The Short Term Memory Structure In State-Of-The Art Recall/Recognition Experiments of Rubin, Hinton and Wentzel

by

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Abstract:

Properties of a short term memory structure are discovered in the data of Rubin, Hinton and Wenzel (1999): Recall (recognition) probabilities and search times are linearly related through stimulus presentation lags from 6 seconds to 600 (350) seconds. This data suggest that only one memory structure is present in the Rubin, Hinton and Wenzel data. The data also suggest that the memory items have a finite effective size that shrinks to zero in a logarithmic fashion as the time since stimulus presentation increases, away from the start of the search. According to the logarithmic decay, the size of the memory items decreases to a couple of neurons at about 1200 seconds for recall and 350 seconds for recognition – this should be the time scale for a short term memory being converted to a long term memory. The incorrect recall time saturates, suggesting a limited size of the short term memory structure: the time to search through the structure for recall is 1.7 seconds. For recognition the corresponding time is about 0.4 seconds, a non-Sternberg experimental result to compare with the 0.243 seconds given by Cavanagh (1972)).

1. Introduction

Rubin, Hinton and Wenzel, (1999) wished to settle once and for all how memory decays with time. Previous data had been found to lack in sufficient accuracy for this purpose (Rubin and Wenzel (1996)) so these authors created a set of data on word recall and recognition over a large time lag range from 6 to 600 seconds with the smallest statistical error bars to date. This invaluable source of information for memory researchers contains cued-recall and recognition probabilities and response times.

In this paper I will investigate just what the Rubin, Hinton and Wenzel, 1999 data can tell us about the structure of short term memory. In particular, I will consider the correlation between probability of identifying a memory item and the search time and how this search time depends upon the lag time. I will also try to set a size limit on the memory items by analyzing the incorrect responses.

2. Materials and methods

Undergraduate students from the University of Iowa were asked to learn lists of uncommon words and word pairs to test cued recall and recognition (Rubin, Hinton and Wenzel, 1999). 20% of the student data was removed for being outside the normal distribution – unusual responses occurred presumably because the task was extremely boring: 430 trials that took a total of 43 minutes. The data was reported in “lags”. Each trial took six seconds which means that lag of 0 corresponds to 6 seconds after the stimulus presentation started and N lag corresponds to 6*N+6 seconds after stimulus presentation. Response time for recall was defined by the response latency. The data I will use is restated here from the original paper. Throughout the paper, the cued recall of the experiment will be simply referred to as recall.

Lag	Seconds after end of stimulus presentation (calculated)	Probability of recall (all 3 measures)	Cued recall response times in seconds for correct responses – (all three measures)	Response times in seconds for incorrect responses – (all three measures)
0	0	.944	1.356	2.292
1	6	.646	1.822	2.722
2	12	.434	2.017	2.938
4	24	.379	2.086	2.872
7	42	.335	2.111	2.960
12	72	.301	2.238	3.001
21	126	.231	2.279	2.970
35	210	.183	2.402	2.978
59	354	.133	2.540	2.969
99	594	.112	2.427	2.927

Table 1 – Recall data (corresponding to table A1, A4 and A5 in Rubin, Hinton and Wenzel (1999)):

Lag	Seconds after end of stimulus presentation (calculated)	Probability of recognition (all 3 measures)	Reaction time in seconds for correct recognition	Reaction time in seconds for incorrect recognition
0	0	0.81	1.128	1.324
1	6	0.642	1.214	1.456
2	12	0.503	1.227	1.509
4	24	0.475	1.247	1.481
7	42	0.401	1.261	1.505
12	72	0.358	1.282	1.517
21	126	0.278	1.254	1.463
35	210	0.195	1.292	1.485
59	354	0.141	1.278	1.472
99	594	0.134	1.287	1.472

Table 2 – Recognition data (corresponding to table ASOMETHING in Rubin, Hinton and Wenzel (1999)):

3. Results:

3.1. Correct recall (recognition): Response time is linearly related to probability of recall (recognition) R^2 of 98% (83%).

