FIRST DIRECT EVIDENCE OF TWO STAGES IN FREE RECALL

Eugen Tarnow

Avalon Business Systems
18-11 Radburn Road, Fair Lawn, NJ 07410, USA

I find that exactly two stages can be seen directly in sequential free recall distributions. These distributions show that the first three recalls come from the emptying of working memory, recalls 6 and above come from a second stage and the 4^{th} and 5^{th} recalls are mixtures of the two.

A discontinuity, a rounded step function, is shown to exist in the fitted linear slope of the recall distributions as the recall shifts from the emptying of working memory (positive slope) to the second stage (negative slope). The discontinuity leads to a first estimate of the capacity of working memory at 4-4.5 items. The total recall is shown to be a linear combination of the content of working memory and items recalled in the second stage with 3.0—3.9 items coming from working memory, a second estimate of the capacity of working memory. A third, separate upper limit on the capacity of working memory is found (3.06 items), corresponding to the requirement that the content of working memory cannot exceed the total recall, item by item. This third limit is presumably the best limit on the average capacity of unchunked working memory.

The second stage of recall is shown to be reactivation: The average times to retrieve additional items in free recall obey a linear relationship as a function of the recall probability which mimics recognition and cued recall, both mechanisms using reactivation (Tarnow, 2008).

Key words: free recall, working memory, reactivation, short term memory, working memory capacity

Introduction. Free recall stands out as one of the great unsolved mysteries of modern psychology (for reviews, please see, for example, Watkins [28]; Murdock [19]; Laming [14]; some believe existing computer models provide important insights, I do not). 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. The results have defied explanation. Why do we remember primarily items in the beginning and in the end of the list, but not items in the middle, creating the famous u-shaped curve of probability of recall versus serial position? Why can we remember 50-100 items in cued recall but only 6-8 items in free recall? If one may speak about a consensus in memory psychology, that short-term memory has a limited capacity store typically named "working memory", where can this store be seen in free recall and what is its capacity?

The effort to calculate the capacity of working memory, what was then termed "primary memory," using free recall, was reviewed by Watkins [28]. These calculations were based on indirect evidence of a division of memory, and sometimes *a priori* assumptions were used. The capacity was generally found to be three items. This was long before recent experiments finding a limit of working memory of exactly three items [1; 11], for an opposing view see Bays and Husain [4] and Bays, Catalao and Husain [5].

In the Watkins [28] review, "primary memory" is at the beginning defined narrowly as "the mechanism underlying the recency effect in free recall". This is an unfortunate assumption because it prevents models from giving *ab-initio* pictures of working memory content. He notes that the recency effect is relatively constant against experimental manipulation of list length, presentation rate, frequency of list items occurring in the language, semantic association, phonological similarity and concurrent activity. Several methods of measuring the capacity of primary memory were discussed, some of which calculate a capacity of about 3 items, all of which are problematic.

Watkins [28] noted, for the methods he reviewed, that there were not necessarily an agreement between methods or even within the methods as to which items are in primary memory and which are not. Within the same method there is sometimes no consistency of the ratio of secondary to primary memory when varying list lengths, presentation rates and number of languages per list (in particular for the Waugh & Norman [29], method and its variation and for the Murdock [18] method).

The following methods used the least assumptions: Legge defined primary memory capacity as the longest lists length for which recall is perfect [cited in 7]. Legge's approach does not consider the possibility of cuing of items, potentially overestimating working memory. The model is *ab-initio* with respect to the capacity but does not predict the item content of working memory in list long enough to not be perfectly recalled. Glanzer [9] calculated the capacity of primary memory using the difference of total recall curves with and without a delay (during which subjects were asked to count out numbers starting with a given number data from [9]) and found that the capacity was 3. The differences in recall distributions in Glanzer & Cunitz [9] indicated that primary memory is responsible for the recency effect. The measurement is *ab initio* as is the localization of primary memory though in both cases the evidence is indirect.

In this contribution I will show that exactly two stages can be seen *directly* in free recall distributions. The first stage is the emptying of working memory and the average capacity of working memory can be calculated *ab-initio* and is 3 for unchunked items and 3-4.5 for chunked items. The second stage is a reactivation stage: I will show that this can be seen in the second stage mimicking reactivation in recognition and cued recall.

