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A New Look at Memory Retention and Forgetting

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The forgetting curve is one of the most well known and established findings in memory research. Knowing the pattern of memory change over time can provide insight into underlying cognitive mechanisms. The default understanding is that forgetting follows a continuous, negatively accelerating function, such as a power function. We show that this understanding is incorrect. We first consider whether forgetting rates vary across different intervals of time reported in the literature. We found that there were different patterns of forgetting across different time periods. Next, we consider evidence that complex memories, such as those derived from event cognition, show different patterns, such as linear forgetting. Based on these findings, we argue that forgetting cannot be adequately explained by a single continuous function. As an alternative, we propose a Memory Phases Framework, through which the progress of memory can be divided into phases that parallel changes associated with neurological memory consolidation. These phases include (a) Working Memory (WM) during the first minute of retention, (b) Early Long-Term Memory (e-LTM) during the 12 hr following encoding, (c) a period of Transitional Long-Term Memory (t-LTM) during the following week or so, and (d) Long-Lasting Memory (LLM) memory beyond this. These findings are of significance for any field of study where being able to predict retention and forgetting is important, such as training, eyewitness memory, or clinical treatment. They are also important for evaluating behavioral or neuroscientific manipulations targeting memories over longer periods of time when different processes may be involved.

Keywords: consolidation, forgetting, memory, retention

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The science of memory should be predictive. One of the most basic things that we should be able to predict is how long various types of memories will last, on average, before they are forgotten. Predicting such changes over time is a foundational principle of many other sciences, such as predicting the decay rate of radioactive materials, the growth of a child at birth, or the trajectory of climate change. A major implication of Ebbinghaus's (1885) original work is that memory accessibility changes over time in a systematic way. However, a great embarrassment of memory research is that we cannot quantitatively predict these changes. At this point we should have the basis for doing so, but there are important aspects of changes to memory over time that have been missed in well over a century of research. The aim of this article is to assess default assumptions of memory retention and forgetting and show how the current understanding is limited. We outline new principles that should be considered regarding patterns of forgetting over time.

Knowing the patterns of retention and forgetting would be useful across a broad range of circumstances. As a sampling, in educational and training environments it would be helpful to know how long memory lasts and to know when it would be best to reteach or retrain for a given set of knowledge. It would also be useful for treatment programs to know how long patients or clients will remember instructions and other useful information. In the area of eyewitness testimony, it would be useful to know how long an eyewitness can reliably remember various aspects of a witnessed event. Finally, a better understanding of retention would help future studies, such as neuroimaging work, to target periods in time that would be of interest for scientific questions of the nature of long-lasting memory.

For this article, we first identify why the issue of retention and forgetting over time is important, some default assumptions in the scientific community about how this works, and some definitions of key terms. After this, we consider time periods over which we might expect memory and forgetting processes to vary, based on cognitive models of memory as well as salient changes in memory that have been reported in the literature. Next, we consider whether different patterns of forgetting might be observed for different kinds of memories. Particularly, in clear contrast to the idea of negatively accelerating patterns of forgetting, in some cases linear forgetting is

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observed. Finally, we present a theoretical account of our findings that can be used as a framework for future work.

The Retention and Forgetting Curve

The clearest finding in research on memory is that as more time passes from when information was first learned, the less likely it is that it will be remembered. The most basic understanding of changes in memory over time stems from the early work by Ebbinghaus (1885) on his own retention of nonsense syllables up to a month later. His memory retention, measured as savings in the ability to relearn a set of materials, is shown in Figure 1. Note that although this is often referred to as a *forgetting curve*, it is actually the amount of information retained over time, so it is better described as a *retention curve*. The core idea here is that to study and understand memory well, we must assess how it changes over time.

This classic Ebbinghaus (1885) curve is a negatively accelerating function, with most forgetting occurring right after the information was learned. A common modern view is that this pattern is well captured by a power function (Anderson & Tweney, 1997; Averell & Heathcote, 2011; Wixted & Ebbesen, 1991). Although this may be the case in most of the reported studies, some work suggests that individual memory traces may be forgotten at an exponential rate, and that the averaging across them is best fit by a power function (Murre & Chessa, 2011).

Thus, a great deal of work suggests that a power function best captures the pattern of forgetting (e.g., Anderson & Schooler, 1991; Averell & Heathcote, 2011; Rubin & Wenzel, 1996; Wickelgren, 1974, 1977; Wixted & Carpenter, 2007; Wixted & Ebbesen, 1991). A power function of forgetting also suggests a progression in a constant manner: $M = at^b$, where M is memory performance, a is a constant, t is time, and b is an exponent capturing the rate of forgetting over log time. There is a great deal of evidence in support of power functions. For example, across three experiments, Wixted and Ebbesen (1991) found that the power function describes the pattern of memory better than five other functions (linear, exponential, logarithmic, hyperbolic, and exponential-power). Moreover, Averell and Heathcote (2011) analyzed data from a longitudinal study measuring memory up to one month later. Using a Bayesian model, they suggest that, although an exponential function may provide the best fit for individual memory traces, a power function that emerges by averaging over individual items offers the best description of forgetting over time. In addition, the power function can describe individual forgetting (Wixted & Ebbesen, 1997), suggesting that it is not always an artifact of averaging over individual data. Thus, the power function appears to capture the rate of forgetting just as well or better than others. Thus, the current study uses a power function to assess the pattern of retention and forgetting.

The retention curve is well-established and has been observed for many kinds of materials and retrieval tasks. These include, among others, the degree of savings for nonsense syllables (e.g., Ebbinghaus, 1885), free recall and recognition of words (e.g., Raymaekers et al., 2014), cued recall of paired associates (e.g., Kleinsmith & Kaplan, 1963), recognition memory for pictures (e.g., Gehring et al., 1976), and implicit memory for words (e.g., Roediger et al., 1992). This finding is so well established that most researchers view this a solved problem, with only three publications (Averell & Heathcote, 2011; Murre & Chessa, 2011; Murre & Dros, 2015), outside of our own work, that specifically addressed this subject in the past 10 years. In fact, when speaking to colleagues at conferences, a typical remark is "don't we know everything about that already?" No, we don't. In fact, there remain several unanswered questions about the nature of forgetting that preclude our ability to accurately predict future memory.

Given the memory curve's replicability, if we know memory performance for at least three time points, we should be able to fit a power function to those data and estimate memory at some time in the future. Going a step further, if we have several studies for materials of a certain type, we should have some general knowledge of what the rate of loss should be for that type of information in the absence of any interventions. From this, we should be able to provide a good estimate of how much of a set of information will be remembered after the passage of a certain amount of time given how much is remembered at another time point, such as immediately after learning.

Presumably, different kinds of information (words, faces, pictures, etc.) have different rates of forgetting (as might be captured by the exponent of a power function), and this may be influenced by the type of memory test involved, such as whether it is recall, recognition, savings, and so on. With enough of these estimates, it is theoretically possible that predictions could be made based on a single data point. But we cannot make such predictions.

In fact, research on the forgetting curve is remarkably thin.[1] The exact nature of this change, especially over very long periods of time, is unknown. Part of this gap in knowledge stems from the fact that many long-term memory studies focus on relatively short periods of time, often less than an hour. Yet memories persist over the course of days, weeks, months, and years. Emerging evidence suggests that there may be differences in the types of memory operating at different periods. Here we review this literature and consider the implications for tracking and predicting memory progression at different timescales. We identify exceptions to conventional views of the retention curve, suggesting that some foundational assumptions about the continuous negatively accelerating nature of this curve are wrong.

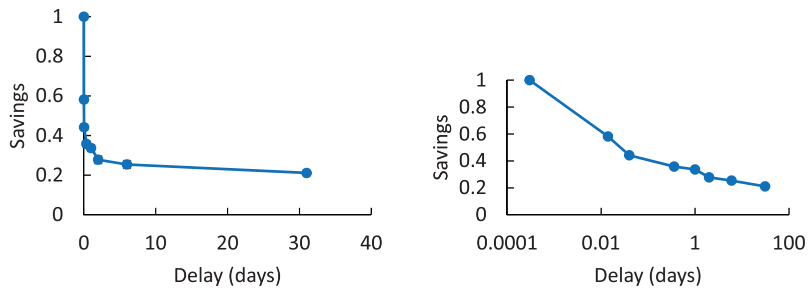
Default Assumptions

Most memory scientists in particular, and psychologists and neuroscientists in general, either explicitly or implicitly hold *default assumptions* about retention and forgetting. These include the ideas that (a) the retention curve has been well-researched (Averell & Heathcote, 2011; Wixted, 2004), (b) apart from deviations in the speed of forgetting, the shape of forgetting (indicated by a particular function) is similar across materials and manipulations (Wixted & Ebbesen, 1991), (c) the retention function is negatively accelerating, although it may be unclear just what type of function this may be (i.e., power or logarithmic; e.g., Rubin & Wenzel, 1996; Wixted & Ebbesen, 1991), and (d) memory over time follows Ribot's (1882) gradient. We consider each of these assumptions in turn.

The first assumption is that the retention curve is well-researched. There have been many assessments of memory change

[1] Based on our count, there are fewer than two dozen articles in the literature, from Ebbinghaus (1885) to the present, addressing the issue of the forgetting curve, per se.

Figure 1
Ebbinghaus's (1885) Original Classic Retention Curve Data



Note. The data on the left are plotted with a linear ordinate, and those on the right are plotted with a logarithmic ordinate. See the online article for the color version of this figure.

over time. However, the granularity of many of these studies is lacking, the range of material types is limited, and the data have been assessed assuming that a power function is the pattern that is observed. More specifically, the granularity of a study covers either relatively short spans of time, such as seconds, or very long spans, such as decades. Often there is little consideration of how the choice of which intervals to assess influences the observed patterns of data, which we show can reveal important qualities of the progression of memories. In our coverage of the literature, the bulk of studies that have looked at changes over time have either used impoverished materials (e.g., lists of nonsense syllables, words, or paired associates), or assessed complex events by probing isolated bits of knowledge (e.g., peoples' names, landmarks) that may or may not be integrated within a larger event.

The second assumption is that the functions are similar across studies (Sadeh & Pertzov, 2020), and that the loss of memories is monotonic. The span of retention, material type, and other factors are not critical to the form of forgetting, only the speed with which it occurs. One example is an exploration of different time scales by Wixted and Ebbesen (1991). They assessed forgetting curves for memory for words at short intervals of time (on the order of seconds), memory for faces at long intervals (on the order of weeks), and pigeons' memory for colored shapes in a delayed matching to sample task (on the order of seconds). They found that a power function fit all these data better than other functions (e.g., logarithmic). What differed was the speed of forgetting. However, a problem here is that very general principles were advocated for based on only three studies. Moreover, there have not been any other studies that systematically assessed memories at different time scales as Wixted and Ebbesen did.

