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A Model of Free Recall for Multiple Encounters of Semantically-Related Stimuli with an Application to Understanding Cognitive Impairment

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Abstract

The free recall of triadic comparisons, a task used in clinical settings, presents a unique analysis challenge for many memory models, because learning occurs incidentally and items are presented multiple times in triads. To account for this design, we extend the SIMPLE (Brown et al., 2007) model of memory, which assumes to-be-remembered items are stored as separate logarithmically-compressed temporal traces. The ability to retrieve these traces depends on the acuity of memory probes and the semantic similarity between the items represented by the traces. We applied this model to a real-world clinical data set including healthy controls, people with mild cognitive impairment (MCI), and people with Alzheimer's dementia. We found that people with MCI had lower acuity than healthy controls, but both groups placed roughly equal weight on temporal and semantic cues. People with dementia had both lower acuity and placed much more weight on temporal cues than semantic cues.

Keywords: free recall; triadic comparison; episodic memory; semantic memory; SIMPLE

Introduction

Within research and clinical settings, a common test of memory is the free recall task (Healey & Kahana, 2014). In the usual version of this task, a list of to-be-remembered items is presented to a participant, and they are asked to recall as many of those items as possible in any order, either immediately or after some delay. While the free recall task is a valuable tool for both basic and applied research, the design of the task may seem somewhat artificial. In everyday life, there are only some situations in which someone needs to memorize a clear-cut list of items. More often, learning occurs incidentally; people encounter information that they need to remember while accomplishing other unrelated tasks. As an example, consider how people remember which food items to buy when they go shopping. Sometimes, this may be based on recalling a sequential prepared shopping list of required items, consistent with the rote learning of a study list in a standard memory experiment. More often, people have to recall what grocery items to buy from the act of cooking, where ingredients are encountered repeatedly and inter-mingled over many episodes. While preparing a meal, if someone goes to look for oregano in their pantry and sees that they have run out, they must simultaneously think of a substitute ingredient while also remembering to pick up more oregano the next time they are at the store. Once at the store, selecting a jar of oregano can be a memory cue itself for other spices that need to be replenished.

In this project, we examine the results of a triadic-recall task, an incidental learning task that is one component of the Mild Cognitive Impairment Screen (MCIS: Shankle et al., 2009), a diagnostic tool for cognitive impairment associated with Alzheimer's disease. In this task, items are presented multiple times and occur in groups of three. Importantly, these items are encountered as part of a separate choice task and participants are unaware that they will be asked to recall them at a later time. We compare the memory performance of healthy controls against patients with mild cognitive impairment (MCI) and Alzheimer's patients with moderately severe dementia.

An important step to understanding any cognitive capability is to develop models of people's behavior. However, the design of the triadic-recall task creates complications that are not addressed by most traditional memory models. One model that potentially allows for the required flexibility in modeling the complicated pattern of stimulus encounters is the Scale-Independent Memory, Perception, and LEarning model (SIMPLE: Brown et al., 2007). When applied to standard study-test free recall tasks, SIMPLE assumes that each study item is stored as a separate memory trace, and these traces are logarithmically compressed along a dimension of time within psychological space. This logarithmic compression naturally allows for common observations in free recall, such as primacy and recency. SIMPLE also allows for traces to differ on multiple dimensions, and we use this component of the model to allow for the influence of semantic similarity as well as temporal similarity of the memory traces. While the standard version of SIMPLE does not explicitly incorporate mechanisms such as rehearsal or item repetition, it can easily be extended by storing each repeated encounter with a study item as a separate memory trace.

