Reactivation of Short Term Memory

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Abstract:

The reactivation mechanism of short term memory is studied. In recognition and cued recall, reactivation is externally driven and accounts for the linear relationship between recognition probability and response time. In free recall the reactivation is internal. The free recall initial item distribution indicates that the mechanism is imprecise and reactivates several memory items at the same time. A competition ensues and the winners are the items which can be reactivated the quickest. Those items that take longer to reactivate are heavily suppressed. The internal reactivation mechanism also activates erroneous items, proportional to the internal reactivation time, in effect erasing memory while searching it. We find no discontinuities in the error rate which challenges the notion of a limited capacity, "quantized," working memory. Internal reactivation of long term memory does not seem to have the same erasure effect.

Keywords: Free recall;recognition; short term memory;memory search; memory reactivation

Introduction

In this paper we will focus on how short term memory is reactivated after study. It is easy to understand how memory gets activated: a word is read on a computer screen, neurons fire in many places until those responsible for the meaning of a word are active. Reactivation from recognition is also straightforward – the pattern of neuronal firing is set up again. But how does the brain reactivate those same neurons if it does not have an outside stimulus?[1]

Let's begin with reactivation using an outside stimulus: consider a typical recognition experiment such as the one by Malmberg et al earlier in this journal (Malmberg et al, 2012). The probability of correct answers as a function of time is shown in Fig. 1(a)[2]. Premature responses occur for times less than or equal to 0.5 seconds - subjects have no information to convey. From about 0.6 seconds to about 0.8 seconds the amount of information is quickly increased to a maximum and after 0.8 seconds the information drops linearly. After 3 seconds very few responses remain (see Fig. 1(b)) and they are scattered. Let's focus on the portion with the linear drop. It shows that it takes more time to respond the less the test item is remembered. If an item is almost fully activated the response is quick, otherwise it takes some time to

[1] For those interested, I am a physicist by training and thus do things differently than psychologists. In physics, experiments and theory are typically separated; a physicist usually does one or the other, not both – there is too much competition for one person to be able to do both. Theorists can further be divided into fundamentalists and phenomenologists. The former link experimental data to fundamental theories (string theory is an example) and the latter link various experimental data to other experimental data until there is enough information for the fundamentalists to take over. The memory field does not have enough information for fundamental theories (we do not know how short term memory works on the cellular level let alone the genetic level) and thus I am a phenomenologist. Rather than starting with a hypothesis and then testing it, I examine experimental data and look for patterns that can be related and explained by theory with as few parameters as possible. It is important that the number of parameters is minimal: one can always fit data with many parameters and the more parameters needed the less real information is in the model itself. Note that my approach is consonant with the findings of McCaffrey (2012) that progress in psychology experiments is done by noticing obscure features and Gupta et al (2012) that creativity is based on avoiding high-frequency solutions.

[2] I thank Kenneth Malmberg for access to the data.

reactivate it.[3] The straight line accounts for 85% leaving 15% to statistical error. The same straight line dependency also occurs in other sets of recognition data as well as in cued recall data (Tarnow, 2008).

