RETRIEVAL PROCESS IN FREE RECALL CREATES ERRORS IN SHORT TERM MEMORY BUT NOT IN LONG TERM MEMORY

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An analysis of free recall errors shows that the free recall retrieval process in short term memory is accompanied by a linear rise in errors, without discontinuities, invalidating short term memory models in which stores or states are sequentially emptied. The frequency of errors increases at roughly 1% per second and exponentially if the items to be recalled are strongly related. This leads to a "Heisenberg uncertainty principle" situation: the more items recalled, the less accurate is the recall of those items. The error probability does not reach a plateau, is independent of time passing without a retrieval process being engaged, suggesting that the retrieval process itself introduces errors in short term memory. In contrast, in long term memory the error probability remains constant, indicative of a single store without retrieval induced errors. Error terminated short term memory free recall distributions are the same as distributions terminated by correct items.

Key words: long term memory, short term memory, free recall errors, retrieval process.

Free recall stands out as one of the great unsolved mysteries of modern psychology. Items in a list are displayed or read to subjects who are then asked to retrieve the items. It is one of the simplest ways to probe short term memory but the results [14; 16] have defied explanation.

The overwhelming amount of work in free recall has focused on what subjects get right. In the present contribution I will focus on the opposite: analyzing errors that subjects make when they retrieve items that were not in the list.

What would existing theories (reviewed recently by Jonides et al. [9]) predict about free recall errors? If there was just one store, there would be just one error probability for each item (Fig. 1, upper left panel; the scales in the figure are arbitrary). Multi-store models would predict different error probabilities for each store. If a working memory store is emptied first during the recall, then there should be a discontinuity in the number of errors when the next short term memory store is emptied (Fig 1, upper right panel). If the size of working memory varies somewhat between subjects, or some items are chunked by some subjects but not by others, the discontinuity should become rounded out (Fig. 1, lower left panel). Thus the hypothesis of this article will be that ***the probability of errors should show a discontinuity or a rounded discontinuity as a function of the number of items recalled***. If, on the other hand, there is significant coupling between the memory stores, in which working memory items and items from outside working memory are retrieved randomly, one might expect the result in Fig. 1, lower right panel. The figures can be generalized to more stores by adding further error probability levels.

Errors supply important information about the underlying processes as was pointed out already by Freud [6] when he studied slips of the tongue. It is known that there are two types of free recall errors: items that belong to a previous list [25; 26] and items that are close associations [4; 11; 18]. The more recent a previous list item, the more likely it is to be erroneously recalled [26] and the closer an incorrect item is associated with the correct list items the more often the incorrect item is recalled [4].

Unsworth et al. [24] studied "externalized" free recall in which subjects were asked to recall not only words in the presented lists but also other words that came to mind (there is an obvious parallel to the free association technique and the censor concept of Freud [5]). They found that the subjects tended to sample correct responses initially, then erroneous items that "came to mind" increased in frequency but as the number of errors increased the subjects were able to proportionally reject more of them. Recalls were terminated with errors "that came to mind" 72% of the time.