In this paper we develop an extended version of the SIMPLE model and demonstrate its ability to account for free recall behavior in the triadic-recall task by applying it to a real-world clinical data set. In the next section, we describe the data set and the tasks used in this project. Then we describe our extension to the SIMPLE model and how we account for the design of the triadic-recall task. We use a hierarchical Bayesian design and compare memory performance across three groups of people: healthy controls, patients with MCI, and patients with moderately severe Alzheimer's dementia. We find that as impairment increases, not only does accuracy

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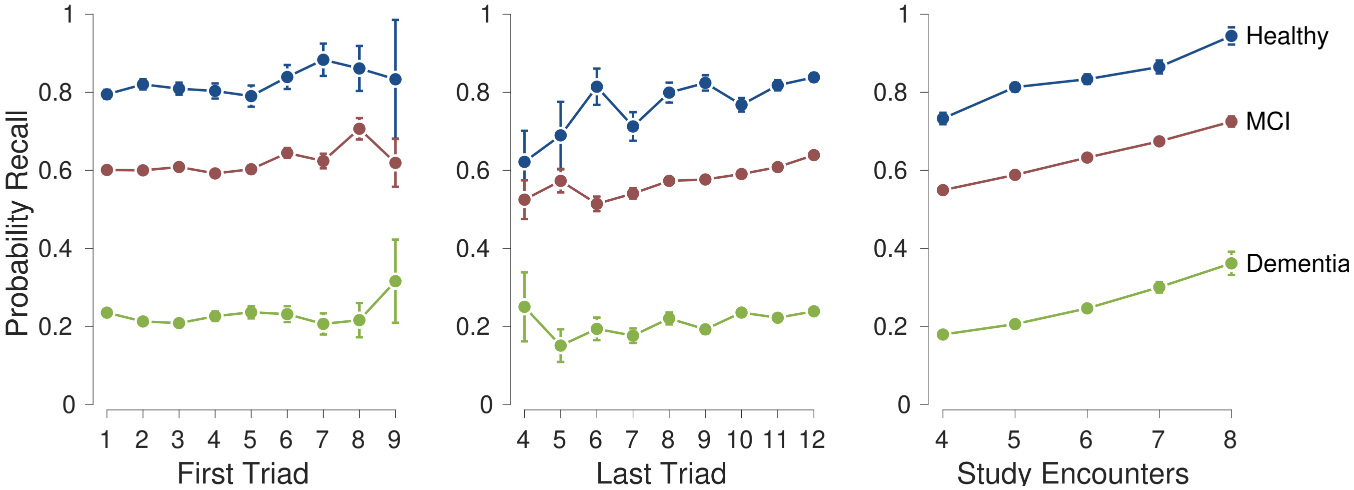

Figure 1: Probability of item recall as a function of their encounters. (*left panel*) There is no evidence for primacy effects for any group – An animal name that appeared for the first time early in the triadic comparison task was no more likely to be recalled as an animal name that appeared for the first time later in the task. (*middle panel*) There is modest evidence of recency effects for all groups – An animal that appeared for the last time later on in the triadic comparison task was more likely to be recalled than an animal that appeared for the last time earlier in the task. (*right panel*) The more often an item was encountered during the study phase, and chosen as the odd one out, the more likely that animal name was to be recalled.

of recall decrease, but patients come to rely more on temporal context to the exclusion of using semantic similarity of the items as cues.

Behavioral Data

We use data from the MCIS administered at a clinic specializing in neurodegenerative disorders. This screening tool is used as part of a routine assessment of Alzheimer's patients and their caregivers and includes a task that requires an odd-one-out triadic comparison of animal names, followed by an unexpected free recall task of those animal names. The triadic comparison task uses 21 animal names as stimuli: antelope, beaver, camel, cat, chimpanzee, chipmunk, cow, deer, dog, elephant, giraffe, goat, gorilla, horse, lion, monkey, rabbit, rat, sheep, tiger, and zebra. In accordance with a balanced incomplete block design (Burton & Nerlove, 1976), nine animal names are drawn from the pool of 21 animal names for each patient, and each of the selected animals is presented verbally in a triad with every other animal over the course of 12 trials. For each triad, the patient must choose which animal is least like the other two. For example, someone presented with the words "cow", "elephant", and "giraffe", might choose "cow" as the odd one out. There is no correct answer for this task, and so the clinician does not offer any feedback after each choice. After a delay during which people complete other unrelated tasks, there is an unexpected free recall task of these animal names. The instructions are to try to recall as many of the animal names as possible, in any order.

