Computation & Cognition: Assignment 1
Memory

Group 6

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1 Introduction

Recognition memory is a fundamental concept of cognitive science. It allows us to determine whether an individual has previously encountered an item or not. Over time, multiple models regarding recognition memory, and its underlying processes were developed, with two being the most influential in the field: Dual-Process Signal Detection (DPSD) theory and Unequal Variance Signal Detection (UVSD) theory.

DPSD proposes that recognition memory is operated by two separate processes: familiarity and recollection. On the other hand, UVSD is solely based on familiarity, though its conception of familiarity differs from that of DPSD, which will be further discussed in the following section [1, 2] .

This report explores the mechanisms through which these models explain recognition memory by implementing and analyzing them through experimentation. More specifically, we will compare Receiver-Operator Characteristic curves in order to determine which of them best describes human behavior. Additionally, a random guessing model will be implemented to be used as a baseline for comparison with the different models.

2 Background and Theory

Before implementing the two models, we will first examine the foundations of signal detection and recognition memory through two publications by Yonelias (1994) [1] and Wixted (2007) [2]. These two papers introduce and compare the two competing models of recognition memory. We will look at how they represent memory, how familiarity and recollection are defined, and compare the theory between the two models.

2.1 Memory Representation

To understand the model the mind employs to process memories, the following experiment is set up: participants are exposed to a set of words, namely targets. After some time of alternative activities, they are tested to determine how many of these words they recall. For this, the researcher exposes the participant to another set of words that includes both the targets and new words (lures). These results are then used to deduce a theory that explains this model. Through this experiment, it has been attempted to deduce which of the two theories better explains the phenomena, by matching the theoretical and the practical results. So far, UVSD has been the most evidenced. However, around 2007 several experiments, especially those related to visual memory, have shown promising results for the DPSD model [1, 2].

Both theories assume a memory representation. This means that every memory has an associated level of "awareness". The higher the level of "awareness", the more likely the person believes this word is a target.

However, they differ in their understanding of how this awareness is distributed and used, making them incompatible [2] [1]. It is difficult to explain the difference without diving into the specifics, thereby the two models will first be explained and then compared. Before explaining the theories two concepts, namely familiarity and recollection will be explained.

2.2 Familiarity vs. Recollection

Familiarity-based recognition relies on a mental strength spectrum and a series of decision thresholds that determine a participant's confidence in their answer. Inside the participant's brain, each item is assumed to be assigned a mental strength value, which is compared against the predefined thresholds to decide the confidence level of recognition.

Recollection, on the other hand, is a discrete, all-or-none memory process that allows a person to retrieve specific details about a previously encountered event. If recollection occurs, the individual remembers specific contextual details (i.e. "I saw this word on the second line of the study list"). If recollection is passed with a specific word, this word is assigned with the highest (in some models it can also be some high, not necessarily the highest) level of confidence. Unlike familiarity, which is based on a continuous strength signal, recollection functions like a binary switch—either the details are retrieved, or they are not.

2.3 Recognition Memory Models

2.3.1 UVSD Model

Wixted (2007) challenged dual-process assumptions, demonstrating that the UVSD model—where targets and distractors follow Normal distributions with unequal variances—better accounts for empirical ROC data. Key assumptions:

- Targets: Higher mean $\mu_{\text{target}} > 0$ and greater variance $\sigma_{\text{target}} > \sigma_{\text{distractor}}$.
- ROC Slope: Reflects the variance ratio $\sigma_{\text{distractor}}/\sigma_{\text{target}}$, typically < 1.

2.3.2 DPSD Model

The Dual-Process Signal Detection (DPSD) model, proposed by Yonelias (1994) [1], advances that recognition memory is dictated not only by familiarity but also by recollection. Unlike UVSD, Yonelias introduces a high-threshold process of recollection on top of the familiarity-based recognition of UVSD.

There are a few fundamental assumptions in Yonelias' DPSD model. First of all, he explains in his paper that recollection is a binary decision rule, where a specific word, is either recalled fully or not at all. When a word is recalled it is done so at a high confidence

Another assumption of the model is that recollection happens first, and is then followed by familiarity if recollection fails. This assumption explains the reason why DPSD models tend to have asymmetric ROC curves, where high-confidence results cause a steeper initial slope in the curve [1].