The third assumption is that functions are negatively accelerating, as was found by Ebbinghaus (1885). This may be a power function, or maybe a logarithmic, or some other curvilinear function, so long as it is negatively accelerating. For example, a review by Rubin and Wenzel (1996) of 210 data sets found that forgetting data from many studies were well-fit by a power function, or some other negatively accelerating function. Here, we will show that more complex memories can exhibit radically different patterns of memory retention, such as linear forgetting. Such patterns are present in the data of studies, but researchers have assumed that a power function was present, and analyzed it as such, even when this was not the case (e.g., Carpenter et al., 2008).

The fourth assumption is that memory consolidation continues to protect memories for years after learning. This is captured by Ribot's (1882) gradient. This gradient stems from reports that newer memories are more likely to be disrupted than older memories, and that after a trauma, if memories return, older memories return first followed by the newer memories. Ribot's gradient implies that there is a change in the rate of forgetting, such that the more time that has passed, the more likely that any remaining memories are more resistant to forgetting. Thus, in contrast to the Ebbinghaus retention curve, which emphasizes the decreasing amount of information retained in memory over time, Ribot's gradient emphasizes the increasing likelihood of retaining whatever information remains.

This Ribot gradient, and findings like it, are used to support the idea that memory consolidation continues for years and decades after learning (e.g., Brown, 2002). Some evidence for this comes from retrograde amnesia studies. With retrograde amnesia, recent memories are more likely to be affected, and older memories are more likely to be intact. However, the recent memories may not have yet had an opportunity to undergo consolidation (McGaugh, 1966), that is, stabilization as memories become more strongly represented in long-lasting memory stores. That said, it has been suggested that this is a problem at retrieval, not consolidation (Riccio et al., 2003). Some of this evidence is anecdotal (Ribot, 1882), some of it comes from controlled studies, often with animals (e.g., Duncan, 1949; Nader et al., 2000), and some comes from studies involving neurological disruption in humans (Brown, 2002). It should also be noted that there are exceptions to Ribot's gradient that can emerge with certain types of retrograde amnesia (e.g., Nadel & Moscovitch, 1997).

Some Definitions

To talk sensibly about these issues, we need to be clear what we mean by a few key terms. First, the term ***retention*** refers to memory maintenance over a time in a usable form. We acknowledge that what "usable form" means can vary under different circumstances. Our concern is with the retention over time given similarities in a particular task. Thus, we focus on the degree of *accessibility* of a set of memories, not the degree of *availability* (Tulving & Pearlstone, 1966). Moreover, we set aside the issue of memory *precision* (i.e., the specificity with which memory can be expressed), which differs from accessibility in its progression over time (Berens et al., 2020). We are interested in how the pattern of accessibility changes across time (or not).

Second, and as a corollary to this, the term ***forgetting*** refers to the loss of the ability to use information on a given memory task. This may occur because of a *decay* process, such as when largely unused connections between neurons atrophy (e.g., Hardt et al., 2013), a *displacement interference* process, in which new information alters or displaces older information (e.g., Waugh & Norman, 1965), a *competition interference* process (e.g., Radvansky, 1999), such as when there are multiple memory traces that compete with one another at retrieval, or the active *inhibition* of irrelevant memories (e.g., Anderson & Neely, 1996). For our purposes, we are agnostic about the mechanisms operating. Moreover, and importantly, for us forgetting is an inability to *access* information in memory, not necessarily an absence of memory availability. Just because something is forgotten does not mean that it cannot be remembered later. Reminiscence (e.g., Payne, 1987), in which previously forgotten information is remembered later, in some form, is possible.

The third term, ***consolidation***, is more vexing. Researchers often use this term to refer to two different processes, sometimes conflating them. The first is an *encoding-consolidation* sense which is synonymous with the encoding of a memory trace. For example, it is not uncommon to refer to information being consolidated into working memory (e.g., Vogel et al., 2006) or long-term memory (Meeter & Murre, 2004). At a neurobiological level, encoding consolidation is thought to be supported by synaptic plasticity in hippocampal and, to a lesser extent, cortical areas, such that there is a strengthening of associations between cells that were recently coactive (Dudai et al., 2015). Such processes serve to instantiate the memory into a psychological or neurobiological system. The occurrence of encoding consolidation, in some form or another, is uncontroversial. Investigations into encoding consolidation are focused more on how and when it happens, not if it happens.

The other way that the term "consolidation" is used is in a *persistence-consolidation* sense to convey the idea that, after they are encoded into a system, traces become more firmly established and resistant to sources of disruption, such as interference, retrograde amnesia, or any other mechanism of memory loss. This is often appealed to by studies of retrograde amnesia (e.g., McGaugh, 1966). Persistence consolidation would involve improving memories' durability over time, resulting in the Ribot gradient. The nature of persistence consolidation is less clear. Over long periods of time (from days to years), it is often thought to be the result of a process of systems consolidation in which memories are gradually strengthened in cortical regions through interactions with the hippocampus (cf. McClelland et al., 1995). It remains a matter of debate whether these changes reflect increased durability of the original memory, as argued by standard consolidation theory (Alvarez & Squire, 1994), or a shift in the quality of memory expression, as argued by trace transformation theory (Winocur & Moscovitch, 2011). Consistent with the standard consolidation theory, hippocampal damage disproportionately impairs recent as compared with remote memories (Alvarez & Squire, 1994). Consistent with trace transformation theory, contextual details are often lost or made inaccessible over time due to decay of hippocampal memory traces (Sadeh et al., 2014), resulting in increased semanticization of remote memories. Despite their differences, the standard consolidation and trace transformation theories share the premise that hippocampal and cortical memory representations are distinct and that their expression follows different time courses.

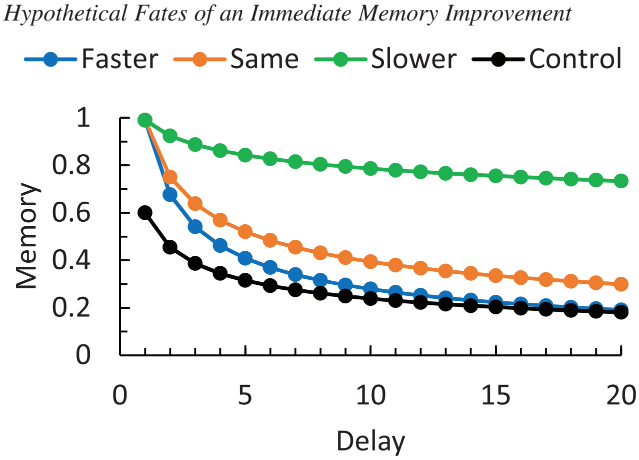
The Importance of Retention Over Time

Accurate retention functions would allow us to predict future memory. For example, looking at Ebbinghaus's original data (see Figure 1), we can fit a power function to these data and predict what his memory would have been at any time in the future beyond when he stopped collecting his data. Again, the most important lesson of Ebbinghaus's (1885) work is that memory changes over time. However, relatively few studies systematically assess this. Instead, most often, memory is tested only once. This is unfortunate because knowing how interventions change memory over time can be insightful. Although there was a brief flurry of activity around this issue (Bogartz, 1990a, 1990b; Loftus, 1985a, 1985b; Loftus & Bamber, 1990; Slamecka & McElree, 1983, 1985; Wixted, 1990), it has largely fallen by the wayside (but see Sadeh & Pertzov, 2020). Take an example of immediately improved memory in one condition (e.g., mental imagery), relative to a control, given soon after learning (e.g., 2 minutes). There are three basic possibilities for the fate of this improvement, shown in Figure 2.

The first possibility is that the forgetting rate is faster in the experimental condition, and memory improvement disappears over time. That is, memory change is temporary. There is something about the processing of the information that makes it initially more accessible (e.g., distinctive features), but over time this is gradually lost until the level of performance of the control condition is reached. An example of this is a study of voluntary and involuntary memories by Staugaard and Berntsen (2019) in which voluntary memories were forgotten faster than involuntary memories. The second possibility is that the forgetting rate is similar in the experimental and control conditions, and memory improvement stays relatively constant. That is, additional information is stored in memory, but forgetting processes are largely the same. This may occur if the overall amount of information is increased, but

Figure 2

Hypothetical Fates of an Immediate Memory Improvement



Note. Faster refers to faster than control rate of forgetting, same refers to same rate of forgetting as control, and slower refers to slower than control rate of forgetting. See the online article for the color version of this figure.

the processes operating on that greater amount of information is the same. An example of this is a study of word memory by Wixted and Ebbesen (1991). The third possibility is that the forgetting rate is slower in the experimental condition, and the benefit of the memory improvement grows over time. This might imply that some information is better consolidated and is more protected against forgetting. An example of this is a study of the testing effect by Roediger and Karpicke (2006).

Let's look more closely at the study by Roediger and Karpicke (2006). This was a study of the testing effect in which, after an initial study period, people either studied again or took a test. Then, a final recall test was given 5 minutes, 2 days, or 1 week later. Roediger and Karpicke treated retention delay as a categorical variable and plotted their data using a bar graph (their Figure 1). However, we treat it as a continuous variable and plot it as a line graph, as shown in Figure 3. The aspect of the data highlighted by Roediger and Karpicke was that the testing condition showed a benefit over the study condition, but only after a delay. One can easily see that this is due to the slower rate of forgetting for the testing condition.[2] Thus, differences in the rates of forgetting under different conditions can lead to important insights into those mechanisms involved in memory processing.

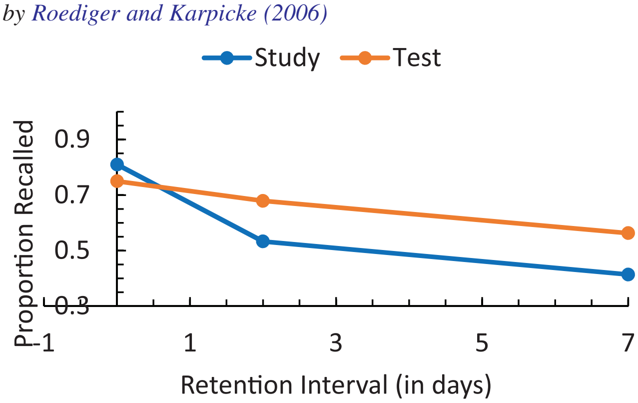
Retention Intervals

The first two default assumptions of the retention and forgetting curve we consider are that memory can best be described with a negatively accelerating function, which many researchers agree that memory is well-captured by a power function (Averell & Heathcote, 2011; Rubin & Wenzel, 1996; Wixted & Carpenter, 2007; Wixted & Ebbesen, 1991). If so, then this should hold across multiple retention intervals. The first issue we consider is how to classify different retention intervals. To do this, we turned to the memory literature for guidance.

The first span of time that we define is from immediately after encountering something to 60 seconds later. This is generally considered the time when information is in short-term/working memory (Atkinson & Shiffrin, 1968). Beyond this, information is traditionally thought of as being in long-term memory. We refer to the time from immediately after presentation up to 60 seconds later as **Period 1**.

Figure 3

Patterns of Retention and Forgetting in the Testing Effect Study by Roediger and Karpicke (2006)



Note. See the online article for the color version of this figure.

