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Abstract

Normal aging is associated with an increase in word finding problems. Competing explanations posit that age impairs access to phonological representations (transmission deficit) or leads to a deterioration of semantic representations (under-activation). Because these accounts are difficult to disentangle in a highly interactive language system, we employed a neurobiologically grounded spiking network model which was lesioned to reflect transmission deficits or under-activation. Results of three simulated picture naming paradigms were in line with the transmission deficit account that normal aging impairs access to representations during word production. These initial findings suggest that this is a promising approach for understanding age-related changes to language ability in an interactive system.

Keywords: neural network; aging; neurobiology of language

Introduction

Normal aging is associated with an increase in word finding problems, which is one of the most common concerns of old age (Reese et al., 1999). One explanation of age-related word retrieval failure is the Transmission Deficit (TD) hypothesis, under which weakening of the connections between linguistic representations leads to problems retrieving complete phonology during word production (e.g., Burke et al., 2000). An alternative explanation is that normal aging leads to degradation of linguistic representations, in particular semantic representations (e.g., Verhaegen & Poncelet, 2013), so that they are under-activated during word retrieval. Understanding whether normal aging primarily affects access to phonology or impairs semantic integrity has important implications for cognitive aging, but it can be difficult to disentangle these mechanisms in non-computational interactive activation models of language. The aim of the current study is to compare the predictions of the TD and under-activation (UA) accounts in a neurobiologically-motivated spiking network model.

Word production declines in normal aging

Aging leads to increased word retrieval deficits, including increased numbers of dysfluencies in naturalistic speech, picture naming errors and temporary retrieval failures known as tip-of-the-tongue states (see Shafto & Tyler, 2014 for a review). The TD hypothesis explains these effects in an interactive activation model of language and memory called Node Structure Theory (NST; MacKay & Burke, 1990). In common with other localist connectionist models of language (e.g., Foygel & Dell, 2000), NST posits hierarchically organized interconnected representations. Word production involves first activating semantic representations, with activation cascading to lexical and phonological representations.
The TD hypothesis posits that age weakens connectivity between representations throughout the system. This differentially impairs phonological access during production because each of many top-down connections from lexical to phonological representations must succeed for a word to be produced. In contrast, while connections from semantic-to-lexical representations also weaken with age, the convergence of this activation supports lexical access, even in older adults. TD predictions are supported by priming studies where improving access to phonology reduces naming errors. For example, if participants cannot retrieve a word like *abdicate*, reading words with overlapping phonology (like *abstract*) improves naming by increasing the accessibility of the key phonology (James & Burke, 2000). In contrast, prior exposure to semantically-related alternatives (like *renounce*) does not improve recovery (e.g., Cross & Burke, 2004).

In contrast to a phonological access deficit, some researchers suggest age-related naming deficits are due to weak semantic activation caused by age-related semantic deterioration (Verhaegen & Poncelet, 2013). These researchers highlight evidence of age-related changes in semantic processing, including increases in semantic interference (Tun et al., 2002), semantic error rate (Goral et al., 2007), and difficulty in selecting between semantic alternatives (Britt et al., 2016). During word production, under-activation of semantic representations would initiate an impaired retrieval process ultimately meaning that lexical and phonological representations could not be successfully activated.

In an interconnected system like NST, it is difficult to disentangle semantic under-activation from weak connectivity leading to phonological access deficits. For example, there is evidence that impaired phonological access is associated with more semantically-related errors (Bormann, 2011), which could be taken as evidence for either position.

Using computational models to disentangle interactive mechanisms

While computational models of word production have not been widely applied to normal adult aging, they have been successfully applied to understanding speech error patterns in acquired aphasia (Foygel & Dell, 2000). However, the neural changes associated with normal aging are not relatively localized as in acquired brain damage, but are gradual and system-wide, including key language regions (Shafto & Tyler, 2014). Thus, in the current study we adopt two system-wide candidate mechanisms to represent transmission deficits and under-activation, respectively. First, we assume that age-related transmission deficits reflect demyelination of white matter tracts, in keeping with evidence that declines in white matter integrity in the superior longitudinal fasciculus, connecting frontal and temporal language centers, is associated with age-related increases in word finding problems (Stamatakis et al., 2011). Second, we assume that under-activation reflects a decline in neural spike generation due to calcium dysregulation, given evidence that normal aging has a disruptive effect on calcium buffering (Riascos et al., 2011). Specifically, aging is associated with an increase in the slow afterhyperpolarization (sAHP) current due to the accumulation of calcium in intra-cellular space, leading to an increase in the duration of the sAHP which ultimately results in a decrease in firing frequency (Scutt et al., 2015).