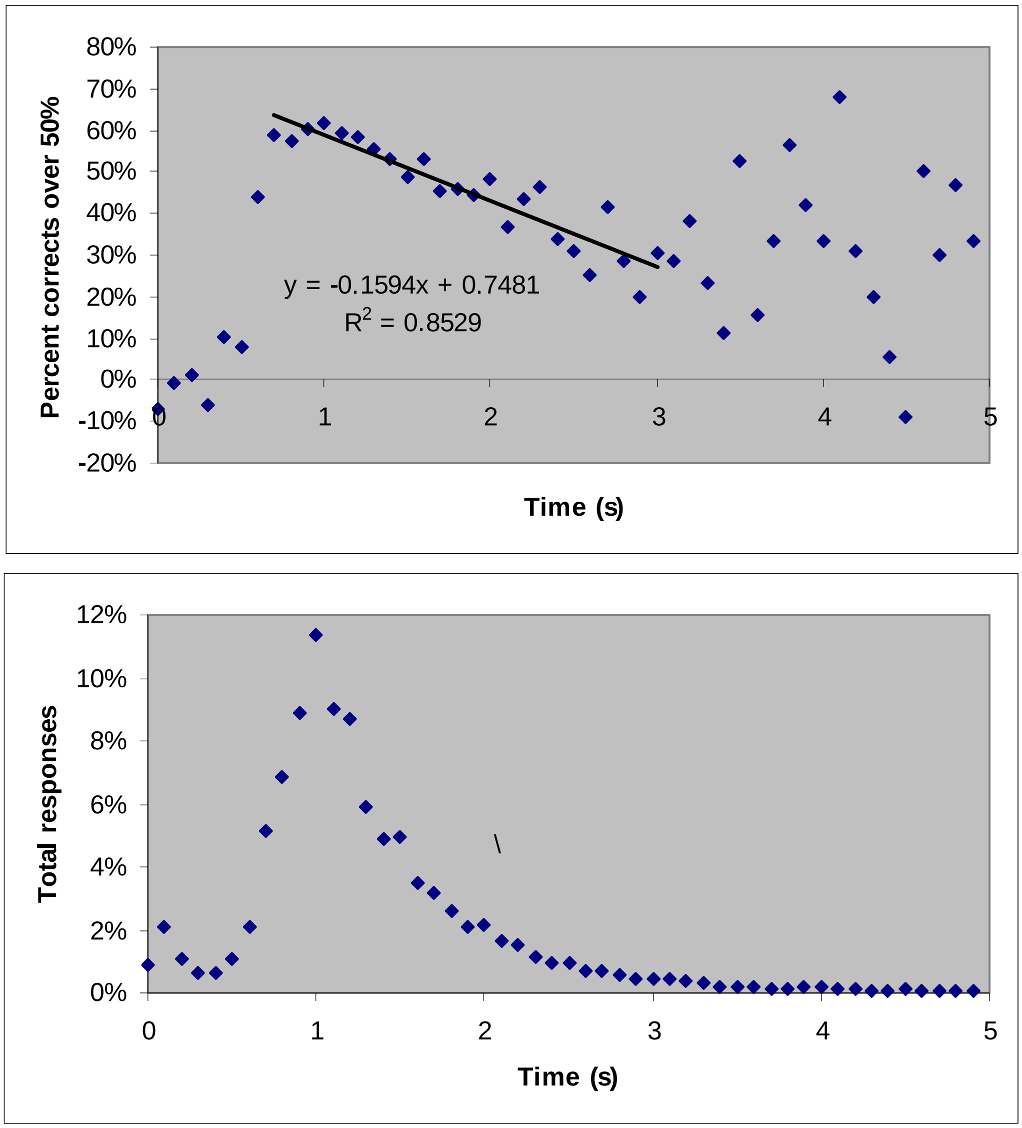

Figure 1. (a) Top panel shows the probability of recognition versus time for the large block responses in Malmgren et al (2012). (b) Bottom panel shows the probability of response versus time in the same data.

[3] If, on the other hand, an item is either there or not as in interference theory it is hard to see why a subject should hesitate.

INTERNAL REACTIVATION OF THE FIRST ITEM IN FREE RECALL

Reactivation in free recall is more complex. It occurs internally without an outside stimulus and can be a minute long. The number of items remembered is a lot fewer than in recognition. In the recognition experiment of Malmberg et al (2012) one can argue that the number of items remembered is the probability of remembering the first item multiplied by the total number of studied items. This yields about 47 items[4]. In a free recall experiment the total number of items remembered is only about 8 (Murdock, 1962)!

In Figure 2 is shown both the total recall and the initial recall in a typical ten item recall experiment (the 10-2 data from Murdock, 1962 – see Appendix 1). Both curves show the famous bowing effect - intermediate items are remembered less well than initial or final items and this has been noted before. If we look a little closer, the initial recall distribution seems to have item differences amplified compared to the overall recall distribution and three of the items in the initial recall distribution have close to 0 recalls. I.e., instead of (initial recall)=(overall recall) we have (initial recall)=offset + (overall recall) * amplifier.

[4] After the first recognition, there is a decrease in recognition probability in Malmberg et al, 2012, which is shown to be an artifact of the experimental procedure. I suggested it can be related to the effective "study" of foil items occurring on the left hand side, see Tarnow, 2012)