The DPSD model also differentiates between weak and strong conditions in recognition memory. Weak conditions can be described as when the items are studied for a short time or where during the learning process there was interference. In weak conditions, the ROC curves show that the curve is more symmetrical, like that of UVSD, with a less steep initial curve. On the other hand, in strong conditions, where the individual is allowed to study the words for a longer period of time, or with less interference, the role of recollection can be more clearly seen on the ROC curve as it shows a steeper initial curve.

2.3.3 Comparison of UVSD and DPSD models

To continue with the comparison between DPSD and UVSD, the key distinction between both models is how they interpret the memory strength distribution and the process behind detection. DPSD, distributes the memory strength based on EVSD, thereby there are two normal distributions with the same standard deviation, but different means. The target's mean is larger than the lures. On the other hand, UVSD believes that the standard deviations are also different. Specifically, the distribution of the targets is wider, thereby having a larger standard deviation than the lures. Additionally, when it comes to the decision-making process, UVSD believes there is only one method, namely familiarity. Whereas DPSD believes a method exists before familiarity, namely recollection. This makes the signal detection a two-step process, instead of one. Additionally, the result of familiarity is dependent on the memory strength distribution and both methods' representations differ in their results for familiarity also do.

3 Inspecting Data

3.1 Contingency Tables

A contingency table organizes recognition responses into four categories. Hit: Correctly identifying an old item as “old” False positive/false alarm: Incorrectly identifying a new item as “old”. False negative: Incorrectly identifying an old item as “new”. Correct Rejection: Correctly identifying a new item as “new”. To understand the data from this table it is possible to take different analyses, for instance, accuracy, hit rates, and false alarm rates. Note that to calculate the false alarm and hit rates the reported number of false alarms and hits is divided by the real amount of lures and targets respectively. In general, looking at hit rates and false alarm rates is more informative than just inspecting accuracy because it helps differentiate true memory ability from response bias. Accuracy measures overall correctness, but it does not distinguish between different types of errors or biases. Two people can have the same accuracy but very different memory strategies: One person might have high sensitivity (good memory) but be very conservative in responding ”old”. Another might guess ”old” frequently, leading to both more hits and more false alarms. Instead of just looking at correct responses, hit rate and false alarm rate measure two different cognitive factors, namely sensitivity to old items and propensity to say ”old” to new items, respectively.

3.2 Receiver-Operator Characteristic (ROC) Curves

We were successful in plotting a ROC curve for each of the models. These curves show the relationship between hit rates and false alarm rates for different confidence thresholds. The process consisted of computing hit rates and false alarm rates for progressively lower confidence thresholds, and plotting the result on a ROC graph. The information required to plot these graphs were available in the provided datasets. A complete explanation of the implementation of each model, how the contingency tables were generated, and how the ROC curves were plotted for each model will be explained in the respective sections for Random Guessing, UVSD, and DPSD.

3.3 Advantages of ROC curves over contingency tables

Hit rate and false alarm rate together allow us to plot Receiver Operating Characteristic (ROC) curves, which allows for a deeper analysis of the results than the contingency table offers. A contingency table provides a single snapshot of performance but ignores confidence levels, and does not show the trade-off between hits and false alarms when decision thresholds change. Additionally, the ROC curve reveals how adjusting the confidence threshold affects performance, and helps differentiate between memory models, such as the UVSD and DPSD. To build a ROC curve different contingency tables hit rate and false alarm rate for different confidence intervals are plotted on the same graph.

The UVSD model predicts a smooth, concave ROC. On the contrary, the DPSD model predicts an asymmetric ROC due to recollection boosting high-confidence responses.

4 Model 1: Random Guessing

4.1 Implementation Details

The guessing model is a “toy” model that simulates random guessing and serves as a baseline to compare against more advanced memory models such as UVSD and DPSD. If a memory model performs no better than random guessing, it fails to capture real recognition memory processes. This ensures that models like UVSD and DPSD actually improve recognition decisions beyond mere chance.