Current study

The aim of the current study is to use a neurobiologically grounded computational model to ask whether age-related word finding problems result from a decline in either representational access (particularly phonological access) or representational integrity (particularly affecting semantic activation). We instantiated a portion of NST in a spiking neural network (see Figure 1) and lesioned it either by reducing the weights between representations (TD hypothesis, demyelination) or by reducing neural excitability via an increase of the duration of the sAHP current (UA hypothesis, semantic degradation). We assessed phonological retrieval in healthy and lesioned simulations of a picture naming task, a phonological priming task, and a semantic priming task.

Methods

Spiking neural network model

Healthy model. To create a spiking network model, we replaced the representational nodes of NST with pools of spiking neurons (assemblies). Each assembly was composed of the same ratio of excitatory and inhibitory neurons (80% and 20%, respectively). Synaptic connections within each assembly and between any two assemblies were created using a probabilistic connectivity rule to ensure, for example, that out of the 100 neurons in each assembly only a subset would randomly be connected to another assembly and every neuron would have the same number of incoming connections (fixed in-degree). Similarly, the connectivity rule ensured that within each pool only a subset of excitatory neurons would be connected to the inhibitory neurons. The strategy was to embed the general connectivity profile of NST within the connectivity profile of the spiking network by appropriately changing the connection probabilities (e.g., by using a lower probability for between-assembly connections and a higher probability for within-assembly connections). Thus, the overall connectivity pattern was manually defined at the macro level but at the micro level it was kept probabilistic (see Supplemental Table 1 for the complete list of connectivity parameters).

Neurons were modelled as adaptive exponential units (Brette & Gerstner, 2005) with conductance-based alpha synapses (Roth & van Rossum, 2009). This approach allows for a direct translation of neuroscientific hypotheses (i.e., decline of neuronal excitability due to accumulation of intracellular calcium) into the neuro-computational model.

In biological networks, there is some correlation between pre- and post-synaptic spiking activity, and neurons which fire together in close temporal proximity tend to become more strongly connected. In our simulation, we implemented this learning mechanism as spike-timing dependent plasticity (STDP) to capture how biophysical changes in the components that mediate spike generation (e.g., calcium concentration) and signal transmission can affect information processing capabilities (i.e., retrieval of phonological representations).

Model lesioning. For each of the simulations we first ran the "healthy" network and then lesioned it in two separate simulations representing the TD and UA hypotheses (see Supplemental Table 1 for parameters). First, the Age-Net_TD model instantiated the loss of connectivity from the TD hypothesis as a reduction in the connection probability between layers (e.g., lexical to syllable nodes; parameter cEbLS). Second, the AgeNet_UA model instantiated the under-activation from the UA hypothesis as an increase in the duration of the spike-triggered adaptation current (tau_w) for neurons in the semantic system, leading to a reduction in neuronal excitability.

Model performance. For all the simulations, the goal was to retrieve the correct phonological form (combination of phonological nodes) given input to the propositional layer. Performance of the model was assessed by computing the average spike count over time windows of 100 ms for each node in each layer. A spike count larger than 1 for any neuronal node was taken as an indication of correct activation in that neuronal pool.

Experiment overview

We measured correct phonological retrieval of healthy, TD, and UA models in three experiments: (1) Picture naming, (2) Phonological priming, and (3) Semantic priming.