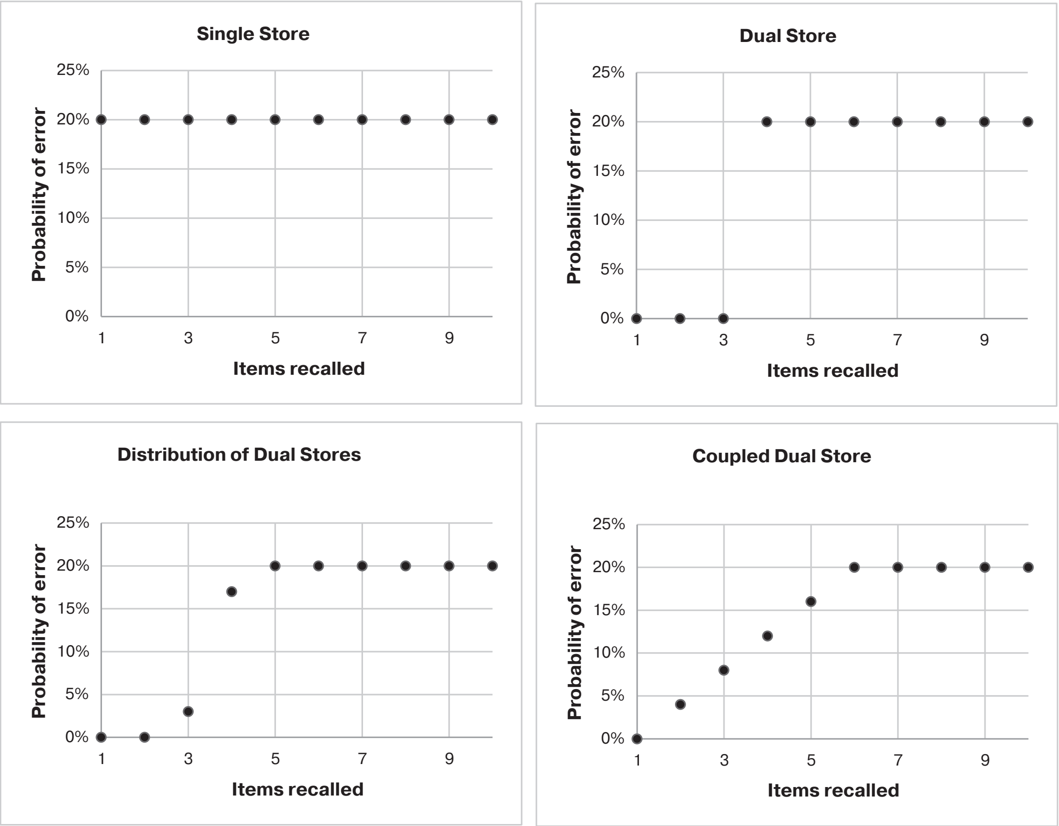

Fig. 1. Proposed error probabilities as a function of items recalled if short term memory consists of a single store (upper left panel), dual stores with 3 items in working memory (upper right panel), dual stores with small distribution in working memory size (lower left panel) and dual stores with coupling between the stores (lower right panel)

In this paper I will analyze the free recall error probability as a function of number of items retrieved, presentation time, retrieval time, how closely associated the free recall items are and whether the free recall comes from short term or long term memory. I will also analyze whether error-terminated distributions are different from correct item terminated distributions.

Method

This article makes use of existing experiments and statistically analyzes and synthesizes their data. In Table 1 is summarized the experimental processes which generated the data sets used in this paper. In all of them a set of words were displayed or read to the subjects after which the subjects were asked to recall the words in any order they chose. All of them studied short term memory and one, McDermott [11], also studied long term memory.

The Murdock [14], Murdock and Okada [15], Howard and Kahana [8] and Kahana et al. [10] free recall raw data sets can be downloaded from the Computational Memory Lab at the University of Pennsylvania (http://memory.psych.upenn.edu/DataArchive). These experiments all relate to free recall of common words.

I also included limited results from two experiments in which the free recall items all were associated with a “lure”, encouraging the subjects to incorrectly recall the lure: Roediger and McDermott [18] and McDermott [11]. These authors wanted to study how false memories could be created. In the Roediger and McDermott [18] experiment subjects were encouraged to start recall of each list with the last few items, one could perhaps label this as “semi-free” recall. The full data sets could not be obtained.

Results

The probability of making an error increases the more items are recalled as displayed in Figs. 2(a)-(c). The increase is linear with the number of items recalled. The initial 3-4 items are not recalled error free and there are no large discontinuities in the data as was hypothesized. Indeed there may be no discontinuities in it at all (the small discontinuity from 4 to 5 items in the left panel of Fig. 2(a) may be a statistical fluke), not even changes in slope as function of the number of items retrieved. Also contrary to all our predictions in Fig. 1, the error rate never is a constant, nor does it asymptote to a constant.

In Fig. 2(a) the error probability linear increase is faster for the faster presentation rate. The difference between the error probabilities for the two presentation rates is displayed in Fig. 3.

A linear increase in error probability also occurs as a function of the total response latency as shown in Figs. 4(a)-(b). In other words, the longer the retrieval takes, the more errors are recalled. The proportionality constant indicates that the probability of error increases 0.4%-1% per second retrieval time.

The errors are not a function of time passing. In Fig. 4(b) the time between item presentations is taken up by a different amount of a mathematical distractor task (0, 2.5, 8 and 16 seconds long). The slopes are independent of the length of the distractor task (0.57%, 0.67%, 0.49% and 0.78%, respectively).

