Short-Term Memory Resonances

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Abstract

A cascading neural loop model is proposed to address the question of how to represent continuous experience. A prediction of the model is that short-term memory decay should exhibit a set of bumps or dips superimposed on a smooth exponential base. The prediction was tested using a Brown-Peterson distractor task, with distractor intervals from 1 to 24 seconds spaced every second apart. In one study with 22 participants, fits of nested regression models indicated that peaking functions with periods near harmonics of 1.6 seconds provided a better description of the data than an exponential function alone. In a replication study with 29 participants, peaking functions with a period of 3.2 seconds provided the best fit. In both studies, 5% rises above an exponential base were evident near 7, 10 to 11, 13 to 14, and 16 seconds. This short-term memory effect has not been reported before and needs further replication.

Introduction

The paradigmatic treatment of short-term memory in experimental psychology has been relatively stable for a long time, though still not resolved. After Miller's (1956) identification of an information processing bottle-neck, Brown (1958) and Peterson and Peterson (1959) established a smooth, rapid decay as the principal empirical characteristic of short-term memory, and Broadbent (1958) and Atkinson and Shiffrin (1968) formalized models in which short-term memory was theoretically separate from other forms of memory. However, while providing a clear focus for empirical and theoretical questions, decay was never universally accepted as the actual mechanism of forgetting. Keppel and Underwood (1962) immediately cast doubt on a simple trace decay interpretation of the Peterson and Peterson (1959) results, and the decay versus interference question is still with us today (Laming, 1992, Crowder, 1993). Similarly, Atkinson and Shiffrin's (1968) model has spawned more debate than consensus. In general, Baddeley's (1992) more complex view of multiple working memory components has become more accepted than their proposal of a single short-term memory store, but even the question of whether separate stores exist is still quite open (Cowan, 1988).

Another, less well recognized facet of this paradigmatic view is how closely short-term memory has been thought to resemble a computer data buffer. Broadbent (1958) was quite explicit in this regard, and most other models have followed in exactly the same tradition. One result of this relatively unquestioned assumption is that no model can adequately address what James (1890) had described as a "stream of consciousness".

Introspection would lead me to believe that both my immediate experience and the recollection of that experience are continuous, yet the typical model of short-term memory would suggest otherwise. That is, short-term memory supposedly can maintain only a small set of information at any given time, some or all of which can be replaced a short time later only by another small set of information. However, if this were the case, then where does that feeling of continuity come from? Any continuous function can be approximated by a sufficiently high enough resolution digital function, but, using neural firing rates as a guide, this implies a digitalization rate on the order of 10 to 100 items per second. Short-term memory may be narrow in width, as suggested by Miller's (1956) seven plus or minus two chunks, but, in effect, must be much longer in length to capture continuity of experience. Even selective attention, unitary store models like Cowan's (1988) do not escape this problem in that recollection of sequences of events somehow must be maintained in memory that can only allow the passage of time to be represented as scanning across different locations in memory.

This admittedly simplistic analysis forces one to ask the question of how any neurologically realistic model can maintain streams of experience instead of merely cross-referencing static "snapshots" of that experience. Neural network models (Rumelhart & McClelland, 1986) provide a good class of candidates, but, by design, the inputs and outputs of these models are restricted to fixed values. Even when the inputs and outputs represent sequential information, as in Jordan (1986), the sequence consists of a series of fixed values. Or, when the time course of processing actually is the subject of interest, as in Kawamoto and Kitzis (1991), the time-varying signals are restricted to approaching fixed asymptotic values. In short, there are no neurologically realistic models available that address the question of maintaining sequences of dynamically varying signals.

On the other hand, dropping the restriction of neurological plausibility would allow all sorts of engineering-like models to be considered. The basis for these would be the equivalent of any sequential recording device, like a tape recorder, or random access computer memory or disc used to store a sequence of data. In essence, storage elements remain empty until filled, maintain perfect data integrity until overwritten, and then are overwritten with new data without any interference from the prior data stored at that location. It seems very unlikely that real neurons would maintain information in such a localist, completely nondistributed, manner. If nothing else, the idea of a neuron "waiting" for that first input, and then maintaining that single fixed value forever after just seems very biologically wasteful.