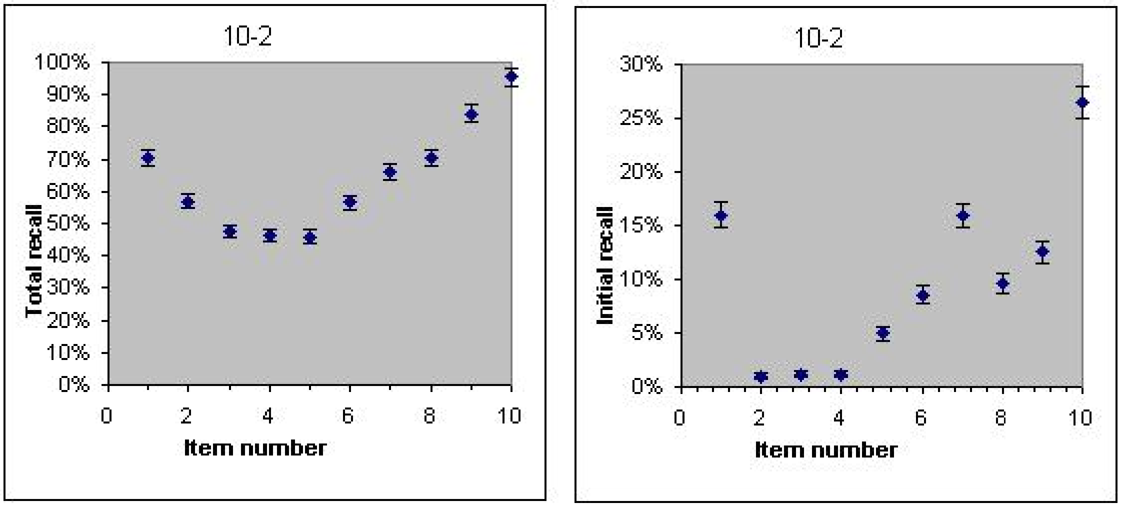

Fig. 2. The left panel shows the famous bowed curve of total recall versus item number. The right panel shows the bowed curve of initial recall versus item number. The error bars in each direction are the standard deviation of a Poisson distribution (no systematic errors were considered). Experimental data from Murdock (1962).

The zero recall probabilities in the initial recall curve are not statistical aberrations. Figure 3 shows the number of initial recalls of each item as a function of the total number of item recalls for all the Murdock data (which covers two presentation rates - one per two seconds and one per second - and five item list lengths – 10, 15, 20 for the two second presentation rate and 20, 30 and 40 for the one second presentation rate). The graphs would be a straight proportionality if the initial recall was no different from subsequent recalls. Instead, we find graphs offset with low probability items almost never being recalled in the initial recall. Figure 4 shows that the offset in each case is the <u>same as the total recall probability of the least recalled item.</u>