So far the items memorized have been relatively unrelated words. Fig. 5 shows the probability of eliciting a target word for presented items that are designed to be closely associated to the target word (“lure”). The rate is no longer linear but a faster exponential (note the vertical axis has changed to logarithmic). It is not clear why there is a difference in slope but one of the differences in the experimental method was a request to start remembering the items from the end of the list [18].

Table 1

Information about experiments included in the study

Work	Item types	List length	Presentation interval	Interval between last presented item and recall	Recall interval	Item presentation mode
Murdock (1962)	*Selection from 4000 most common English words*	*10,15,20 words in a list each word presented every 2 seconds* *20,30, and 40 words in a list, each word presented once a second*			1.5 minutes	Verbal
Murdock and Okada (1970)	Toronto word pool (1150 of the 4000 most common English words which have two syllables words not more than eight letters long with homophones, proper nouns, contractions, and archaic words deleted.)	20	One and two words per second	Immediate after the presentation of the last item	1 min	Visual
Roediger and McDermott (1995)	The word lists used were constructed to get the subjects to recall an incorrect target word such as “chair” by using the list words “table”, “sit”, “legs”, “seat”, “soft”, “desk”, “arm”, “sofa”, “wood”, “cushion”, “rest”, and “stool”.	12	One word per 1.5 seconds	Immediate after presentation of last item (experimenter would say “recall”). Subjects were encouraged to start recall of each list with the last few items and then the remainder of the words in any order	2.5 minutes	Verbal
McDermott (1996) experiment 1	Lists were taken from Roediger and McDermott (1995) Appendix	15	One 1.5 words per second	Three conditions: immediate free recall, 30 second delay and 2 day delay	1.5 minutes in the first two conditions, 15 minutes in the condition with a 2 day delay	Verbal
Howard and Kahana (1999) experiment 2	Toronto Noun Pool	16	Varied. 1.2 seconds per word plus either 0, 2.5 sec, 8 sec or 16 se of distractor task	16 second delay	1 minute	Visual
Kahana et al. (2002)	Toronto Noun Pool	10	One word per 1.5 seconds	Immediate recall and a 16 second arithmetic distractor task	30 seconds	Visual

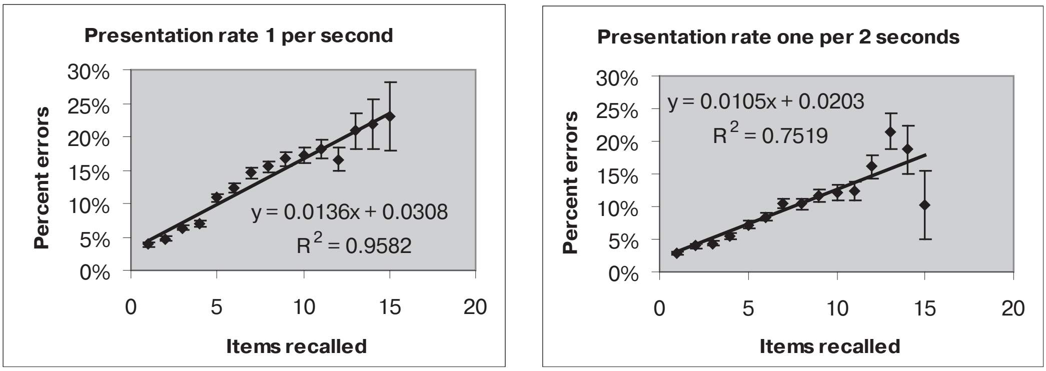

Fig. 2 (a). Error probability as a function of items recalled for the data in Murdock [14] averaged over the list lengths for each presentation rate. The left panel shows the average over the data with a presentation rate of one word per second and the right panel one word per two seconds

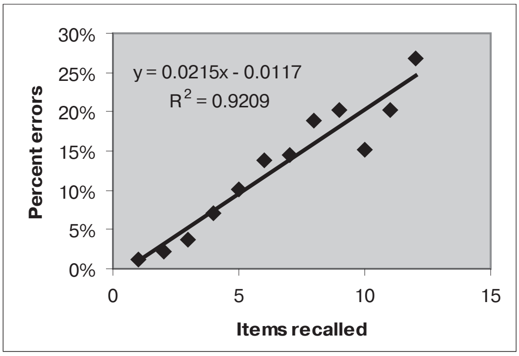

Fig. 2 (b). Error probability as a function of items recalled for the data in Murdock and Okada [15] averaged over the two presentation rates. The last data point (13 items recalled in 8 observations) was omitted