For these and other reasons, I was led to consider a recurrent neural network approach towards memory in which sensory and cognitive experience is recorded in a series of closed neural network loops. Within a loop, a specific experience at a specific time is recorded as a set of feature values sufficiently rich enough to represent that experience. Parallel to that set of units is another set that records the prior experience in time, followed by another and another. In short, time is represented as distance along a loop "perpendicular" to the units actually maintaining the experience, and experience "flows" along a loop as successive copies of prior experience. Where a loop closes back on itself, current experience coming into a loop is blended with the recording of prior experience from one time cycle before. The loop cycle time would be determined by the physical length of a loop and the time required to copy information from one set of units to the next. Finally, to complete the picture being drawn here, loops are arranged in series such that shorter duration, higher experiential resolution loops provide inputs to longer duration, lower resolution loops. And, some series of loops are dedicated to maintaining specific types of sensory experiences, and others to more progressively integrated sensory or cognitive information.

In many ways, the conceptual basis of this model is that of Jordan's (1986) recurrent network model, but with the emphasis on maintaining potentially longer sequences of information rather than learning a common, efficient set of weights to maintain shorter sequences. If anything, learning is not an immediate consideration, as each individual memory loop acts much like Atkinson and Shiffrin's (1968) conceptualization of sensory memory. Alternatively, each loop could be considered to act like a continuous experiential tape recorder, but with the recording of current experience being affected by prior experiences. However, learning parameters would enter into the model when details of blending information within and between loops are specified. For example, the blending process should allow for different weights to be given to the present and prior experiences, and this could conceivably vary with loop duration and type. Although it is beyond the scope of this paper, it is assumed that as in Cowan's (1988) model, selective attention can focus or amplify information stored at different locations. Here, this would involve focusing on different loops or loop positions and, of course, whatever was recollected and became part of the current cognitive experience would then re-enter the system all over again.

Within this cascading neural loop model, the usual distinctions made between sensory, short-term, and long-term memory (Atkinson and Shiffrin, 1968), or between episodic and semantic memory (Tulving, 1972) have become blurred. What is being proposed, instead, is that memory ranges all the way from highly detailed, short duration sensory memory to semantic memory with little experiential recall but of long duration, and everything in between. Looked at in this way, short-term memory is not a categorically different type of memory but just another set of specializations within the complete system.

Even though the model outlined here is not defined well enough for rigorous testing, there is one prediction that should be amenable to an empirical check. If a loop has the equivalent of a fixed pickup point and information is flowing through it at a constant rate, then recall should be best whenever the relevant information happens to be right at the pickup point or, conversely, worst whenever it just went by and has to go all the way around again. In other words, if there is any reality at all to neural loops, accuracy of recall should rise or fall to some degree with a period equal to a loop cycling time.

This suggests that the decay curve for short-term memory should exhibit a set of nonmonotonic bumps or dips superimposed on the already well established smooth decay curve, resonant with any loops cycling in the range of about 3 to 10 seconds. This constitutes an entirely new testable prediction but, as short-term memory already has been extensively studied, how could such an effect not have been previously observed? The most obvious possibility is that the effect does not exist or is so small as to be lost in the "noise" of interparticipant variability. A second possibility is that loop cycling times vary greatly between participants, and any averaging together of individual results would completely blur away any resonance effects. A third possibility is more interesting and exploits a small methodological oversight.

Short-term memory decay has always been measured in conjunction with some distractor task to prevent item rehearsal (Crowder, 1993). However, as a convenience, researchers never measure every possible distractor interval but only a convenient representative set, such as every 3, 4, or 5 seconds. Peterson and Peterson (1959) and Murdock (1961) used the most complete interval set of every 3 seconds, but researchers thereafter used only every 4, 5, 6, or 9 seconds (see Laming, 1992, for a summary). Apparently, distractor intervals of 7, 11, 13, 14, 17, 19, 21, 22, and 23 seconds have never been sampled, and no study has used distractor interval spacings less than 3 seconds. If the resonance effects in question happen to be relatively narrow in terms of timing width and not fall on any of the typically sampled interval times, then they could have been missed. This is equivalent to fine-grained features in physics or astronomy, such as spectral lines, not being observable until a device with a high enough resolution was built capable of measuring them. In this case, we don't need to build a better device but only to use a more complete, methodologically well controlled sampling interval.