For the present study, we examined the results of the MCIS for three groups of people: healthy controls, patients with MCI, and patients with Alzheimer's disease. The control group shows no functional cognitive impairment, while patients in the MCI group are beginning to show objective deficits in accomplishing more complex tasks, such as managing finances (Reisberg, 1988). The patients with Alzheimer's disease have been diagnosed with moderately severe dementia and are beginning to show difficulty accomplishing tasks from the Activities of Daily Living (ADLs: Katz et al., 1963), such as dressing, bathing, and grooming. The full data set contains 398 tests completed by healthy controls, 3808 completed by patients with MCI, and 1154 completed by patients with dementia. We intended to randomly sample 100 tests from each of the three groups to analyze for this project, but due to a coding error sampled 102 tests in the MCI group. The 100 healthy controls (56% female, mean age 75 years) recalled an average of 7.4 animals, with individuals recalling a minimum of 1 animal name and a maximum of all 9. The 102 MCI (65% female, mean age 76 years) and 100 dementia patients (49% female, mean age 75 years) spanned the full range between no animals and all of the animals being recalled, but with a difference in the mean number recalled of 6.3 and 2.0 respectively.

In an initial analysis of the data, we looked for regularities commonly found in free recall data, such as effects of primacy and recency. Primacy is an advantage to recall for items occurring at the beginning of a list, while recency is an advantage to recall for items presented at the end of a list (Murdock, 1962). The left panel of Figure 1 shows no evidence of a primacy effect for any of the three groups. An animal name may be encountered for the first time in triads 1 through 9, according to the test design. As each animal name appears in a total of 4 triads, it cannot appear for the first time in triads 10 through 12. Here we can see that an animal name that appeared for the first time early in the triadic comparison task was no more likely to be recalled as an animal name that appeared for the first time later in the task. In the middle panel of Figure 1, there is modest evidence of a recency effect for all three groups. An animal name may be encountered for the last time in triads 4 through 12. As each animal name appears in a total of 4 triads, it cannot appear for the last time in triads 1 through 3. An animal that appeared for the last time later in the triadic comparison task was more likely to be recalled than an animal that appeared for the last time earlier in the task. These findings are consistent with other research involving incidental learning in which effects of recency but not primacy were found in surprise free recall (Marshall & Werder, 1972).

Another common finding in memory research is that the probability of item recall increases when that item is repeated during study (see Toppino & Gerbier, 2014, for a review). Following the presentation of each triad, the patient must make an odd-one-out choice. Therefore, through the entirety of the triadic comparison task, someone may encounter an animal name a minimum of 4 (i.e., the animal name was only ever said by the clinician and was never chosen as the odd-one-out) to 8 times (i.e., the animal name was chosen as the odd one out in every triad in which it appeared). In the right panel of Figure 1 it is clear that the more study encounters someone had with an animal name—in other words, the more often that item was chosen as the odd one out—the more likely that animal name was to be recalled.

An Extension of the SIMPLE Model

For the purposes of the cognitive assessment, the triadic comparison task acts as the study phase for the surprise free recall task. However, the design of this task is very different from the standard study phase of a typical free recall task. Words are presented in triads, and each word is repeated a total of four times so that it appears exactly once in a triad with every other word. Ideally, an appropriate model of free recall for this data set would need to be able to account for some recency effects, attenuated primacy effects, and allow for variable repetition of items at study. As people make odd-one-out judgments, they say their choice out loud, and choosing an animal as the odd-one-out may have some effect on whether that animal is later successfully recalled.