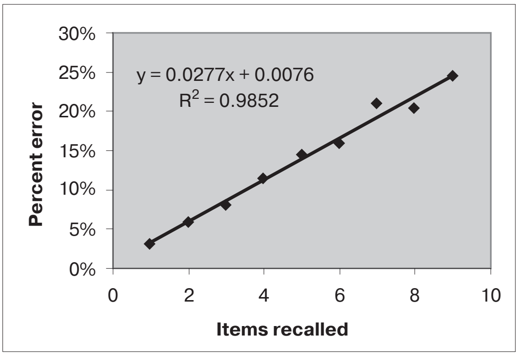

Fig. 2 (c). Error probability as a function of items recalled for the data in Howard and Kahana [8]

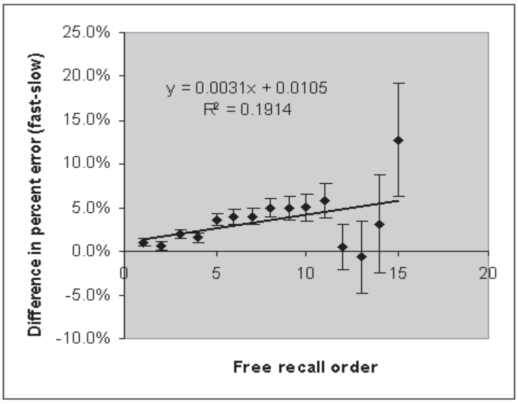

Fig. 3. Difference in number of recall errors for the two presentation rates in Murdock [14] (low presentation rate results subtracted from the high presentation rate). At high number of recalls there are very few data points causing large errors. These presumably cause the low R^2

In contrast, Fig. 6 displays the probability of errors in long term memory two days after the presentation of list items. The error rate, in distinction from the error rates of short term memory discussed, does not change with time. Note the difference in time scales — even after 15 minutes the probability of error remains near 17%, much lower than most of Figs. 2 (a)-(c). The error rate in long term memory did behave as we predicted in Fig. 1 (upper left) for a single memory store/state. This result shows that it is much harder to introduce errors in long term memory than in short term memory.

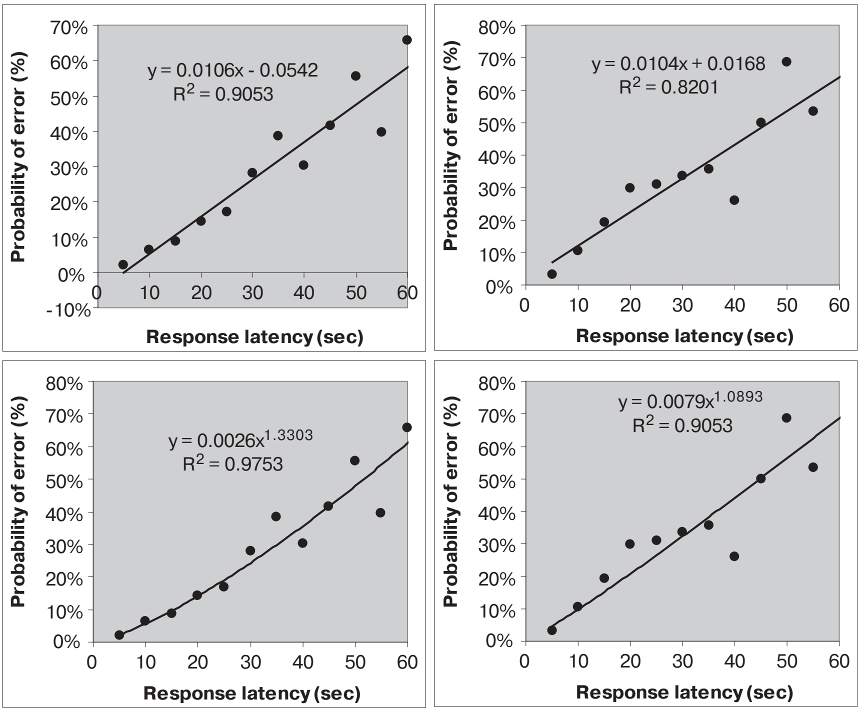

Fig. 4 (a). Average probability of error versus total response latency, data from Murdock & Okada (1970). In the left panes the presentation rate is one word per second, in the right panels the presentation rate is two words per second. Data points with fewer than 10 errors were not reported. Top panels fit to linear model, bottom panels fit to power model