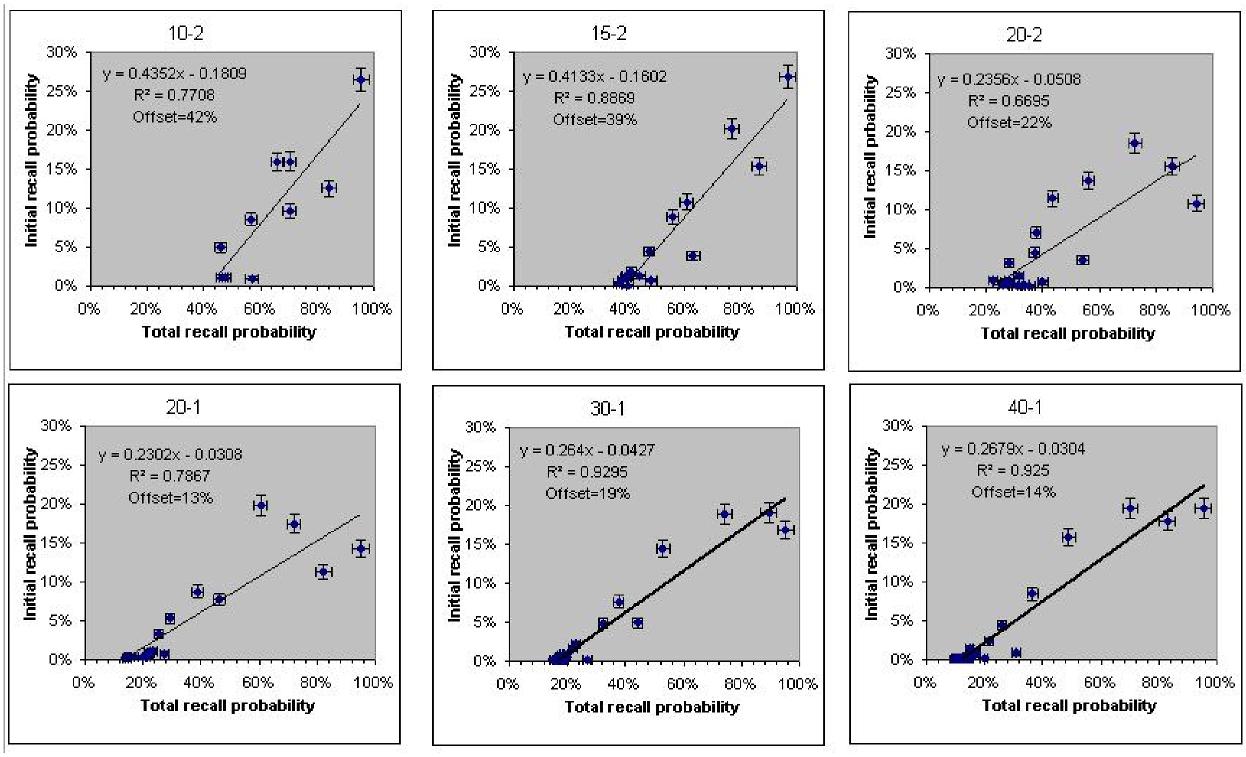

Figure 3. Number of initial recalls for each item versus the total number of recalls for that item. The six panels correspond to the six Murdock (1962) experiments labeled on top as M-N. M is the number of items in the list and N is the number of seconds between item presentations. Note the well defined intercepts. The error bars in each direction are the standard deviation of a Poisson distribution (no systematic errors were considered).

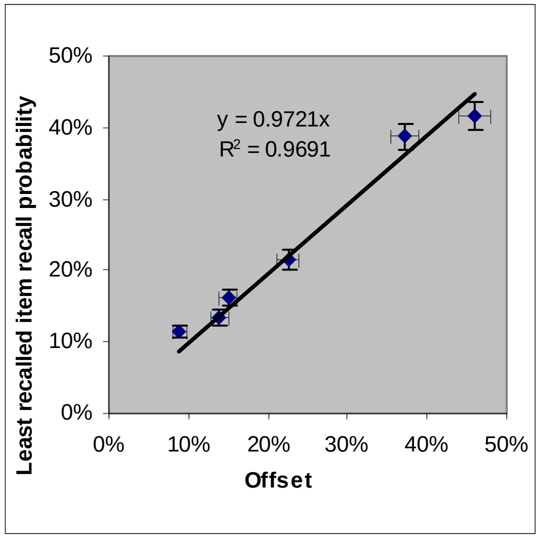

Figure 4. Recall probability of the least recalled item versus offset from the curves in Figure 3. Note the relationship ***Offset=least recalled item recall probability.*** *The error bars in each direction are the standard deviation of a Poisson distribution (no systematic errors were considered)*

The activation level of a memory item is defined to be the same as the probability of recall or recognition of the item (Tarnow, 2008):

Activation level of item=Probability of recall or recognition of item (equation 1)

The activation level is 100% when a memory item is completely activated but can then decay. For a word to be reported in a recall experiment the item has to be reactivated and the activation level has to increase back to 100%.

The internal reactivation time is proportional to 1 – (activation level). Since internal reactivation mechanism cannot be precise (otherwise no reactivation would be necessary because the item would already be known), it might probe more than one item at the same time. [5]

[5] If the internal reactivation mechanism only probes one item at a time the reactivation time is irrelevant and the initial recall distribution would be the same as the overall recall distribution. If the internal reactivation mechanism probes two items at a time, the reactivation time becomes important: items with the higher activation level would be the first to be reactivated and they beat out items with lower activation levels and the initial recall distribution looks different from the overall recall distribution. The single item with the lowest probability of being recalled would not be recalled at all and the items with the highest probability of recall would be more likely to be recalled than in the overall distribution giving rise to

Thus activation theory provides the following prediction of the initial recall of item i:

Probability of initial recall of item $i=\Sigma_n D(n,N)*P(n,i)$ (equation 2)

where D(n,N) is the normalized probability distribution of the number of items being reactivated at any one time and N+1 is the average number of items being simultaneously reactivated. n=0 corresponds to a single item and n=1 corresponds to two simultaneously reactivated items, etc. N is the only unknown quantity. It should be proportional to the number of list items (the more items the more simultaneous reactivations), so for various list lengths we write N as:

N=(number of list items)*a (equation 3)

Thus activation theory has only one constant that is unknown, a. We will approximate D_n with the Poisson distribution. P(n,i) is the probability of reactivating item i when n+1 items are simultaneously reactivated. P(0,i) is the activation level of item i, i.e. the overall distribution of item probabilities. P(1,i) is the sum over all item pairs in which i is a member; the individual terms are 0 if the activation level of item i is lower than the activation level of the other item and 1 if the activation level of item i is the higher one. The following rules apply:

$\Sigma_n \Sigma_{,i} D_n P(n,i)=1$ (exactly one item is recalled in the initial recall). (equation 4)

and

$\Sigma_i P(n,i)=1$ (exactly one item is recalled if n items are reactivated at the same time) (equation 5)

With a=0.14 (a is the average fraction of items probed from equation 3), and let me stress that this is the ONLY fitting parameter, we obtain the results in Fig. 5. The results are excellent with an average R squared of 80%.

