

Distributed practice and distributed representations:
Investigating the spacing effect using EEG

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Abstract

The spacing effect shows that studying information at distributed intervals leads to better long-term memory than continuously studying over the same cumulative amount of time. Prior research has not made explicit predictions about neural activity in the EEG domain that should occur at different study repetition lags under different spacing effect theories. Knowledge about neural patterns underlying the spacing effect can shed light on why this effect occurs, supporting or challenging the hypotheses presented here. One main purpose of this thesis is to make these predictions in terms of the neural activity expected under different spacing effect hypotheses, and to test them to the best of our ability.

Keywords: spacing effect; subsequent memory effects; EEG; ERP; oscillations; encoding; learning

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“You can get a good deal from rehearsal,

If it just has the proper dispersal.

You would just be an ass,

To do it *en masse*,

Your remembering would turn out much worsal.”

—Ulric Neisser,

quoted in “Retrieval practice and the maintenance of knowledge” (Bjork, 1988)

Introduction

The Latin phrase *repetitio est mater studiorum* tells us that “repetition is the mother of learning,” and psychological research shows us that how we distribute those repetitions has an important impact on memory performance. From the beginnings of empirical research on memory it has been shown that distributed practice, with gaps between study sessions, leads to better long-term memory performance than massed practice. Ebbinghaus documented this effect and wrote, “With any considerable number of repetitions a suitable distribution of them over a space of time is decidedly more advantageous than the massing of them at a single time” (Ebbinghaus, 1885/1913, p. 89). This seemingly simple result is known as the spacing effect, or the distributed practice effect, and has been the subject of extensive research over recent decades (for reviews, see Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Cepeda et al., 2009; Delaney, Verkoeijen, & Spriegel, 2010).

The spacing effect is robust and has been demonstrated in studies that employ various memory tests including free recall, cued recall, recognition, and frequency judgments. It is found not only in laboratory studies but also in real-world training and learning settings. Research on this topic could have important practical consequences regarding how information is presented in applied settings such as classrooms (Carpenter, Cepeda, Rohrer, Kang, & Pashler, 2012; Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013; Khajah, Lindsey, & Mozer, 2014) and how students are instructed to study on their own, though this chance to enhance memory in applied settings depends on effectively utilizing the knowledge gained from research (Dempster, 1988; Pashler, Rohrer, Cepeda, & Carpenter, 2007).

The reasons why this almost ubiquitous effect occurs are still debated and levels of prominence for different theories have changed over the years. Three theories have come to dominate, each of which has been supported by behavioral results and different verbal and mathematical models of learning. These three theories are typically known as deficient processing, contextual variability, and study-phase retrieval.

Although behavioral studies and modeling efforts have done a commendable job of investigating the spacing effect during decades of research, few publications have investigated its neural correlates. Because these theories emphasize several different processes underlying the spacing effect, it is proposed that each may be supported or challenged by examining how particular patterns of neural activity during spaced and massed learning lead to different memory outcomes, thereby revealing the true mechanisms behind why distributed practice is so effective. Note that the theories are not mutually exclusive.

Ancillary to this main goal, even if decisive conclusions cannot be drawn regarding what is truly at the root of spacing effects, the proposed research will describe the neural correlates of the spacing effect that align with each hypothesis. If existing mathematical models that account for the spacing effect are accurate (reviewed later), this will likely involve interactions between the theories. Thus, this proposal focuses on gaining a better understanding of the neural processes involved during spaced and massed learning episodes as recorded in the electroencephalogram (EEG). The present and proposed experiments will use EEG to infer the relative involvement of various cognitive factors, thereby providing evidence relevant to assessing the theories.

Background

Deficient Processing

The deficient processing theory focuses on the cognitive processes that are active during encoding. This hypothesis predicts that when an item is repeated in a massed fashion (immediate repetition), because it is familiar and already in working memory there is a greater decrease in attention or encoding effort to the second presentation than there would be to a novel item or spaced repetition. According to Greene (1989), this could manifest as less rehearsal relative to a spaced repetition due to the stimulus's level of familiarity, and not to an experimental variable such as a difference in the relative amount

of rehearsal time available for massed and spaced items. This could happen either voluntarily through the explicit control of attention (Greene, 1989), or involuntarily via a habituation mechanism like neural repetition suppression (Callan & Schweighofer, 2010; Hintzman, 1974; Van Strien, Verkoeijen, Van der Meer, & Franken, 2007; Wagner, Maril, & Schacter, 2000; Xue et al., 2011) or via short-term priming and transfer-appropriate processing (Challis, 1993; Mammarella, Russo, & Avons, 2002; Russo, Parkin, Taylor, & Wilks, 1998).

Even though this theory has been supported by recent research examining the neural basis of the spacing effect (specifically in relation to neural repetition suppression; Callan & Schweighofer, 2010; Van Strien et al., 2007; Xue et al., 2011), the deficient processing hypothesis cannot completely explain the spacing effect for a few reasons. The first is because of its reliance on working memory, such that it only seems to be a viable explanation at short timescales. Past research has shown that the spacing effect occurs across multiple days, weeks, and even months (Cepeda et al., 2006, 2009). It might be possible to test whether different extents of deficient processing occur using a gradation of spaced inter-study lags (e.g., deficient processing should decrease as lag increases), but other mechanisms are still needed.

Second, Delaney et al. (2010) called deficient processing an “impostor” spacing effect. Massed items are put at a disadvantage rather than giving the spaced items an advantage, and so this theory accounts for the spacing effect with a relative difference between the two. Since we want to know about a true spacing effect (i.e., an advantage for spaced items), we must assume that other mechanisms are at play.

Finally, decades of theoretical and mathematical accounts of human memory have stressed the importance of the context that accompanies studied material in influencing memory performance, and the deficient processing theory does not consider this aspect. (Include references or another sentence about context?) In summary, the deficient processing effect is still interesting to investigate due to the recent attention it has been

given in functional magnetic resonance imaging (fMRI) publications regarding neural repetition suppression, but other theories are needed because it cannot completely account for the spacing effect.

Contextual Variability

Contextual variability theory assumes that item study presentations are associated with a slowly drifting background context that also gets encoded in a memory trace (Bower, 1972; Estes, 1955; Melton, 1970). The set of features that constitute context is not completely consistent across different theories and models of memory, but most accounts agree to a basic extent. Context typically includes the incidental background stimuli that are present during encoding (e.g., the experimental backdrop and non-relevant stimuli) as well as the internal state of the learner; it drifts or fluctuates as time passes (Bower, 1972; Delaney et al., 2010; Glenberg, 1979; Malmberg & Shiffrin, 2005; Raaijmakers, 2003). The contextual state can be impressionable, influenced by recent experiences (e.g., the other items in a list) (Howard & Kahana, 2002; Sederberg, Howard, & Kahana, 2008). This means that context can change depending on the information that is encoded or retrieved from memory. This proposal takes the view that the contextual state fluctuates over time and is influenced by the contents of memory, as this is how spacing effects are typically accounted for in mathematical models of memory.

Because episodic context drifts with time, the context encoded with repeated study events will differ more as inter-study lag increases (Estes, 1955). This was first proposed as a reason for spacing effect by Melton (1967) and was integrated into more elaborate theories (Bower, 1972; Glenberg, 1976, 1979). Subsequent retrieval of an item during test depends, at least partially, on the similarity between the study and test contexts (in line with the encoding specificity principle Tulving & Thomson, 1973). Consequently, spaced items are recalled better due to the higher probability that the contextual state at test will match that of the spaced repetitions compared to the less variable (or nearly identical)

massed repetitions; essentially, there are more retrieval cues for spaced items. To account for decreased performance at especially long study repetition lags, Glenberg (1976) proposed that the test context would not overlap with the first presentation and memory would rely solely on the second study presentation.

As a side note, attempts to deliberately vary the context encoded with massed and spaced repetitions (e.g., changing the paired associate, using homonyms, varying the level of processing), have typically not produced spacing effects (e.g., Glanzer & Duarte, 1971; Hintzman, Summers, & Block, 1975) (but see Braun & Rubin, 1998, Experiment 3; Malmberg & Shiffrin, 2005). This is typically accounted for by assuming that when context is too variable the item is no longer encoded as a repetition. Therefore, attributing spacing effects to temporocontextual drift rather than strictly defined contextual cues seems more promising (Greene, 1989).

To extend contextual variability's predictions in this proposal, it seems natural that contextual drift should apply to the learner's ongoing neural activity. Importantly, this has been considered with respect to memory models (e.g., Sederberg et al., 2008) and demonstrated in analyses of intracranial EEG in rats (Manns, Howard, & Eichenbaum, 2007) and humans (Manning, Polyn, Baltuch, Litt, & Kahana, 2011). Therefore, this theory can be assessed by measuring the neural similarity between study repetitions as well as during test trials.

Study-Phase Retrieval

Study-phase retrieval proposes that the repetition of an item induces the retrieval of the memories of its earlier presentation(s), including both item and contextual information, and that this retrieval during study is important for improving subsequent memory (Greene, 1989; Thios & D'Agostino, 1976). Critically, the learner must recognize that the repeated item has been encoded previously in order to benefit from spacing (Hintzman & Block, 1973; Hintzman et al., 1975; Johnston & Uhl, 1976; Raaijmakers, 2003). Surely

massed items will be recognized as being repeated as well, so why do the spaced items benefit more (the crux of the spacing effect)? As in contextual variability, context varies more across spaced repetitions; a repetition is assimilated into the existing memory trace, and this provides an addition set of retrieval cues for spaced items. Importantly, if study-phase retrieval occurs, this supersedes the contextual variability hypothesis. As lag increases between repetitions it becomes more difficult to retrieve the prior study event, but if a longer lag item is retrieved then the memory trace is strengthened to a greater extent (Delaney et al., 2010). Notably, this retrieval difficulty idea is in line with research on the testing effect (e.g., Karpicke & Roediger, 2007). (TODO: AH asked: how is it in line?)