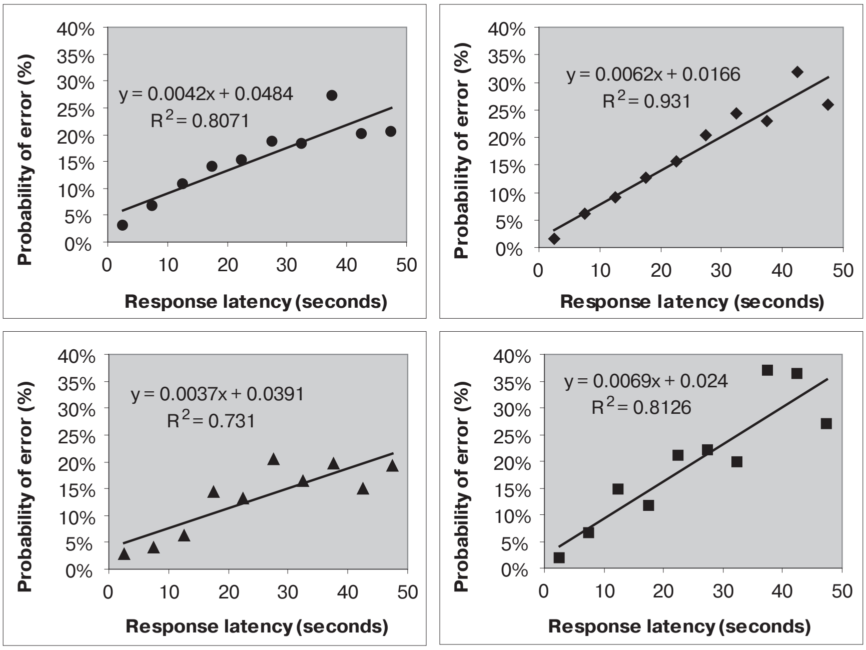

Fig. 4 (b). Average probability of error versus total response latency for a variety of distractors between item presentations: no distractor (upper left) 2 second distractor (upper right) 8 second distractor (lower left) and 16 second distractor (lower right) in data from Howard and Kahana [8]

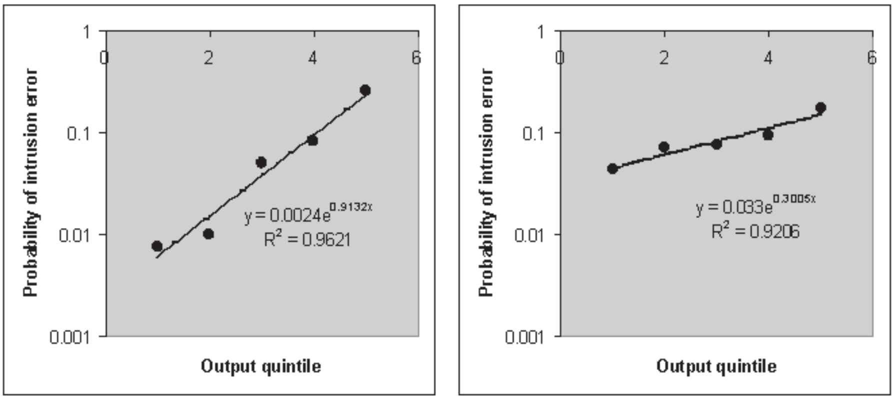

Fig. 5. Probability of retrieving erroneous lure item in Roediger & McDermott [18], left panel, and McDermott [11], right panel. Note that the y-axis is logarithmic so a straight line corresponds to an exponential function. The output quintiles correspond to first 20% of items recalled, the second 20% of of items recalled, etc.