Although long-term memory is traditionally any period beyond the duration of short-term/working memory, there are meaningful changes that occur during this time. One of these that has garnered much research support is the influence of sleep on memory (e.g., Diekelmann & Born, 2010). In general, it is thought at least for the first night, there is some beneficial influence of sleep on retention. Specifically, sleep is thought to include periods of increased memory consolidation. In most studies reported in the literature, unless noted otherwise, retention intervals less than 12 hr are likely to occur during a single day, whereas those longer than this are likely to involve a period of a night's sleep. Thus, we can identify a second period of memory retention from 60 seconds (the end of the short-term/working memory duration) to 12 hr, after which some of the influences of a night's sleep are likely to have had an effect. We refer to the time from 60 seconds to 12 hr later as **Period 2**.

Finally, it has recently been observed that memory may show a shift in performance around 7 days (Fisher & Radvansky, 2018). There may be some change in memory retention after this time, although not for all information. Regardless, based on this, we also used seven days as another divider of retention time. Thus, our third period of time is from 12 hr to 7 days. We refer to this as **Period 3**. This leaves anything beyond 7 days. We refer to this as **Period 4**.

Assessing Retention and Forgetting Across Time

To assess whether there are differences in memory retention and forgetting during and across these periods of time, we analyzed a large corpus of data. This was done in two ways. One was to use prior performance on a memory task to see to what degree it predicted future performance. If the default assumption of a single, continuous process holds true, then, apart from some random deviations, prior performance should predict future performance. However, if there are notable changes in retention and the rate of forgetting at different time periods, then prior performance should over- or underpredict future performance, depending on the nature of the change.

The other way to assess for changes in retention and forgetting was to fit forgetting functions (power functions) to the data from each study. This was done to derive an estimate of the rate of forgetting (the exponent of the power function). If the default assumption of a single, continuous process holds true, then, apart from random deviations, the exponents should be relatively similar to one another. However, if there are notable changes in retention and the rate of forgetting at different time periods, then there should be systematic differences in these exponents.

The Prediction of Retention and Forgetting

If the default assumptions are accurate, then prior performance should predict later performance. If not, then any deviations need to be explained. To test the ability of a power function to predict performance, we compared actual to predicted performance and found systematic errors.

[2] Sadeh and Pertzov (2020) considered the rate of forgetting to be equivalent in these two conditions.

We first reviewed the literature.[3] We selected studies in which there were five or more retention intervals to determine how well initial data from a set of retention intervals predicted later memory performance. This review included studies from 1885 to 2020. From these data, we estimated the degree to which prior memory predicted later performance.

The data from published studies were selected when there were five or more retention intervals and performance was operationalized in terms of proportion remembered (or for which this could be calculated), including free recall, cued recall, savings, multiple choice, and recognition.[4] Our survey of the literature produced 43 articles with 311 data sets in which there were five or more retention intervals. We then included studies in which (a) the experimental design did not involve a distractor task (which could impede consolidation; 46 data sets from 17 articles), (b) the data showed a decline in performance over time (38 data sets from 23 articles), and (c) performance did not reach floor by the fourth retention interval (7 data sets). This survey netted a total of 83 articles, including 227 data sets, providing us with a total of 838 predicted data points. Supplement A in the online supplemental materials provides the data used. The data for this and all other analyses in this article are publicly available on the Open Science Framework at https://osf.io/7u6x4/. It is important to note that the data come from several different studies, done in different labs, at different times, using different methods, and having different materials.[5] Thus, any systematic patterns that we observe that shine through all this variation are likely to reflect stable and robust aspects of human memory.

We excluded data with a distractor task because these tasks are likely to disrupt memory consolidation, thereby compromising normal retention. This criterion was primarily an issue for studies with shorter retention intervals (i.e., less than a day). For studies in which retention had reached floor by the fourth retention interval, it was not possible for any further forgetting to occur. Thus, any prediction from these studies would be meaningless. Seven studies were excluded because memory accuracy at the fourth interval was .05 or lower. We only included studies that provided assessments of memory operationalized as the number of items or proportion remembered (or their converse, in terms of error rates). Finally, we only included data sets in which there was a loss of memories over time. This is because we are interested here in cases in which there is forgetting. If there is no forgetting or if there is improvement over time, this may reflect cognitive processes outside of our interest in basic forgetting, such as the operation of different retrieval processes.

To assess predictive ability, retention intervals were converted into approximate number of seconds to put all studies on a common footing. For each study, a power function was fit to the first four data points. This served as the basis for the prediction of future memory. From this function, memory was predicted for the fifth and any subsequent retention intervals.[6] Predictions were then compared with actual performance. If actual memory was better than predicted, this resulted in a positive score, whereas if memory was worse than predicted, this resulted in a negative score. If the default assumptions are correct, then we would expect that prior memory should do well at predicting later performance, with some deviation attributable to random error. The results of this assessment are shown in Figure 4. Each data point is a different predicted retention interval performance.

As can be seen, the predictability of memory is not uniform, but varies across different retention intervals. Prior to one minute (Period 1), performance is mixed. During the first few hours after that (Period 2), retention is largely better than predicted. During the period from then to about one-week (Period 3) memory moves from being better than predicted to being worse than predicted. After that (Period 4), memory is largely worse than predicted.

Our next step was to calculate the average deviation from the predicted value for each time period. These data are shown in Figure 5.[7] Again, positive values reflect memory that is better than predicted, and negative numbers are memory that is worse than predicted. The pattern of prediction is in line with the idea that there are different phases of retention. First, comparing actual performance to predicted performance, the data were as predicted for Period 1, $t(35) = -.96$, $p = .34$, $d = -.16$, better than predicted for Period 2, $t(119) = 8.56$, $p < .001$, $d = .78$, and worse than predicted for Periods 3, $t(76) = -2.02$, $p = .047$, $d = -.23$, and 4, $t(582) = -13.43$, $p < .001$, $d = -.56$. Second, during Period 1 ($n = 36$), memory is about as predicted, if not slightly worse. In contrast, during Period 2 ($n = 121$), memory is better than predicted. During Period 3 ($n = 78$) memory is worse than predicted again, and this gets even worse for Period 4 ($n = 591$). There is a significant change from Period 1 to 2, $F(1, 170) = 20.34$, $MSE = .004$, $p < .001$, $\eta_p^2 = .11$,[8] from 2 to 3, $F(1, 195) = 33.89$, $MSE = .006$, $p < .001$, $\eta_p^2 = .15$, and from 3 to 4, $F(1, 658) = 7.54$, $MSE = .011$, $p = .006$, $\eta_p^2 = .01$. Thus, performance in the four time periods shows noticeable differences.

Overall, the results suggest that memory does not conform to expected predictions but varies with some regularity depending on how much time has elapsed.

[3] Note that the new analyses reported in this article are not meta-analyses in the traditional sense, which often make quantitative comparisons of effect sizes. That is not going on here. Instead, our meta-analyses foci are as qualitative as they are quantitative, focusing on deviations from predicted values, and the rate of forgetting.

[4] We do not include signal detection measures, such as d', because they do not indicate the *amount* of information remembered. They are indices of *discrimination*. For such measures it is possible that the amount of knowledge in memory can change, but discrimination measures remain stable. For example, if the hit rate is .8 and the false alarm rate is .6, d' is .588. However, if, after a delay, the hit rate is .4 and the false alarm rate is .2, d' is still .588 (although bias is changing). We did analyze memory predictability for signal detection measures (see Supplement B in the online supplemental materials). We found patterns like the data used here, but more variable because of the small number of data sets. More generally, for recognition test data, we used what was reported in the published articles. When only hit rates were reported, we used those. When hits and correct rejections were reported or could be calculated (such as by taking the inverse of the false alarms to get the correct rejection rate), we reported the average of the correct hit and correct rejection responses. We acknowledge that this loses any influence of bias. However, our approach does capture the *amount* of information accessible in memory.

[5] See Supplement D in the online supplemental materials for a breakdown of analyses by test and material types.

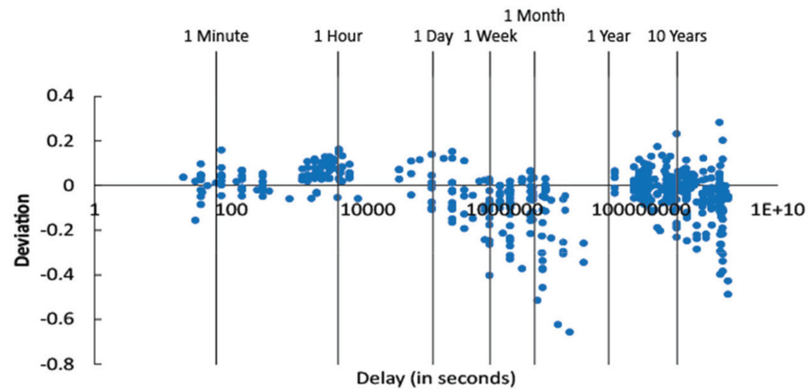
[6] Using at least five retention intervals enabled the derivation of a power function for the first four data points. Four points were used rather than the minimum needed (three), because the derived curves are more stable.

[7] Exponents that were greater than 3 standard deviations from the mean within a phase were trimmed.

[8] Note that these, and all other comparisons reported here, were planned.

Figure 4

Prediction Data of the Fifth or More Retention Intervals Plotted Against Log Time as a Function of Deviation From Predicted Memory



Note. For Period 1 (0–60 s) 61% of the data points are worse than predicted. For Period 2 (60s to 12 hours) 76% of the data points are better that predicted. For Period 3 (12 hours to 7 days) 56% of the data are worse than predicted. For Period 4 (more than 7 days) 70% of the data points are worse than predicted. See the online article for the color version of this figure.

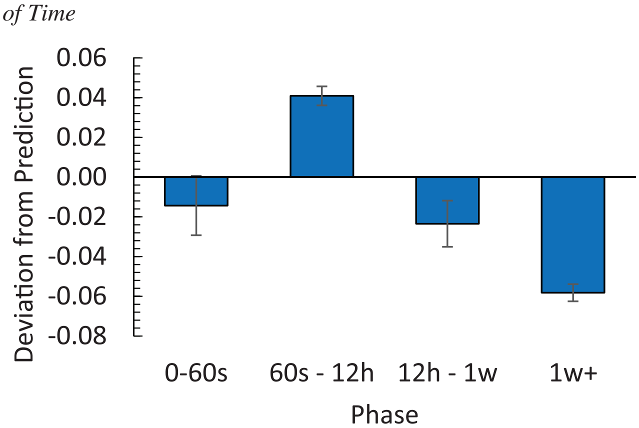
The Rate of Forgetting Within and Across Time Periods

Having looked a predictability, we now turn our attention to the rate of forgetting. Specifically, we were interested in whether the rate of forgetting remained stable within each of these time periods, or if it changed in a regular way. We were also interested in whether the rates of forgetting were the same from one time period to the next, or whether there were meaningful changes.

We used a meta-analytic approach to address the issues at hand. We first regressed the exponent against longest retention interval on a log scale to determine whether there are changes in the rate of forgetting within each time period. Deriving this information from a large set of studies helps avoid an influence of particular characteristics of individual studies.

