on the screen for two seconds.

For spatial memory trials, participants were instructed to move the cursor to the location corresponding to the ship's location when the computer says "Ready-Set-Go". For spatial language rating trials, on the other hand, participants were instructed to rate on a scale of 1 ("definitely not above") to 9 ("definitely above") the extent to which the word "above" described the spaceship's location relative to the reference disk and say their rating when the computer said "Please give your 'Above' rating." The spoken stimuli that indicated which response to provide were each 1500ms in duration. In No Delay conditions, completion of the spoken stimulus was timed to coincide with the offset of the spaceship target. In the 10s Delay conditions, completion of the spoken stimulus occurred exactly 10 seconds after the disappearance of the target. Spaceship targets appeared at a constant radius of 15cm at 19 different locations relative to the vertical axis (0°): every 10° from -70° to $+70^\circ$ as well as $\pm 90^\circ$ and $\pm 110^\circ$. Responses to the $\pm 110^\circ$ targets were not formally analyzed because they were at the extremes of the task space.

Empirical Evidence: General Results

Consistent with previous findings, we expected that spatial language ratings would be highest for targets that appear along the vertical axis (centered at 0°) and fall off systematically as the target locations shifted to the left or right of this axis. Beyond these established findings, however, we also conjectured that ratings provided after a 10s delay should show a delay-dependent "drift" away from the vertical axis analogous to spatial memory "drift" away from this axis. In particular, we expected that ratings would be systematically lower after a 10s delay relative to ratings produced immediately after target offset. Why might this be the case? Given that location memories drift away from the vertical axis, they also drift away from the prototypical "Above" location at that axis. If ratings and memory processes are integrated in real-time, then ratings produced after a delay should reflect this memory drift away from prototypical "Above" and yield lower ratings. Recall that Crawford et al. used the memory drift effect to differentiate non-linguistic prototypes at the diagonals from linguistic prototypes along the cardinal axes. If ratings exhibit the analogous "drift" effect over delay, then memory biases can no longer be used as an index of linguistic and non-linguistic spatial prototypes; the ratings drift effect would

constitute a bias in the direction away from the “Above” prototype. Indeed, if prototypes truly underlie delay-dependent biases as the CA model predicts, then “Above” ratings should exhibit bias towards the prototype and increase over the delay.

The top portion of Figure 1 shows the effect of delay on spatial memory, with the dotted line representing responses in the 10s delay condition and the solid line representing no delay responses. Positive values reflect errors away from the vertical axis. Overall, the elevated dotted line indicates that spatial memories were biased away from the vertical axis over the delay, particularly for targets appearing just to the right or left of the vertical axis (e.g., the $\pm 10^\circ$ - 50° targets).

The bottom portion of Figure 1 shows the effect of delay in spatial language ratings, with the dotted line representing responses in the 10s delay condition and the solid line representing no delay ratings. Critically, ratings were significantly lower after a 10s delay, suggesting that spatial language ratings are indeed subject to the same delay effects manifest in spatial memory.

SPAM-Ling: Towards Integration

At the broadest level, we have argued that an understanding of the integration of sensory-motor and linguistic systems depends heavily on sensitivity to real-time performance characteristics. Our empirical examination of spatial memory and spatial language supports this broader argument. Critically, however, we need to specify the real-time processes at work in these tasks in a way that can both account for the current data and yield testable predictions. Thus, in the next section we describe a new model—SPAM-Ling—that integrates the dynamics of Spatial Planning And Memory with Linguistic processes.

SPAM-Ling: An Overview

SPAM-Ling is a neural network that builds on the Dynamic Field Theory (DFT) originally proposed by Thelen et al. (2001) to explain reaching errors in infancy and extended by Spencer, Schutte, and Schöner to explain the development of spatial working memory beyond infancy (Schutte, Spencer, & Schöner, 2003; Spencer & Schöner, 2003). This new model captures the empirical effects described above and makes novel predictions regarding the influence of enhanced perceptual structure and spatial language semantics on spatial working memory.

SPAM-Ling consists of 4 dynamically coupled layers (see Figure 2): a Perceptual Field that is primarily input driven and in an egocentric frame of reference (ID_{ego} ; Fig.2A), an object-centered Spatial Working Memory Field (SWM_{obj} ; Fig. 2C), an associated Long Term Memory Field that is also in the object-centered frame (LTM_{obj} ; Fig. 2D), and a layer of localist Word neurons (Fig. 2E).