This theory brings up the question of how the memories are stored. Is a recognized repetition stored as a new trace, or is the original trace strengthened? As alluded to above, Raaijmakers (2003) explained that a repetition should strengthen (and add to) the initial stimulus trace. If each repetition was instead stored as a separate trace, the first trace will decay at longer lags (effectively a long retention interval) and subsequent memory may rely solely on the second trace, a potential issue for the contextual variability theory. However, this is not the typical result of a spacing manipulation, except at very long lags as Glenberg (1976) explained. Updating an existing trace with new information is implemented in other models as well (e.g., Howard & Kahana, 2002; Polyn, Norman, & Kahana, 2009).

If a stimulus repetition brings to mind its prior occurrence(s), study-phase retrieval theory predicts contextual reinstatement at a neural level (Lohnas & Kahana, 2014). List L has n presentations, some of which are repetitions. Say L_1 and L_{n-1} are the same item presented at two different points in time, with intervening items (e.g., $n > 10$). Study-phase retrieval says that the neural activity during L_{n-1} will be more similar to its initial presentation L_1 than to L_{n-2} . This is different than what would be expected under the contextual variability theory where context should simply drift (L_{n-1} would be more similar to L_{n-2} than to L_1). Turk-Browne, Simon, and Sederberg (2012) demonstrated this by showing that the same visual scene presented on different lists but preceded by the same

stimulus (i.e., the same context) was found to evoke more similar neural activity compared to when it was preceded by different stimuli (i.e., different contexts). This can support the contextual reinstatement aspect of study-phase retrieval because the presentation of the same information puts the brain in similar states.

Contextual reinstatement is also thought to occur during a memory test. Some memory models assume that the current contextual state is used as a cue during retrieval attempts, especially during a free recall test without experimenter-supplied cues. When an item is recalled, the present context is updated with that item's associated context (Howard & Kahana, 2002; Sederberg et al., 2008). This assumption helps account for particular patterns of recall in experimental evidence (Kahana, 1996; Lohnas & Kahana, 2014). Additionally, evidence for similar neural activity during study and recall of a given stimulus shows that this kind of contextual reinstatement occurs in the brain (Manning et al., 2011; Polyn & Kahana, 2008; Xue et al., 2010). Thus, under study-phase retrieval we would expect study repetitions and seeing the item during a subsequent test to reinstate prior context.

Hypothesis interactions

It is important to note that these theories are not mutually exclusive or necessarily competing, and it would be difficult, if not impossible, to test each independently. In fact, they can work well together, and the consensus in the literature is that a hybrid account is needed to explain spacing effects (Delaney et al., 2010; Greene, 1989; Lohnas & Kahana, 2014; Lohnas, Polyn, & Kahana, 2011; Raaijmakers, 2003). Most hybrid accounts agree that each presentation is encoded with drifting context (contextual variability) and that an item repetition is assimilated with prior occurrences (study-phase retrieval). This combination seems necessary to account for the effect when fitting models to empirical data (e.g., Lohnas & Kahana, 2014; Mozer, Pashler, Cepeda, Lindsey, & Vul, 2009; Pavlik & Anderson, 2005).

Formal models accounting for the spacing effect

An important way to constrain explanations of the spacing effect is with the mechanisms implemented in computational models that can account for patterns of human performance. Most of these models contain interacting mechanisms that involve more than one of the hypotheses described here.

Raaijmakers (2003) made an influential model based on the Search of Associative Memory model (SAM; Mensink & Raaijmakers, 1989) using the spacing effect theory proposed by Glenberg (1979). It accounts for the spacing effect in cued recall using contextual variability and study-phase retrieval mechanisms.

An activation-based account of the spacing effect was implemented by Pavlik and Anderson (2005) in ACT-R, and can explain the effect at multiple timescales, which the SAM-based model cannot. Here, all repeated items receive a strength increment, but the rate of decay for the resulting trace is positively correlated with the level of activation for that item at the time of its repetition. This leads to a spacing effect that fits their behavioral data well. The quick decay for a massed item is reminiscent of deficient processing, but the mechanism is not explicitly defined in this way.

The Multiscale Context Model (MCM; Mozer et al., 2009) can also account for the spacing effect at multiple timescales. It makes impressively accurate predictions at various inter-study lags and retention intervals, as well as for different study materials, using relatively few parameters. It implements contextual variability and study-phase retrieval (“retrieval-dependent update”) in a method similar to the SAM model for storing and retrieving context and item information. Additionally, it uses a mechanism similar to the ACT-R model’s decay to predict a forgetting function.

The Context Maintenance and Retrieval model (CMR; Lohnas & Kahana, 2014; Polyn et al., 2009) can account for the spacing effect in free recall. As its name implies, contextual variability is an essential aspect for modeling the encoding of context as it fluctuates, and a study-phase retrieval mechanism helps it reinstate previous contextual

states. These two aspects allow it to capture patterns of spacing effect results in a paradigm that the other models were not designed to fit.

Overall, contextual variability and study-phase retrieval are clearly important theories, as these mechanisms are central to successful models that capture the spacing effect. Even though none of these models use deficient processing, it should be given attention due to its recent popularity in empirical investigations involving neural recordings.

EEG studies of the spacing effect

Van Strien et al. (2007) published the only study investigating the spacing effect using event-related potential (ERP) and time–frequency analyses, which was based on stimulus repetition research. They used a continuous recognition paradigm (repeatedly judge word presentations as being new or old) followed by a surprise recall test. Unfortunately, some of their EEG effect interpretations do not agree with episodic memory research and instead are explained as being specific to working memory paradigms, though it seems unclear whether theirs is a working memory task (spaced repetitions were 6 items/9 sec apart). This does not seem ideal to base new episodic memory research on.

Although the behavioral results of Van Strien et al. (2007) indicate higher recall for spaced *vs.* massed repetitions, they did not analyze neural data for an interaction between spacing and memory which seems like an important factor to investigate in a study of the spacing effect. Also, their use of continuous recognition may have confounded their interpretation of the data because this paradigm induces a testing effect (every trial is an old/new test). Behavior may differ qualitatively compared to simply studying and encoding stimuli at spaced and massed intervals (Delaney et al., 2010, p. 91). Thus, further research is needed to understand the EEG patterns and cognitive processes that underlie the spacing effect. Despite these shortcomings, their results can be used as a basis for future experiments to make effect predictions when modulated by subsequent memory, an

analysis that has not been previously explored using neural data.

Proposed dependent measures

The terms subsequent memory and subsequent retrieval were mentioned earlier. To be clear on these and related terms, subsequent memory effects (SMEs) show differences during encoding that are contingent upon later memory performance, and examining these differences sheds light on why some things can be remembered later while others are forgotten.

Because the spacing effect predicts a long-term memory advantage for spaced compared to massed study repetitions, it seems likely that there will be differences between spaced and massed repetitions that interact with subsequent memory. However, it also seems likely that when encoding is successful for both spaced and massed repetitions, the active memory mechanisms should be qualitatively similar. There may be a quantitative difference (the difference is in the degree of processing), but it remains possible that memory will not be critical to determining why the spacing effect occurs; many factors besides encoding mechanisms can influence subsequent memory. Although we will investigate neural patterns known to be associated with memory encoding and retrieval, other cognitive factors must be considered. For example, attention and semantic processing likely influence the spacing effect. Effects of spacing for repetition events without a subsequent memory interaction can also reveal processing differences between spaced and massed items.

EEG/ERP Overview

TODO: Explain a bit more about EEG here, including ERPs, power (particularly desynchronization), etc.

Goal 1: Effects of attention and semantic processing

Assessing how attentional and semantic processes are modulated by spaced and massed presentation is central to the deficient processing theory. The present understanding is that an involuntary decrease in stimulus processing occurs for repetitions of recently encountered (massed) items, while this does not occur for spaced repetitions.

Under the deficient processing hypothesis, massed repetitions should involve decreases in attentional processes. Because early ERP components have been related to attentional processing (Luck, Woodman, & Vogel, 2000), these may show spacing effects. The visual N1 ERP component (early negative occipitoparietal peak) shows effects of selective attention (Klimesch et al., 2004) particularly during discrimination tasks (Vogel & Luck, 2000), and is related to increased visual analysis (Curran, Tanaka, & Weiskopf, 2002). It also shows effects of lexical and semantic processing (Proverbio & Adorni, 2009). It does not typically show subsequent memory effects (e.g., Curran et al., 2002; Duarte, Ranganath, Trujillo, & Knight, 2006; Duarte, Ranganath, Winward, Hayward, & Knight, 2004), and may act like an early attentional gating mechanism and attenuate for massed repetitions.