Figure 5

Average Deviation From Predicted Memory Grouped by Periods of Time



Note. Error bars are standard errors. See the online article for the color version of this figure.

We also compared memory across periods; that is, how memory changed. Thus, we can look at shifts in the rate of forgetting. Much of the literature does not allow us to directly address this by looking at individual studies, which would need to satisfy certain criteria. First, there must be retention intervals in at least two time periods. Second, there must be at least three intervals in each period to allow a forgetting function to be fit. Finally, they would need to assess the amount of information held in memory. Unfortunately, there are only a handful of scattershot studies that reach these criteria, each of which may have issues that compromise their utility for directly assessing our questions.

So, what we did was derive the rate of forgetting in previous experiments. We surveyed the literature for studies in which human memory was tested at a minimum of three retention intervals[9] and performance was operationalized in terms of proportion remembered (or for which this could be calculated).[10] As an additional criterion, we restricted ourselves to data that showed a decline in performance over time. Excluding data that showed either no change or an improvement over time led to 99 data sets from 47 articles being dropped. The final sample in our corpus included 165 articles, with 576 data sets, providing us with a total of 2972 data points. Supplement B in the online supplemental materials provides the data used. For our assessment, we fit a power function to the data. The equation for a power function is $M = at^b$, where M is the level of memory, t is the amount of time that has passed, a is a scaling constant, and b, the exponent, conveys the rate of memory change.

These studies were categorized in two ways: the duration of the longest retention interval (e.g., the time period) and explicit

[9] A minimum of three points are needed to fit a power function.

[10] Again, data were excluded if memory was assessed only using a signal detection measures such as d'. Signal detection measures are not comparable with other measures in terms of how much is remembered (see also Rubin & Wenzel, 1996). Analyses involving signal detection measures are provided in Supplement B in the online supplemental materials.

exposure to the materials (single or multiple). We present separate analyses for single and multiple exposure studies because multiple exposures to materials can change the pattern of observed results (e.g., Ebbinghaus, 1885). It is important to note that when these data are broken down by test and material types, the basic pattern of performance persisted. That is, there is no clear evidence that the patterns of our results are due to different memory tests or materials being present in the different time periods. These analyses are provided in Supplement D in the online supplemental materials for interested readers.

Period 1

Although we define Period 1 as being less than 60 s, none of the studies was longer than 40 s. For the single exposure data ($N = 91$), the exponents were plotted against the longest retention interval (see Figure 6). A logarithmic regression revealed that the forgetting rate increased with retention delay, $r^2 = .07$, $t(84) = -2.45$, $p = .02$. Thus, the more time that has elapsed within Period 1, the faster the rate of forgetting was. For the multiple exposure data, there was a single article (Hellyer, 1962) with three experiments. Because of this small sample size, we did not analyze these data for Period 1.

Period 2

As a reminder, this is the time from 60 seconds to 12 hr. First, looking back at the Prediction Analysis in Figures 4 and 5, we see that during Period 2, future memory performance, in contrast to the Period 1, is now underpredicted. Thus, these are different periods of memory retention. We divide our further consideration of Period 2 into two sections. First, we consider differences between Periods 1 and 2. We then consider performance within Period 2. First, we look at the single exposure studies, which are shown in top half of Figure 7. The speed of forgetting during Period 1 was less than during Period 2, $F(1, 120) = 5.14$, $MSE = .035$, $p = .03$, $\eta_p^2 = .04$. For the multiple exposure studies, again there was only a single article for Period 1. Thus, in bottom half of Figure 7, there is no Period 1 comparison value.

Next, we assessed changes in the rate of loss within Period 2. First, for single exposure studies (see Figure 6). As can be seen, the forgetting rate decreased over the course of the 12 hr, $r^2 = .15$, $t(35) = 2.50$, $p = .02$. Thus, the rate of loss is slowing during this time. In comparison, for the multiple exposure studies, there was no change in the rate of forgetting (see Figure 8), $r^2 = .10$, $t(11) = -1.05$, $p = .32$.[11] A likely explanation is that with repeated exposures, there was an increase in encoding strength. This is evident by the overall slower rates of forgetting for multiple exposure ($M = -.12$) than single exposure studies ($M = -.21$). As such, there is simply less room for improvement in these cases.

Overall, memory during Period 2 is underpredicted by earlier performance (the prediction analysis), with the rate of forgetting slowing down during this time. For information that people were exposed to once, the rate of forgetting slows as time progresses. This is not the case for the data from studies in which there were multiple learning exposures. This may be because that material was better learned overall, leading to a slower overall forgetting rate at the outset.

Period 3

As a reminder, this is the time from 12 hr to 7 days. First, looking back at the Prediction Analysis in Figures 4 and 5, we see that during Period 3, future memory performance, in contrast to the Period 2, is now overpredicted. Thus, these are different periods of memory retention. Turning to the exponent analysis, we compared the overall forgetting rates for Periods 2 and 3. For the single exposure studies (see Figure 7), the exponents during Period 3 were less than those during Period 2, $F(1, 130) = 45.28$, $MSE = .012$, $p < .001$, $\eta_p^2 = .26$. Thus, forgetting is slower during this time, and almost serves as a period of relative stability in memory. Similarly, for the multiple exposure studies, the exponents were smaller for Period 3 than for Period 2 (see Figure 7), $F(1, 79) = 7.91$, $MSE = .004$, $p = .006$, $\eta_p^2 = .09$. Although the rate of forgetting is slower during this time, the difference is nominally smaller than for the single exposure studies. Again, this may be because these materials were better learned overall, making it harder to detect a difference.

Within Period 3, during this time, for single exposure studies, there were no changes in the rate of forgetting (see Figure 6), $r^2 = .01$, $t(93) = -1.16$, $p = .25$. There was also no change in the forgetting rate for the multiple exposure studies (see Figure 8), $r^2 = .03$, $t(68) = 1.53$, $p = .13$.[12] Thus, again, this appears to be a more stable period of memory retention.

Period 4

As a reminder, this is the time beyond 7 days. Again, looking back at the memory prediction data in Figure 4 and 5 we see that as memory retention moves into Period 4, there is even more overprediction. Thus, forgetting is occurring faster than it previously had been. The stable period of memory retention during Period 3 has faded, and mechanisms of forgetting are reasserting themselves. Next, comparing the exponents for the Period 3 and Period 4 (see Figure 7), for the single exposure studies, exponents during Period 3 were less than those during Period 4, $F(1, 130) = 11.19$, $MSE = .008$, $p < .001$, $\eta_p^2 = .05$. Similarly, For the multiple exposure studies, the Period 3 exponents were less than those for Period 4, $F(1, 269) = 12.33$, $MSE = .013$, $p < .001$, $\eta_p^2 = .04$.

Looking within Period 4, we see that for the single exposure studies, the rate of forgetting increased with longer delays (see Figure 6), $r^2 = .20$, $t(146) = -6.02$, $p < .001$. In comparison, for the multiple exposure studies, the forgetting rate did not change across the retention intervals (see Figure 8), $r^2 = .00$, $t(201) = -.02$, $p = .99$.[13] It should also be noted that while the rate of forgetting for the multiple exposure studies does not show a systematic change across this time, the average rate of forgetting is greater throughout Period 4 ($M = -.12$) compared with Period 3 ($M = -.07$). Thus, there is a general speed-up in the rate of forgetting from one period to the next.

Summary

At this point, it is clear that a default view of retention and forgetting over time being a single continuous function is inadequate. First of all, looking across a large number of studies, we were able to show that prior performance generally does not predict future

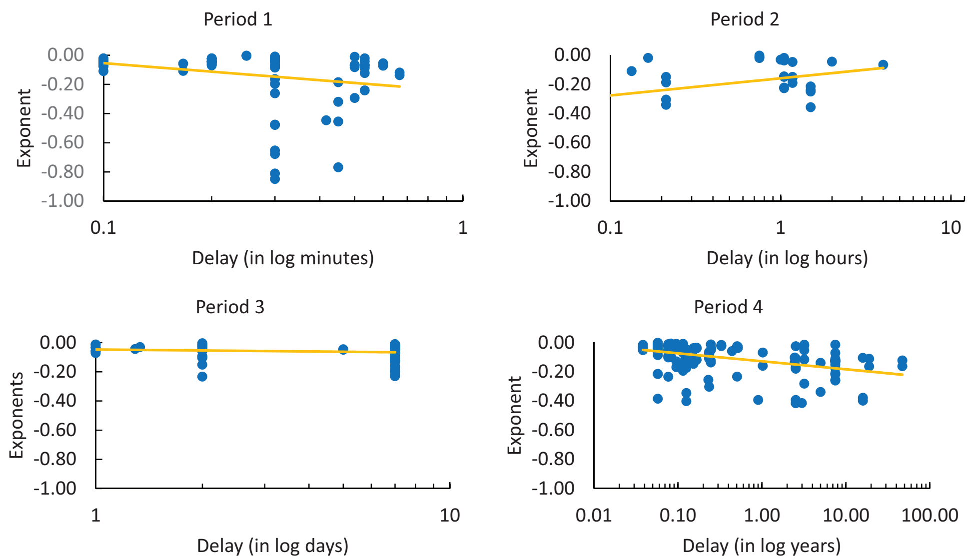
[11] This null outcome was supported by a Bayesian regression, $B_{10} = .66$

[12] Both of these null effects were confirmed by Bayesian analyses, $B_{10} = .39$ and $B_{10} = .67$, respectively

[13] This null result was confirmed by a Bayesian analysis, $B_{10} = .15$.

Figure 6

Plot of the Exponents for Single Exposure Studies During Periods 1 (0 Minute to 1 Minute), 2 (1 Minute to 12 Hours), 3 (12 Hours to 7 Days) and 4 (Beyond 7 Days), Against the Longest Retention Interval



Note. See the online article for the color version of this figure.

performance. It comes close to doing this during Period 1, with better than predicted performance for Period 2, close but worse than predicted performance for Period 3, and much worse than predicted performance for Period 4.

Moreover, there were changes in the rate of forgetting (as defined by the exponent of the best fitting power function). During Period 1, there is a modest rate of forgetting that grows larger as time progresses toward Period 2. Period 2 is a time of more rapid forgetting, although it appears to slow down as Period 3 approaches. Period 3 is a stretch of relative stability with relatively shallow forgetting rates. For Period 4, there is an increase in the rate of forgetting again. This pattern was more pronounced when there had been a single exposure to the learned material. With multiple exposures, not surprisingly, the rates of forgetting were less, consistent with the idea that this information has been better encoded into memory.

Thus, this approach cast serious doubt on ideas that memory retention and forgetting follow a single continuous pattern, as suggested by the classic Ebbinghaus (1885) forgetting curve. However, even in the face of this, it might still be possible to retain the idea that the pattern of forgetting always follows some curvilinear function, such as a power function. The next section challenges even this idea.