The purpose of the following two studies was to examine the short-term memory decay curve in better detail to determine whether resonance effects might be present. The task used was equivalent to a Brown-Peterson distractor task, with distractor intervals sampled from 1 to 24 seconds, spaced every second apart. Though not exclusive of other possible explanations, short-term memory resonance effects were predicted by, and would be consistent with, the cascading neural loop model outlined above. However, the primary purpose here is not to support that or any other model, but to describe an interesting empirical short-term memory effect that has not otherwise been predicted.

Experiment 1

Ideally, to detect short-term memory resonance effects, a wide range of closely spaced, tightly controlled, repeated measures from the same individual should be taken. The reason for a wide range would be to get as many resonance cycles as possible; closely spaced, to detect narrow resonance effects; tightly controlled, to prevent blurring of those effects; repeated measures, since memory is more likely to be stochastic than deterministic; and the same individual, since different individuals are unlikely to have exactly the same resonance cycle times.

However, people are not physical particles or photons, and psychological research requires compromises. After a number of small pilot studies, it was found both that participants improved with experience across sessions, but also became fatigued or bored if a session went on for too long. The few attempts made to gather extensive data from single individuals quickly led to the conclusion that, assuming rest breaks were sufficient, the quantity of useful data quickly fell off in terms of increasingly lower error rates. And, of course, task vigilance soon became next to impossible without sufficient rest breaks. On the other hand, these same pilot studies unexpectedly also seemed to indicate that resonance effects did occur for many individuals with a period of roughly 6 seconds. Accordingly, the decision was made to follow up this pilot result with a more rigorous study in which the task was restricted to three half-hour sessions, the range of 1 to 24 seconds was sampled with a resolution of 1 second, and to average data across participants.

Method

Participants Twenty-two university undergraduates, mainly psychology majors and approximately two-thirds female, participated in the study in exchange for extra credit. Neither age nor gender was restricted.

Apparatus Micro-computers (286 processor) running programs written by the author were used to present instructions and each trial of the short-term memory task. All times were measured by the computer as differences between successive calls to the onboard clock function. Estimated accuracy was no better than that of the screen refresh rate, approximately 32 milliseconds.

Procedure Up to four participants worked at the same time in the same testing room at divider-separated work stations. Instructions were presented by the computer, but a research assistant was always available to answer questions. Each memory trial consisted of three random but nonrepeated consonants presented on the computer screen for 1 second, followed by a series of random two-digit numbers presented at the rate of two per second for an integer number of seconds between 1 and 24. Participants were to repeat the numbers out loud until a prompt appeared, at which point they were to enter the three consonants. The research assistant first made participants practice the distractor task until they could comfortably do it, and then remained in the room to ensure that participants continued to do so throughout all three sessions.

Each session lasted about 25 minutes, and participants were encouraged to take a short rest break between them. Sessions began with practicing the distractor task and then doing 6 practice memory trials to gain (or regain) familiarity with the task. Participants then did the actual memory test consisting of three filler trials followed by two blocks of 24 trials in which all 24 intervals were randomly presented. Participants were tested a total of six times at each interval. Participants had an unlimited time to respond on each trial, and would push a key to indicate when they were ready for the next trial. For each trial, a target consonant was scored as remembered correctly if it appeared within the entered response, regardless of position.

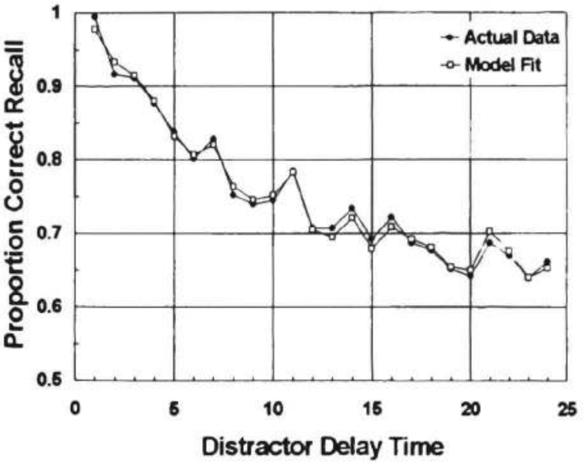

Figure 1: Actual mean proportion correct and best model fit as a function of distractor delay time, experiment 1.