The analysis of neural oscillations has become an important tool for cognitive neuroscientists (for reviews, see Hanslmayr & Staudigl, 2014; Nyhus & Curran, 2010). Oscillatory desynchronization (decrease in power) in the lower alpha band (8–10 Hz; widespread) is related to increased attention (Klimesch, 1999; Klimesch, Sauseng, & Hanslmayr, 2007; Pfurtscheller & Lopes da Silva, 1999). Because deficient processing occurs for massed items, we would expect lower alpha to show more power (less desynchronization) for massed than spaced. It should be noted that the functional interpretation of lower alpha is generally less clear than for other bands (Klimesch et al., 2007).

Another idea tied to deficient processing is priming, specifically semantic (Challis, 1993) and perceptual priming (Mammarella et al., 2002; Russo et al., 1998). A primed and

still-active representation during a massed repetition will require less activation of semantic or perceptual features compared to spaced repetitions, and thus less processing will occur. In repetition paradigms the N400 ERP component (negative central peak) is associated with semantic priming and processing (Olichney et al., 2000; Van Strien et al., 2007). A more negative N400 is associated with more semantic unexpectedness. Voltage for immediate repetitions is attenuated compared to initial presentations, and voltages becomes more negative as lag increases (Kim, Kim, & Kwon, 2001); this shows that spaced repetitions elicit semantic activation processes whereas this does not occur for massed repetitions when the information is still in working memory (Van Strien et al., 2007). We would expect this pattern under deficient processing.

A frontal effect called the FN400 (similar to but different from the N400) is related to recognition memory, specifically in relation to whether this is familiar (i.e., old or new; the component attenuates for old items) (Curran, 2000; Mecklinger, 2006; Rugg & Curran, 2007). The FN400 is unlikely to be affected by attentional fluctuations during encoding (Curran, 2004) and should simply differentiate old/new recognition. Since participants are asked to make semantic associations in the present experiments, and because prior work has been done with the N400 in terms of stimulus repetition paradigms, we are going to interpret activity around 400 ms in terms of semantic processing.

For oscillatory effects, upper alpha (11–12 Hz; posterior) desynchronization (decrease in power) is related to the reactivation of semantic information from long-term memory (Klimesch, 1999; Klimesch, Schack, & Sauseng, 2005). Decreases in power in the lower beta band (13–21 Hz; central and temporal) are similarly associated with the semantic processing of to-be-remembered items (Fellner, Bäuml, & Hanslmayr, 2013; Hanslmayr, Staudigl, & Fellner, 2012; Hanslmayr et al., 2011). If these bands reflect retrieving information from memory, we would expect to see less power in both for massed compared to spaced because the information already exists in working memory. However, if the power decreases reflect the processing of semantic information after retrieval, both massed

and spaced should show desynchronization, and massed repetitions may actually show an earlier onset because the information can be accessed faster.

Goal 2: Effects of memory retrieval and encoding

If attention and semantic processing are affected by study repetition lag, it follows that memory processes may also show effects. This goal can address all three theories, but provides a particularly important assessment of study-phase retrieval.

The parietal old/new effect (late positive peak, also sometimes called the late positive component or LPC) is an ERP component that indexes conscious recollection. Its amplitude correlates with the subjective amount of retrieved information (Vilberg, Moosavi, & Rugg, 2006; Wilding, 2000; Wilding & Rugg, 1996). The LPC is also seen in repetition experiments (Olichney et al., 2000; Van Strien et al., 2007), and is linked to successful conscious retrieval of an item's prior presentation. Under deficient processing, there should be a larger effect for massed than spaced repetitions relative to new items due to perceived memory strength. On the other hand, study-phase retrieval requires episodic retrieval during a spaced repetition while deficient processing and contextual variability do not. Because spaced repetitions need to be retrieved from long-term memory but massed do not, if the LPC indexes retrieval then study-phase retrieval theory might predict a larger effect for spaced repetitions than for massed. However, we do not expect this to be the case because of prior stimulus repetition research that showed a larger effect for massed items.

Theta power (4–7 Hz; frontal, temporal, and parietal) is related to memory formation and retrieval, particularly in medial temporal lobe regions (Klimesch, 1999; Klimesch, Doppelmayr, Russegger, & Pachinger, 1996; Klimesch et al., 2006; Long, Burke, & Kahana, 2013; Sederberg, Kahana, Howard, Donner, & Madsen, 2003; for a review, see Mitchell, McNaughton, Flanagan, & Kirk, 2008). It is also thought to reflect item–context binding (Hanslmayr, Spitzer, & Bäuml, 2009; Hanslmayr et al., 2011; Staudigl & Hanslmayr, 2013; Summerfield & Mangels, 2005). Theta power should increase for spaced compared to

massed repetitions, but for different reasons under each hypotheses. Under deficient processing, theta is decreased for massed repetitions simply because the item is not being retrieved or re-encoded well. Under both contextual variability and study-phase retrieval, theta would increase for spaced repetitions because the intervening context (and the prior presentation in the latter case) is also encoded (new information, item–context binding). However, there is a difference between these theories: given that a repetition is properly re-encoded, in comparison to the initially encoded memory (Presentation 1), the “contents” of the two encoding events will be more similar under study-phase retrieval and more variable under contextual. This brings us to the next goal.

Goal 3: Memory reinstatement and contextual variability assessed via neural similarity

We do not just want to know about attention, the extent of semantic processing, and memory strength; we also want to investigate the contents of memory and whether it evolves across study repetitions. This goal assesses whether the similarity of neural activity for an initial presentation and repetition is correlated with subsequent memory performance, and whether this similarity is modulated by spacing. These assessments will bear on both study-phase retrieval and contextual variability. This can be tested both as a main effect of similarity (“Does greater similarity or greater variability in neural activations during encoding lead to better subsequent memory?”) and as an interaction with spacing (“Do spaced and massed repetitions benefit from greater similarity or greater variability during encoding? Are there differences?”).

Although each theory predicts better subsequent memory performance (recognition, recall, etc.) for spaced compared to massed learning (except at very long retention intervals) and naturally includes encoding mechanisms as reasons for the effect, not all implicate processing at the time of test as having an impact on memory performance. The similarity between an item’s study repetitions and its subsequent memory test event is a

meaningful comparison for contextual variability and study-phase retrieval. For a spaced item, encoding variability would predict that the test is similar to only one of the study presentations, while it would likely be similar to both under study-phase retrieval. Comparisons for massed items would be more difficult to interpret since context would not have drifted much.

There are different ways to measure the similarity of neural activity between individual events. For example, Representational Similarity Analysis (RSA; Kriegeskorte, Mur, & Bandettini, 2008) has been used in the fMRI literature recently (e.g., Xue et al., 2010) but has hardly been applied to EEG (e.g., Groen, Ghebreab, Lamme, & Scholte, 2012; Su, Fonteneau, Marslen-Wilson, & Kriegeskorte, 2012) and has never been used in a memory experiment. Other multivariate analyses have been used in electrocorticography (ECoG, or intracranial EEG) in relation to contextual drift (e.g., Manning et al., 2011), and would likely be suitable if modified appropriately. Regardless of the method used, a measure of neural similarity will help assess the nature of neural representations detectable at the scalp. A challenge of this goal is that it is difficult to know whether similarity measures are comparing item features, contextual features, the currently engaged mechanisms, or some combination of these; this analysis would benefit from separating item and context features in neural representations.

Summary

The overarching goal of this proposal is to assess the major hypotheses for why the spacing effect occurs by examining data from experiments that capture this effect. We recognize that we are relying on reverse inference to test these psychological theories of the spacing effect (Poldrack, 2006; Poldrack & Wagner, 2004): patterns of neural activity are used to make assumptions about active cognitive processes, as related to prior research. Since there is so little research on the EEG correlates of the spacing effect, reverse inference provides an initial direction for our analyses. To briefly recap the factors that

likely influence each theory, deficient processing emphasizes attention and semantic processing, contextual variability emphasizes contextual drift and study–test matching, and study-phase retrieval emphasizes episodic retrieval of the prior presentation during a repetition. We expect that both theory- and data-driven analyses of ERPs, oscillatory power, single trials, and study–study and study–test neural similarity will support or challenge the theories, and will provide insight into the cognitive underpinnings of the spacing effect.

Experiment 1 involved a paired associates memorization task in which participants studied word–image pairs at two points in time in either a spaced or a massed fashion. After a brief distractor task, a cued recall test was given where participants were required to remember the word originally paired with each image. ERP and oscillatory effects were used to assess how attention, semantic processing, and memory retrieval and encoding mechanisms operate under spaced and massed learning and as modulated by subsequent memory. Neural similarity was performed via dimensionality reduction techniques to attempt to understand memory content and contextual reinstatement. Experiment 2 was an extension run using additional study repetition lags and used a similar design as well as similar analyses.

General Research Design

Method

Approximately 40 undergraduate students at the University of Colorado Boulder were recruited for each of two experiments. In EEG sessions, participants were either given course credit (**AH: How many?**) or paid \$15 per hour, and all experiments lasted approximately 2.5 hours. All research was conducted under the guidelines for human studies research at the University of Colorado Boulder. The method for both experiments is nearly identical (random stimulus assignment, hand counterbalancing, EEG recording and processing, analysis, etc.).

EEG Recordings and Analysis

EEG recordings provide a fine-grained time course of the electrical activity of neurons, on the order of milliseconds, which is important for determining when neural processes occur with respect to behavioral responses. Event-related potentials and average oscillatory power were used for analyses, as well as single-trial data.

Experiment 1

This experiment provides an investigation into how neural activity during paired associate learning changes as a function of massed or spaced practice.