Linear Forgetting for Events and Other Complex Information

At this point, there is substantial evidence in support of the idea that there are different periods of memory retention. Each of these shows a different rate of forgetting. This is inconsistent with the default idea that there is a continuous, negatively accelerating function that captures memory retention and forgetting. In this section, we consider some patterns of data that, while also being inconsistent with the idea of negatively accelerating forgetting, might also be seen as being inconsistent with the idea of multiple phases of retention. However, a closer examination suggests that such inconsistency may be more apparent than real.

Much of the research on human memory involves simple materials (e.g., nonsense syllables, letters, digits, words, pictures, paired-associates, and so on) that are presented in lists or sets where the items are typically not meaningfully related to one another. If they are related, it is through some semantic relationship, such as being part of the same category. These sorts of materials made up about 63% of our corpus. However, much of the information that we encounter daily (e.g., novels, film, autobiographical experiences) is not like this. Of importance here, recent evidence has shown that memory for these sorts of materials shows a pattern of *linear forgetting*. To illustrate this, we discuss in detail a study by Fisher and Radvansky (2019).

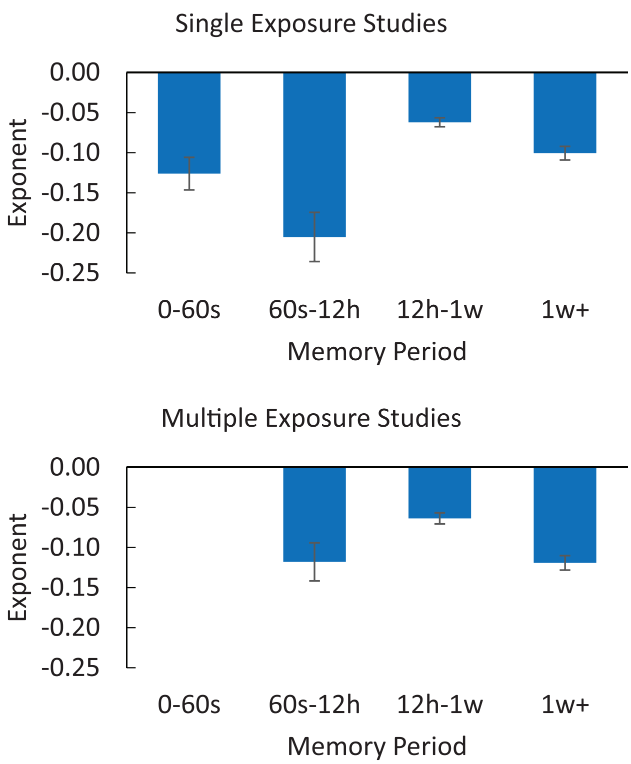
Linear Forgetting

For the Fisher and Radvansky (2019) study, people memorized sets of materials, such as lists of sentences about objects in locations (e.g., the ceiling fan is in the library). These materials produce event models because they describe a specific situation that involves a spatial-temporal framework (the location is in the library now), entities (the ceiling fan), and has properties (people can imagine what a library with a ceiling fan would look like). After memorization, people took a recognition test. The results are shown in Figure 9. As can be seen, the pattern of memory retention and forgetting is very linear.

Why is the observation of linear forgetting so interesting? With negatively accelerating functions, there is a constant loss in the *proportion* of information over time, with a decrease in the *amount* of information lost at longer retention intervals. In contrast, with

Figure 7

Differences in Rates of Forgetting (as Indicated by the Average Exponent Value) for the Four Retention Periods for Single and Multiple Exposure Studies



Note. See the online article for the color version of this figure.

linear forgetting, the same *amount* of information is lost per unit of time. Thus, the proportion of memory loss is *increasing* at longer retention intervals. This touches on Wixted's (1990) "fourth strategy" of understanding forgetting; that is by considering the mathematical form of forgetting functions. This is not readily accounted for by most models of memory.

An important way that we conceptualize our everyday interactions with the world is in terms of events. For us, an event is a situation that occurs within a spatial-temporal framework. It contains entities, such as people and objects, that have properties, such as being old, red, smart, being broken, having goals and emotions, and so forth. These entities may have meaningful structural relationships to one another, such as spatial, functional, ownership, social, familial, and so on. Moreover, multiple events may be related to one another via temporal or causal linking relationships (Radvansky & Zacks, 1997). These sorts of events are represented in memory within *event models* – referential representations that capture what a situation is about (Radvansky & Zacks, 2014).

A simple way to encourage people to create event models that are stored and retrieved from memory is to have them learn sets of meaningful sentences (Garnham, 1981; Radvansky et al., 1990; Radvansky & Zacks, 1991). This likely occurred for participants in the Fisher and Radvansky (2019) study.

Linear forgetting is observed in many other studies. As reported by Fisher and Radvansky (2019), linear forgetting is observed in studies by Bahrick et al(1975), Burtt and Dobell (1925), Carpenter et al. (2008), Cepeda et al. (2008, 2009), Jeunehomme et al. (2018), Kristo et al. (2009), Meeter et al. (2005), Nunoi and Yoshikawa (2016), Runquist (1983), Thompson et al. (1996), and Wagenaar (1986), although none of these researchers explicitly noted that linear forgetting was present.[14] Thus, this finding of linear forgetting has been replicated over a dozen times. There are other studies that also show evidence of linear forgetting, at least for some conditions (e.g., Craig et al., 1972; Davidson, 1994; Smith & Graesser, 1981). Linear forgetting patterns are reliably observed and are clearly deviant from the negatively accelerating function of the default perspective.

Another study to show linear forgetting is the Roediger and Karpicke (2006) study presented in Figure 3. Whereas the study condition data follow a power function, the test condition data follow a linear function. This article, as well as published work that followed from it, has focused on the fact that testing effects are more likely to observed after a delay. What has been left undiscussed (and perhaps unnoticed) is the difference in the nature of the forgetting functions in the two conditions, which likely reflects differences in the underlying memories and how they are retrieved.

What Brings About Linear Forgetting?

Fisher and Radvansky (2019) suggested that two factors may be important in bringing about linear forgetting. First, rather than using sets of isolated items (e.g., word lists), the material involved making associations and elaborations between at least two things, such as paired associates, sentences, or narratives. Second, linear forgetting is more likely to be observed at higher levels of encoding. This could be done either by exposing people to the materials multiple times, testing people on the material prior to final testing, or embedding the material in a narrative.

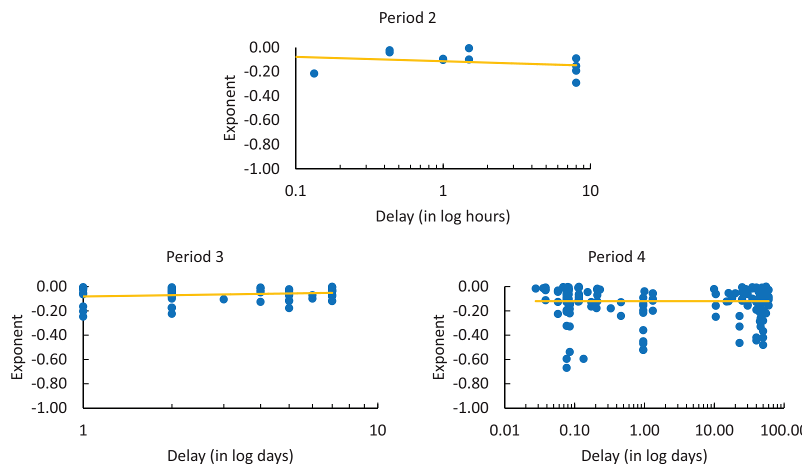
Why do these characteristics give rise to linear forgetting? To understand this, Fisher and Radvansky (2019) created a simulation, the Retention Accuracy from Fragmented Traces (RAFT) model, which was able to produce linear forgetting. This simulation assumed four things:

1. Each memory is made of multiple components.
2. Inferences can be drawn by elaborating on material. These inferences result in more memory trace components.
3. Each component in a memory trace is lost in a negatively accelerating Ebbinghaus manner (e.g., an exponential function), although the rate of forgetting is different for each component. That is, some parts of an event are remembered better than others.
4. Retrieval can involve either a partial match with whatever remains in a memory trace (as with recognition), and/or some sort of reconstructive process when a certain proportion of the components is present.

These are general principles that are accepted by most memory researchers. For linear forgetting, first, more trace components

[14] Note that all of the studies discussed in this section on linear forgetting were also included in our other analyses.

Figure 8
Plot of the Exponents for Multiple Exposure Studies During Periods 2 (1 Minute to 1 Day), 3 (12 Hours to 7 Days), and 4 (Beyond 7 Days), Against the Longest Retention Interval



Note. See the online article for the color version of this figure.

allow for more of a trace to be present when a retrieval decision is made, even if some have been forgotten. This makes it more likely that an accurate response can be made using a partial matching and/or reconstructive process. Multiple components can occur either (a) through the drawing inferences, which is an integral part of event model construction, or (b) through better learning of the materials to a higher degree. The more time that is spent encoding materials, the more likely that inferences will be drawn to better comprehend and remember the information (e.g., Bousfield, 1953).

Second, inferences generated during learning become part of the memory trace. As such, they can be used during retrieval. Third, with this simulation, the standard Ebbinghaus pattern of forgetting that is observed with isolated units of information is preserved at the level of the trace components. Thus, while the linear pattern of forgetting is seen for the complex event memories as a whole, we do not abandon the pattern of forgetting that is so regularly observed with other types of materials. It is there, but it gets lost in the averaging of performance across all elements.

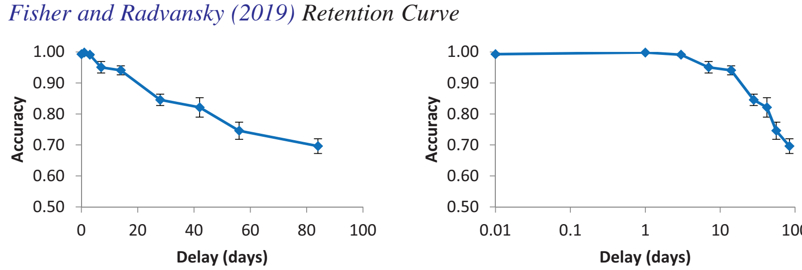
Finally, when people forget, they remember some bits and forget others. However, it is still possible to provide an accurate response using partial information. This is easier when a trace needs to line up with the probe just enough for people to verify that the information was encountered before. Alternatively, people can draw upon prior knowledge to fill in the gaps in a memory. They engage in reconstruction. This allows a response to be made.

Overall, when these factors are present, it is possible to observe linear forgetting. This is important because much of our experience involves complex events, and that is what we wish to remember. These can be autobiographical experiences, crimes or accidents that we may witness, stories that we see, read, or hear, games that we play, and so on. If our science is to be predictive, we should be able to tell how long people will remember events, and when this knowledge can be productively drawn upon. To do that, we need to know what the shape of the function is for those types of memories.