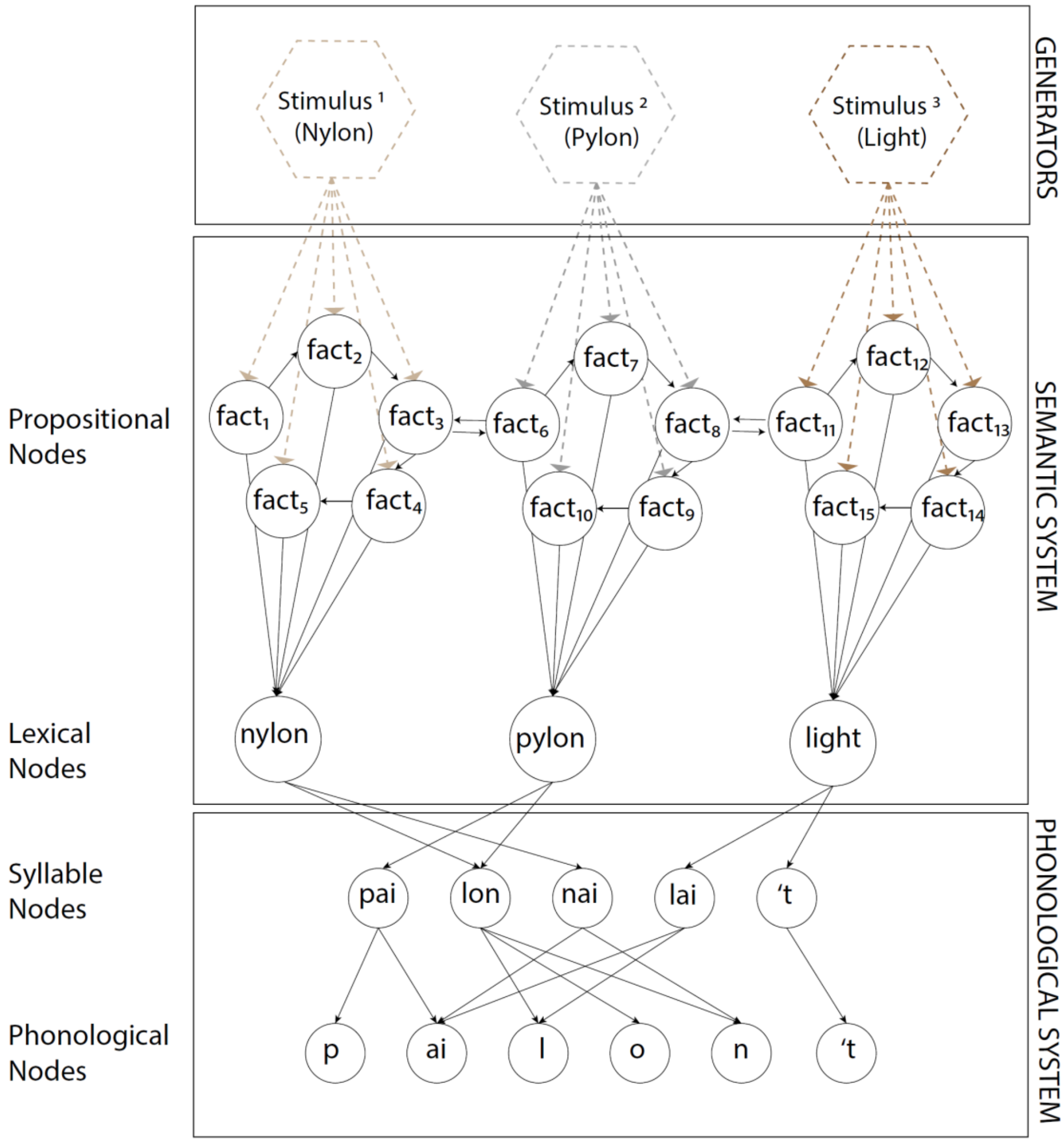

Figure 1. Architecture of the spiking neural network model (AgeNet) with semantic and phonological layers. Stimulus currents were applied to the propositional nodes 1 to 5 coding for semantic information about *pylon*, nodes 6 to 10, coding for semantic information about *nylon*, or nodes 11 to 15, coding for semantic information about *light*. Inputs to the system were direct currents produced by one of the stimulus generators. Model outputs were spikes produced by the phonological nodes.

Experiment 1: Picture naming. This experiment simulated a task where participants are presented with pictures of known objects and are asked to name them as quickly as possible. Performance measures typically include response times and naming error rates. Our simulation represents the retrieval of one target concept as direct current injected into the propositional nodes in the semantic layer representing the facts pertaining to the concept. The goal of the simulation is to test whether neural activity percolates to the phonological system and activates the correct phonological nodes. Current was injected at a constant amplitude of 800 pA for 1 s, representative of typical stimuli duration in a behavioral experiment. The parameters of the neuronal model were set as in Brette & Gerstner (2005) to reflect adaptive spiking behavior. For the synapses and the STDP mechanism, we set the parameters (see Supplemental Table 1) as reported in experimental studies (Song et al., 2000). After the injection of the current, the system was left to stabilize for an additional 500 ms to evaluate post-stimulus processing effects. Both TD and UA models should lead to retrieval failures, with semantic under-activation leading to more frequent and severe failures compared to phonological retrieval deficits.