Method. This article makes use of the Murdock [17], Murdock & Okada [20], Kahana et al. [12] data sets (downloaded from the Computational Memory Lab at the University of Pennsylvania (http://memory.psych.upenn.edu/DataArchive). In the former the experiments were labeled N-M where N is the total number of words presented and M is the interval in seconds between word presentations. In Table 1 is summarized the experimental processes which generated the data sets used in this paper.

Table 1

Information about experiments included in the study

Work	Item types	List length and presentation interval	Recall interval	Subjects	Item presentation mode
Murdock [17]	Selection from 4000 most common English words, referred to as the Toronto Word Pool.	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, no delay	103 undergraduates	Verbal

Table 1

Work	Item types	List length and presentation interval	Recall interval	Subjects	Item presentation mode
Murdock & Okada [20]	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 or two words per second	1.5 minutes, no delay	72 undergraduate students from larger low level psychology courses	Visual
Kahana et al. [12]	Toronto Noun Pool	10. One word every 1.5 seconds.	30 seconds. Immediate and with a delay (a 16-s arithmetic distractor task)	Two groups of 25 subjects, one older (74 mean age) and one younger (19 mean age),	Visual

Results & Discussion. In Fig. 1a (Fig. 1b) is shown the recall distributions of recalls 1-8 from the 10-2 (40-1) dataset of Murdock [17]. These distributions show direct evidence for a two stage process. By definition the first recall comes from working memory, and from the similarity of the 2nd and 3rd recalls these also come from working memory. The last three recalls all appear similar and originate from a second stage. Recalls 4 and 5 are a combination of the two. In each recall is plotted a best linear fit which expresses the balance between recency (positive slope) and primacy (negative slope). As we see the slopes go from primacy for the emptying of working memory to recency for the second stage. Working memory can be seen as responsible for recency (consistent with previous work, see Watkins [26] and Glanzer [7]); primacy comes from the secondary process though working memory adds the first items in the shorter 10-2 list; together they create a U-shaped serial position curve.

The slopes of the linear fits in Fig. 1 as a function of recall are plotted in Fig. 2. The curve is a smoothed step function, to separate the emptying of working memory from the second stage. The middle of the step function, which corresponds to the capacity of working memory, is 4 for the 10-2 data and 4.5 for the 40-1 data.

The boundary between the two stages is illustrated not only by the change from the emptying of working memory to the second stage in the recall distributions of Fig. 1a and 1b, but also by the first recall itself. In it some of the word recall probabilities are amplified compared to the overall recall distribution (the first and last items). The middle items are not present in the initial recall at all.

The total recall is a simple sum of the items in working memory and recalls from the second stage, there is no additional memory process. Fig. 3 displays the results of the *ab-initio* fitting of the total recall with a linear combination of working memory content and secondary recall (minimizing the sum of squares). The top panels are, from left to right, the 10-2, 15-2 and 20-2 data sets; the bottom panels are, from left to right, the 20-1, 30-1 and 40-1 data sets. The fits are good. Deviations are presumably due to the