Results

The overall proportion of correct answers was .75, with minimal changes across (in order, .75, .75, and .76) and within sessions (largest difference between blocks occurred in the third session, .77 and .75). Figure 1 provides the mean proportion of correct responses for each of the 24 distractor intervals. As found in earlier studies, such as Peterson and Peterson (1959), the overall shape was that of a descending exponential. In contrast to those studies, however, the points did not form a visually smooth curve but exhibited as many as six peaks: at 3, 7, 11, 14, 16, and 21 seconds. These happened to fall between the usual intervals sampled by previous studies and, in particular, restricting the data set to every 3, 4, 5, or 6 seconds would produce a much smoother curve.

To quantitatively test for the existence of these peaks, three nested regression models were fitted to the data. The base model is an exponential of the form: $y = b0 + b1*\exp(b2*t)$, where y is the proportion correct, t is the distractor interval, and $b0$, $b1$, and $b2$ are free parameters. The next inclusive model adds a three-parameter cyclic peaking function, where $b3$ is the starting time, $b4$ is the period, and $b5$ is the amplitude to be added to the base exponential model. If $b3$ plus the next multiple of $b4$ does not produce an integer value, then $b5$ is split between the two adjacent time points in proportion to the complement of the time difference. For example, if a peak of 10 units occurs at 4.7 seconds, then 3 units would be added to the 4 second interval and 7 units to the 5 second interval. This is equivalent to representing the peaking function as a series of isosceles triangles separated by $b4$ seconds, each with a 2-second wide base and a height of $b5$ units. The most inclusive model adds a second three-parameter peaking function of the exact same form, but independent of the first series.

The base exponential model accounted for 95% of the total variance. The other models produced a number of different "best" fits which were significantly better than the base exponential. For the single-series model, three fits were found to be significantly better than the base model and accounted for another 2% of the total variance, with $F(3,18) = 5.3$, $p < .01$, $F(3,18) = 5.1$, $p < .01$, and $F(3,18) = 4.9$, $p < .05$ respectively. The first case picked up the peaks at 11, 16, and 21 seconds, with a period of 5.2 seconds; the second, peaks at 3, 7, 11, 14, and 21 seconds, with period 3.5; and the third, peaks at 11, 14, 16, and 21 seconds, with period 1.6. Peaking amplitudes added an extra .05 or .06 to the correct response rate above the base function. The case 1 and 2 periods were close to integer multiples (3.3 and 2.2) of the case 3 period.

For the double-series model, six fits were found to be significantly better than the best single-series fit, all being combinations of single-series fits. The best double-series fit, $F(3,15) = 8.0$, $p < .01$, picked up all six peaks and accounted for 99% of the variance, a 4% improvement over the base model. This particular fit is the one shown along with the actual data in Figure 1. Other types of peaking functions were tested in addition to the triangular, including polynomial power series, sinusoidals, and series of exponential shaped peaks with variable widths. None produced better fits than the simpler triangular shapes.

Discussion

These results imply that short-term memory resonances can be found superimposed on a more basic exponential decay curve. This does not constitute an enormous effect, only about 5%, so it could easily have been previously overlooked.

In a small way, this study does support the cascading neural loop model outlined earlier, as resonance effects were a direct prediction of that model. The fact that the best fitting periods occurred as close harmonics of some base period, 1.6 seconds, also would be very consistent with such a model though not necessarily a hard prediction. That is, the simplest systematic arrangement of a cascade would be a doubling or some other multiple of the smallest loop. As logical as this may sound, however, other more random arrangements can not be excluded on biological or any other grounds. Of course, further tests of the model are necessary before it can be considered more seriously. These might involve looking for similar effects on longer time scales, such as minutes, hours, or even days. Given the fact that distractor tasks are not realistic over such durations, more subtle procedures would be necessary to minimize the possibility of purposeful practice. Misleading participants about the true target information or perhaps recording the times of spontaneous reminiscences might be techniques by which to accomplish this.