Method

Participants. Thirty-seven University of Colorado Boulder undergraduates participated in the experiment for either course credit ($n = 17$) or payment of \$15 per hour ($n = 20$) (ages 18–26, $M = 20.5$; 13 female). All participants were right-handed native-English speakers and had normal or corrected-to-normal vision. Informed consent was obtained from each participant, and the study conformed to the Institutional Review Board guidelines.

Materials. The experimental stimuli were randomly selected from 1521 common nouns (the PEERS word pool¹) and 832 images (two categories: 371 face images and 461 living room scenes). Face images were shoulder-up photographs taken in front of an off-white background with the center of the face generally in the center of the image (Phillips, Moon, Rizvi, & Rauss, 2000). Scene images were photographs taken from the SUN image database within the “Living Room” category (Xiao, Hays, Ehinger, Oliva, & Torralba, 2010). Words were presented in Courier font (size 24) and all images were cropped to be the same size (480 × 320 pixels). Stimuli were presented on a 17-in flat-panel display with a resolution of 1024 × 768 (60 Hz frame rate) placed 1 m in front of the

¹<http://memory.psych.upenn.edu>

participants. All portions of the display not occupied by stimuli or text were filled with gray pixels.

The experiment was programmed in MATLAB (versions R2012b and R2014a; The MathWorks, Inc., Natick, MA) using our experimental framework² and was presented using Psychtoolbox (Brainard, 1997).

Design. Experiment 1 consisted of six blocks of four experimental phases (Figure 1): exposure, study, distractor, test. The session, including application of the electrode net and running in the task, lasted approximately 2.5 hours. Stimuli were randomly shuffled prior to creating the list for each phase at the beginning of the session. The study phase contained the conditions that were manipulated within subjects, namely the viewing of spaced and massed paired associates.

Procedure. An electrode net was applied to each participant's head, and the session began with a shortened practice version of the experiment to familiarize participants with the study and test procedures (two spaced, two massed, and two single presentation items, with a lag of 4 items between spaced presentations; two new images were included at test).

In the exposure phase, participants viewed the 50 images (half faces and half scenes, randomly intermixed) that they would subsequently see on the study list and rated each on a four-point "appealing" scale: very appealing, somewhat appealing, somewhat unappealing, and very unappealing. Only the images from the upcoming study period were presented; the words were not shown. The keys D, F, J, and K were used to make the response, and the scale-to-keyboard mapping was counterbalanced across participants. An image denoting the key-response mapping was shown at the bottom of the screen at all times, but participants were encouraged to memorize the keys so they could keep their eyes on the fixation cross at the center of the screen. On each trial, a cross was shown for 1.0–1.2 s (jittered), then the cross and image were shown for 1.0 s, after which the cross

²<https://github.com/warmlogic/expertTrain>

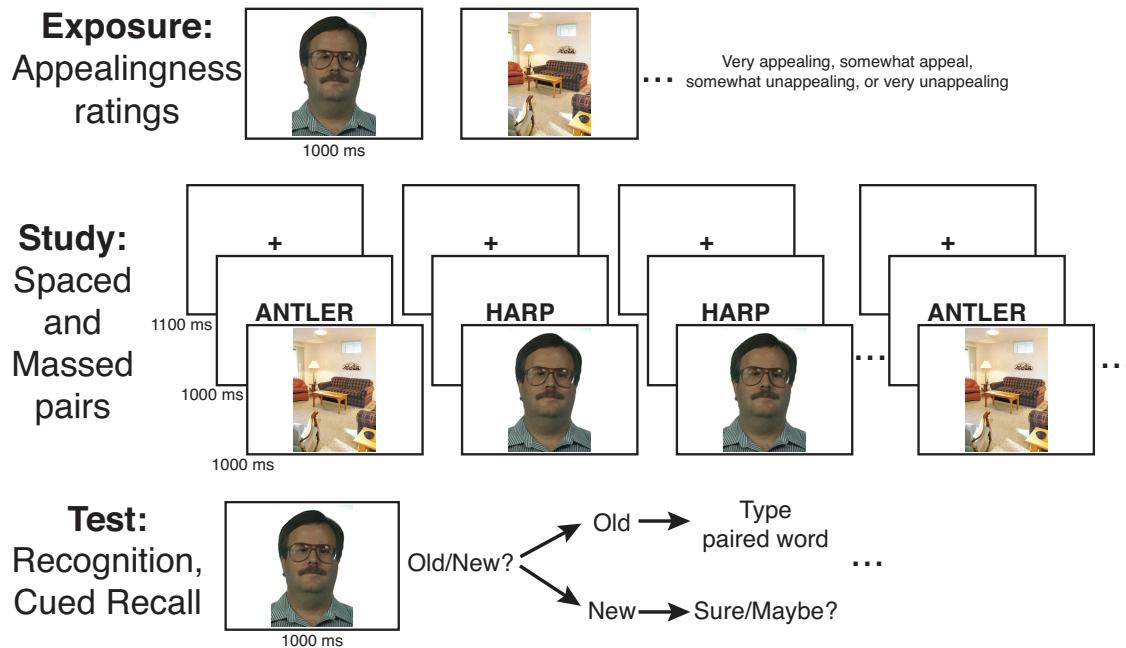


Figure 1. Experiment 1: Exposure, study, and test phases

changed to a question mark prompting participants to make a response. Participants were allowed to respond during the initial 1.0 s image presentation; if this occurred, the image stayed on screen for a total of 1.0 s. If they waited longer than 1.0 s and the cross changed to a question mark, the image remained on screen until a response was made or 3.0 s passed. No more than three images from the same category could occur in a row. This phase lasted approximately 3 min.

In the study phase, participants viewed 50 word–image pairs and were asked to think of a relationship between them or to make up a story pairing them. They were told that a subsequent test would require them to remember the word associated with each picture, but they were not told that some pairs are repeated. For each of the two image categories there were seven two-presentation spaced pairs, seven two-presentation massed pairs, seven pairs presented only once, and four additional single-presentation buffers (two at the beginning of the list and two at the end). Only images from the spaced and massed items were included on the test list. Spaced items were presented at a lag of 12 (12 intervening

pairs between presentations 1 and 2), and massed items were presented at a lag of zero. On each trial, a fixation cross appeared for 1.0–1.2 s (jittered), then the word was presented first for 1.0 s followed immediately by the image for 1.0 s. No more than three images from the same category could occur in a row, and no more than two trials with the same lag (including single-presentation pairs) could occur in a row. Each study phase lasted approximately 5 min.

In the distractor phase, participants answered simple math problems of the format $A+B+C=?$ for either 2 min or until they answered 60 problems, whichever came first. They typed their responses with the keyboard. Different tones occurred for correct and incorrect answers, and mean accuracy and response time was reported to the participant at the end of the phase.

Finally, in the test phase, participants performed recognition and cued recall tasks. Twenty-eight old images (seven spaced and seven massed from each category) and 14 new images (seven lures from each category) were mixed together and presented one at a time, at which point participants made two responses. First, they had to decide whether the image was studied earlier (“old”) or had not been seen before (“new”) using the F and J keys (counterbalanced). If they answered “old”, they saw ??????? below the image and had to type the word previously paired with the image; they could pass if they could not remember the word. If they answered “new”, they either said that they were “sure” it was new or it was “maybe” new using the F and J keys (counterbalanced); this confidence judgment was used so the same number of responses occurred for both “old” and “new” items. An image showing the key-response mapping was shown at the bottom of the screen when appropriate, but participants were encouraged to memorize the keys so they could keep their eyes fixated on the cross. On each trial, a fixation cross appeared for 1.0–1.2 s (jittered) and the image was shown for 1.0 s, at which point the cross turned to a question mark and participants were asked to make their initial recognition response. With lures mixed in, no more than four images from the same category could occur in a row.

Importantly, test images were presented in a sequence similar to the study order. To construct the test list, the positions of the second presentations of study stimuli were divided into five contiguous groups and each group was randomly shuffled. This was done to approximately preserve a similar amount of time between the second presentation and the test across all “old” stimuli. Each test phase lasted approximately 4 to 5 min.

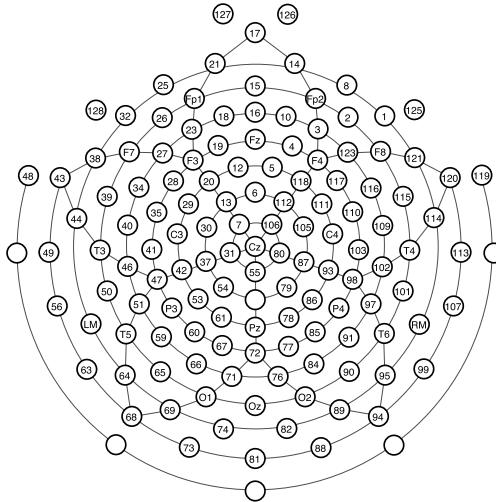


Figure 2. The 128-channel HydroCel Geodesic Sensor NetTM used to measure the EEG. In this top-down schematic the participant’s nose is toward the front.

Electrophysiological recordings and data processing. A 128-channel HydroCel Geodesic Sensor NetTM (GSN 200, v. 2.1; Tucker, 1993) was used to measure the EEG at the scalp using a central vertex reference (Cz) with a sampling rate of 250 Hz and a low-pass hardware filter at 100 Hz (see Figure 2). The net was connected to an AC-coupled, high-input impedance amplifier (300 MΩ, Net AmpsTM; Electrical Geodesics, Inc., Eugene, OR) and recordings were made using the Net Station application. The electrodes were adjusted until impedance measurements were less than 40 kΩ.