Experiment 2: Phonological priming. In the second experiment, we simulated a picture-picture phonological priming study, where participants name a prime picture (*nylon*), followed by a target picture which is phonologically related to the prime (*pylon*). This simulation tests the TD prediction that phonological priming can attenuate the effects of weak connectivity. In the simulation, "prime" retrieval was followed by the "target" retrieval, with the prime and target stimuli represented as two separate currents injected into the propositional pools of the associated stimulus in the semantic system. Each stimulus presentation lasted for 1 s with an interval of 500 ms between stimuli. Behavioral evidence indicates that phonological priming should overcome the effects of phonological access deficits (TD model) but should not improve naming if semantic access has failed (UA model).

Experiment 3: Semantic priming. In the third experiment, we simulated a picture-picture semantic priming study, where participants name a prime picture (*light*), followed by a target picture which is semantically related to the prime (*pylon*) but phonologically unrelated. This simulation tests the TD prediction that semantic priming does not attenuate age-related phonological retrieval deficits. In the simulation, "prime" retrieval was followed by the "target" retrieval, with the prime and target stimuli represented as two separate input currents injected into the propositional pools of the associated stimulus (either *light* or *pylon*) in the semantic system. Each stimulus lasted for 1 s with an interval of 500 ms between stimuli. For semantically-related pairs, semantic overlap was represented by increasing the connection probability (parameter pEB) for lateral connections between propositional assemblies (see Supplemental Table 1). Lateral connections were included for one of the five propositional assemblies for each lexical item (e.g., connecting fact 8 for *pylon* with fact 11 for *light*,). Critically, *light* and *pylon* do not share syllables, therefore allowing for an assessment of semantic priming effects not influenced by phonological overlap (see Figure 1). As in previous experiments, each stimulus lasted for 1 s with an interval of 500 ms between stimuli. Behavioral evidence suggests that semantic priming does not overcome phonological access deficits (TD model) but could facilitate semantic access if representations are degraded (UA model).

Software. The spiking network model was implemented in NEST (Gewaltig & Diesmann, 2007) interfaced with Python (pyNN).

Results

For each experiment, we examined correct retrieval (spike rate count larger than 1) of phonological representations and temporal characteristics of neuronal firing in the healthy, AgeNet_TD and AgeNet_UA models.

Experiment 1: Picture naming

Healthy model. In the healthy network, input injected into the propositional clusters percolated through the synaptic connections between neuronal assemblies and layers, progressively recruiting assemblies and ultimately the correct neuronal pools in the phonological layer (see Figure 2A). Specifically, initial current led to rhythmic behavior in the lexical node (*pylon*) marked by five volleys of signals (peaks in the plots), which are regular (have similar intervals between volleys) and show gradually increasing intensity (more spikes with each volley). The increase in firing rates is due to the STDP mechanism leading to potentiation of synapses which have been activated before (in the correct temporal order). There was also an after-stimulation volley (bin 10) generated by the current circulating through the system. Activity propagated with the same spatio-temporal characteristics (synchronous, regular) to the syllable nodes and phonological nodes, leading to the activation of only the correct nodes.

AgeNet_TD. Application of the injected current resulted in reduced activation in the syllable nodes. This in turn led to lower neuronal activity with only one volley of spikes reaching the phonological nodes, leading to diminished retrieval of phonological information (spike rate of 1 at time bin 8). The implication of this result is compatible with the phonological retrieval deficit: while semantic retrieval was successful, phonological retrieval failed 80% of the time compared to the healthy network.

AgeNet_UA. Results indicate that the network was able to retrieve information only in the initial stimulation period (0-100 ms) but the activation quickly died out. Naming was successful only in the first time period (0-100ms) with a single volley which is in line with what is experienced by normal older adults, who can successfully recall semantic information during word production (Burke & Shafto, 2004).

Experiment 2: Phonological priming

Healthy model. Results show the correct sequential activation of *nylon* (lexical node 1) and *pylon* (lexical node 0). Similarly, the firing patterns correctly transfer to the syllable and phonological nodes, maintaining a synchronous, regular behavior (see Figure 2B).