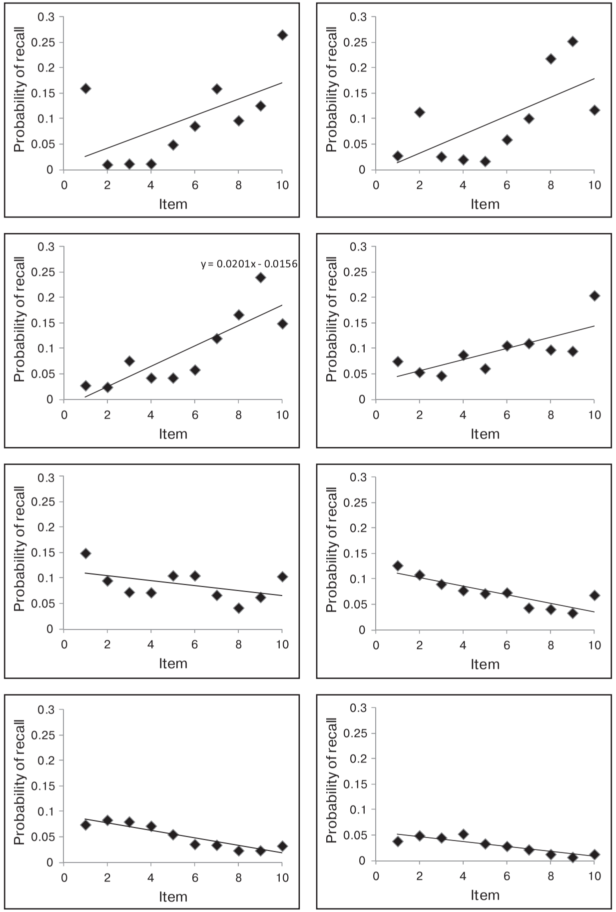

Fig. 1a. Recalls 1-4 (top panel) and 5-8 (bottom panel) for the 10-2 experiment. The first three recalls are from working memory, last three recalls from second stage recall, and the 4th and 5th recalls are from a combination of working memory and second stage recall

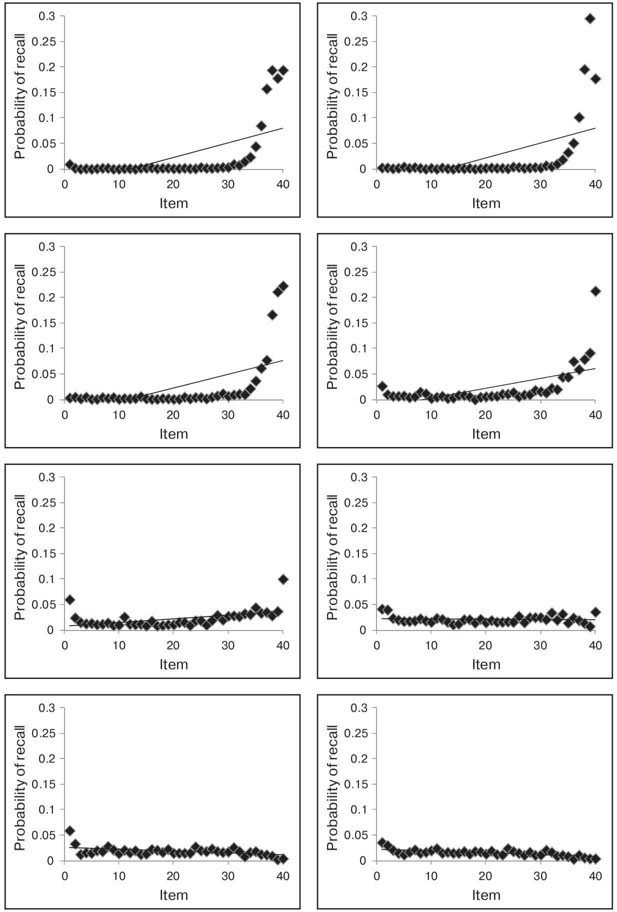

Fig. 1b. Recalls 1-4 (top panel) and 5-8 (bottom panel) for the 40-1 experiment. The first three recalls are from working memory, last three recalls from second stage recall, and the 4th and 5th recalls are from a combination of working memory and second stage recall

initial recall being a statistical representation of all of working memory for short lists (for very short lists the initial recall will simply consist of the first item). In Table 2 is shown the fitting parameters which provide *ab-initio* values of the capacity of working memory ranging from 3.0 to 3.9 items. The coefficient that indicates working memory capacity increases with the number of items in the list. Perhaps this increase indicates an increased probability of chunking working memory content as the number of items increases. This increase is half of the increase in the coefficient for secondary recall.