As mentioned above, the SIMPLE model of memory may be able to handle these difficulties. In SIMPLE, each encounter with a study item is stored as a separate memory trace. SIMPLE emphasizes the effect of elapsed time on free recall and has four basic assumptions. First, each memory trace is represented in psychological space along a time dimension, beginning at retrieval and going back in time; this time dimension is logarithmically compressed. Second, a memory trace is easier to retrieve to the extent that it is more easily discriminated from other traces within psychological space. Third, the temporal discriminability of memory traces from each other is a function of the ratio of their distances from the time of retrieval. Finally, the probability of retrieval of a specific memory trace is an increasing function of that trace's discriminability over the total discriminability of the other traces in psychological space.

As an example, consider Figure 2. The top panel contains a one-dimensional depiction of the triadic comparison task as it is completed in real time. Each colored tick mark represents an encounter with an animal name, either as part of a triad read out loud by the clinician or the odd-one-out choice made by the participant. Here we assume that the clinician reads out loud animal names at a rate of 1 per second and the participant responds with their odd-one-out choice within 2 seconds. In this example, the most recently presented animal triad (A) was "deer", "zebra", and "giraffe". The participant's odd-one-out choice (B) for this triad was "giraffe". Following a retention interval (C), the participant must recall as many of the animal names as possible, in any order. The bottom panel of Figure 2 depicts how SIMPLE represents the memory traces in psychological space after logarithmic compression. The ability to recall an animal name, such as the word "giraffe", will depend on how easily discriminable that memory trace is from others within this psychological space.

This figure shows the influence of time on memory recall, but other factors, such as the similarity between items, are assumed also to be able to affect recall. In free recall tasks in particular, people tend to recall items in clusters of semantic similarity (Bousfield, 1953; Romney et al., 1993). Within SIMPLE, the psychological space can be expanded to have both temporal and semantic dimensions, with some weight given to each. The distance in this two-dimensional space is then used to determine the discriminability between traces. To allow the effect of semantic similarity to be considered, we retrieved the pairwise semantic similarity of the 21 animal names from Westfall & Lee (2021).[1] Pairwise similarity values ranged from 0 to 1, with each animal having maximal similarity with itself.

Model description

The temporal similarity of two memory traces is a function of their separation in time and the acuity with which they are accessed. Formally, the temporal distance η_{ij} between two memory traces i and j, encountered at times T_i and T_j relative to the time of retrieval is represented as,

$$\eta_{ij} = \exp\left(-\lambda \left|\ln(T_i) - \ln(T_j)\right|\right), \qquad (1)$$

which incorporates the key logarithmic compression assumption. The parameter $\lambda > 0$ is a temporal distinctiveness parameter, representing a participant's memory acuity. The temporal discriminability of an item i, with trace T_i, relative to a

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[1] The similarity between two animal names was calculated as the proportion of choices for healthy controls when both animals appeared together in a triad and neither one was chosen as the odd one out.