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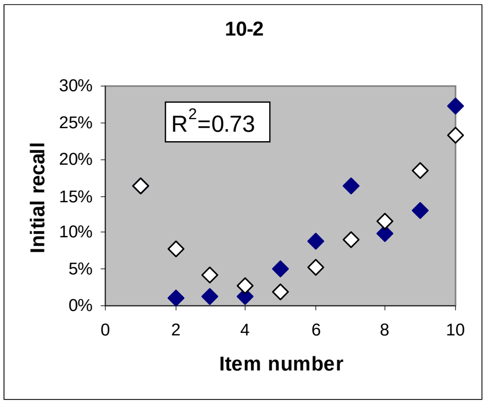
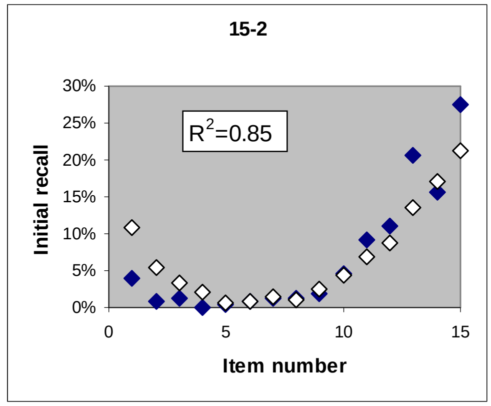
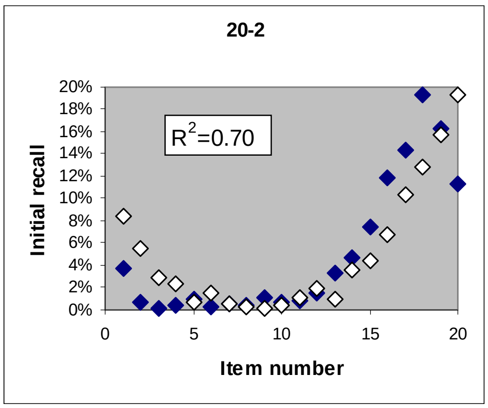
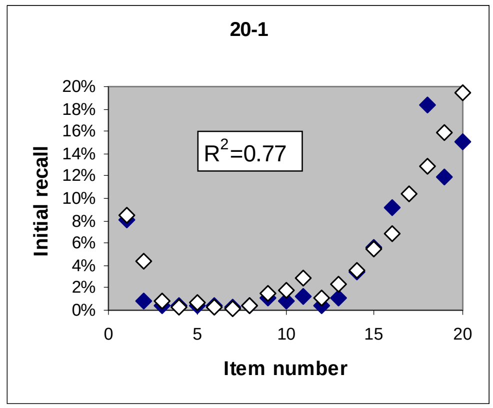
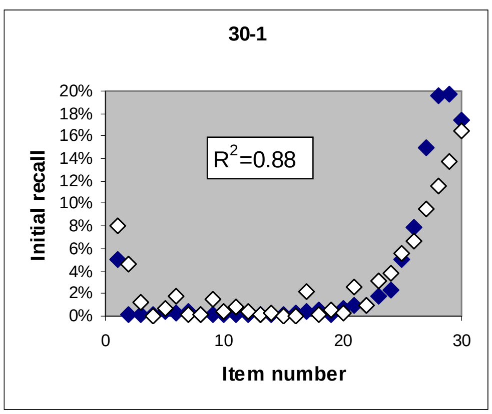
the amplification effect mentioned in the introduction. If the reactivation mechanism probes all items at the same time, the item with the highest activation level would be the only one recalled – all other items would not be recalled. If n items are being reactivated at the same time the outcome would be somewhere in between.