Let us begin by plotting the response time against the probability of correct recall (Figure 1(a)). The response time is linearly related to the probability of recall with R squared being 98% over a very large time range of 6 seconds to 600 seconds. A recent item (6 seconds after start of stimulus presentation) requires a total response time of about 1.3 seconds while an item that is typically no longer to be found for most participants (600 seconds after stimulus presentation) requires 2.6 seconds.

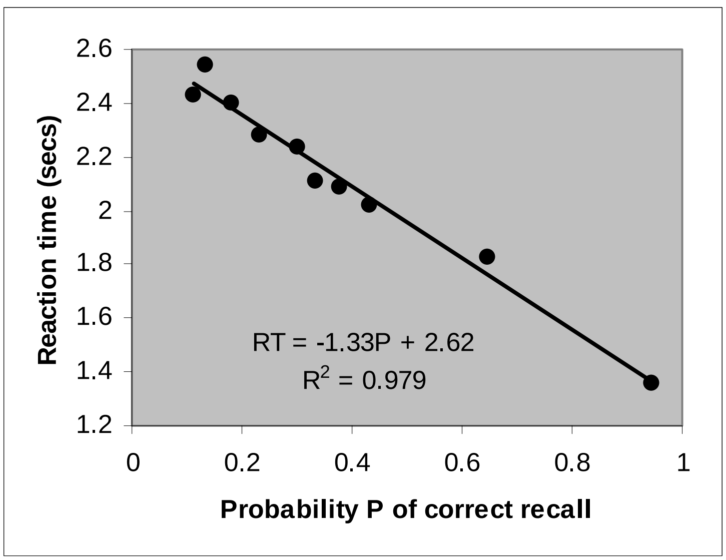

Figure 1 (a): Response time as a function of the probability of correct recall. The time after stimulus presentation is not shown but short times correspond to high probability of recall and long times correspond to low probability of recall. Data from Table 1.

In Figure 1(b) is shown the corresponding data for recognition. It also obeys a linear relationship. A recent item requires a total response time of about 1.13 seconds while an item that is old and typically no longer to be found requires 1.33 seconds. The time scale is much smaller than for recall and the level of statistical noise present in the experiment lowers the R^2 but it is still an impressive 83%.

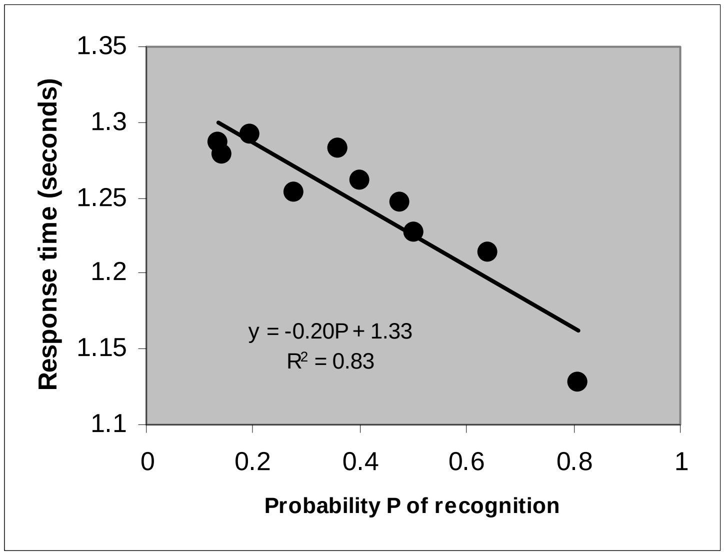

Figure 1 (b): Response time as a function of the probability of recognition. The time after stimulus presentation is not shown but short times correspond to high probability of recognition and long times correspond to low probability of recognition. Note that the time scale is much smaller than the time scale in Figure 1 (a) so the experimental noise accounts for a larger amount of R^2. Data from Table 2.