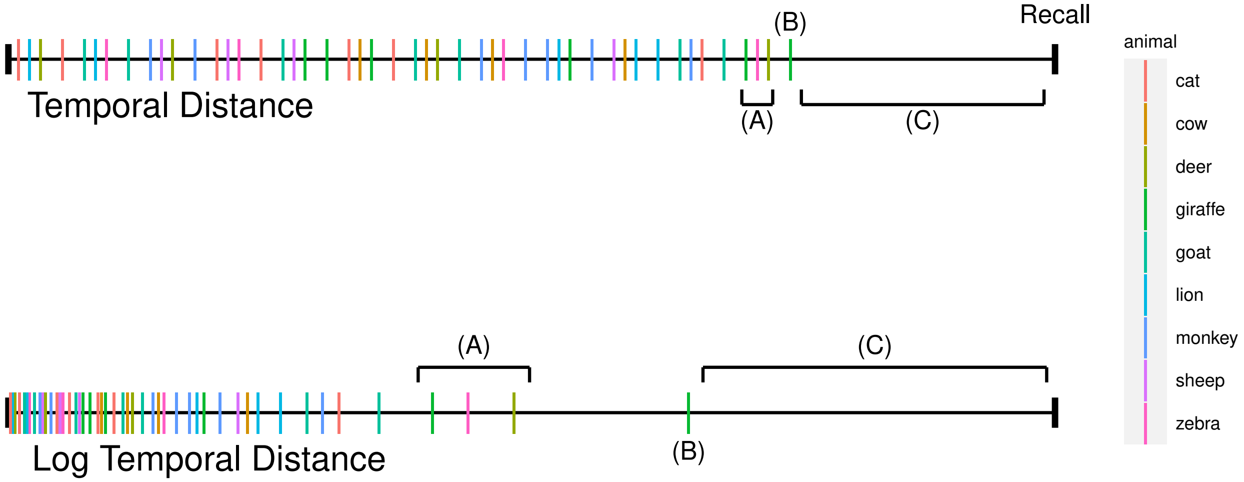

Figure 2: An illustration of the triadic comparison task. In both panels, the task begins on the left side, and each tick on the timeline represents an encounter with an animal name. In this example, the most recently presented triad (A) was "deer", "zebra", and "giraffe". The patient's odd-one-out choice (B) for this triad was "giraffe". After the retention interval (C), a surprise free recall task is presented. The top panel represents the distance in real time, while the bottom panel shows SIMPLE's logarithmically compressed time dimension within psychological space.

probe j, aiming to retrieve the item with trace T_j, is then calculated as

$$\pi^T_{ij} = \frac{\eta_{ij}}{\sum_{k=1}^{n} \eta_{ik}}. \tag{2}$$

The pairwise semantic similarity of the two traces, π^S_{ij}, is incorporated into the model via a weighting parameter ω, which determines the relative importance of temporal versus semantic similarity to the overall evaluation of similarity of the two traces,

$$\pi_{ij} = \omega \pi^T_{ij} + (1-\omega)\,\pi^S_{ij}. \tag{3}$$

The SIMPLE model transforms the retrieval probabilities via a logistic function,

$$\pi^*_{ij} = \frac{1}{1+\exp\left[-\beta\left(\pi_{ij}-\tau\right)\right]}, \tag{4}$$

where π^*_{ij} represents the probability that probe j will yield trace i. This function serves as a mechanism to allow for study words to be omitted at test. Parameter $\tau \in (0,1)$ is the threshold value, above which a trace is successfully retrieved. Parameter $\beta > 0$ represents the scale, or the noisiness of the threshold value. A large β value would indicate that all traces above the threshold are retrieved and all traces below the threshold are not, whereas a smaller β value indicates a more gradual transition from low to high retrieval probabilities. Following the correction noted by Lee & Pooley (2013), the probability that a trace i will be retrieved at least once is calculated as

$$\theta^T_i = 1 - \prod_{j=1}^{n} \left(1-\pi^*_{ij}\right). \tag{5}$$

Previous applications of SIMPLE have not considered the possibility of multiple traces representing the same item, as happens for the animal names in the triadic comparison task. This extension, however, is straightforward. The probability that animal a will be recalled is naturally measured as the probability that at least one trace representing that animal is retrieved. That probability is given by

$$\theta_a = 1 - \prod_{i=1}^{n} \left(1-\theta^T_i\right)^{z_{ia}} \tag{6}$$

where $z_{ia} = 1$ if animal a occurred in trace i, and $z_{ia} = 0$ otherwise.

Application to Clinical Data

For the triadic-recall task, the behavioral data take the form $y_{pa} = 1$ if patient p recalled animal a and $y_{pa} = 0$ if they did not. For each patient, this probability is given by Equation 6 in the basic model above, based on individual-specific parameters for their temporal acuity λ_p, temporal versus semantic weighting ω_p, threshold noise β_p, and threshold τ_p.