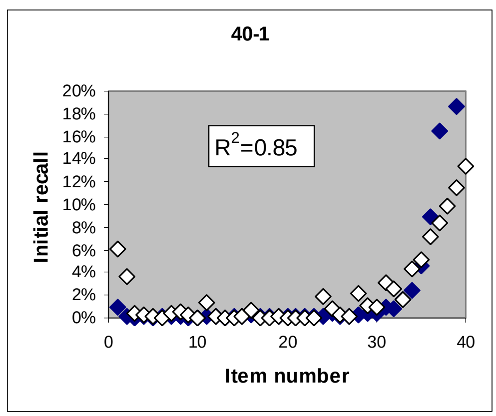

10-2
R2=0.73
Initial recall
Item number
30%
25%
20%
15%
10%
5%
0%
0
2
4
6
8
10

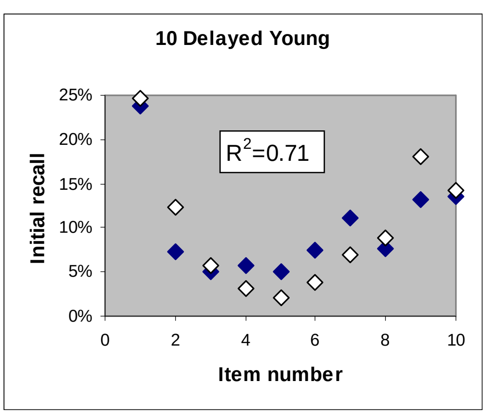

15-2
R2=0.85
Initial recall
Item number
30%
25%
20%
15%
10%
5%
0%
0
5
10
15

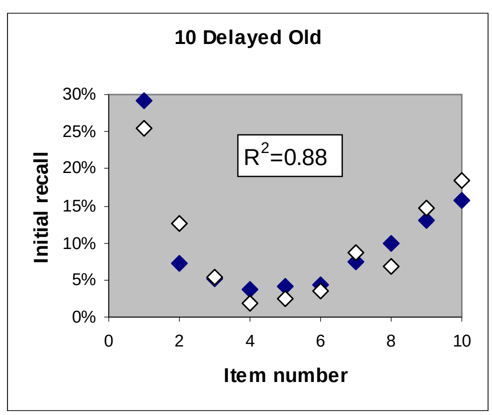

20-2
R2=0.70
Initial recall
Item number
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
0
5
10
15
20


20-1
R2=0.77
Initial recall
Item number
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
0
5
10
15
20


30-1
R2=0.88
Initial recall
Item number
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
0
10
20
30


40-1
R2=0.85
Initial recall
Item number
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
0
10
20
30
40


10 Delayed Young
R2=0.71
Initial recall
Item number
25%
20%
15%
10%
5%
0%
0
2
4
6
8
10


10 Delayed Old
R2=0.88
Initial recall
Item number
30%
25%
20%
15%
10%
5%
0%
0
2
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10

Fig. 5. Activation theory prediction of the initial item seclection in the Murdock (1962) and Kahana et al (2002) data fitted with the a parameter by minimizing the sum of least squares. The theoretical values are shown in open diamonds and the experimental values in filled diamonds. R squared varies between 0.70 and 0.88, the average is 0.80.

INTERNAL REACTIVATION CAUSES ERRORS

Why does free recall return so many fewer items than recognition, a long standing controversy in memory psychology? It may be a combination of the internal reactivation not completely sampling the total item space and that the internal reactivation mechanism, presumably by `being imprecise, as we will see next, incorrectly activates non-studied items.

In the Murdock & Okada (1970) data we plot the number of erroneous items as a function of the internal reactivation time and find that the probability of an error proportional to the overall search time (Fig. 6). The error rate is about 1% per second search time; in other words, for every second searched, about 0.01*(number list items) new items are activated.