The Fate of Linear Forgetting

One important difference between linear forgetting patterns and traditional negatively accelerating functions is that linear functions

Figure 9
Fisher and Radvansky (2019) Retention Curve



Note. The data on the left are plotted with a linear ordinate, and those on the right are plotted with a logarithmic ordinate. See the online article for the color version of this figure.

eventually go to zero, whereas the other functions can eventually asymptote. Does this mean that memories that follow a linear pattern of forgetting will eventually be completely forgotten, whereas other types of memories will not? Well, no. For the RAFT theory, the linear pattern arises out of an averaging of many different Ebbinghaus-like functions for the various components of more complex memory traces, along with reconstruction and partial matching. Linear patterns of forgetting are observed only when there are enough elements in the memory trace. When the number of elements drops to a small number, then the curvilinear pattern reasserts itself, and an asymptote would be reached.

It should also be noted that when linear forgetting patterns are observed, the overall rate of forgetting is shallower that those observed with traditional laboratory materials. Thus, the time to reach asymptote would be far longer than would otherwise be the case.

Why Doesn't the Rate of Linear Forgetting Appear to Change Over Time?

Earlier, we demonstrated that that are changes in the pattern of forgetting in different periods of memory retention. Sometimes the rate of forgetting is speeding up, sometimes it is stable, and sometimes it is slowing. However, for data that exhibit linear forgetting, no such shifts are clearly observed. Why is this so? First, when linear forgetting is observed, it often appears that the overall rate of loss is less than for cases in which negatively accelerating Ebbinghaus forgetting is observed (cf. Fisher & Radvansky, 2019). Thus, the change in memory over time is much smaller. This smaller change makes it harder to detect any changes in performance.

Second, and probably more importantly, linear forgetting is observed with more complex materials and/or when people have elaborated on the materials. What this does is create more memory trace components that can be used during the retrieval process to generate a correct response using reconstruction and/or partial matching. This difference between high and low complexity is shown in output from the RAFT model, shown in Figure 10. As can be seen, when complexity is high and a more linear pattern of forgetting is observed, the shift from one period of retention is very subtle and would likely be detected with human data only with very high power. In comparison, when complexity is low, as with nonsense syllables and word lists, and a more negatively accelerating pattern of forgetting is observed, the shift from one period to another is more pronounced. Thus, it is not surprising that changes in the rate of forgetting might not be observed with more complex materials, such as those that elicit the construction and use of event models.

Memory Phases Framework

At this point, we have presented evidence suggesting that memory retrieval during different periods of time have different retention and forgetting characteristics. Based on this, we present a theoretical framework for understanding why this might be the case. We hope that this framework can be used as a guide for exploring and understanding memory retention at different intervals of time. The default view of describing retention and forgetting as something like a power function assumes a uniform progression of memory loss over time. However, the data we considered suggest that this is not the case. Rather, patterns of forgetting vary over time. Here we consider the cognitive and neural mechanisms that might explain why this occurs. We refer to this as the *Memory Phases Framework*.

The basic principles underlying this framework are provided in Figure 11. These phases include Working Memory (WM; 0 seconds to 60 seconds), Early Long-Term Memory (e-LTM; 60 seconds to 12 hr), Transitional Long-Term Memory (t-LTM; 12 hr to 7 days), and Long-Lasting Memory (LLM; beyond 7 days). These periods were selected on the basis of cognitive and neurobiological models of memory, yet we acknowledge that there may be other ways of dividing these phases. Nevertheless, we see this framework as a starting point for considering how forgetting changes over time. For earlier periods of long-term memory, retention involves memories supported by specific, episodically bound representations in the hippocampus. However, with longer delays, the role of the hippocampus diminishes. It should also be noted that this division, in some ways, parallels other divisions of memory retention that have been suggested in the literature. This includes the division of long-term potentiation (LTP), which is often hypothesized as a mechanism for memory, into LTP-1, LTP-2, and LTP-3 (cf. Abraham, 2003),[15] as well as the division of consolidation processes into fixation, cellular, and long-term memory consolidation (Meeter & Murre, 2004).[16] We cover each phase in turn, considering potential underlying neural mechanisms supporting them.

Working Memory

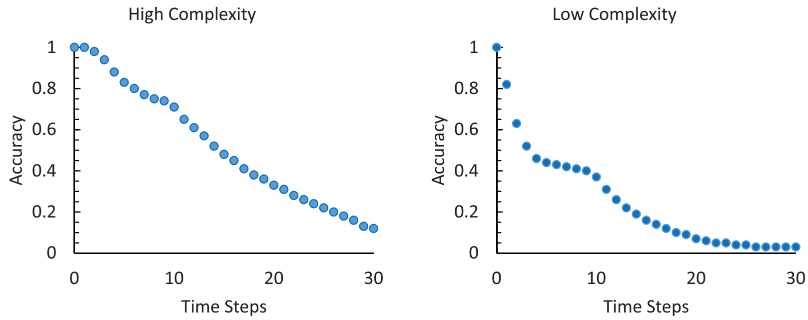
Immediately following encoding, information is temporarily held in an active state, which allows it to be manipulated. This information can be quickly lost, often within 60 seconds (e.g., Atkinson & Shiffrin, 1968). This is the period of time covered by our Period 1. These sensory/short-term/working memory processes are simply labeled here as the **Working Memory (WM)** phase. This is the state of information prior to being stored into what is traditionally considered to be long-term memory. This likely involves cortical representations that are currently active, although some work suggests that there may be some involvement of activity silent connections that also help with the establishment of long-term memories (e.g., Stokes, 2015). The hippocampus may also play a role in maintaining and retrieving information in working memory, especially for novel or relational information (Yonelinas, 2013), as hippocampal damage has been associated with impairments in working memory for relationships among object features (Pertzov et al., 2013) and their locations in space (Hartley et al., 2007).

This state is limited in duration, and can be rapidly forgotten when not attended to (Brown, 1958; Peterson & Peterson, 1959). The amount of time that information remains in working memory is generally a function of the degree to which people actively

[15] LTP-1 is early-phase LTP that is more protein synthesis dependent that animal work has suggested as decaying within 2 hours. LTP-2 is late-phase LTP that may decay after 3.5 days. Finally, LTP-3 is also late-phase LTP that is more transcription dependent and that may decay after about 21 days.

[16] Fixation is from acquisition to about a minute, cellular consolidation persists for several hours after acquisition, and long-term memory consolidation persists for periods of time beyond that.

Figure 10
Output From the Fisher and Radvansky (2019) RAFT Model Simulation



Note. The data on the left exhibit a linear pattern of forgetting, and those on the right exhibit negatively accelerated forgetting. See the online article for the color version of this figure.

attend to it, and the presence of incoming information as sources of interference (e.g., Kane et al., 2007). The standard account is that information is displaced if there is interference prior to successful consolidation (e.g., Keppel & Underwood, 1962; Wixted, 2004) or through a combination of interference and decay (Altmann & Schunn, 2012).

As is seen in the data that we analyzed, information in working memory is more likely to have been exposed to the disrupting effects of interference at longer retention intervals, resulting in a greater rate of forgetting as retention approaches 60 seconds, with a greater forgetting rate at longer delays.

Early Long-Term Memory

The second phase of memory retention, which corresponds to Period 2, spans from 60 seconds (the end of the WM phase) to 12 hr, and is labeled the **Early Long-Term Memory (e-LTM)** phase. For the modal model of memory, everything after WM is long-term memory (Atkinson & Shiffrin, 1968). By comparison, for consolidation theory, there are two major types of consolidation: fast, synaptic consolidation and slow, systems consolidation (Alvarez & Squire, 1994; Dudai, 1996; McGaugh, 2000; Wixted & Cai, 2013). In general, researchers have distinguished between the roles of the hippocampus and the neocortex in these processes, with the hippocampus playing a stronger role in accessing memories earlier on.

Although the time-course of synaptic consolidation processes is not fully understood, the available evidence suggests that these processes occur within a few hours of encoding, and extend across several hours (e.g., Abraham, 2003; Dudai et al., 2015; McGaugh, 2000). Thus, synaptic consolidation provides rapid, but often temporary hippocampal storage for memories (e.g., Squire & Alvarez, 1995). This 12-hr cut-off covers periods during which processes such as synaptic consolidation processes occur, but not so long as to extend into the first night of sleep, which may mark a transition to other forms of memory consolidation processes.

During e-LTM, memories become more resistant to forgetting, a form of persistence consolidation. The rate of forgetting can be modulated by interventions during this window, such as the administration of drugs that block or enhance synaptic plasticity or the arousal-related changes in neurotransmitter release and stress hormone binding (McGaugh, 2000). The efficacy of synaptic consolidation may also be influenced by interference after encoding. For instance, if people are given an opportunity to rest after viewing information, this protects the memory from interference, allowing consolidation to proceed (e.g., Bayliss et al., 2015; Dewar et al., 2012).

During e-LTM, the speed of forgetting *decreases* as hippocampal consolidation occurs, making memories more robust. Prior to this, knowledge is more prone to disruption and interference. It is generally agreed that the hippocampus plays an essential role in early stages of memory consolidation but understanding of its role after that is far from settled. Moreover, although the dominant process during this phase is synaptic consolidation in the hippocampus, we acknowledge that cortical consolidation processes have likely begun (e.g., Dudai et al., 2015) in a cascading manner.

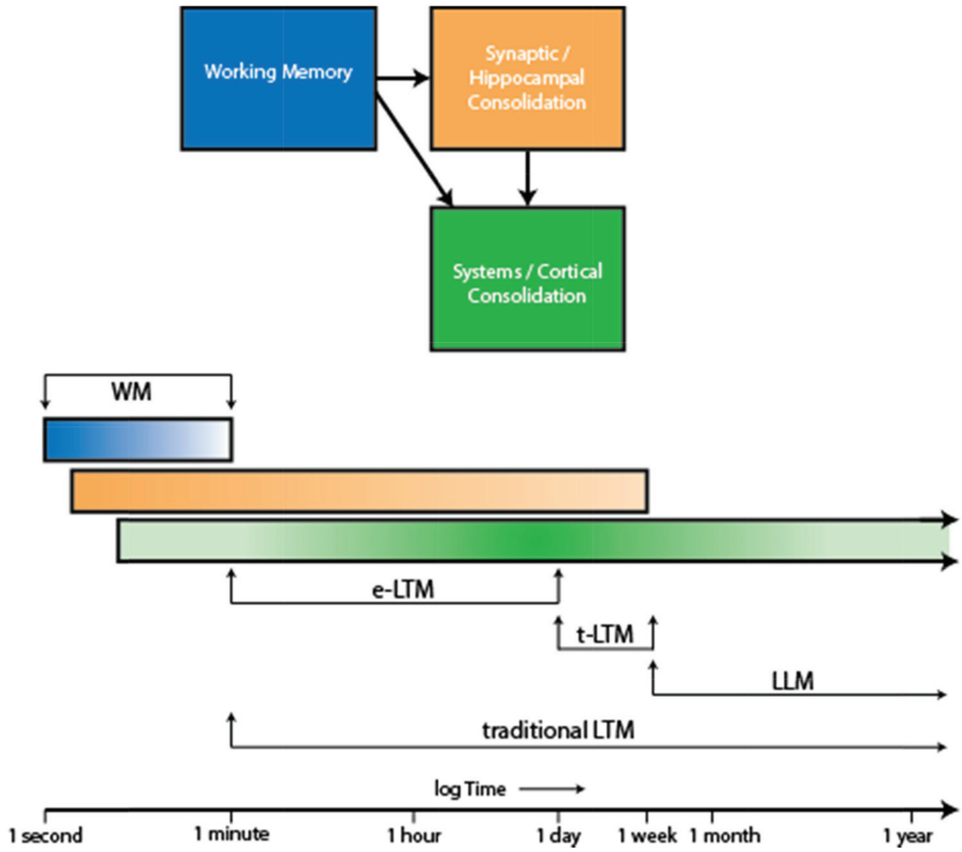
Why would persistence consolidation occur for memories that are hippocampally dependent? An important function of the hippocampus is to bind information into complex, multimodal event representations, which serve as the basis for episodic memory (e.g., Staresina & Davachi, 2009). To the extent that the hippocampus is still involved in memory retrieval, retrieving a partial memory is likely to result in the reactivation of the entire memory through a process of pattern completion. This could operate on the level of learning a list: When the hippocampus is involved, retrieval of the list-learning event (and its effects on pattern completion) would facilitate retrieval of more individual words than would be expected were each word stored independently (cf., Horner & Burgess, 2013). We take this to mean that as long as the hippocampus remains involved in retrieval, memory performance should generally be better than expected.