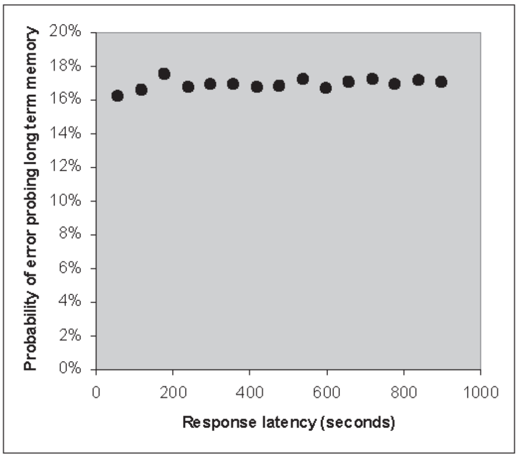

Fig. 6. Probability of error versus response latency two days after list items were presented using data from figure 4 in McDermott [11] and calculating the differences as a function of time. Compare this result with the result in Fig. 5, right panel

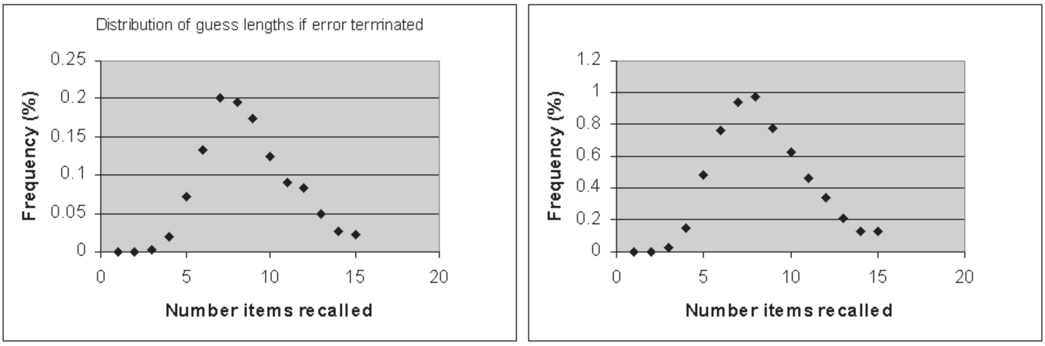

Fig. 7. The distribution of error terminated series (left panel) and non-error terminated series (right panel) are the same. Average over all Murdock [14] data

In the data from Murdock [14] the distribution of subjects' responses ending in errors and those ending in correct items are the same as shown in Fig. 7. Here is presented the distribution of the total number of words written down in (right panel) and the distribution of the total number of words written down if the last word was an error (left panel). The two-sided Student t-test for identical variances is 0.00082 and the probability that two equal distributions would have given that result is 99.94%.

In Table 2 is shown the results of the Student t tests for each of the six sets of data.

Table 2

Values of t and the corresponding chance that two identical distributions would have given that t value

Experimental series	T	t distribution
10-2	0.57	57%
15-2	0.000005	100.00%
20-2	0.05	96%
20-1	0.62	54%
30-1	0.87	38%
40-1	0.09	93%
All together	0.00082	99.94%

Discussion

Our hypothesis, that the error probability should show discontinuities as a function of the number of items recalled has been shown to be false. This invalidates sequentially emptied store/state models of short term memory. In contrast, the error rate in long term memory did behave as predicted in Fig. 1 (upper left) for a single store/state.

A more complex model of short term memory is needed, minimally a store or state model in which the stores or states are not emptied sequentially. There has to be what one might call a coupling between the different stores. I present here such a coupled-store model.

A coupled-store model. If we assume that current working memory theories are correct and there is a capacity of say 3 items in working memory [(Cowan, 2001), there has to be something that can couple those items to the remainder of short term memory. I call this mechanism a ***consciousness pointer***, it is presumably part of the “default network”, see, for example, Andrews-Hanna [1] and I suggest there is one consciousness pointer for each item in working memory. At any one time, one consciousness pointer is primary and it is this consciousness pointer that can retrieve and utilize an item. After the item has been retrieved, the subject can chose to engage another consciousness pointer or stay with the same consciousness pointer. In the latter case, the consciousness pointer will retrieve another item from outside of working memory. Thus retrievals are no longer coming from sequentially emptied stores and we would no longer expect discontinuities in the error probabilities.

So far we may have explained why there are no discontinuities in the error probabilities, but we have not explained why the retrieval process is accompanied by a linear increase in the error probability which does not asymptote to a constant but keeps increasing, ruling out even the last prediction of Fig. 1 (lower right panel). One possible explanation is that the error generation is ***dynamic***. This can be accomplished by assuming an activation model of short term memory in which incorrect items can become activated by the retrieval process itself.