3.2. Correct recall/recognition: The linear relationships point to a single short term memory structure

The established linear relationship between response time and probability of recall (recognition) between 6 and 600 seconds (6 and 350 seconds – please see below) reasonably suggests that only one structure is responsible for recall, and, potentially, recognition, during that time period. If there were several structures, it is unlikely that they would all be displaying the same linear relationship.

3.3. Correct recall/recognition: The short term memory structures seems to be shrinking

The linear relationships between search time and probability of correct recall or recognition tell us something about the geometry of the short term memory structure probed. Let us consider three scenarios (this is not an exhaustive selection of possible scenarios) while making one assumption: that the search speed is relatively constant across the structures.

Scenario 1. A non-redundant randomly decaying memory structure fixed in space. This structure should have a search time for correctly identified items which is independent of the probability of finding the item. The items are either there or not and if they are, they are in the same spot whether the probability of finding them is high or low and take the same time to find. From Figure 2 we see that it is not a fit to the experimental data.

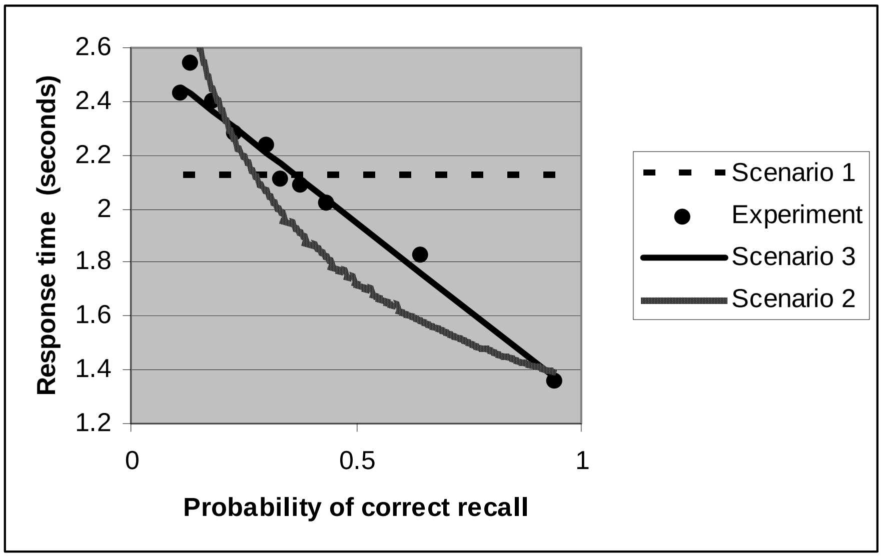

Figure 2. Experimental data from Figure 1 shown with best fits of the three scenarios described.

Scenario 2. A multiple redundant randomly decaying memory structure fixed in space. The response time would not be linearly related to the probability of recall but rather the response time is related to 1/P where P is the probability of recall. For example, if there are two copies of an item randomly positioned, it would on the average take half the time to find the item as compared to if there were only one item and so forth. From Figure 2 we see that it is not a fit to the experimental data. Ratcliff (1978) proposes that it takes a certain number of features to reach a criterion for detecting the item in memory, presumably his theory would fit in this second scenario.

Scenario 3. The memory item has an effective size that shrinks with time after stimulus presentation. The smaller the memory size is, the smaller the probability to find it and the longer away from the starting point it is (Fig. 3). It can be a fit with the experimental data in Figure 2. The size of the memory item may be related to the excitation level of the neuron system surrounding the “core” of the memory: if the system is excited it will be quicker to set up the appropriate firing rates which presumably constitute a memory item.