Transitional Long-Term Memory

The third phase of retention and forgetting is a transition period during Period 3 between the establishment of memories during the e-LTM phase, and the durative phase that follows. Thus, we call this the **Transitional Long-Term Memory (t-LTM)** phase.

In both the standard consolidation and trace transformation theories, memories are initially consolidated in the hippocampus via synaptic consolidation mechanisms. Then, they are strengthened in neocortex through hippocampal-cortical interactions. During

Figure 11
A Hypothetical Progress of Memory Retention Through Four Phases



Note. The first stage is Working Memory (WM), which lasts for the first 60 seconds of retention (presented in blue). The second stage, Early Long-Term Memory (e-LTM), which lasts from 60 seconds to 12 hours, primarily involves hippocampal processes (represented in orange) and cortical processes (represented in green) are beginning to be involved during this stage. Following this is Transitional Long-Term Memory (t-LTM) (12 hours to 7 days), during which the role of the hippocampus diminishes and the cortex becomes primarily involved in memory retention. Finally, beyond 7 days is Long Lasting Memory (LLM), which is driven by cortical processes. See the online article for the color version of this figure.

this time, the patterns held in the hippocampus are used to train the cortex to encode the memory (e.g., McClelland et al., 1995), allowing slower cortical consolidation processes to continue. During this phase, memory representations are gradually integrated with prior knowledge, resulting in longer lasting storage. The process of memory reorganization and reinstatement continues so that those memories can be retrieved from cortical memory (Squire & Alvarez, 1995), perhaps in a qualitatively different way (Winocur & Moscovitch, 2011). The time-course of systems consolidation is not fully understood. Some evidence suggests that changes occur over the first night of sleep or a few weeks after encoding (Dudai et al., 2015), whereas neuropsychological studies are often based on differences emerging on the order of years.

With this in mind, t-LTM starts once a memory has been established in the hippocampus, neocortical memory representations are being strengthened through hippocampal interactions, and the hippocampus remains integrally involved in storing and indexing the memories.[17] Such interactions may occur in the context of spontaneous memory reactivation during wake (Carr et al., 2011), active consolidation processes during sleep (Diekelmann & Born, 2010), or during repeated retrieval events (Antony et al., 2017). Memories that have undergone synaptic consolidation in the hippocampus remain until interfering information is encountered (Abraham et al., 2002).

Because memories are maintained in the hippocampus during cortical strengthening, the speed of forgetting remains largely stable, as seen in our Period 3 data. That said, there is also some indication of a drop-off near the end of this phase or the beginning of the next as memories no longer strongly require the hippocampus. Neuroimaging studies have compared brain activity during retrieval at several different intervals, most often between an immediate test and a delayed test taking place one day or 1 week later. The evidence is somewhat mixed, but some studies have found reduced hippocampal activity and increased neocortical (often medial prefrontal) activity over time. For instance, one study found reductions in hippocampal

[17] We acknowledge that there can be some fast mapping of memories directly into the cortex (e.g., Hebscher et al., 2019).

activity and increases in ventromedial prefrontal activity during scene recognition tested 1, 2, 30, and 90 days after encoding, with the largest change occurring between 1 and 2 days (Takashima et al., 2006). Another study showed that changes in hippocampal retrieval activity after 1 day were related to forgetting of contextual details over time (Ritchey et al., 2008). Thus, there is some neuroimaging support for the idea that memories start to shift in their reliance on hippocampal versus neocortical representation even in the first week after encoding. Finally, note that the duration of t-LTM appears to align with the folk psychology conception of what the phrase "short-term memory (STM)" refers to (see Supplement C in the online supplemental materials).

Long-Lasting Memory

The last phase of retention and forgetting is our Period 4 and what we call the **Long-Lasting Memory (LLM)** phase, after McGaugh (2000). We hypothesize that this phase is marked by decreased reliance on hippocampal memory traces and increased reliance on neocortical memory traces. It is unclear how long hippocampal traces last, even if synaptic consolidation is completed within several hours as new synapses are synthesized (McGaugh, 2000). One possibility is that forgetting in the hippocampus is attributable to a decay process affecting the neuronal connections supporting the memories (Hardt et al., 2013; Sadeh et al., 2014). Another possibility, consistent with McGeoch's (1932) criticism of decay theories, is that a critical factor is the amount of new interfering experience (Abraham et al., 2002). This phase of memory is further supported by neurobiological research showing that, over time, memories become less hippocampally dependent and more cortically dependent (Takashima et al., 2006). There may be exceptions to this transition, however. Although medial prefrontal regions are more strongly involved in representing remote compared with recent autobiographical memories, the hippocampus can remain involved in representing both (Bonnici et al., 2013). In this study, remote memories were vividly recalled, consistent with the idea that hippocampal activity is linked to the retention of contextual details (Winocur & Moscovitch, 2011) or to the construction of vivid scenes (Barry & Maguire, 2019), regardless of the age of the memory. In many cases, however, these vivid contextual details are likely to be lost over time, reducing expected hippocampal involvement—and perhaps marking the transition to the LLM phase. An interesting topic for future research, then, is the rate of forgetting for episodic details versus other more gist-like components of memory (see also Moscovitch & Nadel, 2019).

The timing of these changes remains unclear. However, based on our observation of a shift in the success of memory prediction after about 1 week, we speculate that this may be a time during which significant changes in neural representation occur. Because cortical trace strengthening is thought to occur via memory reactivation, especially during sleep, one might expect that a night of sleep would start to tilt the scale toward cortical representations. It is unclear why several nights would provide an added benefit beyond the cumulative effects of sleep. However, some evidence suggests that there are changes in dream contents that conform to this timeline, such that memory-related details appear in dreams in the first or second night following the event and then again 5 to 7 days later (Eichenlaub et al., 2017).[18] The relationship of these changes to memory representation is not yet understood but may indicate some transformation in memories that occurs around this time.

Because the hippocampus has a smaller influence over memory expression during LLM, the overall rate of forgetting changes relative to t-LTM. This rate of loss may increase because neocortical representations, on their own may be more prone to interference when individual events (e.g., words in a list) are not well-integrated into a schema or other forms of semantic knowledge. A related view is that for remote memories, degradation of hippocampal and neocortical memory traces leads to impoverished memories that must rely more heavily on reconstructive processes during retrieval. For remote memories, such processes are thought to be largely coordinated by the medial prefrontal cortex (Barry & Maguire, 2019; McCormick et al., 2020). However, it is during this LLM stage that arguments in favor of ideas about the continued persistence consolidation, such as Ribot's gradient, have claimed that consolidation is ongoing. Just what this is and how it works is vague. Regardless, the prediction from this view would be that as memories become consolidated, the rate of forgetting will decrease, at least when materials such as word lists are used—and yet this is not what we have observed.

In sum, at this point, neuroscientific evidence suggests that there are different memory processes that contribute to t-LTM and LLM. The extent that the hippocampal and neocortical memory traces vary in how they contribute to memory expression over time could help to explain why a shift in forgetting rates occurs between t-LTM and LLM. However, future work is needed to determine when this shift should occur and whether it maps on to the changes in forgetting rates described here.

While we have identified multiple phases of memory, it is possible that there may be more, which we will be able to identify as our ability to assess wide ranges of performance increases. For instance, Barry et al. (2018) reported using evidence from fMRI studies to suggest that there may be a shift in memory retention somewhere between 1 and 2 years, hinting at the possibility of further stages contained within what we are calling LLM.

Inconsistencies With the Multiple Phases Framework

Having presented a framework for thinking about memory over different phases of retention, we now consider two results of our analyses that might be inconsistent with it. One was the finding of a lack of a change in the rate of forgetting within Period 2 (e-LTM) for multiple exposure studies. As a reminder, the Multiple Phases Framework suggests that during this phase, from 60 seconds to 12 hr, memories are being consolidated. Thus, they are becoming less prone to mechanisms of forgetting, and the rate of forgetting should slow down. Instead, the rate of forgetting was stable during this period.

We suggested earlier that this may be the case because, after all, people were exposed to the material multiple times. This strengthened the memory traces and would have made them more resistant to forgetting overall, attenuating any change in the forgetting rate that may be present. This is supported by the fact that the rate of forgetting during this period is greater for "single" exposure (−.21) than "multiple" exposure studies (−.12). Moreover, we

[18] We thank Björn Rasch for pointing this out to us.

would also expect is that the rate of forgetting should be slower for Period 2 than Period 1 (WM). No such comparison was made in our analyses because there was only a single article (Hellyer, 1962) with multiple exposures during Period 1. That said, the average exponent of the four conditions in that study was greater (−.50) than the average of the studies in Period 2 (−.12). Although this evidence is thin, it is consistent with the framework. Finally, we would also expect that the rate of forgetting should be greater for Period 2 than for Period 3 (t-LTM) because forgetting is slowing during this time and has not reached the stability of Period 3. This comparison was made in our analyses, and it is consistent with the framework. Thus, although the lack of evidence for a slow-down in the rate of forgetting within Period 2 is inconsistent with the Multiple Phases Framework, all the other expected effects are present.

The other piece of evidence that, alone, appears inconsistent with the Multiple Phases Framework is the lack of a change in the rate of forgetting within Period 4 (LLM) for multiple exposure studies. As a reminder, the Multiple Phases Framework suggests that during this phase from 1 week and beyond, performance is less supported by hippocampal memories and become more prone to the influences that cause forgetting. As such, the rate of forgetting should increase. Instead, the rate of forgetting is stable.