All data processing steps and analyses were done in MATLAB using in-house scripts³ and the FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011). A high-pass filter at 0.1 Hz, low-pass filter at 100 Hz, and a notch filter from 59–61 Hz were applied to the

³<https://github.com/warmlogic/mat-mvm>

data. Study and test trials were epoched into 3000 ms segments, 1 s before the onset of each stimulus and 2 s after. Artifact detection was used to reject particularly noisy epochs, as well as those that exceed an amplitude of $\pm 100 \mu\text{V}$. The data were referenced to the average of all channels and individual trials were baseline corrected relative to -200 ms to 0 ms.

We would not expect differences in neural activity between the initial presentations of spaced and massed items, as the locus of the spacing effect occurs after this point. There may exist subsequent memory effects here, though it would be difficult to know whether neural activity during the first presentation is the reason for this effect (e.g., perhaps a subsequently remembered item was encoded poorly on the first presentation and very well on the second presentation). ERP analyses included these initial presentations in analyses as a baseline, but time–frequency analyses focus on the second presentation (the repetition) and show the single-presentation stimuli in data plots. The repetition (second presentation) is therefore the critical part of the trial to analyze, as this is where the massed and spaced manipulation occurs, and plots will focus on the repetition. The first presentation is included in the analysis to see whether activity changes differently across repetitions for massed and spaced items (the ANOVA factor of presentation).

Results

Thirty-one participants were included in behavioral analyses. Fourteen participants were excluded from ERP and time–frequency analyses because they either did not perform the task properly ($n = 1$, completely excluded) or had fewer than 10 artifact-free trials in any of the main trial conditions ($n = 13$; four had extremely low trial counts and were also excluded from behavioral analyses), leaving twenty-three participants in EEG analyses. Similarity analyses included the twenty-eight participants who had six or more artifact-free pairs of initial presentation–repetition image trials.

All analyses contingent on subsequent memory are split by whether words were

recalled or forgotten after the image was correctly recognized as being old. Significant results are reported, and unreported results can be assumed to not be significant. When an ANOVA contains a factor with more than two levels, the reported values are adjusted for violations of assumptions of sphericity using the Greenhouse-Geisser procedure (Greenhouse & Geisser, 1959) even if the factors did not violate Mauchly's test of sphericity.

Behavioral results. On average, scenes were rated as more appealing compared to faces ($M = 2.99$ vs $M = 2.01$) [$t(30) = 9.13, p = 3.6e^{-10}$]. The average response times during the exposure/rating phase was faster for faces (1027 ms) than scenes (1115 ms) [$t(30) = 3.62, p = .0011$]. Because stimuli were presented for 1000 ms, participants had an overall tendency to respond after image offset; this is simply to note that attention is likely paid to the stimulus throughout its presentation, which is relevant to using these trials to train a classifier to discriminate between EEG activity related to faces and scenes.

For the test phase, a two-way repeated measures ANOVA was run on image recognition discrimination (d') with factors of spacing and image category. There was a main effect of spacing [$F(1, 30) = 17.4, p = .00024, MSE = 0.0756$] such that spaced images ($d' = 2.95$) were recognized better than massed images ($d' = 2.74$), and a main effect of image category [$F(1, 30) = 104, p = 3.05e^{-11}, MSE = 0.224$] such that faces ($d' = 3.32$) were recognized better than scenes ($d' = 2.37$). An ANOVA with the same factors was run on cued recall hit rate (for old items called “old”). There was only a main effect of spacing [$F(1, 30) = 81.8, p = 4.51e^{-10}$] such that spaced words ($M = 49.8\%$) were recalled better than massed words ($M = 36.5\%$). Words paired with faces and scenes were recalled at the same rate (faces: $M = 43.7\%$; scenes: $M = 42.5\%$). Thus, there are clear spacing effects for both recognition and recall.

ERP results. ERP analyses were performed on 40 Hz low-pass filtered data using repeated measures ANOVAs; pairwise comparisons were made with t -tests. Peak electrodes and latencies for the ERP effects were found by collapsing all word presentation events

together (using grand averages), finding the electrode with the peak voltage within the effect time ranges, and then locating the peak latency using that electrode and its immediate neighbors. The peak electrodes had to show typical effect patterns, and ended up being near the electrodes used by Van Strien et al. (2007): Cz for the N400 and a parietal electrode just to the right of Pz (electrode 77) for the LPC effect. The N400 peaked at 372 ms (Figure 4). The LPC peaked at 596 ms (Figure 5). For visual N1, the electrode had to show negative peaks between 150 and 250 ms and it should have precedence in the literature. Electrode 58 (T5) peaked at 172 ms (Figure 3). Analyses use these peak electrodes and neighbors; words during the study phase are analyzed because ERPs for images would likely be affected due to immediately following word presentations.

The average voltage and peak latency data used in statistical tests comparing massed and spaced conditions are computed for individual subjects using the electrode locations and time windows described above. Peak latency is determined by averaging the 10 time samples with the largest voltage, and voltage is averaged across the appropriate sized time window at that peak time point. Three-way ANOVAs with factors of spacing (spaced and massed), presentation (1/new and 2/old), and subsequent memory (recalled and forgotten words; all trials were subsequent recognition hits) were performed. Single presentations items were not included because they were not tested, but presentation 1 is analogous to a single presentation item.

Since the N400 and LPC have precedent in the repetition literature, we analyzed these components for semantic processing and memory effects, and analyzed the visual N1 for attentional effects.

If attention is modulated by spacing, early ERP components may show effects. The visual N1 typically shows effects of selective attention, making this component particularly relevant to deficient processing. A three-way ANOVA with factors of spacing, presentation, and subsequent memory was performed. A crossover pattern was borne out in the significant three-way interaction [$F(1, 22) = 10.5, p < .005$] that showed spacing and

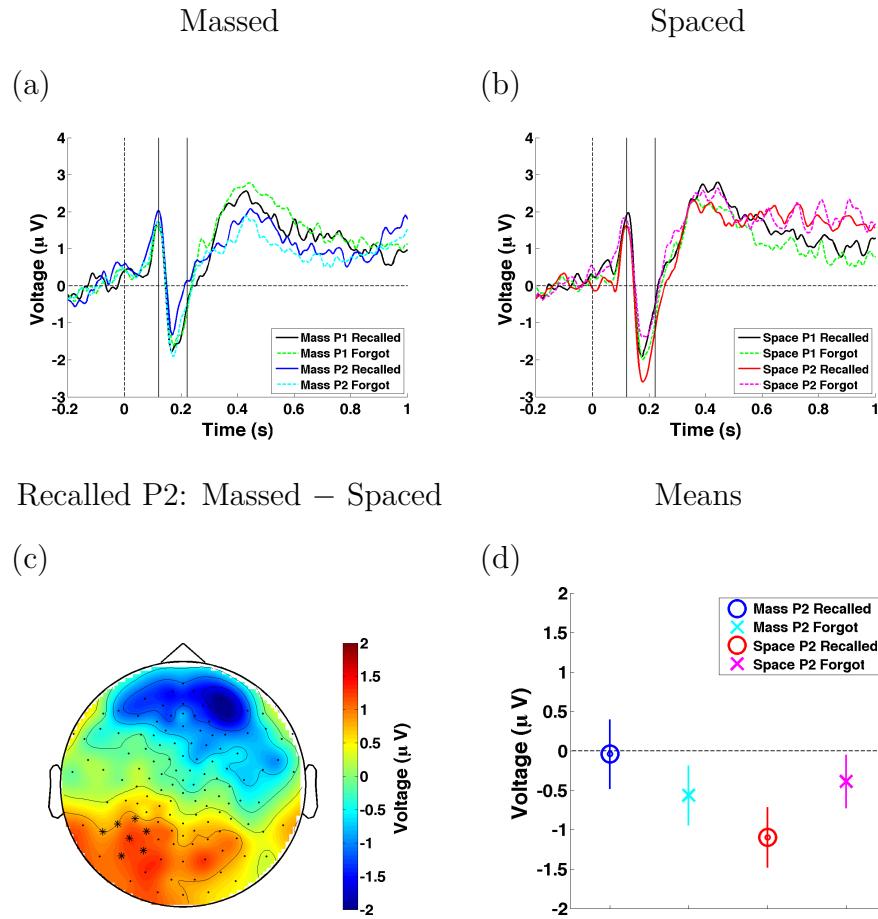


Figure 3. N1 to words at electrode 58 (T5) and neighbors, analyzed window 122–222 ms: (a) Massed ERPs; (b) spaced ERPs; (c) contrast between subsequently recalled massed *vs.* spaced Presentation 2 (P2) across time and electrodes (*); (d) analyzed means (error bars are SEM). The early negative peak is significantly larger for spaced compared to massed repetitions.

subsequent memory only had effects for repetitions, not for initial presentations. Recalled spaced repetitions ($M = -1.1 \mu\text{V}$) were more negative than forgotten spaced repetitions ($M = -0.39 \mu\text{V}$) [$t(22) = 2.73, p < .05$], recalled massed repetitions ($M = -0.04 \mu\text{V}$) [$t(22) = 4.37, p < .0005$], and (marginally) forgotten massed repetitions ($M = -0.56 \mu\text{V}$) [$t(22) = 2.039, p = .053$].