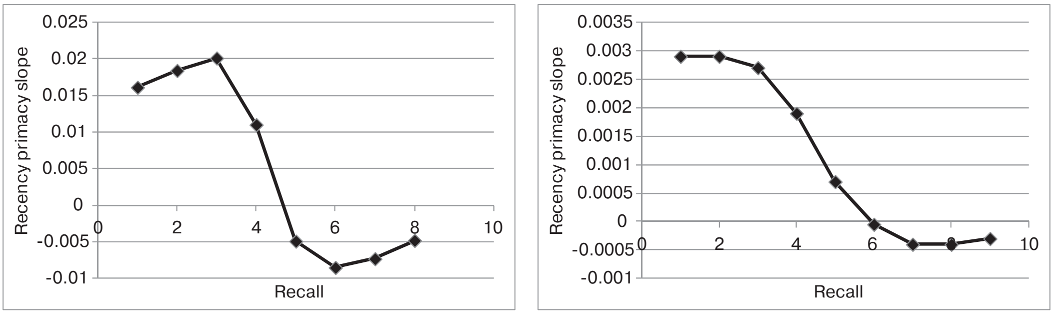

Fig. 2. The slope of a linear fit to the serial position curves for the 10-2 (upper panel) and 40-1 (lower panel) data. Positive slope indicates recency, negative slope indicates primacy. Note the similarity to a step function. The middle of the step function is a little higher than 4, corresponding to the capacity of working memory

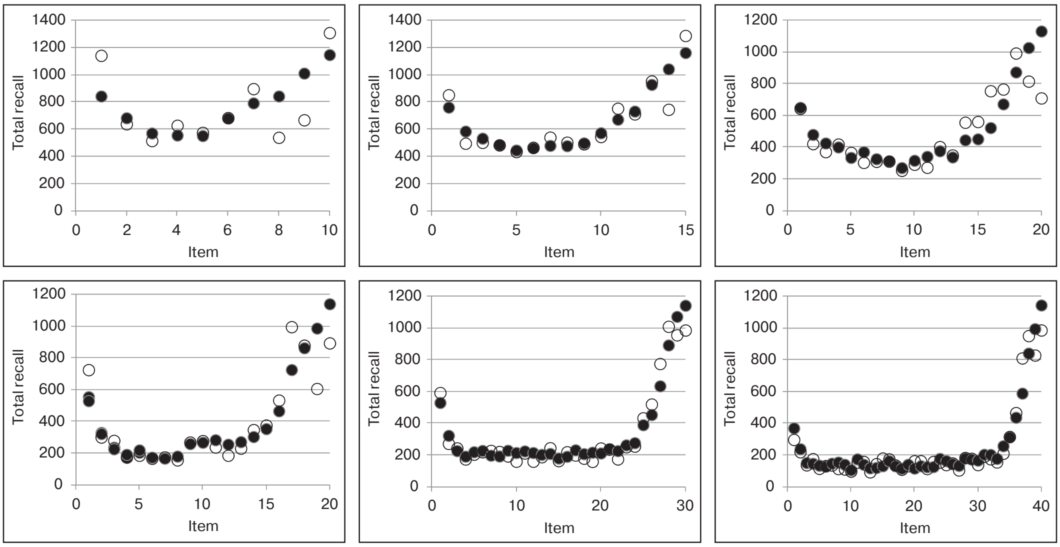

Fig. 3. Total recall (filled circles) and total recall predicted using the optimal linear combination of the initial and final recalls (unfilled circles). Data sets are 20-1 (left panel), 30-1 (middle panel) and 40-1 (right panel). The coefficients of the linear combinations are in Table 4

Table 2

Linear combinations of initial and final recall which provide the best fitting to the total recall and how much of the variance is described by that combination

Series	10-2	15-2	20-2	20-1	30-1	40-1
Working memory coefficient	3	3.4 (13% inceace)	3.9 (30% increase)	3.6	3.8 (6% increase)	3.7 (3% increase)
Second stage recall coefficient	3.4	4.8 (40% increase)	4.5 (32% increase)	3.2	4.7 (47% increase)	4.4 (38% increase)

Table 2

Series	10-2	15-2	20-2	20-1	30-1	40-1
Total recall	6.4	8.2	8.4	6.8	8.5	8.1
Rsquared for proportional line	0.07	0.81	0.70	0.79	0.95	0.94

Note. Numbers in parentheses indicate percent increase over 10-2 (20-1) valuess for the N-2 (N-1) series. Note that both the working memory and second stage recall coefficients increase with list size though the increase is faster for the second stage recall coefficients.