We assume that the two parameters corresponding to the structure of memory vary according to the level of impairment of each patient. Based on our previous work (Westfall & Lee, 2021), we do not expect the structure of semantic memory to differ by cognitive impairment. In other words, we expect the *access* to semantic information to differ by cognitive impairment, but we do not expect the semantic *distance* itself to differ among groups. Accordingly, we use a hierarchical model with group means μ^g_λ and μ^g_ω and standard deviations σ^g_λ and σ^g_ω, where g is the indicator for the healthy, MCI, or dementia group. Individual patient parameter values are modeled as

$$\begin{array}{rcl} \lambda_p & \sim & \text{Gaussian}_{+}\left(\mu^g_\lambda, \dfrac{1}{\left(\sigma^g_\lambda\right)^2}\right) \\ \omega_p & \sim & \text{Gaussian}_{(0,1)}\left(\mu^g_\omega, \dfrac{1}{\left(\sigma^g_\omega\right)^2}\right), \end{array} \tag{7}$$

depending on their group.[2] In contrast, we assume that the thresholding mechanism does not change with impairment, so that there are single means μ_β and μ_τ and standard deviations σ_β and σ_τ. This assumption focuses the explanation of changes in free recall performance on the acuity of memory and the use of semantic information, while still allowing for individual differences in the thresholding mechanism, with

$$\begin{aligned} \beta_p &\sim \text{Gaussian}_+\big(\mu_\beta, \frac{1}{\sigma_\beta^2}\big) \\ \tau_p &\sim \text{Gaussian}_{(0,1)}\big(\mu_\tau \cdot \frac{1}{\sigma_\tau^2}\big). \end{aligned} \tag{8}$$

The triadic-recall task involves 48 memory traces. There are three animals presented per triad, plus the animal given in answer to the odd-one-out question, over a sequence of 12 triads. Consistent with the timing of the administration of the task, we use a one second gap between the presentation of the three animals on each triad, a two second delay before the answer, and a ten second delay between triads. We also use a one-minute delay before the delayed free recall task begins. These assumptions specify the 48 T_i trace values as 218, 217, 216, 214, 204, 203, 202, 200, …, 64, 63, 62, 60. Consistent with previous applications of the SIMPLE model, we also assume that retrieval involves probing all 48 memory traces.

Our model is completed by placing priors on the parameters. Following the idea that priors should capture theoretical assumptions related to parameter values (Lee & Vanpaemel, 2018), we choose a uniform prior for the μ_λ^g parameters based on the timing of the traces just specified. In particular we bound the value to be above the minimum required to ensure that the two temporally closest traces also have temporal similarity of at least 0.5 and bound the value below so that the two most temporally distant traces have similarity below 0.5. These prior constraints formalize the theoretical assumption that recall is not based on pure rote learning, but involves generalization, and that probing memory produces some level of meaningful signal rather than activating all possible traces. For our T_i values this leads to the prior $\mu_\lambda^g \sim \text{uniform}\big(1/2, 150\big)$. The priors on μ_ω^g and μ_τ are naturally set as $\text{uniform}\big(0,1\big)$ and we set $\mu_\beta \sim \text{uniform}\big(0,50\big)$ to allow for both very noisy and very precise thresholds. We set uniform priors on the standard deviations over a large range of plausible values (Gelman, 2006).

Given these assumptions, the model also assumes that every stimulus encounter acts as a probe. For each of these probes, the temporal similarity between a probe and all the traces is calculated using Equation 1. The temporal discriminability, overall similarity incorporating semantic information, and probability of trace retrieval then follow from Equations 2–4, using the individual-specific parameter values. Finally, the application of Equation 6 gives θ_{pa}, the probability participant p recalls animal a, so that the behavioral data are modeled as

$$y_{pa} \sim \text{Bernoulli}\big(\theta_{pa}\big). \tag{9}$$

We implemented the model in JAGS (Plummer, 2003), which provides a high-level scripting language for implementing probabilistic models using Markov-chain Monte Carlo sampling methods (Lee & Wagenmakers, 2013). The results are based on 6 chains of 2000 posterior samples collected after 2000 discarded burn-in samples. We assessed convergence of chains by visual inspection and through the $\hat{R}$ statistic (Brooks & Gelman, 1998).