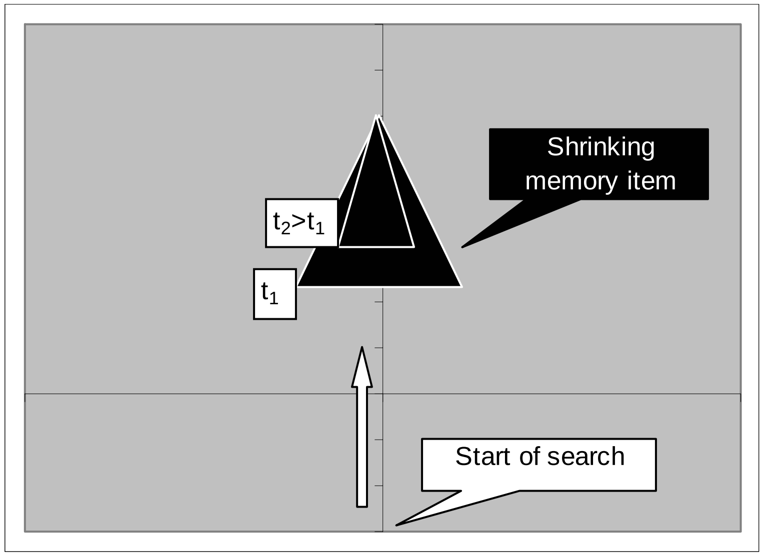

Figure 3: Shrinking memory item. As time passes since the stimulus presentation, the effective size of the memory item shrinks and with it the probability of finding the memory.

Other scenarios are possible. For examples, one could consider a model in which synchronized neuron oscillations are set up and that synchronization defines the memory (see, for example, Gray et al. (1989), Rodriguez et al. (1999) and Jensen and Lisman (1998)). If recall/recognition involves the setting up of such oscillations, it is conceivable that the time to set up such oscillations would increase with time induced changes in synaptic connections: i.e. that the older a memory becomes, the longer it would take to set up such an oscillation to identify a memory item. It would also seem reasonable that large changes in the synaptic connections would result in lower probability of setting up the oscillation and therefore a lower probability of recall.

3.4. Correct recall/recognition: The short term memory items shrink logarithmically with time and suggested times for conversion of short term memory into long term memory

The effective size of the memory shrinks quickly at first and slower later on. I have defined the “size” to mean the distance in search time from the center of the memory core (search time when the probability P of recalling the item is close to 0) to its periphery (the reader can convert the size into units of neurons by dividing the time by, say, 0.02 seconds, a reasonable time to pass through a neuron). At the time scales measured, the shrinking can be described as a logarithmic relationship of t (Figure 4 (a) for recall and Figure 4(b) for recognition). So, for example, the size of the memory item for recognition is 0 seconds when the probability of finding an item is 0 and 1.29 seconds (2.62 seconds-1.33 seconds) when the probability of finding the item is 1. Notice the remarkably good fits with R^2 at 97% and 94% for recall and recognition.

The logarithmic curve breaks down at large times because the size becomes negative. A reasonable lower limit on the size (which is an upper limit on the time after stimulus presentation) is a couple of neurons. If each of them takes about 20 milliseconds to traverse, then the upper limit on the logarithmic formula for recall (recognition) is about 1200 seconds (350 seconds). This can be interpreted as a time limit of the short term memory structure before the information is totally gone or converted into long term memory. The time for the probability of recall (recognition) to drop by 50% is about 11 seconds (10 seconds).

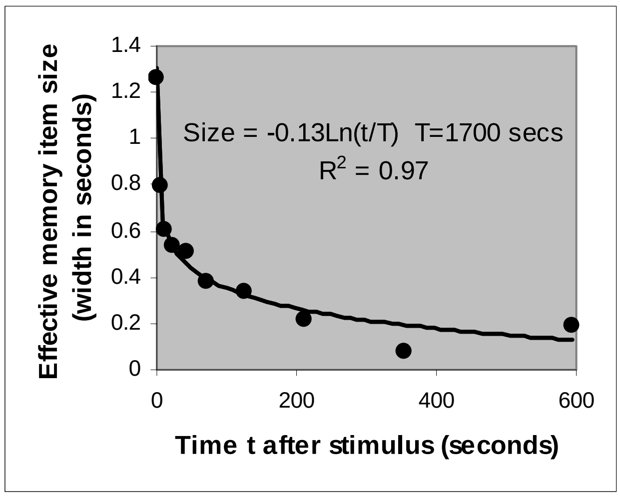

Figure 4(a). Shrinking of the effective size of the recall memory item where "size" is measured as distance in search time from the center of the memory core to its periphery. The curve represents a two parameter logarithmic fit, moving t=0 seconds to t=0.05 seconds to avoid a divergence. Data from Table 1.