To see how this model captures performance on a single 10 s delay trial from the ratings task, consider the simulation in Figure 2. On this trial, we presented a target 30° to the right of the reference dot along the vertical axis.

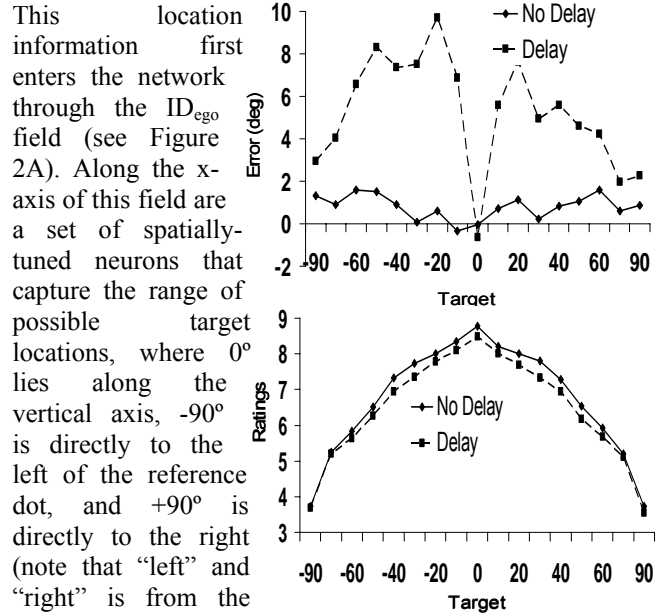


Figure 1. See text for details.

This location information first enters the network through the ID_{ego} field (see Figure 2A). Along the x-axis of this field are a set of spatially-tuned neurons that capture the range of possible target locations, where 0° lies along the vertical axis, -90° is directly to the left of the reference dot, and $+90^\circ$ is directly to the right (note that “left” and “right” is from the participant’s perspective and is reversed in the present picture to show how activation changes during the memory delay). Time, from the start of the trial at 0 s to the end of the trial at 10 s, is on the y-axis, and activation is on the z-axis. The spike of activation at the 30° location in the ID_{ego} field reflects the brief visual input at this target location in the task space.

This input is passed to SWM_{obj} via the reciprocal coupling between SWM_{obj} and the ID_{ego} perceptual field. Because the ID_{ego} and SWM_{obj} fields code location in different reference frames, there must be a dynamic process that aligns these reference frames and keeps them calibrated. This alignment is captured by a dynamical system with fixed-point dynamics captured here by the Δy parameter (Fig. 2B). This parameter maintains a simple translational shift between the two fields.

To capture the characteristics of spatial working memory, location-related information is maintained in the SWM_{obj} field via the dynamic interaction among neurons in

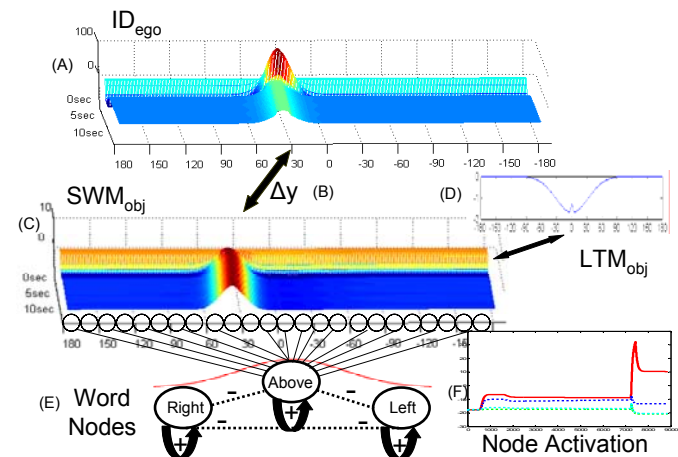


Figure 2. See text for details

this field. In particular, neurons in SWM interact according to a local excitation/lateral inhibition function, consistent with neurophysiological data. The result of this interaction over time is that highly active neurons that code for similar locations excite each other while simultaneously inhibiting neurons that code for more distant locations. The self-excitatory nature of local excitation coupled with broad lateral inhibition allows activation peaks in SWM_{obj} to maintain themselves through time, even in the absence of input from the world (e.g., during the delay period in Figure 2). Although the SWM_{obj} field maintains a memory of the target location, the peak in Figure 2C drifts systematically during the delay away from 0°, that is, away from the 30° target location in a clockwise manner. The location with the maximum activation at the end of the trial corresponds to the remembered target location.