Again, we suggested that this may be the case because people in these studies were exposed to the material multiple times, and this likely strengthened these traces, making them more resistant to forgetting overall, attenuating any forgetting change that may be present. This is supported by the fact that the rate of forgetting during this period is smaller for single exposure (−.10) than multiple exposure studies (−.12). Moreover, we would also expect that the rate of forgetting should be greater for Period 4 than for Period 3 (t-LTM) because forgetting is increasing. This comparison was found in our analyses, and it is consistent with the framework. Thus, overall, although the lack of evidence for a speed up in the rate of forgetting within Period 4 is inconsistent with the Multiple Phases Framework, all the other expected effects are present.

Other Apparent Deviations

The deviations from the traditional forgetting curve that we have covered are not the only ones. There are others that are not often viewed in this light. These are noted here to help show how retention and forgetting are influenced by a variety of important factors. One well-known example is the **serial position curve** with better memory for early and later items from a set: the primacy and recency effects. Serial position curves are found in studies of short-term (e.g., Rundus, 1971) and long-term memory (e.g., Healy et al., 2000; Sehulster, 1989), and conflict with the classic retention and forgetting curve, which would suggest that only a recency effect should be observed. Another deviation from the classic retention and forgetting curve is the **reminiscence bump** (e.g., Rubin et al., 1998; Thomsen & Berntsen, 2008). This is a finding that memory for events, typically from about the ages of 15 to 25, are better remembered than would be expected. There is a bump in the traditional forgetting curve. Several explanations have been given for this, including the idea that this is a time of personal transition, leading to more first experiences (Schrauf & Rubin, 1998), and that we remember more from this time because we are expected to because of cultural scripts (Berntsen & Rubin, 2004). Regardless of the cause(s), this is a distortion of the pattern of retention and forgetting that would be expected. The standard retention and forgetting curve does not account for **hypermnesia** (e.g., Erdelyi & Becker, 1974; Wallner & Bäuml, 2018), when people remember more on subsequent attempts than earlier attempts. This has been attributed to several causes (Erdelyi & Becker, 1974; Roediger et al., 1982; Roediger & Thorpe, 1978; Wallner & Bäuml, 2018). These changes can then affect base level of accessibility, which is not considered in the classical retention and forgetting curve. While reminiscence is the opposite of the forgetting, it is not because the overall pattern of retention and forgetting is fundamentally altered. Instead, in all these theories, prior retrieval has somehow altered the memory itself, such as its strength, or the processes used during retrieval. Thus, this does not speak to the change in retention and forgetting for individual memories, per se.

A Summary and Consideration of Consolidation

In this article we have presented various ideas about the progress of memory retention and forgetting that deviate from traditional default assumptions. This was done by considering a wide range of published data in terms of different periods of time, and within the context of a Memory Phases Framework. Much of the data that we have reviewed and explored are consistent with this framework, and deviations maybe be accounted for using existing memory theory, such as the RAFT model.

Overall, the most important implication of our assessment is that, contrary to the default hypothesis, the pattern of retention and forgetting is not stable, continuous, and always negatively accelerating. Instead, there are shifts in the rate of forgetting, and each of these likely reflects changes in underlying neurobiological processes supporting retention. Also, the conjunction of processes with complex memory can produce a very different pattern of data. For example, linear patterns of forgetting are observed for complex memories, such as those derived from event cognition.

Much of the prior research on memory that examined forgetting patterns does not consider phases of retention. This is likely because the amount and variety of intervals included were insufficient. These changes for the various phases of retention suggest that models of forgetting should take such shifts into account to provide a more accurate prediction of future memory performance.

Implications for Memory Consolidation Theory

A fundamental idea about long-term memories is that they undergo a process of persistence consolidation. One of the first sources of evidence for this was **Ribot's gradient** (Ribot, 1882). This stems from the observation that when people experienced retrograde amnesia, the memories that are more likely to be affected are the newer ones. Moreover, when memories returned, it is more likely that older memories come back first, followed by newer memories coming back later. The implication of this is that the longer memories have been allowed to consolidate, the more resistant they are to disruption.

Related to Ribot's gradient are Bahrick's ideas about *permastore* in which there may be no observable forgetting (e.g., Bahrick, 1983, 1984; Bahrick et al., 1975). This was investigated over periods up to 50 years later in which various types of knowledge were tested, including memory for college Spanish (Bahrick, 1984), names and faces of high school classmates (Bahrick et al., 1975), some aspects of city layout and street names (Bahrick, 1983), and memory for names of researchers and concepts learned in psychology classes (Conway et al., 1991; Ellis et al., 1998). Just exactly what permastore is has been unclear, but there is, again, the idea that some memories are so well encoded that further loss is unlikely. The implication of this is, like that of Ribot's gradient, there is a clear decrease in the speed of forgetting as delays grow longer.

If there is resistance to the factors that result in memory loss, this should have implications for the patterns of forgetting. Specifically, as memories become more consolidated, they should become less likely to be lost through forces that act on the unconsolidated traces. Thus, the prediction is that the rate of forgetting should slow down as time moves on. Although this was observed during e-LTM, the time frames in this data set are typically too short to observe. For longer spans of time (t-LTM and LLM), the studies that we reviewed here do not support this improved persistence of memory.

Ideas about enduring processes of persistence consolidation and Ribot's gradient are intuitively compelling. Here are three reasons why older memories seem to become more robust after weeks, months, and years. These are based on well-accepted principles of memory that are likely operating, even in the face of an overall loss of information over time.

The first is based on the number of accessible memories as retention time grows longer. At longer delays, there are fewer and fewer memories left from a given time. As a result, there are fewer memories that can be affected by the processes of forgetting or that can be affected by amnesia inducing trauma. The bulk of the pool of accessible memories at a given moment are more likely to be recent memories. Thus, based on a simple numbers and probability game, it would appear as though older memories are undergoing more persistence consolidation not because of some ongoing process, but because there are fewer memories in the overall pool that can be disrupted.

A second contributor is the rehearsal of older memories. Specifically, memories that people are likely to retain over long periods of time are also likely to be those that are more rehearsed in some way, either explicitly or implicitly. When the memories are retrieved, these rehearsals may be part of a reminding from an external source, an explicit remembering (now just what did my aunt say to my father to make him so angry?), or the spontaneous retrieval that we engage in repeatedly each day (e.g., Berntsen & Rubin, 2008). Each time a memory is retrieved, it is strengthened, and the more durable it becomes. This gives the appearance of a memory undergoing continued consolidation, when what is actually happening is that either a memory trace is being retrieved and then that experience is reconsolidated, or a new memory trace of that event is created for what people are thinking about at the moment. Regardless, there is an overall strengthening of a select subset of memories.

A third contributor is the reconstruction and partial matching of memories during retrieval. As memories grow older, some parts persist for longer than others. Provided that there is enough of a memory present, missing segments can be accessed through remaining associations (Joensen et al., 2020) or general semantic knowledge, such as schemas (Barry & Maguire, 2019). As a result, it appears as though people remember more than may be the case. Similarly, with recognition, if there are sufficient partial matches to a memory probe, then it is possible to confirm that an event happened. Thus, in the face of overall forgetting, it may seem like there is an ongoing persistence consolidation, when what is really going on is that people are adept at using the partial memories that they have.

At this point, we would like to be very clear that although we see no evidence for universally continuing persistence consolidation during t-LTM and LLM retention, we are not ruling out that some memories can become more and more protected from forgetting over time. It may be that such a process is operating, but only on a smaller proportion of memories, and these may not be memories for the types of information that are typically assessed in laboratory studies. Also, we acknowledge that other processes can serve to refresh or strengthen memories, such as reminding or retrieval, reduce forgetting, and may reset them after some forgetting has occurred (e.g., Sekeres et al., 2016). These are the kinds of processes that contribute to hypermnesia (e.g., Erdelyi & Becker, 1974; Wallner & Bäuml, 2018). This may also result in the formation of multiple traces, which can make the loss of knowledge over time less dramatic (cf., Nadel & Moscovitch, 1997). Thus, the general fate of t-LTM and LLM memories is to be more and more likely to be forgotten, and not be more and more resistant to loss, as implied by Ribot's gradient.

Given these three contributors (and there are likely more) to the appearance of ongoing persistence consolidation during t-LTM and LLM, why is this not observed in our analyses? First, the memories that are often studied in research programs are likely to be for impoverished material that is less likely to be rehearsed or encourage elaborative processing that will produce more memory components that are important to people. Thus, they would not show enhanced durability from ongoing consolidation. These memories are also less likely to be complex sets of knowledge that can be reconstructed based on other experiences or general knowledge. Autobiographical memories would be an exception to this complexity issue. Finally, memories that are more likely to be rehearsed are only a small subset. Thus, overall, the fate of memories is that as more time passes, they are more likely to be forgotten. However, there may be a minority of memories that are not forgotten, are more likely to be rehearsed, and have enough critical elements to allow for reconstruction.

Studies of Memory Retention and Forgetting Are Hard

Although it is important to assess changes in memory retention and forgetting over time, a widespread adoption of this approach is unlikely. There are several barriers to this. First, these kinds of studies take a long time to do. To study memory retention and forgetting there are two general methods. The first is to study the same people at multiple retention intervals (within subjects). With this approach there are fewer participants, and individual retention and forgetting functions can be plotted. However, the time commitment for each participant is magnified. This may lead to greater attrition. Another concern is that with repeated study and/or testing trials, participants develop strategies of how to do the task. The second approach is to have different groups of participants retain information for different retention intervals (between subjects). This reduces attrition and avoids issues of participants learning to do the task. Attrition issues can be mitigated by using online testing approaches (e.g., Berens et al., 2020; Fisher & Radvansky, 2018). One problem is that a larger number of participants are needed.

Conclusions

This article has explored problems with some default assumptions of memory retention and forgetting. First, the default assumption that retention and forgetting curves have been well-researched is simply not true. There have been surprisingly few studies that have tackled this issue head-on. Moreover, we were able to show deviations from the standard pattern which have been largely missed in well over a century. Second, the default assumption that memory performance is captured by a single function runs counter to our finding that there are phases of memory retention and forgetting captured by the Memory Phases Framework, with each phase having different characteristics. We draw on both behavioral data and neuroscientific theories to support this. Third, the default assumption that the progress of memory follows an Ebbinghaus (1885) negatively accelerating (e.g., logarithmic, power, or exponential) function runs counter to our findings. This is true both in terms of the phases of memory, as well as evidence for linear forgetting. Finally, the assumption that memories follow Ribot's (1882) gradient is not true for the bulk of memories, which implies a decrease in the rate of forgetting, although it may be possible for a select subset of memories, perhaps through processes of rehearsal.

By considering these various sources of data, we hope to further push the field forward toward identifying and describing different types of memory that hold sway over different periods of time, which can then effectively inform future studies. Moreover, future studies of memory performance over time should consider the neurobiological processes operating at the times under consideration. This is currently not done enough. Overall, this review provides fundamental knowledge that can contribute to the progression of the field of memory research to a point where we can make predictions about the fate of multiple kinds of memories over multiple time scales. Furthermore, this knowledge can help us better understand how to promote memory and reduce unwanted forgetting.

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