Results

Descriptive Adequacy

We evaluated the descriptive adequacy of the model by comparing the model-described probability of recall to the actual rate of recall observed in the data. This is shown in the lower-right panel of Figure 3. The dashed diagonal line in the figure indicates the model-described probabilities of recall matching the probabilities observed in the data (e.g., among the animal names for which the model gave a 70% probability of recall, 70% were in fact recalled). The data are binned into deciles, and error bars represent the standard error of the mean of the proportions. While there is some small discrepancy, the model generally describes the data well.

Modeling Results

The modeling results for μ_β and μ_τ are presented in the upper-right panel of Figure 3. The value of the threshold parameter μ_τ is near 1.0, and this high threshold indicates that recall was only possible for animal names whose retrieval probabilities were high. The noise parameter μ_β had more moderate values, indicating a gradual and somewhat noisy transition from low to high retrieval probabilities.

The most important results are for the μ_λ and μ_ω parameters, since they detail how memory acuity and the use of semantic similarity change between the groups. These inferences are presented in the larger left panel of Figure 3. Here we can see results for each of the healthy, MCI, and dementia groups. As impairment increases, the distributions for μ_λ move towards smaller values, indicating decreased temporal distinctiveness among the memory traces, and greater confusability overall. The weight parameter μ_ω indicates how much weight is placed on temporal versus semantic similarity when attempting to recall words. A μ_ω of 0.5 can be interpreted to mean approximately equal weight is placed on temporal and semantic cues at retrieval. As groups become more impaired, the distributions for μ_ω approach larger values, indicating that people with greater cognitive impairment rely more on cues of temporal similarity than semantic similarity relative to healthy controls.

Overall, these findings suggest that as impairment increases, the temporal distinctiveness of memory traces decreases. The use of semantic similarities also decreases with

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[2] Note that we parameterize the Gaussian distribution in terms of its mean and precision, consistent with the JAGS software we use to implement the models.