An activation based coupled-store model. One such model [20; 21] states that short term memory items are activated long term memory items. An item in long term memory consists of a particular pattern of synaptic inhibitory and excitory responses created by previous learning. An item in short term memory consists of neurons firing in a steady-state pattern set up by this long term memory structure and this steady-state patter is equivalent to a particular ***synaptic configuration***, a collection of synapses in various stages of saturation. The state of saturation of synapses is determined by the proportions used of the readily releasable pool of neurotransmitter vesicles [21]. The synaptic configuration can be activated/reactivated by an outside stimulus (seeing or hearing an item) or by the internal consciousness pointer.

The activation/reactivation process is linear in time. After 0.2-2 seconds a steady-state synaptic configuration may result. If the primary consciousness pointer is connected to this synaptic configuration we become aware of the item and are able to use it [20]. Only when the configuration is in steady state, in other words 100% activated, AND connected with a consciousness pointer do we become aware of the item and are able to utilize it [20]. If these two conditions are not met, the information may be accessed subconsciously only (for example, via blindsight reviewed by Cowey and Stoerig [4]). When the firing ends, the synaptic vesicles are replenished, a process which is logarithmic in time with most of the item gone after 15 minutes [20; 21]. A less than full replenishment leads to a faster reactivation process next time the item is reactivated.

During the retrieval of the presented items in free recall the consciousness pointer can retrieve items not in working memory by attempting to reactivate them. The number of items identified in free recall is ten times smaller than the number of items that can be identified by recognition or cued recall. This adds the constraint that the consciousness pointers can only reactivate a small part of short term memory, they cannot reactivate all items. This may be explained by the reactivation process being imprecise — it does not know what words were active and cannot reactivate all synaptic configurations, which may need very specific reactivation excitations.

The items that are most likely to be reactivated are those with a synaptic configuration that was recently active with only a partial replenishment of synaptic vesicles. Experiment tells us these include items that were already presented in previous lists but also needs to include items closely associated with presented items. The latter condition necessitates that the synaptic configurations of associated words overlap. Thus when one item is activated, an association is partially activated due to ***overlap activation***. The near proportionality found by Deese [4] suggests that his measure of association strength is related to the level of overlap activation.

To these two types of short term memory information, item memory and associative information between items we must add serial-order information [17]. There is evidence that serial order information is relatively short ranged; during free recall, subjects exhibit a forward bias — transitions from the N to the (N+1) item are more likely than the reverse. This forward bias decays quickly so that when interlist errors are made, the forward bias is gone [23]. This suggests the presence in short term memory of one more piece of information in addition to the memory items themselves: the immediate direction change of the consciousness pointer and to make for a forward bias this change has to be closely associated with the item presented just before it.

All three types of short term memory information have previously been built into the TODAM model [see, for example:16; 17]. Our synaptic configuration may be related to the item vectors of TODAM, the overlap activation may be related to the TODAM item vector convolution. In TODAM the serial order information is represented by a chunking of three or more items. Mathematically, our model is somewhat different: the synaptic configuration can be considered a vector, the associations between items would be the dot products between the item vectors, and the changes in direction between items would also be vectors. In contrast to our activation model, TODAM does not have a biological basis but our replenishment of vesicles may be related to TODAM's "blurring" effect.

Finally, to obey the findings of Unsworth et al. [24] — that the number of free recall errors could increase radically if subjects were told to report items that "came to mind — we need to include a ***reality tester*** which determines whether an activated memory item is an appropriate item.

This is then, finally, how our model might qualitatively account for free recall errors. First, one of the consciousness pointers would retrieve an item in working memory without error. Then this consciousness pointer may attempt to internally reactivate an item which is only partially activated. The items with the highest levels of activation are most likely to be reactivated and they are the items from the current list followed by items from previous lists and items with synaptic overlap. The overall retrieval pattern is then one in which the sequentially emptied store model is broken: with the exception of the first retrieval the remaining retrievals come both from within working memory and from other memory items that are activated outside of working memory. Thus there is no discontinuity in the error rate.

During the retrieval, the consciousness pointer's imprecise reactivation increases the activation levels of many items, also those items that are not recalled. This slowly averages out activation levels of current list items and previous list items and associated items until there is no difference in activation levels. Since high activation level items are those that tend to be fully activated, the error rate becomes very high.