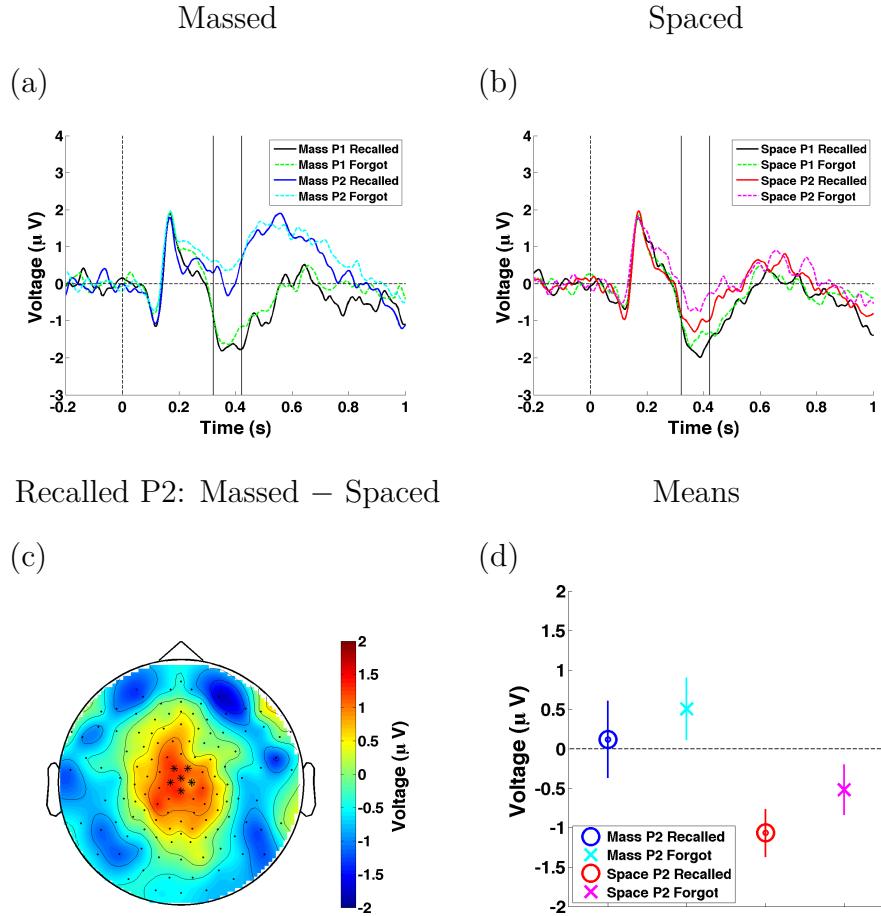


Figure 4. N400 to words at electrode Cz and neighbors, analyzed window 322–422 ms: (a) Massed ERPs; (b) spaced ERPs; (c) contrast between subsequently recalled massed *vs.* spaced Presentation 2 (P2) across time and electrodes (*); (d) analyzed means (error bars are SEM). The negative peak at 400 ms is significantly smaller for massed compared to spaced repetitions.

If the spacing effect results from differences in semantic priming and processing, the

N400 should show effects. For voltage, a significant spacing \times presentation interaction showed a graded pattern [$F(1, 22) = 12.4, p < .01$]: voltage becomes more negative from massed repetition to spaced repetition to first presentation [$p < .01$]. There were main effects of spacing [$F(1, 22) = 9.65, p = .00514$] and presentation [$F(1, 22) = 30.8, p = 1.42e^{-05}$]; spaced items were more negative, and repetitions were less negative. There was also a main effect of memory [$F(1, 22) = 4.47, p < .05$]: remembered items ($M = -1.06 \mu\text{V}$) were more negative than forgotten ones ($M = -0.71 \mu\text{V}$). There were no other interactions, but pairwise comparisons from the three-way interaction showed that, while there were no differences for the initial presentations, remembered spaced repetitions ($M = -1.07 \mu\text{V}$) were more negative than forgotten spaced repetitions ($M = -0.52 \mu\text{V}$) [$p < .05$] and both remembered ($M = 0.12 \mu\text{V}$) and forgotten ($M = 0.51 \mu\text{V}$) massed repetitions [$p < .01$]. No effects of latency were found.

The LPC is related to working memory in repetition paradigms, and may also show subsequent memory effects. For voltage, there was a significant interaction of spacing \times presentation [$F(1, 22) = 5.38, p < .05$]. Massed repetitions ($M = 4.02 \mu\text{V}$) were more positive than all other conditions (spaced repetition: $M = 3.2 \mu\text{V}$; massed initial: $M = 3.06 \mu\text{V}$ [$p < .05$]; marginal for spaced initial: $M = 3.27 \mu\text{V}$ [$p = .055$]). Additionally, there was a main effect of memory for voltage, showing a typical subsequent memory effect: recalled ($M = 3.62 \mu\text{V}$) were more positive than forgotten ($M = 3.16 \mu\text{V}$).

For latency, there was a significant interaction of spacing \times presentation [$F(1, 22) = 5.83, p < .05$]. Massed repetitions ($M = 564 \text{ ms}$) peaked earlier than all other conditions (spaced repetition: $M = 597 \text{ ms}$; massed initial: $M = 597 \text{ ms}$; spaced initial: $M = 587 \text{ ms}$ [$p < .05$]).

ERP discussion. The N1 showed that recalled spaced word repetitions received the most attention; they were more negative compared to the other conditions (repetitions of recalled massed words and forgotten spaced and massed words). Importantly, this implies that attentional processing affects subsequent memory differently for massed and

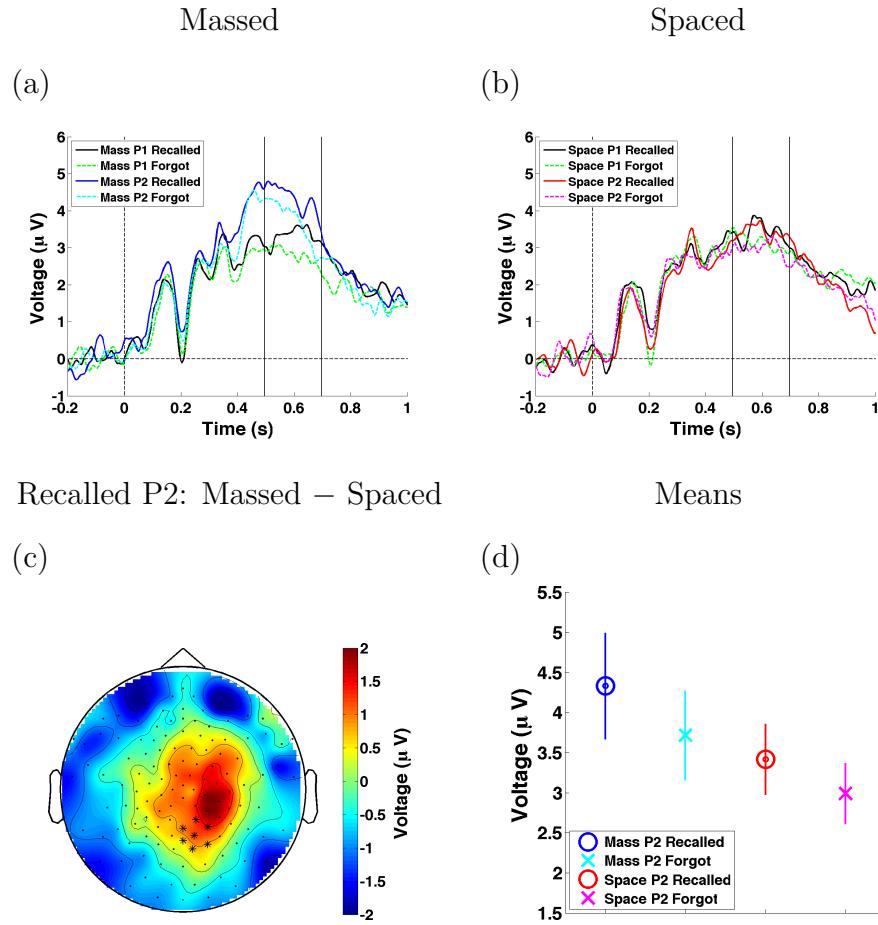


Figure 5. LPC to words at electrode 77 and neighbors, analyzed window 496–696 ms: (a) Massed ERPs; (b) spaced ERPs; (c) contrast between subsequently recalled massed *vs.* spaced Presentation 2 (P2) across time and electrodes (*); (d) analyzed means (error bars are SEM). The positive peak around 600 ms is significantly larger for massed compared to spaced repetitions.

spaced items. Massed items are at a disadvantage compared to remembered spaced items, supporting the deficient processing hypothesis. Because remembered massed items are the least negative, in addition to attention there are likely other mechanisms that influence memory encoding.

The N400 is more negative when semantic processes are engaged to a greater extent. There was a typical repetition effect showing that voltage decreased with repetition lag, and this interacted with presentation (repetitions attenuate but more so for massed). This implies that semantic processing engages more for spaced than massed repetitions, but not as much as initial presentations. Because the significant effect of subsequent memory showed that remembered items have greater negative amplitudes, this indicates that more semantic processing occurs for remembered items. Spaced items seem to have an overall processing advantage, or perhaps massed items have an overall disadvantage due to their attenuated N400. This is all in line with the semantic activation hypothesis of Challis (1993) and the position taken by Van Strien et al. (2007), and therefore supports the deficient processing theory.