In a spatial memory task, SPAM-Ling must capture the delay-dependent memory drift away from the vertical axis. SPAM-Ling accounts for this memory drift through a strong inhibitory long-term memory trace around 0° in the object-centered LTM_{obj} field which is reciprocally coupled to SWM_{obj} (Fig. 2D). This memory trace around 0° reflects activation associated with the vertical symmetry axis of the task space. Note that this trace has an inhibitory trough for locations to the right and left of the vertical axis. As a consequence, neurons on the side of the activation peak closest to the vertical axis will tend to be inhibited. This biases the dynamics of the target activation profile, pushing the peak (and thus the memory) away from the vertical axis over delay. Note that this formalized process accounts for spatial memory bias away from reference axes without positing prototypes (Spencer & Schöner, 2003; Schutte, Spencer, & Schöner, 2003). Thus, contra the CA model, one need not infer the influence of prototypes to account for delay-dependent biases in spatial memory.

SPAM-Ling: Simulating Spatial Memory

To simulate spatial memory performance, we ran a single trial simulation for each individual target (0, ±10, ±20, ±30, ±40, ±50, ±60, ±70, ±90) for both the no delay and 10s delay conditions. Each simulation began with a 200 time step (ts) relaxation period. To map the real-time processes of spatial memory and spatial language onto the SPAM-Ling simulations, each subsequent time step (ts) in the model corresponded to 1.5ms in real time. For example, the 2s target presentation time in the experiment was modeled with a 1333 ts model presentation time (1333ts X 1.5 ms/ts= 2000ms). Responses for the no delay condition were made following a 1s response preparation and execution interval (relaxation (200ts) + stimulus presentation (1333ts) + response preparation and execution (667ts)). The remembered target location was indicated by the spatially coded neuron with the maximum activation at the end of the trial. For 10s delay simulations, model execution was terminated at 8867ts: relaxation (200ts) + stimulus presentation (1333ts)+ response delay (6667ts)+ response preparation and execution (667ts).

Because the dynamic processes of SPAM-Ling operate symmetrically across the right and left sides of the task space, the empirical data presented in the following simulation figures reflect the

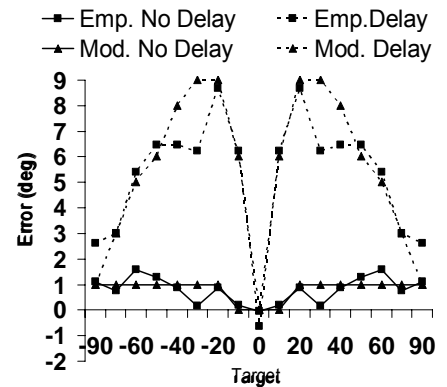


Figure 3. See text for details

the averaging of corresponding target values across the right and left sides (e.g. both the -10° and +10° error values in Figure 3 are set to the average of the observed -10° and +10° values). The data point for each target simulation corresponds to the location of the maximally active neuron at the end of the trial. Positive values reflect errors away from the vertical axis while negative values reflect errors towards the vertical axis.

Figure 3 compares results from our simulations of the model with the previous empirical observations. The x-axis indicates the target location and the y-axis represents memory error. Lines with square data-point markers represent the empirical data. Lines with triangular data-point markers, on the other hand, represent the SPAM-Ling simulated errors. The solid lines correspond to the no delay trials while the dotted lines correspond to the 10s delay trials. Positive errors signify errors away from the vertical axis.

For the empirical no delay results (solid line with square markers), we again see minimal error over all the target locations. Consistent with these observations, SPAM-Ling yielded uniformly low spatial memory errors. In addition, all errors were positive as was the case with the empirical results. Across all targets, results from these no delay simulations deviated from the empirical data by only .39° with a maximum deviation of 1.09°.

Critically, simulation results of the 10s delay also reveals a strong overall similarity between the empirical and simulated results. Specifically, the difference between the empirical and simulated errors for the 10s delay trials was less than 1° for 11 of the 17 targets. Although there were some larger deviations at the ±30° and ±40° targets, the average absolute difference between the simulated and empirical results was only 0.93°. This low deviation is particularly notable given the strongly non-linear profile of delay-dependent memory drift. This correspondence, considered together with the no delay simulations, indicates that SPAM-Ling can accurately capture spatial memory performance with and without delay.