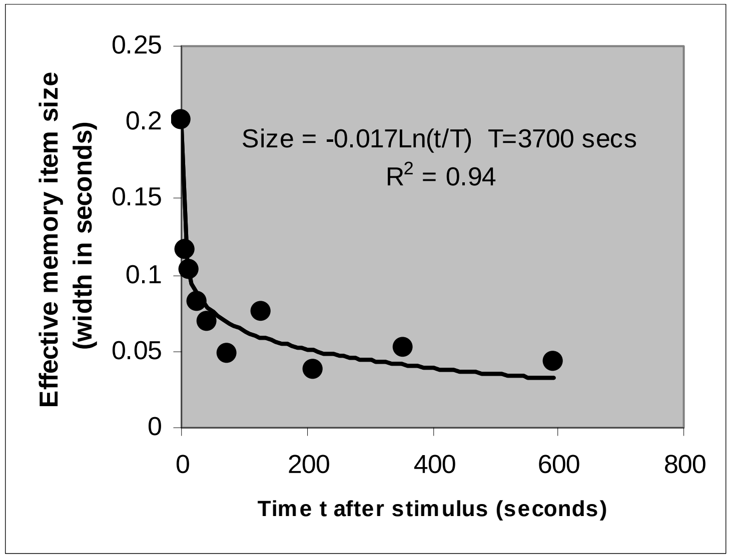

Figure 4(b). Shrinking of the effective size of the recognition memory item where "size" is measured as distance in search time from the center of the memory core to its periphery. The curve represents a two parameter logarithmic fit, moving t=0 seconds to t=0.05 seconds to avoid a divergence. Data from Table 2.

3.5. Incorrect recall/recognition: Saturation of the response time and the total time to search short term memory during recall.

Let us consider the relationship between response time and "incorrect" recall (recognition) as shown in Figure 5 (a) (5 (b)). When the correct recall and recognition probabilities are large, the response times for incorrect recall and recognition changes linearly just like for correct recall and recognition. However, when the correct recall (recognition) probability decreases they saturate and become constant.

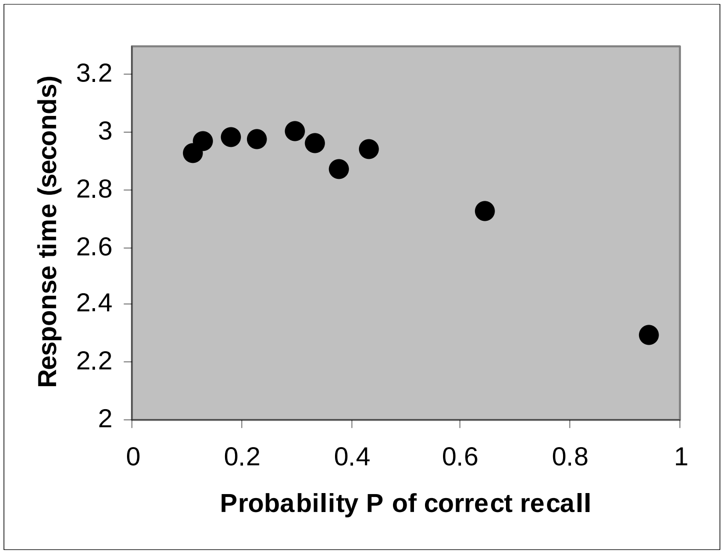

Figure 5(a): Response time for incorrect recall as a function of the probability of <u>correct</u> recall (to keep the scales the same throughout the paper). Data from Table 1.