The typical interpretation of the LPC effect is that it is more positive during the retrieval of an item's prior presentation (Olichney et al., 2000; Van Strien et al., 2007). The present results show that massed repetitions have faster retrieval of the initial stimulus presentation compared to spaced repetitions, and that massed elicit this to a greater extent. In relation to the N400 results (semantic processing does not need to engage for primed representations), it seems possible that the LPC indexes the information that is in working memory. This result does not seem to directly support any of the theories, unless the match to working memory is an indicator for processing to disengage (deficient processing).

Time-frequency results. Spectral decomposition for time-frequency analyses (no low-pass filter) used a set of 38 Morlet wavelets that were logarithmically spaced from 3 to 80 Hz; each wavelet had a width of 6 cycles. Trials were down-sampled to 50 Hz after calculating power and were z-transformed relative to the distribution of all word stimuli

with a reference time of -300 to -100 ms relative to stimulus onset. Only the pre-stimulus periods for words were used because the analogous reference time for images would be while words were on the screen. The following frequency bands were analyzed: theta (4.1 to 7.7 Hz); lower alpha (8.4 to 10.1 Hz); upper alpha (11 to 12 Hz); lower beta (13.1 to 20.5 Hz); upper beta (22.4 to 29.2 Hz); lower gamma (31.9 to 45.5 Hz); upper gamma (49.7 to 77.4 Hz).

Time-frequency differences were assessed using repeated measures ANOVAs due to the large number of factors, but because the effect topographies are not as well defined as in ERP analyses a cluster-based permutation test (Maris & Oostenveld, 2007) was used as the basis for electrode choice. Clustering was done by performing a *t*-test for conditions of interest within each time/electrode bin across subjects, followed by grouping together the adjacent bins which yielded a *p* value of less than .05. Significant differences between pairwise conditions (spaced/massed repetitions, subsequently recalled/forgotten; run separately for words and images) were calculated using a Monte Carlo-style permutation test of the summed *t*-values within a given cluster. Each observed cluster was subject to 500 random permutations of condition labels where its significance was estimated by the proportion of random permutations which yielded clusters that had a summed *t*-value as large or larger than the observed cluster. A given electrode for a given frequency band was included in the analysis if it showed a significant difference in at least two of the six pairwise contrasts. The resulting topographies largely agree with those reported in the memory and attention literature cited in the present paper.

Since oscillatory effects can spread out over time (especially at low frequencies), we analyzed images in addition to words. Because word and image stimuli are presented successively, we need to consider that different patterns may be expected during these to-be-associated stimuli for spaced and massed repetitions. During a repetition trial, there is the potential for both episodic memory, attentional processes, and semantic processes to occur, perhaps at the same time. Using reverse inference, these can be examined by

frequency band (theta, lower alpha, and upper alpha and lower beta, respectively).

Three-way ANOVAs with factors of spacing (spaced and massed), subsequent memory (recalled and forgotten), and time (0–500 ms and 500–1000 ms) were performed for word and image repetitions on power in the theta, lower alpha, upper alpha, and lower beta bands (eight ANOVAs). The two types of stimuli were analyzed separately because their time courses are not necessarily comparable. Only repetition events were analyzed.

(Why only analyze repetition events? Because including P1 would require slogging through so many stats that aren't that interesting. But I should look at them again. Or write, it was clear from ERP analyses that P2 is where the action is.)

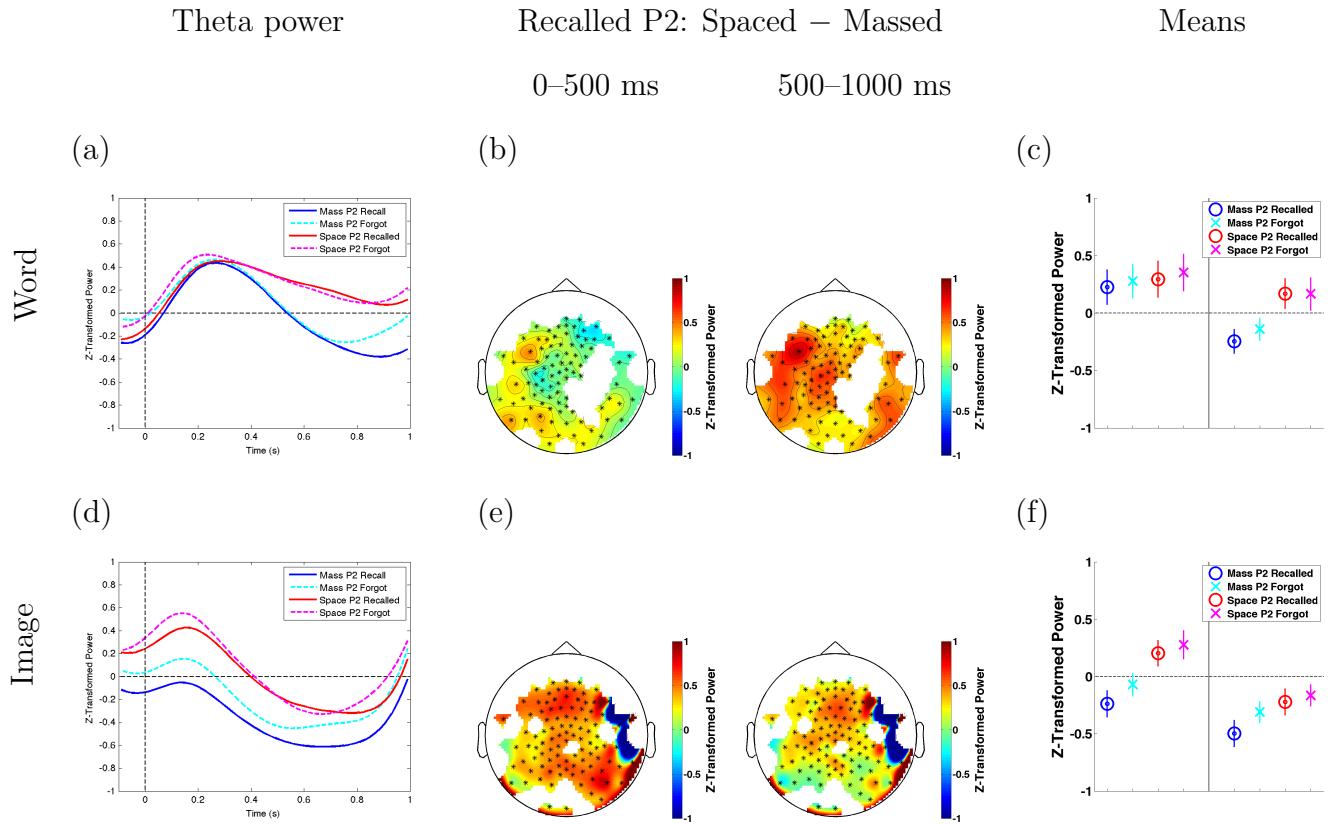


Figure 6. Theta power to words and images. (a) and (d) Grand averages; (b) and (e) contrast topographic plot between spaced and massed subsequently recalled trials displaying only the analyzed electrodes (*); (c) and (f) mean values for the two time windows (error bars are SEM).

Word, theta: Across 89 electrodes (Figure 6, top), theta showed a spacing \times time interaction [$F(1, 22) = 26.8, p = 3.43e^{-05}$] such that spaced words maintained synchrony across the time windows ($M = 0.341$ to $M = 0.163$) while massed repetitions showed a power decrease ($M = 0.267$ to $M = -0.204$); spaced had greater power than massed in the second time window. There were main effects of spacing [$F(1, 22) = 10.3, p = .00399$] and time [$F(1, 22) = 23.6, p = 7.4e^{-05}$] following the same patterns.

Image, theta: Across 99 electrodes (Figure 6, bottom), theta continued to show a spacing \times time interaction [$F(1, 22) = 6.76, p = .0163$] such that spaced images showed greater power than massed in the first time window ($M = 0.239$ vs. $M = -0.158$). Power dropped more for spaced than massed across the time windows: spaced (second window: $M = -0.193$) showed a difference of 0.432 while massed (second window: $M = -0.399$) showed a difference of 0.241. There were also main effects of spacing [$F(1, 22) = 31.2, p = 1.28e^{-05}$] and time [$F(1, 22) = 30.6, p = 1.46e^{-05}$] following the same patterns, as well as a main effect of memory [$F(1, 22) = 6.1, p = .0217$] showing that less power is associated with subsequent recall ($M = -0.189$ vs. $M = -0.067$).