In random model, the agent is equally likely to pick between being new or old. This means that the memory distribution function for both lures and targets. Thereby a single function should decide on all words, regardless of nature. Additionally, to make it dully random, the number of times the agent claims to see an old word needs to happen 50% of times. Based on these two facts Gaussian distribution was used as it is easy to mark the 50% threshold (at the mean), and randomly assigns possibilities in the distribution. For the Gaussian distribution we set the mean to 1. This value however, has no relevance, as the threshold is set at the mean, and in large samples 50% of values will almost aalways be associated to a higher value. The standard deviation was set to 1 (thereby the variance is also 1), this defines how many elements go into every confidence interval. This value should not impact the ROC line’s shape, as model is random. However it does affect the spread of the points, lower variance makes closer points and thus a stronger relationship [2].

4.2 ROC Curve Characteristics

When we bring this code into the ROC curve, a 45-degree diagonal from (0,0) to (1,1) can be seen. This happens because hit and false alarm rates increase at the same rate, at every confidence point showing no ability to discriminate old from new items, regardless of the confidence.

This is caused by the fact that for every word we randomly assign it the same chance of crossing the threshold and being framed as old as it is to being associated to new, namely 50% chance. Consequently, at every confidence level, 50% of the lures should be correctly identified as new, or 50% of the lures should be incorrectly identified as old, and 50% of the targets should be correctly identified as old, or 50% of the targets should be incorrectly identified as new. Thereby, at small confidence thresholds (before the threshold), in other words with words associated with under the threshold memory strengths, the false alarm rate becomes 50% and at high confidence levels (after threshold) the hit rate becomes 50%.

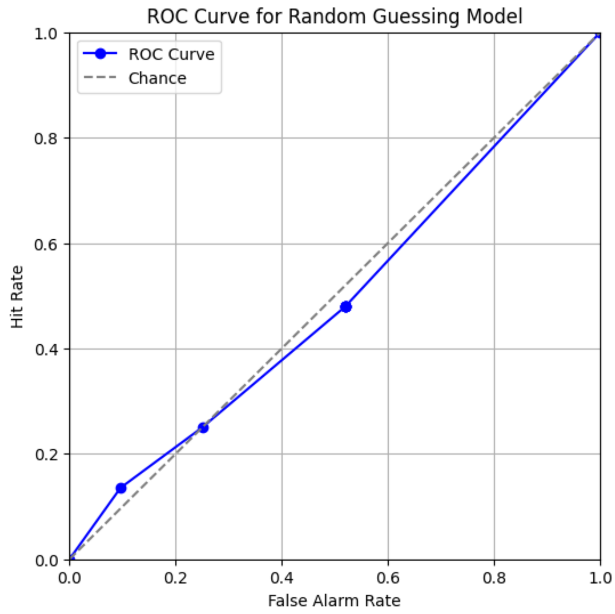

Figure 1: ROC Curve for Random Guessing Model

5 Model 2: Unequal variance signal detection theory

5.1 Implementation Details

The UVSD model (Wixted, 2007)[2] was implemented by simulating memory strengths for target and distractor items using distinct normal distributions. For distractors, memory strengths were drawn from a normal distribution with mean = 0 and standard deviation (SD) = 1, while targets were assigned strengths from a distribution with mean = 2 and SD = 2. The np.random.normal function in Python was used to generate these values. Memory strengths were appended to the dataset, and confidence ratings were derived using a predefined get confidence function, which maps memory strengths to ordinal confidence levels.

5.2 ROC Curve Characteristics

The resulting ROC curve for the UVSD model (Figure 2) plots the hit rate against the false alarm rate across confidence thresholds. The curve demonstrates a characteristic asymmetric shape, rising steeply at lower false alarm rates before plateauing, consistent with unequal variance assumptions. This contrasts sharply with the random guess model, where the ROC curve aligns with the diagonal (hit rate = false alarm rate), reflecting chance-level discrimination. The UVSD curve lies above the diagonal, indicating superior discriminability between targets and distractors. The asymmetry arises because the target distribution's higher variance increases overlap with distractors at lower confidence thresholds, reducing discriminability at higher false alarm rates.