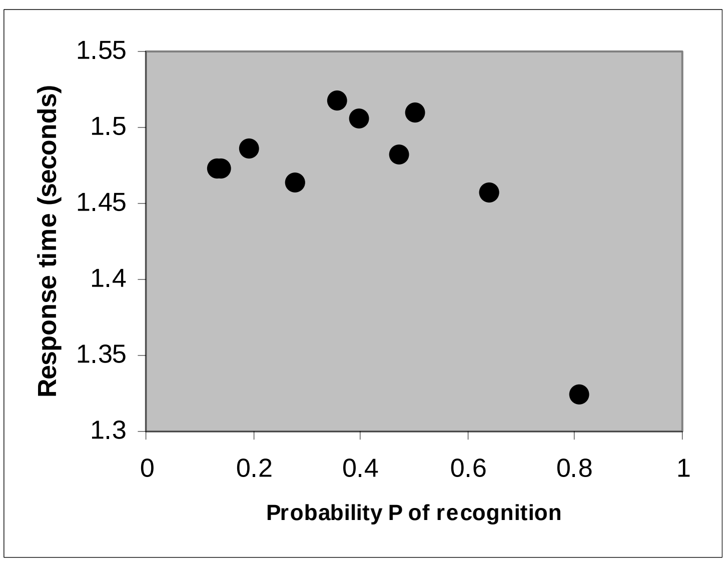

Figure 5(b): Response time for incorrect recognition as a function of the probability of <u>correct</u> recognition (to keep the scales the same throughout the paper). Data from Table 2.

The response times are always larger for incorrect recall or recognition than for correct recall or recognition (the differences in response time between the incorrect and correct searches are shown in Figures 6 (a) and (b) below). The data with the lowest level of noise is the recall data. It is possible to infer the maximal time to search the brain for recall, if we assume that the search yielding the correct result is not exhaustive but the search yielding the incorrect result is.

The time it takes to finish an exhaustive search of the particular brain structure involved is the difference between the total response time for incorrect recall of 3 seconds at low correct recall probability (Figure 5 (a)) minus the shortest response time recorded, the response time for correct recall at P=1 (Figure 1 (a)), 1.3 seconds which yields 1.7 seconds. The noise in the data for recognition makes it more difficult to assess the corresponding time – a rough estimate is 1.5-1.13=0.4 seconds. This latter estimate appears to be the first non-Sternberg task result that can be compared to the Cavanagh (1972) time estimate to fully search short term recognition memory of 0.243 seconds.

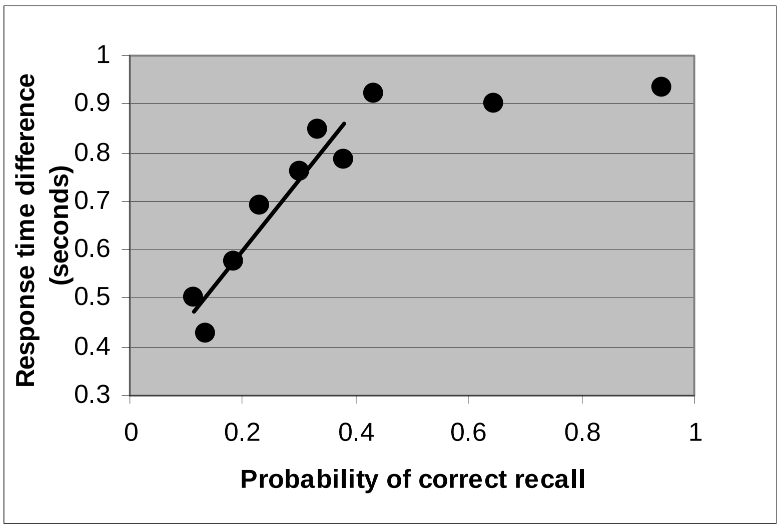

Figure 6(a): Difference in response times between incorrect and correct recall as a function of the probability of correct recall. Data from Table 1.