Table 3

Here is indicated for which items in the Murdock [17] and Murdock & Okada [20] datasets the lowest upper limit of the capacity of working memory is derived

Series	10-2	15-2	20-2	20-1	30-1	40-1	Murdock & Okada 20 items
Lowest TI ratio	3.61	3.60	3.81	3.06	3.65	3.11	3.15
Item with lowest TI ratio	10	10	16	17	27	37	17

Note. The TI ratio refers to the ratio of total recall of a particular item to the initial recall of that item.

Table 4

Characteristics of working memory and second stage recall

Series	10-2	15-2	20-2	20-1	30-1	40-1	Average
Stdev/Average initial	.85	1.27	1.23	1.32	1.85	2.31	1.47
Stdev/Average second stage	.37	.27	.43	.58	.35	.46	0.41

From the requirement that the total recall cannot exceed what is in working memory, item by item, an upper limit on the capacity of working memory can be calculated. This limit is

*For all items i: Working Memory Capacity * initial recall probability of item i <= total recall probability of item i (Equation 1)*

The ratio of total recall to initial recall of all items (the TI ratio for short), i.e. the upper limit on the capacity of working memory, is shown in Figures 4 and 5 and Table 3. The upper limit of working memory capacity is 3.61, 3.60, 3.81, 3.06, 3.65, and 3.11 for the 10-2, 15-2, 20-2, 20-1, 30-1 and 40-1 data, respectively (for the 40-1 data the numbers corresponding to zero initial recalls were omitted from this calculation since they would give rise to infinities). The Murdock & Okada [20] data gives us the slightly higher limit of 3.15 from the 17^{th} item out of 20 items. The overall minimum is 3.06 which is then the upper limit of the capacity of working memory. The statistical error can be estimated as being less than the sum of independent errors = sqrt(1/(total times item recalled)+1/(initial times item recalled))=sqrt(1/725+1/237)=7% since the two measures are not independent and the corresponding errors would tend to cancel out.

The upper limit that is just larger than 3 is a limit that is in some agreement with recent item-disentangled serial recall experiments (Chen and Cowan [6] find a limit of 3) and recent still controversial neuroscientific experimental findings for the capacity of vision working memory (see, for example, Anderson, Vogel and Awh [1]; for an opposing view see Bays and Husain [4]; and Bays, Catalao and Husain [5]). They also agree with the results reviewed in Watkins [28] and Glanzer [9].

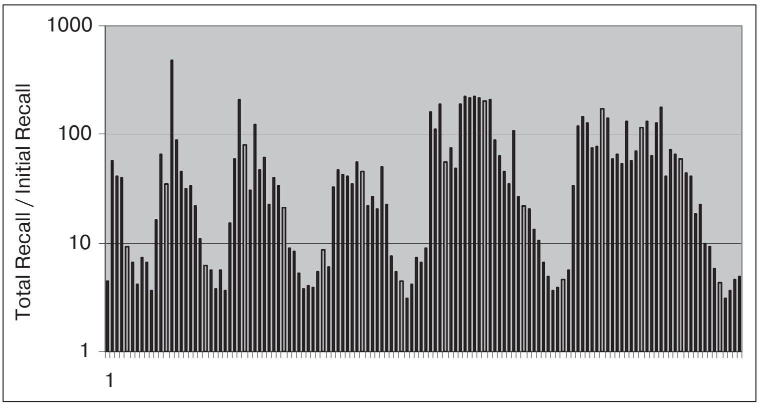

Fig. 4. Upper limits on working memory capacity using the ratio of total recall to initial recall. The points are, in list order, 10-2, 15-2, 20-2, 20-1, 30-1, and 40-1 (with a few items missing from 40-1 in which the total recall is zero). The lowest values, the estimates for the upper limit of the capacity of working memory, tend to come from one of the last word in each series

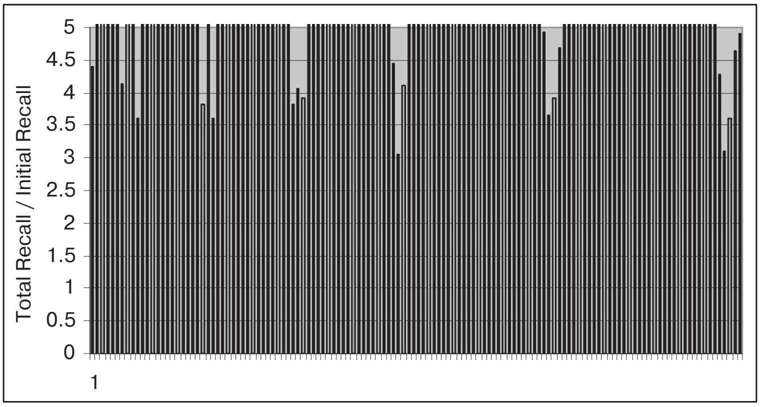

Fig. 5. Upper limits on working memory capacity from Figure 5 with a different scale. The smallest upper limit is 3.06 and comes from the 17th item in the 20-2 series