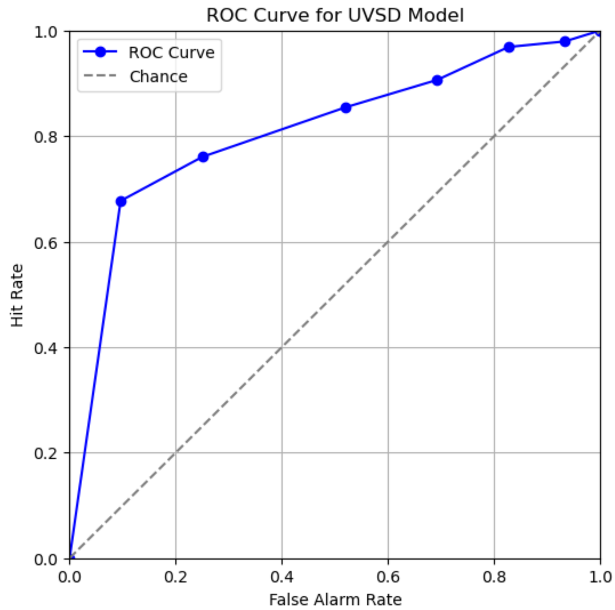

Figure 2: ROC Curve for UVSD model

6 Model 3: Dual-process signal detection theory

The DPSD model, proposed by Yonelias (1994) [1], explains that recognition memory relies on recollection and memory. To test the validity of the DPSD mode, we have implemented a model that separates recollection and memory.

The DPSD model starts with recollection and assigns the word a value of 1 or 8 depending on whether it is a lure or a target. If recollection fails, another process based on familiarity is started. We have simulated this model in code.

As with the other models, in order to evaluate the DPSD model, we calculated the hit rates and false alarm rates and plotted them on an ROC curve. The ROC curve for the DSPD model showed a much more skewed result compared to that of the UVSD model.

6.1 Implementation Details

According to the DPSD theory, recollection is a high-threshold process, which means that a word is either recollected with high confidence or not recollected at all. To simulate this high-threshold recollection process, we randomly selected 20% of all the items and labeled them as recollected items. Among those recollected items, if the word was a target, it was assigned a confidence rating of 1. This represents the highest confidence that the word was on the list. On the other hand, if the word was a distractor, it was assigned a confidence rating of 8, showing the highest confidence that the word was not on the list. Classifying these words with full confidence that they are or are not on the list is representative of the high-threshold process of recollection in the DPSD model.

For the remaining 80% of words that were not recollected, we used familiarity to determine whether a word was in the list or not. In order to do that we assign each word a memory strength. If the word is a distractor they are assigned a value from $\sim \mathcal{N}(0, 1)$, where mean is 0 and variance is 1. If the word was a target, the value is drawn from $\sim \mathcal{N}(1, 1)$. Using these confidence strengths, we then determined their confidence ratings using the `get_confidence` function. Finally, we assigned "yes" or "no" (old or new) based on whether the computed confidence rating was below or above a certain midpoint threshold.

$$\text{Response} = \begin{cases} \text{“yes”} & \text{if confidence} \leq 4 \\ \text{“no”} & \text{if confidence} > 4 \end{cases}$$

This classification of words is similar to the continuous process of familiarity and contrasts with the discrete, binary nature of recollection. It can be noted that familiarity is used when recollection fails.

6.2 ROC Curve Characteristics:

To evaluate the DPSD model, we calculated the hit rate and the false alarm rate at different levels of confidence and plotted the resulting ROC curve (Figure 3).

The ROC curve of our simulation of the DPSD model shows a few important characteristics to note. We can observe that, as expected by the DPSD model, the ROC curve of the DPSD model has an asymmetrical shape. The ROC curve shows a very steep initial slope, which can be attributed by the process of recollection, whereby 20% of recollected items are remembered with a very high certainty. This steeper slope occurs as lower false alarm rates and aligns with the theory.

We can also see that compared to the random guessing model, the DPSD model performs much better. As the curve of the diagonal is constantly above the dotted diagonal line, representative of the random guessing baseline, it shows that the DPSD model has a better ability to distinguish between targets and lures.