As short-term memory resonance effects have not been reported before, it was felt that replication was essential. If resonance peaks were spurious, then they would not be expected to reappear the same way in a second independent study. On the other hand, the same peaks occurring with an entirely different group of participants and a modified task would be a very convincing argument towards establishing their reality.

Experiment 2

The purpose of this study was to replicate the results of the first. The procedure was modified so that the two blocks of three-consonant trials within each session were replaced by a single block of randomly intermixed three and four-consonant trials. One reason for this variation was to eliminate the small possibility of some unique aspect of the procedure accounting for the resonance peaking. Another was to make the task slightly harder as a few participants in the first study managed to have very low error rates. A third reason, subsequently dropped, was the possibility of investigating whether the resonance effects might systematically vary with task difficulty. This would be consistent with some form of subvocal or subconscious rehearsal strategy rather than an automatic physiological mechanism as proposed in the cascading neural loop model. However, the sample size here was not sufficient to reliably establish or exclude any such variations, and the analysis will collapse the three and four-consonant trials together.

Method

Participants Twenty-nine university undergraduates participated in the study in exchange for extra credit. Neither age nor gender was restricted, but participants of the first study could not also participate in the second.

Apparatus and Procedure Apparatus and procedure were the same as before except that each of the three sessions now consisted of 24 four-consonant trials randomly intermixed with 24 three-consonant trials.

Results

Performance in the second study was slightly lower than in the first due to half the trials having four target items to be recalled instead of three. The overall proportion correct was .72, with only a small increase between the first and second sessions (in order, .69, .73, and .74). Figure 2 provides the mean proportion of correct responses and, again, the overall result was that of a descending exponential with superimposed peaks. As in the first study, three nested regression models were fitted to the data, and the best fit is shown in Figure 2.. This time, the base exponential accounted for only 93% of the variance, and there were three single-series fits that were significantly better than the base model, $F(3,18) = 3.7$, $p < .05$, $F(3,18) = 3.6$, $p < .05$, and $F(3,18) = 3.5$, $p < .05$. These accounted for another 3% of the total variance, and all three fits had essentially the same period of 3.2 seconds. This is exactly twice the smallest period found in the first study (1.6), and very close to the next larger period (3.5). There were no double-series fits that were significantly better than the best single-series fit.

Figure 3 provides an averaging together of results from both studies. Qualitatively, the peaks at 3, 7, 10 or 11, 13 or 14, and 16 seconds seem fairly consistent across the two studies, though whether the peaks near 11 and 14 seconds are broad, shifted, or perhaps closely spaced doubles is unresolved by this data.

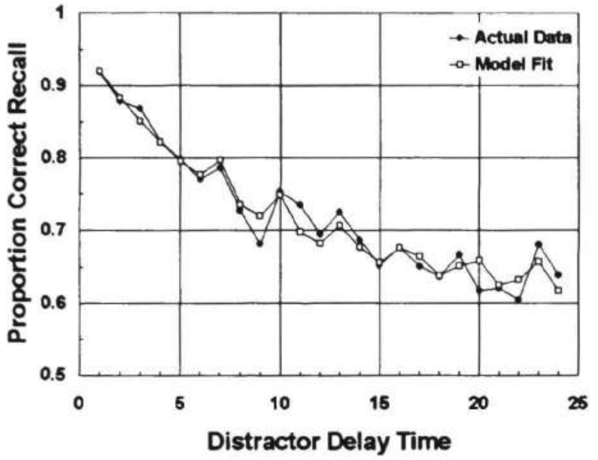

Figure 2: Actual mean proportion correct and best model fit as a function of distractor delay time, experiment 2.

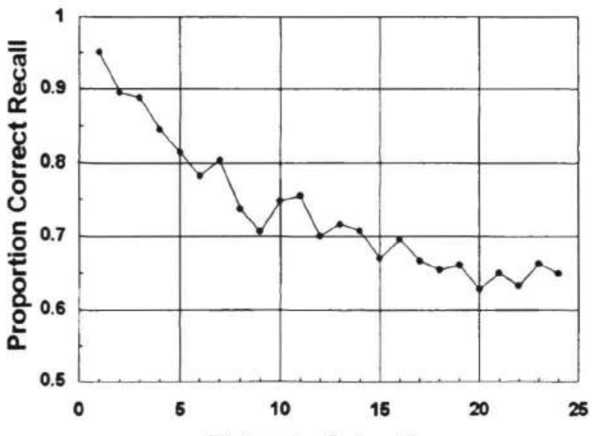

Figure 3: Actual results of experiments 1 and 2 averaged together.