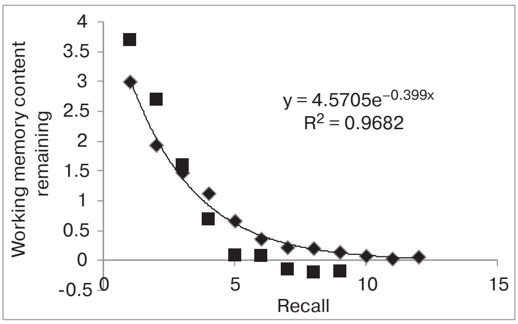

Fig. 6. Initial working memory content remaining in the 40-1 data set calculated by extrapolation from item 37 (diamonds with an exponential decay) and from the coefficient of the linear combination of working memory and second stage recall (squares)

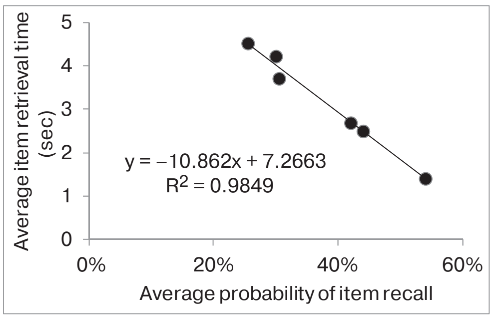

Fig. 7. Average time to find an additional item as a function of the average probability of recall using the slopes of Fig. 2 in [23]. Extrapolation to 0% probability of recall suggests that the largest average time to retrieve an additional item would be 7.2 seconds and 0 seconds if the average probability of item retrieval is 66% or higher