AgeNet_TD. Results show that in the condition where a phonologically-related prime was presented, even when the connection density was reduced by 40%, the correct phonological nodes were activated. In keeping with the role of spreading activation in behavioral studies, phonological nodes which were downstream of an overlapping syllable node between the two stimuli (i.e., syllable node, "lon") showed a significant benefit with roughly twice as many spikes (phonological nodes: "l","o","n"). The nodes which were downstream of non-overlapping syllable nodes (i.e., syllable node, "pai", with downstream phonological nodes: "p" and "ai", respectively) showed less spiking activity but still received enough additional activity to sup-port correct retrieval (one volley). This result is in line with behavioral evidence that phonological access deficits can be overcome by priming relevant phonological representations.

AgeNet_UA. The increase in the duration of the adaptation current led to reduced spiking activity in the propositional nodes which in turn led to less activation percolating down to

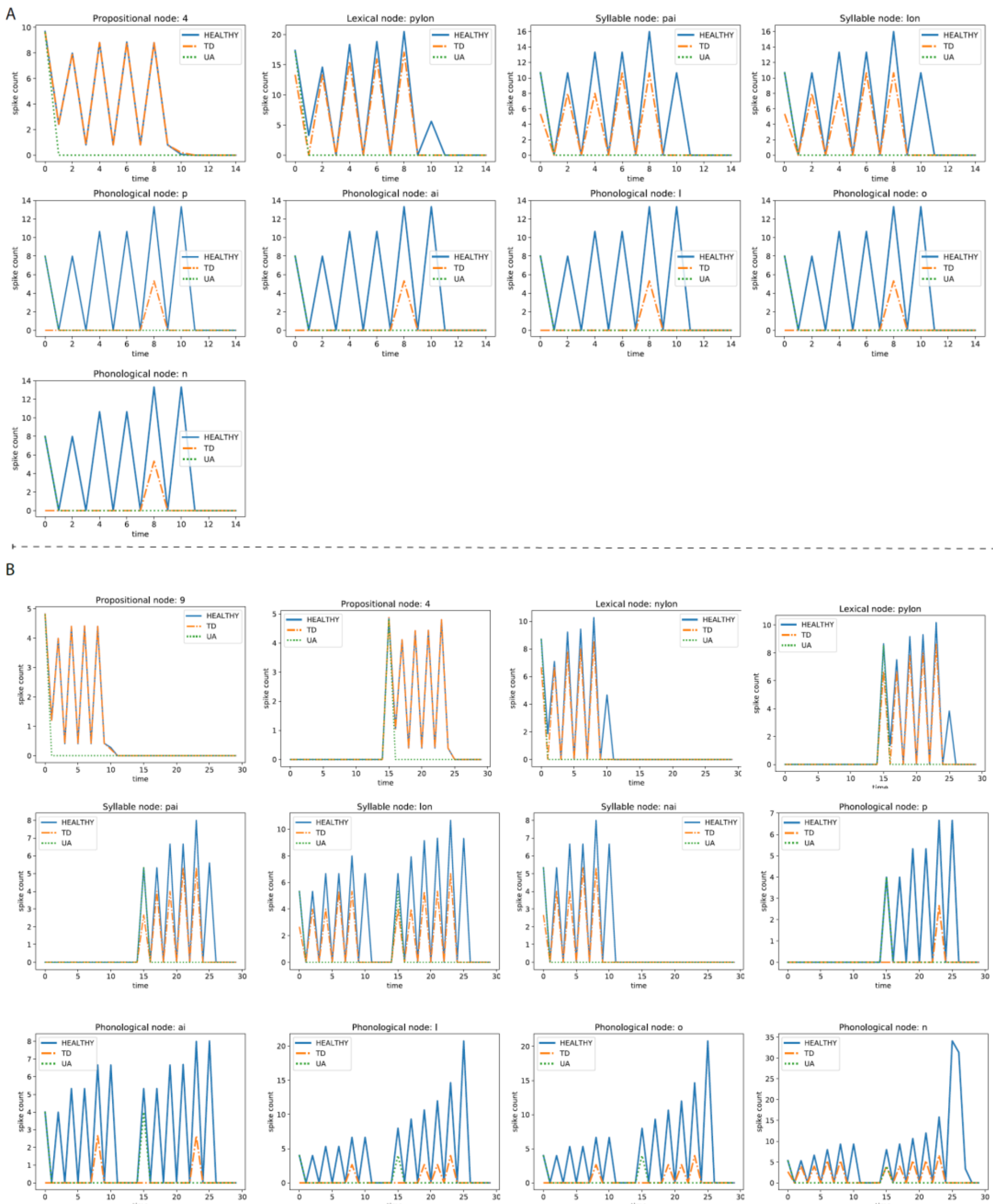

Figure 2. Simulation results for Experiments 1(A) and 2(B) for healthy (blue), AgeNet_TD (orange) and AgeNet_UA (green) networks. Nodes which showed no spiking activity are not reported. For propositional nodes, only one node is shown as representative of the input applied (i.e., node 9 for *nylon*, node 4 for *pylon*).

the phonological nodes. In comparison with the AgeNet_TD model, the results show a minimal and delayed volley of spikes at the phonological level for both the prime and the target. The lack of priming is compatible with a semantic degradation hypothesis but goes against behavioral evidence that phonological priming improves naming in older adults.

Experiment 3: Semantic priming

Healthy model. Results show correct activation at all levels of the network with correct retrieval of the phonological units in the right temporal order (see Figure 3). Furthermore, phonological units which were overlapping between prime (*light*) and target (*pylon*) show a higher spike count during the second activation in comparison to the first one (e.g., phonological node "ai").

AgeNet_TD. Results show a single correct retrieval of the phonological units (see Figure 3). In comparison with Experiment 2, there is clearly no increased correct retrieval for overlapping phonological units (e.g., "ai") indicating that semantic priming alone does not lead to better phonological retrieval.

AgeNet_UA. Like Experiment 2, results show minimal retrieval of correct phonological representations with a single volley of spikes providing no benefit (i.e., higher number of volleys) for overlapping representations at all levels of the network (see Figure 3).