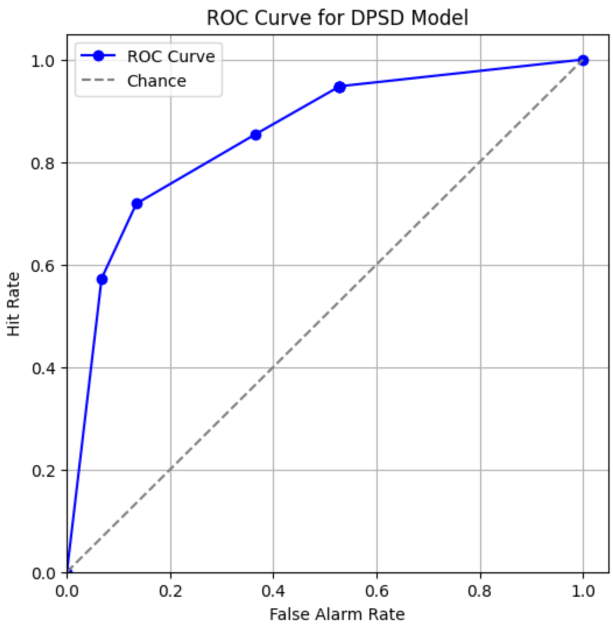

Figure 3: ROC Curve for DPSD Model

7 Evaluation and Discussion

7.1 Importance of Inspecting ROC Curves in Formal Models

Analyzing ROC curves produced by formal models gives us a deeper insight into the different models of memory. ROC curves do not merely show us the number of items that were correctly recollected but give us a deeper understanding of the underlying cognitive processes by showing the trade-off between hit rates and false alarm rates over different confidence levels.

ROC curves can therefore be analyzed in their shape and characteristics in order to assess which of them best fit empirical data from human recognition data.

7.2 Using ROC Curves to Determine the Best-Fitting Model

ROC curves can be used to determine which formal model best explains human memory. This is done by analyzing the shape and asymmetry of the ROC curves of different models such as DPSD and UVSD. By fitting experimental data to the ROC curves of different models, we are able to determine which of these curves determine the best fit and most resembles human memory.

Symmetrical ROC curves can be explained by simple detection theory models that only take familiarity into account. While skewed curves occur when recollection is also taken into account in the model, such as in DPSD. [1]

7.3 Difficulties and Challenges

Through the implementation of the different models and their analysis, a few challenges arose. One of the difficulties that were encountered was ensuring that the selected parameters were following the theoretical assumptions of the models. Ensuring that the chosen parameters (e.g., target mean = 2, SD = 2; distractor mean = 0, SD = 1) align with UVSD assumptions required careful validation. Deviations from these values could have led to ROC curves inconsistent with theoretical predictions. Furthermore, debugging Asymmetric ROC Shapes proved to be another challenge of this assignment. Initial implementations occasionally produced unexpected ROC curves (e.g., symmetric shapes resembling the equal-variance model). Debugging revealed issues such as incorrect loop ordering (e.g., iterating thresholds in descending rather than ascending order) or misaligned hit/false alarm rate calculations.

8 Conclusion

In this assignment, we explored the two main models of recognition memory, DPSD and UVSD, through their implementation and analysis of their resulting ROC curves. We compared these two models against a random guessing baseline, and compared them to each other, in order to gain more insight into the mechanisms of recognition memory. Our results showed that, when looking solely at the resulting ROC curves of the UVSD and DPSD models, both prove to be fitting models explaining human memory. Both models performed significantly better than the random guessing baseline model, showing a concave curve above the baseline.

This assignment, through the implementation and evaluation of the UVSD and DPSD models, provided us with more insight into the mechanisms and complexity of studying recognition memory and signal-detection theory.

References

[1] A. P. Yonelinas, "Receiver-operating characteristics in recognition memory: Evidence for a dual-process model," *Journal of experimental psychology. Learning, memory, and cognition*, vol. 20, no. 6, pp. 1341–1354, 1994.

[2] J. T. Wixted, "Dual-process theory and signal-detection theory of recognition memory," *Psychological review*, vol. 114, no. 1, pp. 152–176, 2007.