SPAM-Ling: Integrating Spatial Semantics

To bring spatial language and spatial working memory together, we have integrated the spatial working memory

layer with a connectionist-style localist Word layer (Fig. 2E). Each node in this layer represents a single spatial language term (e.g., “above”). Figure 2 shows three nodes from the model (“Below” is not shown though it was included in all simulations). The nodes are mutually inhibitory. In addition, each node has a self-excitatory connection and can also receive excitatory input from external speech. Note that these are bi-stable word neurons that can sustain inputs in WM using dynamics similar to those present in the SWM field. Thus, each word node has the capacity to maintain excitation even when the target is no longer present.

Each node is reciprocally coupled to the SWM_{obj} field through a set of spatially-specific connection weights centered on the prototypical spatial location for that word. For instance, the “Above” node is coupled to the SWM_{obj} field through connection weights distributed according to a Gaussian distribution centered at 0° , the prototypical location for the “Above” relation in our task (see Figure 1). Similarly, the “Right” and “Left” nodes are coupled to the SWM_{obj} field through connection weights distributed according to Gaussian distributions centered at $+90^\circ$ and -90° , respectively (not shown). In the current implementation, each Gaussian has a variance of 60 units. These Gaussian distributions are hypothesized to emerge over development as children learn the statistics of spatial term use within an object-centered reference frame.

What are the functional consequences of coupling between the Word nodes and SWM? When the nodes receive input from SWM_{obj} , they become active and compete. A plot of node activations for the 30° ratings trial simulation (Fig. 2F, solid line) shows that the “Above” node quickly dominates. This domination arises for two reasons. First, we provide a 200ts burst of speech input to the “Above” node to elicit a ratings response. This burst mirrors the signal heard during the experiment (“Please give your Above rating”). The timing of this input in all simulations reflects the details of the experimental paradigm; thus, the stimulus presentation differed between the no delay (567 ts) and 10s delay conditions (7234ts). Coinciding with this speech input, the resting level of all the semantic nodes is raised. This elevation engages the entire spatial semantic network, allowing each node to become active, compete, and potentially enter a self-sustaining activation state.

In addition to the elevated node activation and the speech burst, the “Above” node dominance depicted in Fig. 2F is also facilitated by the memory peak at approximately 30° . At this location, the memory peak is most closely aligned with the “Above” node Gaussian centered at 0° , thus provided greater input to that node. Note, however, that because non-vertical targets tend to drift away from the vertical axis over memory delays, the alignment of the memory peak with the “Above” node Gaussian declines over delay and increasingly favors the competing “Right” or “Left” nodes. SPAM-Ling accounts for the delay-dependent ratings “drift” effect through this delay-dependent shift of node activation and node competition.

To get a closer look at how SPAM-Ling rating simulations work, Figure 4 depicts the activation level of all nodes (above=red, right=blue, left=aqua, below=green) when the target was presented at 30° in a no delay ratings trial. Note that the time steps are marked along

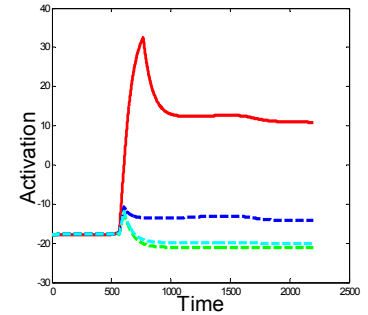


Figure 4. See text for details

the x-axis and activation level marked along the y-axis. At the beginning of the trial, the node activations are uniformly low. At 567ts the activation levels rise for all the nodes and the “Above” node (red solid line) additionally receives the speech input signal. These changes lead to sudden activation increases for all nodes, but especially for the Above node. After the input boost, the “Above” node then begins to suppress its competitors, thus driving down their activation. Nonetheless, the “Right” node (elevated dashed line) has a somewhat higher activation level. The elevated “Right” node activation level is due to the sustained peak of activation in SWM_{obj} near the 30° location which partially overlaps with the “Right” node Gaussian. Delayed ratings trials operate in a similar manner but with the delayed speech signal parameters.

To convert “Above” node activation to a linguistic rating, we first identified the largest node activation value across all targets and delay conditions (the 0° target in the no delay condition). Next, we scaled all the other node activations by this value, dividing each by the maximum activation. This converts activation values to a percentage of this maximum. Finally, we multiplied each activation level by 9.