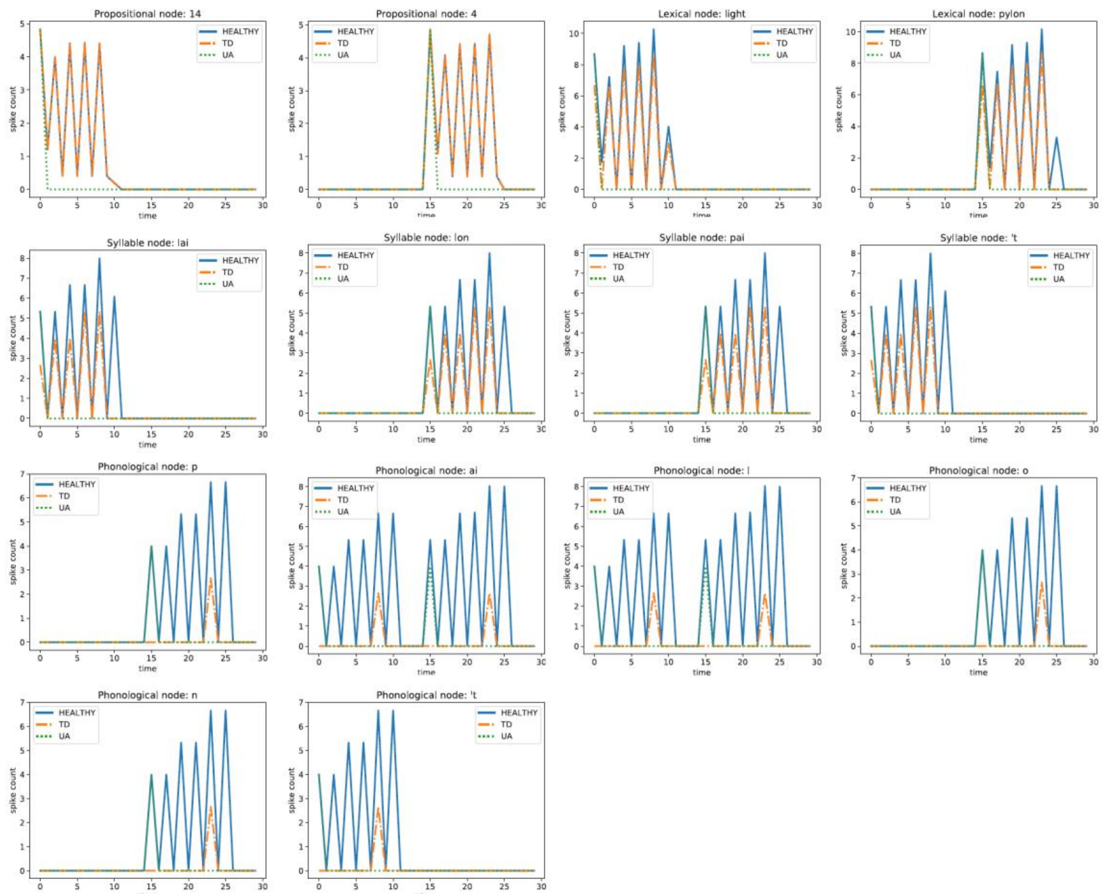

Figure 3. Simulation results for Experiment 3 for healthy (blue), AgeNet_TD (orange) and AgeNet_UA (green) networks. Nodes which showed no spiking activity are not reported. For propositional nodes, only one node is shown as representative of the input applied (i.e., node 14 for *light*, node 4 for *pylon*).

Discussion

The results of three experiments support the predictions of the TD hypothesis that age-related word finding problems reflect phonological access failures due to transmission deficits: First, compared to a network with successful phonological retrieval, weakening the connection strength between nodes leads to phonological retrieval failures. Second, temporarily strengthening these connections through phonological priming attenuates retrieval failures. Third, semantic priming does not improve phonological retrieval in the AgeNet_TD model. In contrast, a semantic "under-activation" (UA) hypothesis was not supported, as phonological representations could not be retrieved reliably following lesioning and both phonological and semantic priming did not systematically improve performance.

This type of neurobiologically grounded model holds promise for further investigations of language processing. Using realistic timings for picture presentation, we simulated correct picture naming, phonological facilitation and semantic interference. Moreover, by instantiating a cognitive/behavioral model in a computational setting we have been able to contrast predictive mechanisms (transmission deficit and under-activation) that are difficult to disentangle behaviorally. Finally, using a neurobiologically-motivated model has the potential to inform the original behaviorally-based models by suggesting plausible mechanisms. For example, the results of Experiment 2 suggest that phonological facilitation is underpinned by a mechanism of entrainment. The first activation of *nylon* elicits a constant, tonic firing of all the assemblies participating in the representation from propositional to phonological layers. The constant activation of *nylon* provides the basis for the activation of *pylon* in two ways. First, it keeps the neuronal populations stimulated with excitatory and inhibitory currents, creating the opportunity for an easier emission of spikes. Second, it provides temporal windows for selective synchronization. Additional elements get recruited on an incremental basis.