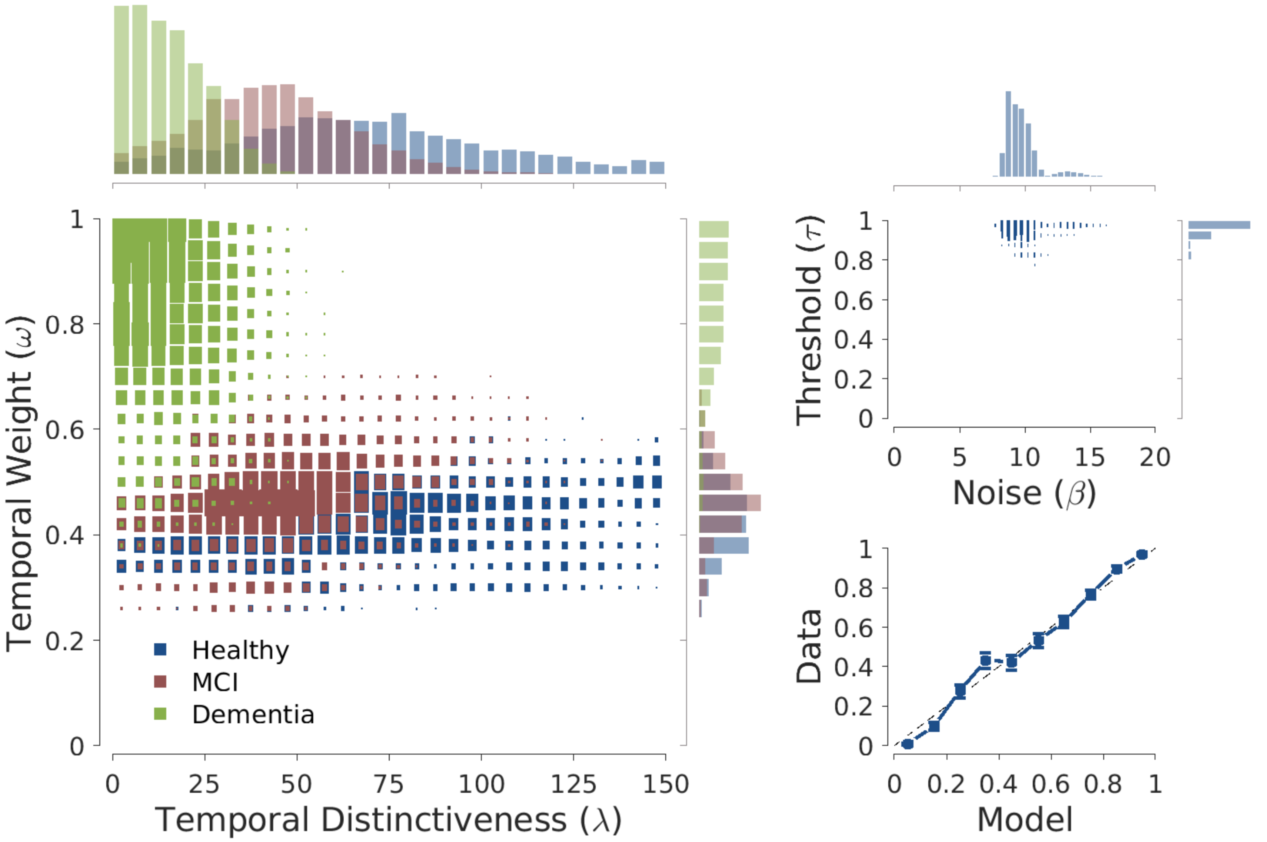

Figure 3: Modeling results. (*left panel*) The joint and marginal posterior distributions for temporal distinctiveness μ_λ and temporal weight μ_ω indicate that as impairment increases, the temporal distinctiveness of memory traces decreases and people rely more on cues of temporal similarity than semantic similarity. (*top right panel*) People had a relatively high threshold μ_τ and a noise μ_β that indicated a more gradual change from low to high recall probabilities. (*bottom right panel*) The model-described probability of recall as compared to the probability of recall in the data indicates the model is descriptively adequate.

impairment, perhaps because of a loss of access to the relevant semantic information (Westfall & Lee, 2021). Healthy controls give significant emphasis to semantic similarity, consistent with previous research stating that in free recall, people tend to recall items in semantically related clusters both within and between categories (Bousfield, 1953; Romney et al., 1993). The loss of both memory acuity and access to useful semantics jointly seem to cause the worsening recall performance, particularly for patients in the dementia group.

Conclusion

In this project we extended the SIMPLE model to account for the free recall of animal names learned incidentally during a triadic comparison task in a real-world clinical data set. We found that cognitively healthy people had higher values of acuity or temporal distinctiveness overall and placed roughly equal weight on temporal cues and semantic similarity. Patients with MCI had relatively lower values for acuity, but also tended to put roughly equal weight on temporal and semantic cues. Patients with Alzheimer's dementia had both lower memory acuity and placed much more weight on temporal cues than semantic cues.

The results of this project suggest both theoretical and clinical implications. The standard SIMPLE model does not incorporate item repetition, but repetition is an essential component of the triadic comparison task. We accounted for the repetition of items on recall by storing each encounter with an item as a separate memory trace. This extension of the model allowed for improved recall for items that were encountered more frequently and therefore were associated with more memory traces. Our model thus provided an example of how free recall can be predicted when stimuli are encountered in more complicated ways than standard study-test designs. Furthermore, the use of cognitive models to measure latent variables affords a more complete understanding of how memory changes with cognitive impairment, over and above more basic measurements such as recall accuracy.

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