Note that we were generally conservative in our approach to generating ratings of “Above”. In particular, all nodes were connected to SWM using the same Gaussian profile, just centered over a different prototypical value. In addition, we engaged the semantic network uniformly at the “go” signal. The only competitive advantage given to the “Above” node was the speech input which reflected the structure of the experimental paradigm. All other simulation details were identical across nodes. One advantage of this conservative approach is that it allows us to easily predict ratings performance in other tasks in which the to-be-rated word (e.g. “left”, “right”, “below”) is signaled only by the specific instructions given on each trial.

SPAM-Ling: Simulating Spatial Language Ratings

To simulate spatial language ratings performance, we again ran a single trial simulation for each individual target ($0, \pm 10, \pm 20, \pm 30, \pm 40, \pm 50, \pm 60, \pm 70, \pm 90$) for both the no delay and 10s delay conditions. Note that the only difference between the memory and ratings simulations was the engagement of the semantic network and the addition of the speech input: all ID_{ego} , SWM_{obj} , and LTM_{obj} field

parameters were identical across the memory and ratings simulations for both no delay and 10s delay trials.

Figure 5 compares ratings simulations for both the no delay and 10s delay conditions at all target locations with the previous empirical observations. The x-axis indicates the target location and the y-axis represents the rating. Lines with square data-point markers represent the empirical ratings. Lines with triangular data-point markers, on the other hand, represent the SPAM-Ling simulated ratings. The solid lines correspond to the no delay trials while the dotted lines correspond to the 10s delay trials. As with spatial memory simulations, we assume symmetry across the left and right sides. The empirical data shown are thus the average of the corresponding targets across the left and right sides.

The first observation is the strong correspondence between the empirical and simulation ratings profiles for both the no delay and delay conditions. Although the simulations are slightly higher for targets near the vertical axis, the overall shape suggests that SPAM-Ling effectively captures the core empirical spatial language ratings gradient. In addition to capturing this core behavior, SPAM-Ling captures the effects of delay. Examination of the empirical ratings shows a generally lower ratings gradient but also a tapering of those differences for the $\pm 70^\circ$ and $\pm 90^\circ$ target locations. Likewise, the simulations show generally lower ratings with delay as well as a reduced delay effect for the $\pm 70^\circ$ and $\pm 90^\circ$ targets, although the simulated delay effect for targets at and very near the vertical axis (0° , 10°) is somewhat underestimated. Overall, these simulation results for both the no delay and delay conditions indicate that SPAM-Ling can indeed capture the essential details of spatial language ratings behaviors.

Summary and Future Directions

In the present report, we used results from the domain of spatial language to show how emphasizing representational structure to the exclusion of real-time processes can lead to unresolved theoretical and empirical conflicts. Consideration of these real-time processes led to the discovery of a new empirical finding—language ratings “drift”—directly analogous to the well-established delay-dependent memory drift effect. To account for both of these findings, we introduced SPAM-Ling, a new dynamical systems model of spatial language and spatial memory. Results from a series of simulations showed that SPAM-Ling can account for both no delay and delay performance across the memory and ratings tasks. This is notable given the strongly non-linear performance profiles of both tasks as well as the marked performance differences between them. These results clearly demonstrate how taking real-time processes seriously can not only enhance our understanding of integration across systems, but also yield informative empirical outcomes.

Additional consideration of SPAM-Ling’s structure and real-time dynamics have led to several other novel predictions which we are currently testing. Chief among

these is the influence of feedback on location memory trials. According to the model, feedback about location memory performance should build up memory traces in the LTM_{obj} field. If SPAM-Ling is correct, then systematically erroneous feedback about target

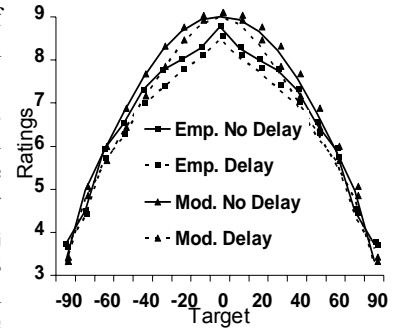


Figure 5. See text for details.

memory performance received only during the memory trials, should shift delay-dependent biases in the direction of that feedback for both the memory and ratings even though feedback was never provided during the ratings trials. Through these and related efforts, we hope to further establish SPAM-Ling as a model that can account for canonical spatial language and spatial memory performance and also generate novel, testable predictions about the real-time processes underlying the integration of sensory-motor and linguistic systems.

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