Future application of this approach would benefit from broadening the linguistic network and investigating the effects of different degrees of connectivity loss in the AgeNet_TD model. Additionally, while we chose a decrease in neuronal excitability as a neurobiologically-motivated mechanism for under-activation, the AgeNet_UA model failed to consistently activate the correct phonological nodes in Experiments 2 and 3. While these findings do not support the UA hypothesis, it is also possible that another mechanism would better reflect semantic deterioration and provide a more robust competitor to the TD hypothesis. While the UA and TD models make different predictions about the locus of age-related word finding failures, the mechanisms underpinning these models are not necessarily mutually exclusive. In many models of conceptual semantics, semantic representations are distributed networks, so that semantic degradation could reflect weakening of the connections within a representation, a mechanism in keeping with the Transmission Deficit Hypothesis (Au et al, 1995). We chose a mechanism for the UA model which targeted the proximal cause of its key predictions (semantic under-activation), but a future instantiation of this model with an expanded semantic network could examine the qualitative differences in model behavior (i.e., whether phonological and semantic access are affected) achieved through quantitative variation in system-wide connectivity deterioration (e.g., by making transmission deficits increasingly more severe). Similarly, the results of Experiment 3 suggest our manipulation of semantic overlap led to massive interference at the propositional level. Future comparisons of the effect of semantic priming on the AgeNet_TD and AgeNet_UA models should use parameters that replicate behavioral studies more closely, where lexical access is impaired but still possible following semantic interference.

In conclusion, the current study presents a promising approach for understanding age-related changes to language ability in an interactive system. Current findings are in line with the hypothesis that while normal aging impairs access to linguistic representations, this impairment is limited to particularly vulnerable processes and the underlying representations remain intact.

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