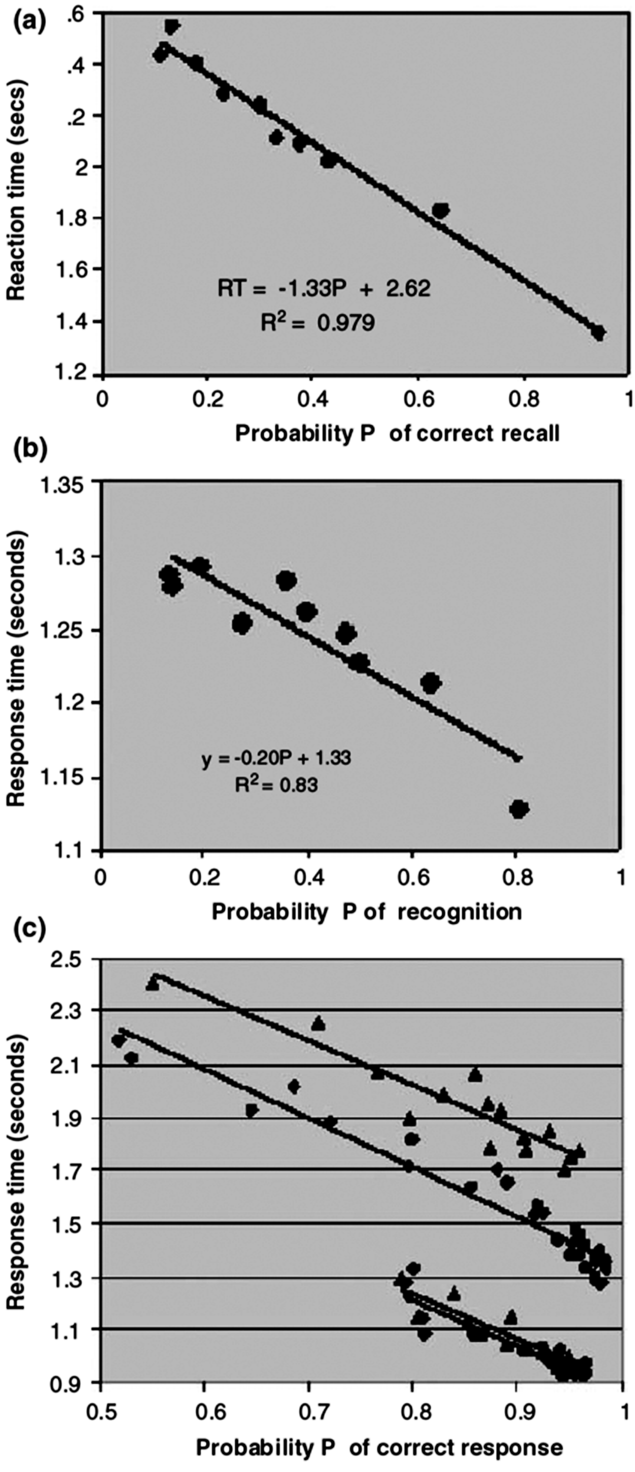

Fig. 8. Figure taken from Fig. 1 of Tarnow [21]. Response times as a function of the probability of recognition / cued recall. Top panel displays cued recall, middle panel displays recognition and bottom panel displays a different dataset with the upper curves from cued recall and the lower curves from recognition

I should note that the limit of 3.06 refers to a statistical average over individuals (thus some subjects may have a 4 item limit or the remainder above 3 may correspond to a small chunking effect) and to words, not chunks, and, strictly speaking, it refers to words from the Toronto Word Pool.

How quickly is working memory emptied? Using the 40-1 data, Fig. 6 displays the memory content that remains as a function of recall for item 37 (see Table 3), an item which is predominantly in working memory (diamonds). The probability of working memory recall decays exponentially (supporting a conjecture in Murdock [17]). Fig. 6 also displays the working memory coefficient of the fit of each recall distribution (squares). In both cases it appears that working memory is empty after 4-5 recalls, as was also indicated by the recall distributions in Fig. 1a-b.

Finally, what is the nature of the second stage in free recall? In the last issue of this journal I described how the average time to retrieve an additional item in free recall was constant and the value depended upon the experimental parameters [23]. In Fig. 7 is displayed the times to retrieve additional items as a function of the overall probability of recall. They form a second linear relationship similar to those describing recognition and cued recall (Tarnow [21]; reproduced in Fig. 8): the more likely items are to be recognized or recalled via cues, the shorter is the response time. This suggests that the second stage free recall retrieval mechanism is the same in recognition and cued recall; and that the mechanism is a reactivation mechanism [21; 22]. The only difference is in the time scale: the largest reactivation time for recognition and cued recall varies between 0.2-1.8 seconds while the largest retrieval time in free recall is 7.2 seconds from extrapolating the line in Fig. 7.

General Discussion. The present direct evidence of a two stage model from the separate free recall distributions confirms earlier indirect evidence. Glanzer & Cunitz [10] proposed that the serial position curve consists of short-term storage which corresponds to a rising recency effect and a long term storage corresponding to a decline from the beginning to the end and what I find is similar but also different: ***two stages*** which presumably map to the same memory store, activated long term memory. The two stages are the emptying of working memory and reactivation of earlier activated items.

The large size of activated long term memory can be seen in cued recall and recognition but not in free recall presumably because the second stage retrieval process cannot find more than a few items in addition to what was kept activated in working memory.

Since working memory is quantized and consists of exactly N items for a subject where N=3 or 4, my assumption is that there are N nerve bundles or similar corresponding to those N items which keep the items activated. The representations of those items in long term memory should be the same as the items reactivated in the second stage.

The discontinuity in the linear slope (see Fig. 2) shows that there are two and exactly two stages. Previously the search for such discontinuities in word free recall have yielded little. For example, there is no discontinuity in word free recall response times [23], nor in errors [24] and latency distributions are the same for all but the first recall [13]. McElree [15] showed that there is no discontinuity in item recognition time beyond the first item. Balakrishnanl and Ashby [3] 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.