Discussion

Not only did the results of the second study replicate the first, but the peaks appear as even more regular features than before. This strongly suggests that short-term memory resonances do in fact exist and that efforts to replicate and further investigate them would be warranted. Though systematic variations in memory recall on the order of 5% may not have any immediate practical applications, they do imply that short-term memory is a more complicated phenomenon than many theorists might have thought. But one that still is amenable to classic experimental techniques.

These results need further replication and extension. To me, personally, the most unexpected finding was the high degree of consistency in cycle timing between individuals. Though memory itself is a stochastic process, the existence of relatively narrow peaks implies that the underlying physiological parameters may be relatively constant. One extension would be to use essentially the same methodology to expand the resolution of observation in smaller regions to better determine the width or shape of selected peaks and how much variability is normal. For example, sampling every half second between 5 and 16 seconds probably would be sufficient to determine the actual shape of the peaks near 11 and 14 seconds. Another extension would be to extend the range of observations to longer intervals. An example here would be to sample every second between 8 and 31 seconds to determine whether that hint of an upturn in Figure 6 starting at 20 seconds happens to be spurious or not. In either case, increasing the task difficulty might allow single-participant studies to be more feasible, which should provide even more stable results. However, all extensions of the same basic methodology have to balance task difficulty and a reasonable limit on how much time or effort any one participant can be expected to contribute to the task. The critical element always will be to maintain as much consistency as possible in temporal sampling, both between and within participants.

Assuming such replications continue to produce reliable resonance effects, an entirely different level of extension then becomes necessary. This involves the determination of the causes of these cycles, and perhaps even factors that cause consistent variations in their timing. The latter potentially would include any of the factors that now are known to affect attention or vigilance, such as sleep deprivation, drugs, task complexity, prior experience leading to task automaticity, and, of course, time on task without a break. The former would involve looking for the actual physiological correlates of these resonance effects, and determining whether they are innately neural or a matter of experience, such as a learned subvocal rehearsal cycle. If nothing else, if the 1.6 or 3.2 second periods found in these studies were consistent across individuals, it would provide an empirical basis against which EEG or perhaps even functional MRI data could be compared. On the other hand, it would be even more impressive if variations in short-tern memory resonances between individuals were matched by related variations in specific neurological cycles. In effect, it would be interesting if individuals could be categorized by relatively unique patterns of neural loop-related "spectral lines" superimposed on the short-term memory decay curve, much as stars can be classified by their spectra.

General Discussion

These studies were motivated by the asking of a simple question: how is continuous experience neurally represented? This led to the conceptual development of a potential answer, the cascading neural loop model, which led in turn to the prediction and observation of a previously unreported memory effect. Though the model is supported by this outcome, it is more important that a new empirical phenomenon may have come to light that ultimately will require some form of theoretical explanation.

In terms of empirical phenomenon that need theoretical explanation, I'd like to point out an interesting coincidence between the results here and from another empirical paper. Kristofferson (1980) found evidence for discrete steps in the discrimination of time durations when participants have had sufficient practice at the task. He determined values for four different "time quantum": 13, 25, 50, and 100 milliseconds. If these temporal discrimination step values were assumed to be related to a cascade of neural loops and the doubling progression continued, the next values would be 0.2, 0.4, 0.8, 1.6, and 3.2 seconds. Those last two, of course, are extremely close to best fitting resonance periods found in this paper. As mentioned in the discussion at the end of the first study, one of the most logical arrangements for a cascading neural loop model would be a simple doubling of duration for each loop in a cascade. This happens to be exactly the pattern found in Kristofferson's (1980) series of temporal quantal steps. It would be truly exciting if this were not a coincidence, but a convergence of evidence from completely different time scales onto a single model of memory.

Acknowledgments

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