If the synaptic overlaps between list items are small, partial reactivations affect items one at a time giving a linear increase in error probability. If the synaptic overlaps are large as in the case when all items overlap with a lure item, the partial reactivations all affect the lure item and the increase in error probability becomes faster and, according to Fig. 5, the error rate increases exponentially. In contrast, the retrievals from long term memory of these same items do not increase the error rate, see Fig. 6 , because the number of activated items is very small.

If items after reactivation pass the reality tester the subjects should no longer be able to tell whether the items are correct or not which is evidenced by the distributions of error terminated recalls and correct item terminated recalls being the same in Fig. 7. Subjects have no way to differentiate between reactivated list items and activated erroneous items so they do not change behavior when an error is found.

General Discussion

This is not the first time a discrepancy between free recall data and the sequentially emptied multiple store model has been identified. The u-shaped curves in the free recall experiments of Murdock [14] were unsuccessfully modeled with a limited capacity buffer [see, for example: 22]. Balakrishnanl and Ashby [2] did not find any discontinuity in reaction time distributions in an experiment asking for enumeration of colored blocks when the number of blocks increases from 1 to 8. McElree [12] showed that there is no discontinuity in item recognition time beyond the first item. We were able to show that a coupled multiple store model might describe the data.

The retrieval mechanisms of short term memory and long term memory are different: the short term memory retrieval is accompanied by an increase in errors while the long term memory retrieval process does not introduce errors either linear or exponential with retrieval time, but is a constant (on the time scale of 15 minutes). That there should be a difference is clear: reactivation of partially activated items works in short term memory since there are hundreds of items already partially active (previous list items, current list items and associated items). In long term memory these items are not activated at all.

Others have studied how subjects end their searches. Harbison et al. [7] noted that the time between the last reported item and the decision to terminate the retrieval process is a monotonically decreasing function of the total number of items retrieved, thus what terminates the retrieval process might be a feeling of being done, not an awareness of making errors. Unsworth et al. [24] found that subjects are very good at editing out “come to mind” errors but that there is a number of errors that cannot be edited out which is equivalent of saying that the subjects are unaware of making those errors. They found that termination is more likely to occur after a “come to mind” error than after a correct recall. However, since “come to mind” errors are more likely at the end of the retrieval process this may be same as saying termination tends to occur as the number of items retrieved increases as in Harbison et al. [7]. In a review of experimental data from fourteen different publications Miller et al. [13] stated that termination is more likely to occur after a recall error than after a correct recall but that the correlation they found between errors and termination is not proof of causation. Their data shows that the probability of termination ***decreases*** with the output position for positions 6 and higher, which I cannot explain.

The only way an insightful subject can lower the error rate is to limit the retrieval time which would also limit the number of correct items reported. It is the Heisenberg uncertainty principle of short term memory free recall: the more you try to remember, the less correct your short term memories are!

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ПРОЦЕСС ПОИСКА ПРИ СВОБОДНОМ ВОСПРОИЗВЕДЕНИИ СОЗДАЕТ ОШИБКИ В КРАТКОВРЕМЕННОЙ, НО НЕ В ДОЛГОВРЕМЕННОЙ ПАМЯТИ

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Анализ ошибок свободного воспроизведения показывает, что процесс поиска в кратковременной памяти сопровождается непрерывным линейным ростом количества ошибок, что ставит под сомнение модели кратковременной памяти, предполагающие последовательное «опустошение» (очищение) ее ячеек. Частота ошибок возрастает по экспоненте примерно на 1% в секунду при условии, что воспроизводимые единицы тесно связаны между собой. Это приводит к ситуации «принципа неопределенности Гейзенберга»: чем больше единиц воспроизводится, тем меньше точность их воспроизведения. Так как вероятность ошибки не достигает плато и не зависит от времени, прошедшего до начала воспроизведения, предполагается, что сам процесс поиска продуцирует ошибки в кратковременной памяти. В отличие от этого в долговременной памяти вероятность ошибок остается постоянной, что свидетельствует об одном хранилище и отсутствии ошибок, индуцированных поиском. Распределение ошибок при воспроизведении из кратковременной памяти аналогично распределению правильных ответов.

Ключевые слова: долговременная память, кратковременная память, ошибки воспроизведения, процесс поиска.