I arrived at the two different types of values of the capacity of working memory. The smallest, 3.06, which has a small error bar, presumably is the value associated with an item that is not chunked. The other values, ranging from 3 to 3.9 for the total recall fit (Table 2) and 4-4.5 for the transition of the slope in Fig. 2 presumably includes chunking of working memory. It is consistent with the values going up as the number of list items increases.

Also consistent with the assumption that the initial recall is working memory is that I have shown elsewhere that there is substantial individual control over the initial recall: individual differences are the strongest for the initial recall — see Tarnow [25]).

I have previously suggested that the recognition and cued recall mechanism is one of reactivation [21], specifically, synaptic exocytosis [22]. I arrived at this suggestion by showing that the response time increases linearly with the probability of correct recognition / cued recall, just like synaptic exocytosis. The probability of correct recognition / cued recall decays logarithmically with time, just like synaptic endocytosis. In the present contribution I showed that in free recall the average retrieval time increases linearly with the probability of correct recall and that the time scale for free recall retrieval is the same order as the time scale of recognition and cued recall. To show the second step, that the decay is logarithmic in time just like synaptic endocytosis, I would need a dataset from a delayed free recall experiment in which the delay was varied.

The consequences are important not only for the understanding of short term memory but also for an important area of clinical practice: the construction of short term memory tests. For example, if we want to test for the presence of Alzheimer's disease, the existing number of short term memory tests is huge (see, for example, http://www.nia.nih.gov/research/cognitive-instrument and select "memory" as the cognitive domain and about 88 tests can be found as of June 30, 2015). But if there are only two types of damage possible to short term memory — damage to working memory and damage to reactivation — this should cut down the number of tests to two: one for the presence of reactivation issues and another for the presence of working memory issues. Whether the tests measure recognition, cued recall or free recall should be irrelevant. One of the known facts about short term memory damage in Alzheimer's disease comes from the three word recall test of the MMSE [8]: early Alzheimer's can be identified by delayed free recall of these words and later stage Alzheimer's can be identified by the inability to add the three words to working memory [2]. There may be no other short term memory test necessary beyond refinements of the MMSE.

Finally, let's return to the serial position curve in Fig. 1. If free recall, recognition and cued recall probe the same two types of memory, how come we never see anything so complex in recognition or cued recall? The answer is that in recognition and cued recall, working memory and reactivation are always probed together, they are never separated out. In addition, since the recognition and cued recall probes also display items, those items keep displacing items in working memory largely removing the effects of working memory. In free recall, however, working memory is separate from reactivated memory — working memory is recalled in a first stage and only then is reactivated memory recalled. The linear relationships presented here presumably apply only to the second stage.

Free recall, while seemingly complex, continues to elucidate how our memory works.

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ДОКАЗАТЕЛЬСТВО ДВУХ СТУПЕНЕЙ СВОБОДНОГО ВОСПРОИЗВЕДЕНИЯ ИЗ КРАТКОВРЕМЕННОЙ ПАМЯТИ

Юджин Тарноу

Авалон Бизнес Систем
18-11 Рэдбэрн Роад, Фэйр Лоун, 07410, США

Автор приводит доказательства двух ступеней воспроизведения информации из кратковременной памяти. Характер распределения ответов показывает, что первые три единицы воспроизводятся из «опустошающейся» оперативной памяти, шестая и последующие единицы относятся ко второй ступени воспроизведения, а четвертая и пятая — имеют пограничный характер. Об этом свидетельствует наличие «разрыва» в ступенчатой функции распределения ответов, что приводит к предварительной оценке объема оперативной памяти — 4—4,5 единицы. Показано, что общее воспроизведение является линейной комбинацией содержания оперативной памяти и единиц, воспроизведенных на второй ступени, что ведет к уточнению объема оперативной памяти — 3—3,9 единицы. В итоге определен верхний предел объема оперативной памяти (3,06 единицы), который предположительно наиболее точно оценивает неделимый объем оперативной памяти.

Показано, что вторая ступень воспроизведения имеет характер реактивации: среднее время для получения дополнительных ответов описывается линейной функцией, подобной функциям вероятности распознавания мимики и реплик, в которых используются механизмы реактивации.

Ключевые слова: свободное воспроизведении, оперативная память, объем оперативной памяти, реактивация, кратковременная память