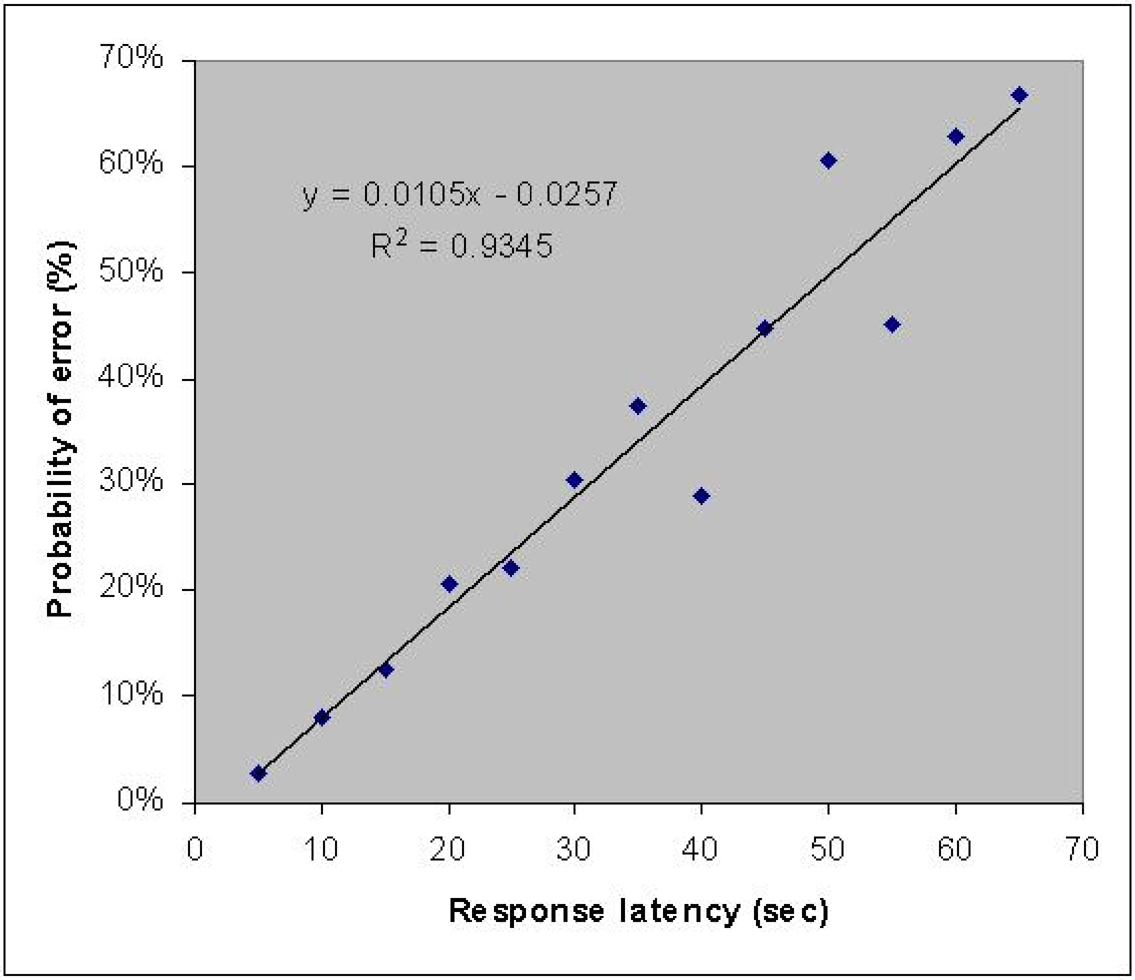

Fig. 6. Probability that a response is erroneous versus (total) response latency. Data from Murdock & Okada (1970).

Can errors plausibly increase because of subjects' increased willingness to be less cautious as time passes and allow more errors? That this is likely not the case is shown in Fig. 7 which displays the probability of an erroneous identification in long term memory two days after the presentation of list items (McDermott, 1996). Note the difference in time scales – even after 15 minutes the subjects are not becoming less cautious and the error remains near 17%, much lower than most of Fig. 6. Rather, the errors in Fig. 6 result from incorrectly activated new items and once activated there is little difference between the new and the studied items. Since all recalled items eventually are errors, the reactivation mechanism in effect erases information from memory.