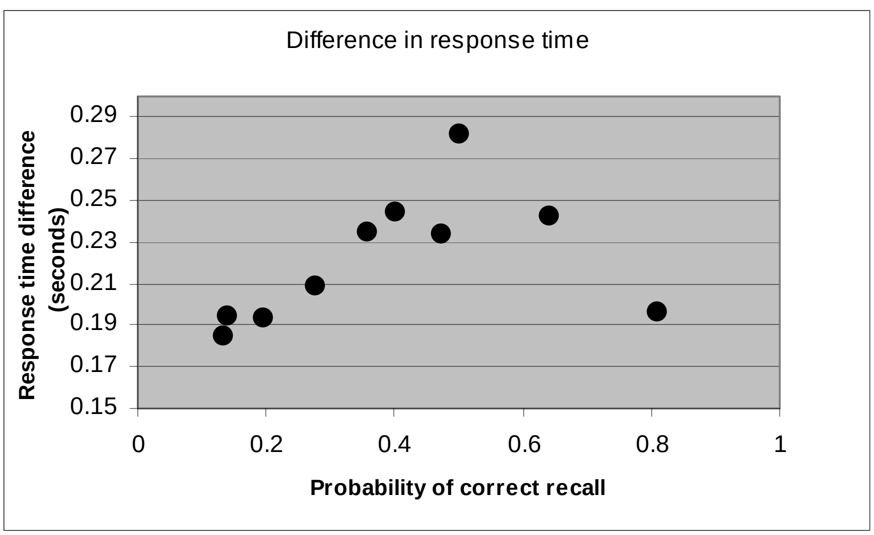

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Figure 6(b): Difference in response times between incorrect and correct recognition as a function of the probability of correct recognition. Data from Table 2.

3.6. Comparing recognition and recall.

In this experiment, recognition could potentially be thought of as a first order process and recall as a second order process. I.e. to get recall, a word has to first be recognized and then the association has to be found. The Rubin, Hinton and Wenzel data show that probability of recall is pretty much the same as the probability of recognition throughout the range of time lags (see Figure 7). If the cue and the recalled item were separate memory items, one would expect the probability of recall to decay quicker than the probability of recognition as the memory items shrink and stop overlapping causing the association to disappear. The data therefore suggest that the subitems for recall (the cue and the recalled item) are part of the same memory item.

What instead differentiates recall from recognition are the large differences in response times with recall being much slower and varying over a much larger time scale. This is presumably because the recall item carries more information than the recognition item.

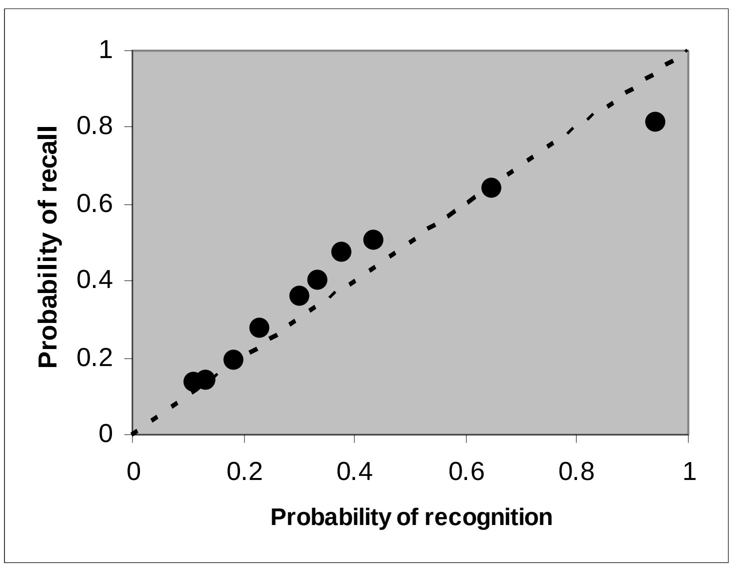

Figure 7: Probability of recall vs. probability of recognition. The dashed line is the line probability of recall=probability of recognition.