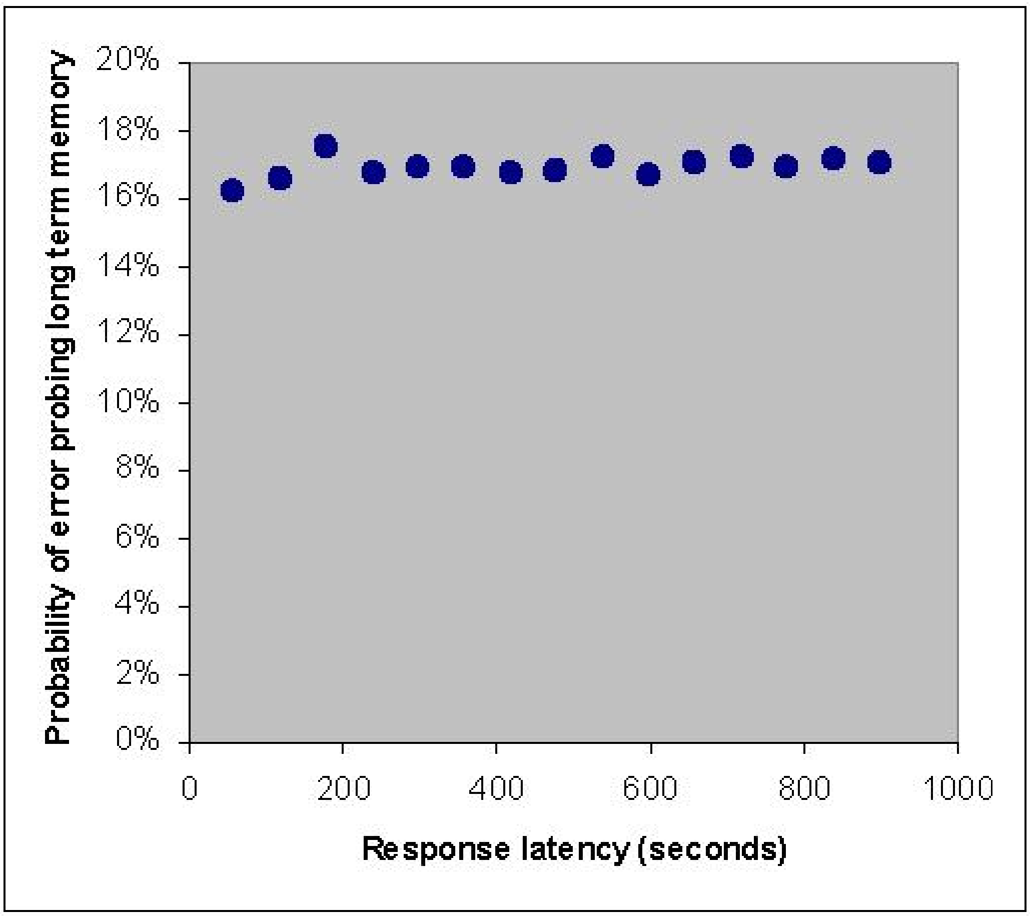

Fig. 7. Probability that a response is erroneous versus response latency when probing long term memory (two days after list items were presented). Data calculated by reading off values from figure 4 in McDermott (1996) and calculating the differences as a function of time. Compare this data with the data of Fig. 6.

Summary & Discussion

We have studied memory reactivation in recognition, cued recall and free recall. In recognition and, to some extent in cued recall, reactivation is externally driven while in free recall it is internal. The externally driven reactivation is precise and linear in time. In free recall, the reactivation is internal. This internal reactivation mechanism is imprecise. It reactivates several items at the same time, those items that are most quickly reactivated win and this competition act to amplify recall probability differences. This explains the curious initial free recall distributions of the Murdock (1962) data and the Kahana et al (2002) data in which low probability items are suppressed. This suppression is substantial ranging from 9 in the 10-2 data to 58 in the 15-2 data. In activation theory it is proportional to a, the average fraction of simultaneously reactivated items. The more simultaneous comparisons made, the more the least remembered items are suppressed.

Interference theories and other context sensitive theories hold that the final and initial recall distribution cannot be highly correlated - the particular order of items recalled is primary. Since the total recall distribution explains 80% of the variance in the initial recall distribution, the two distributions are highly correlated. Thus we have a limit on how important effects of interference and other context sensitivity are for the initial item distribution – they only amount to 20% or less of the variance. The insensitivity to context is presumably due to there being little or no context before the first item is recalled. Once the first item is recalled, a context is set and Kahana (1996) has shown that it is more probable that the next item will be the item subsequent rather than previous in the studied list.

We also found out that in free recall the internal reactivation mechanism activates new items. This supports the concept that the internal reactivation process is imprecise. We find that the error creation rate 1% per second for search times up to 60 seconds in the Murdock & Okada (1970) data. Murdock & Okada (1970) found interresponse times were inversely related to the number of words yet to recall, consonant with a search by random sampling, also testifying to the imprecise nature of the free recall internal reactivation.

The proportionality in Figure 6 is quite striking. A similar linear fit in Sternberg (1966) described the time to search through a previously displayed series of digits. Its simplicity caused a paradigm shift challenging researchers to consider information processing aspects of cognition. Here I suggest that theories of short term memory retrievals need to include three more straight lines: a proportional relationship between response time and response probability for recognition and cued recall, response errors as a function of search time in free recall, and, in a logarithmic plot, the probability of cued recall and recognition versus time after list presentation (see Fig. 4 in Tarnow, 2010a).

The linear error function does not exhibit a discontinuity as the subjects move from items presumably inside working memory to items presumably outside of working memory. This seems inconsistent with a limited capacity working memory model (see, for example, Cowan 2001): one would have expected that the error rate would start at zero and not increase until all of working memory is exhausted. I have earlier found another inconsistency with the limited capacity working model: if there is a buffer, as the item list number of the first remembered item decreases, the total number of items remembered should decrease and in the Murdock (1962) data they do not (Tarnow, 2010b).

Also of interest is that the search mechanisms of short term memory and long term memory seem to be have different impacts: the short term memory search is accompanied by errors while the long term memory seemingly does not introduce errors (in 15 minutes of search the error rate in Figure 7 does not exceed 18%). Reactivation can presumably make many erroneous items look the same as presented items because the search time is several times longer than the reactivation time. It may be that the same suppression mechanism that occurs in recognition due to foils (Tarnow, 2012) also occurs in free recall. In contrast, long term memories take longer to create and if the search time is shorter than the memory creation time (which is on the order of the time scale of protein synthesis Lynch & Baudry, 1984; Kandell, 2001) no errors have time to form to make internal reactivation created foil items mimic remembered items.

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