4. Discussion

Rubin, Hinton and Wenzel (1999) data is the most accurate data on recall to date. It reveals several properties of the short term memory structure:

The short term memory structure shows a linear correlation of recall (recognition) probability with search time from 6 to 600 (350) seconds after the start of the stimulus presentation (compare with Pachella (1974), . I draw the conclusion that there is only one memory structure present in the Rubin, Hinton and Wenzel data because there seems to be only one functional form for all the data points (one for recognition and another one for recall). This does not square with the conclusion in Rubin, Hinton and Wenzel (1999) that there are three different memory structures present. Their conclusion is based on improvements in R^2 when using 5 parameters to 9 recall data points which seems excessive. Nevertheless, the current author also agrees with Rubin, Hinton and Wenzel that the probability versus lag time curve they present seems to show real structure not accounted for by fewer parameters. The curves presented here (probability versus response time and effective memory size versus lag time) do not show such structure. One way to potentially settle the issue is to expand the experiments in part using data points where the large changes occur in recall and recognition probabilities at 5-10 seconds.

The linear correlation I find of recall/recognition probability with time may be useful for memory modeling researchers because it presents a simple test for models (though the particular experimental circumstances have to be remembered, see, for example, MacLeod and Nelson (1984)). This is in contrast to modeling efforts of, for example, the serial position effect (see, for example, Davelaar et al (2005)) in which the exact formula of the curve is unknown.

The memory items in the Rubin, Hinton and Wenzel (1999) experiment can be described as having an effective size that shrinks with time in a logarithmic fashion. The effective size might be related to the state of activity of the neurons surrounding a core memory and the higher the activity, the quicker it is to find the core memory. The shrinking is quick in the beginning, lowering the probability of correct answers by 50% in ten seconds. Though this is a tempting time to use as a time scale for short term memory, the shrinking continues to follow the same logarithmic curve until perhaps 1200 seconds for recall and 350 seconds for recognition at which point either memory item is the size of a few neurons. Eimas and Zeaman (1963) showed that correct response times decreased as overlearning increased: in our parlance the overlearning stimulates the core memory and increases its effective size.

The nature of the connection of short term to long term memory is still unknown (Cowan (1993)). Cowan (2001) writes that “at present, the basis for believing that there is a time limit to STM is controversial and unsettled … any putative effect of the passage of time on memory for a particular stimulus could instead be explained by a combination of various types of proactive and retroactive interference from other stimuli.” The limits found in this paper suggest that 350-1200 seconds is the time scale to look for a potential conversion. There are other estimates in the literature of the duration of short term memory and non-permanent changes to motor memory appear to last a full 5 hours (R. Shadmehr, and T. Brashers-Krug (1997)).

The time it takes to finish an exhaustive search (as calculated from the saturation of the response time for errors, see Millward (1964) and Thompson (1977)) is 1.7 seconds for recall and 0.4 seconds. This latter estimate is a non-Sternberg task result to compare with the Cavanagh (1972) time estimate to fully search short term recognition memory of 0.243 seconds.

The Rubin, Hinton and Wenzel data show that probability of recall is pretty much the same as the probability of recognition throughout the range of time lags which suggest that the subitems for recall (the cue and the recalled item) are part of the same memory item. What differentiates recall from recognition are the large differences in response times with recall being slower (Nobel and Shiffrin (2001)) and varying over a much larger time scale. In my interpretation, the recall item is a much larger memory item than the recognition item because it carries more information.

5. Summary

Properties of a short term memory structure are discovered in the data of Rubin, Hinton and Wenzel (1999): Recall (recognition) probabilities and search times are linearly related through stimulus presentation lags from 6 seconds to 600 (350) seconds. This data suggest that only one memory structure is present in the Rubin, Hinton and Wenzel data. The data suggest that the memory items have a finite effective size that shrinks to zero in a logarithmic fashion as the time since stimulus presentation increases, away from the start of the search. According to the logarithmic decay, the size of the memory items decreases to a couple of neurons at about 1200 seconds for recall and 350 seconds for recognition – this should be the time scale for a short term memory being converted to a long term memory. The incorrect recall time saturates, suggesting a limited size of the short term memory structure: the time to search through the structure for recall is 1.7 seconds. For recognition the corresponding time is about 0.4 seconds, a non-Sternberg experimental result to compare with the 0.243 seconds given by Cavanagh (1972)).

6. ACKNOWLEDGEMENT

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