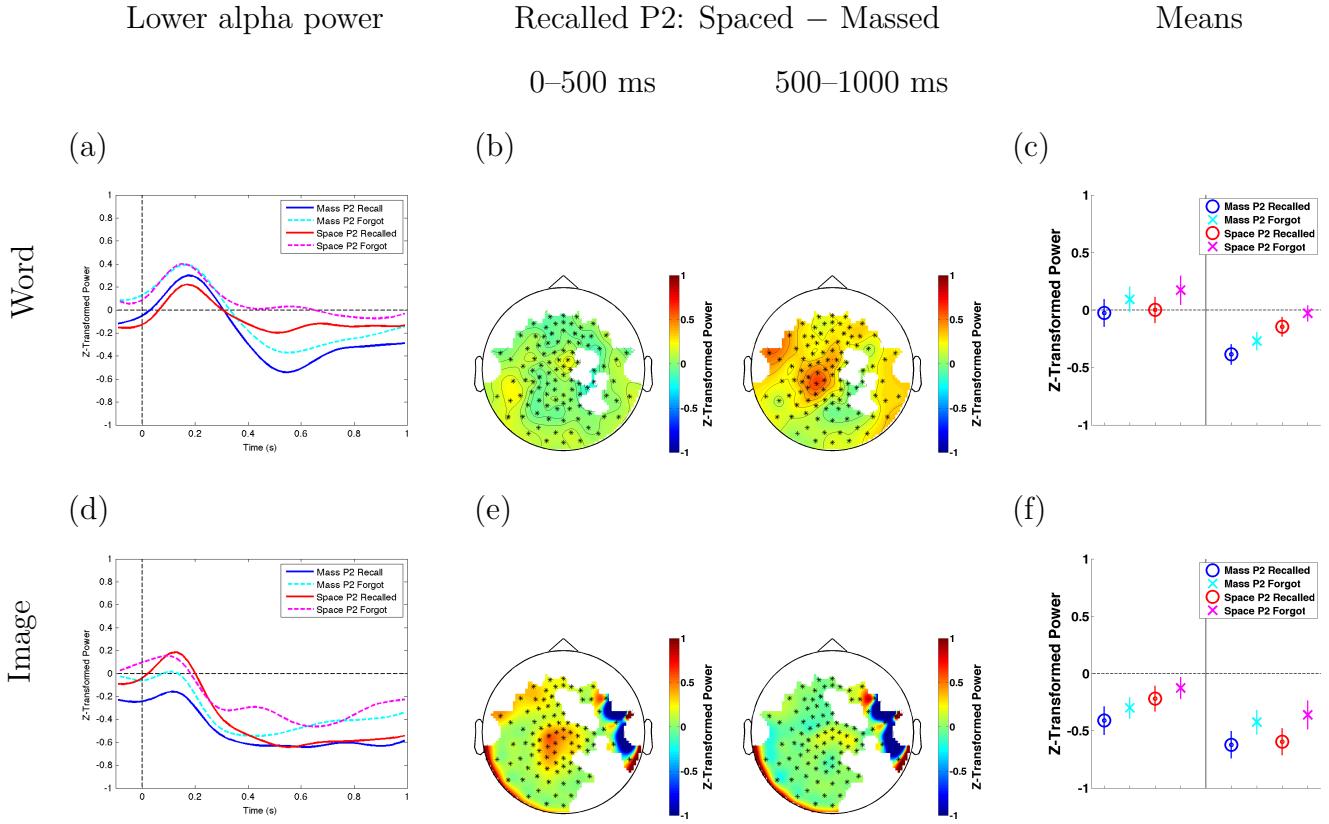


Figure 7. Lower alpha power to words and images. (a) and (d) Grand averages; (b) and (e) contrast topographic plot between spaced and massed subsequently recalled trials displaying only the analyzed electrodes (*); (c) and (f) mean values for the two time windows (error bars are SEM).

Word, lower alpha: Across 101 electrodes (Figure 7, top), lower alpha showed a spacing \times time interaction [$F(1, 22) = 8.77, p = .0072$] such that massed words showed decreased alpha power compared to spaced in the second time window ($M = -0.323$ vs. $M = -0.087$). There were also main effects of spacing [$F(1, 22) = 7.64, p = .0113$] (massed showed less power), subsequent memory [$F(1, 22) = 5.4, p = .0298$] (recalled words showed less power), and time [$F(1, 22) = 15.3, p = .00074$] (less power in the later time window).

Image, lower alpha: Across 89 electrodes (Figure 7, bottom), lower alpha for images showed the same results: a spacing \times time interaction [$F(1, 22) = 5.19, p = .0329$] such that

massed images had decreased power compared to spaced spaced in the first time window ($M = -0.352$ vs. $M = -0.183$) but not the second ($M = -0.533$ vs. $M = -0.497$). There were also the same main effects of spacing [$F(1, 22) = 4.34, p = .0491$] (massed showed less power), subsequent memory [$F(1, 22) = 12, p = .0022$] (recalled words showed less power), and time [$F(1, 22) = 21.4, p = .000131$] (less power in the later time window).

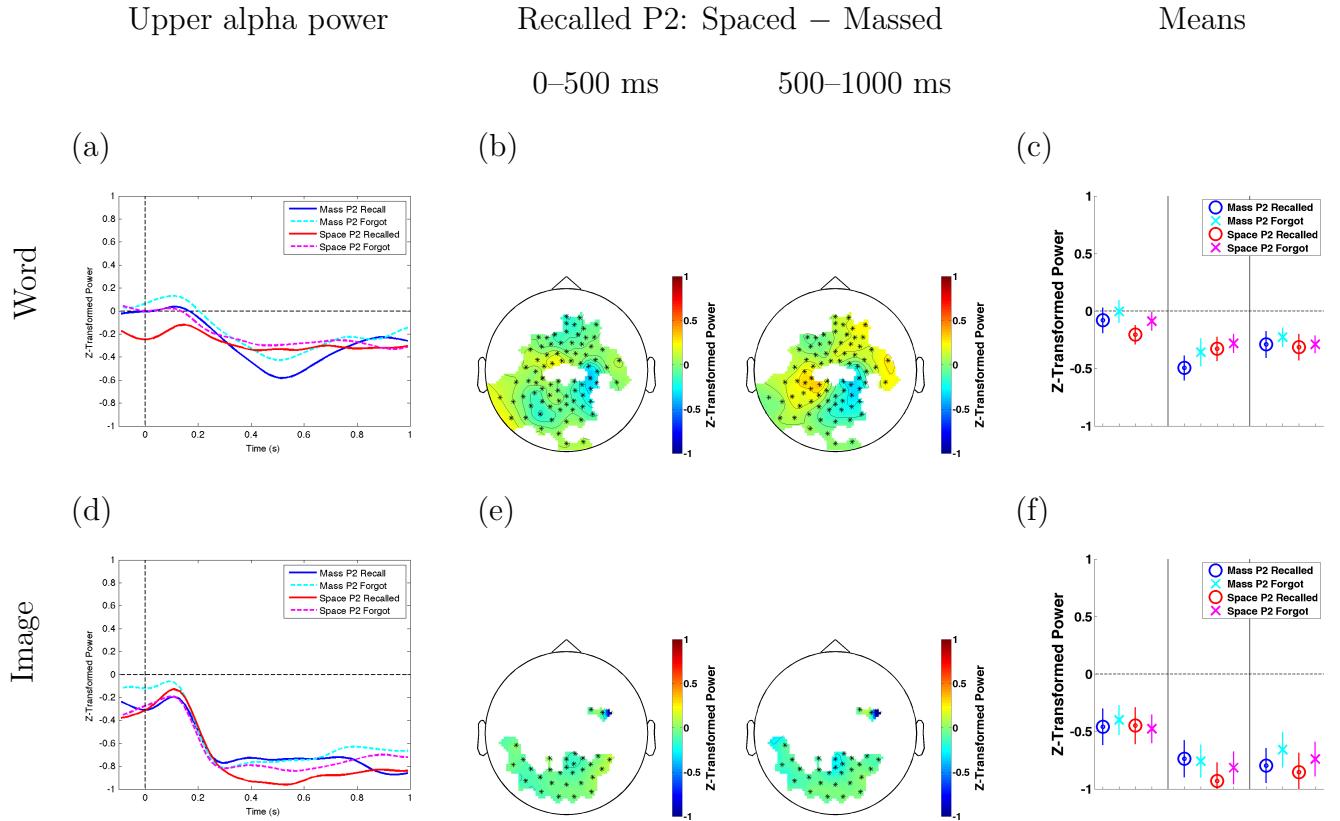


Figure 8. Upper alpha power to words and images. (a) and (d) Grand averages; (b) and (e) contrast topographic plot between spaced and massed subsequently recalled trials displaying only the analyzed electrodes (*); (c) and (f) mean values for the three time windows (error bars are SEM).

Word, upper alpha: Across 82 electrodes (Figure 8, top), upper alpha only showed a main effect of time for words [$F(1, 22) = 4.47, p = .0461$]; there was less power in the second time window than the first ($M = -0.309$ vs. $M = -0.183$). However, because the

data clearly show a negative peak for recalled massed repetitions near 500 ms we divided time into three successive windows. There was a robust spacing \times time interaction [$F(2, 44) = 7.46, p = .00377$]. Massed were more negative in the middle time window than in neighboring time windows [$p < .05$], and were more negative than spaced in the first and second time windows [$p < .05$].

Image, upper alpha: Across 30 electrodes (Figure 8, bottom), upper alpha showed main effects of spacing [$F(1, 22) = 4.88, p = .0379$] (spaced had less power) and time [$F(1, 22) = 21.2, p = .000138$] (less power in the later time window). Under the three time window ANOVA, there was also a significant three-way interaction [$F(2, 44) = 3.28, p = .05$]: recalled spaced repetitions in the middle time window were more negative than recalled massed repetitions in all time windows [$p < .005$], and recalled spaced repetitions in the late time window were more negative than the first two windows for massed [$p < .05$]. The same pattern was seen when comparing recalled spaced repetitions to forgotten massed repetitions [$p < .05$]. Additionally, recalled spaced repetitions were more negative in the middle time window and were more negative than forgotten spaced repetitions in the first and last time windows [$p < .05$].

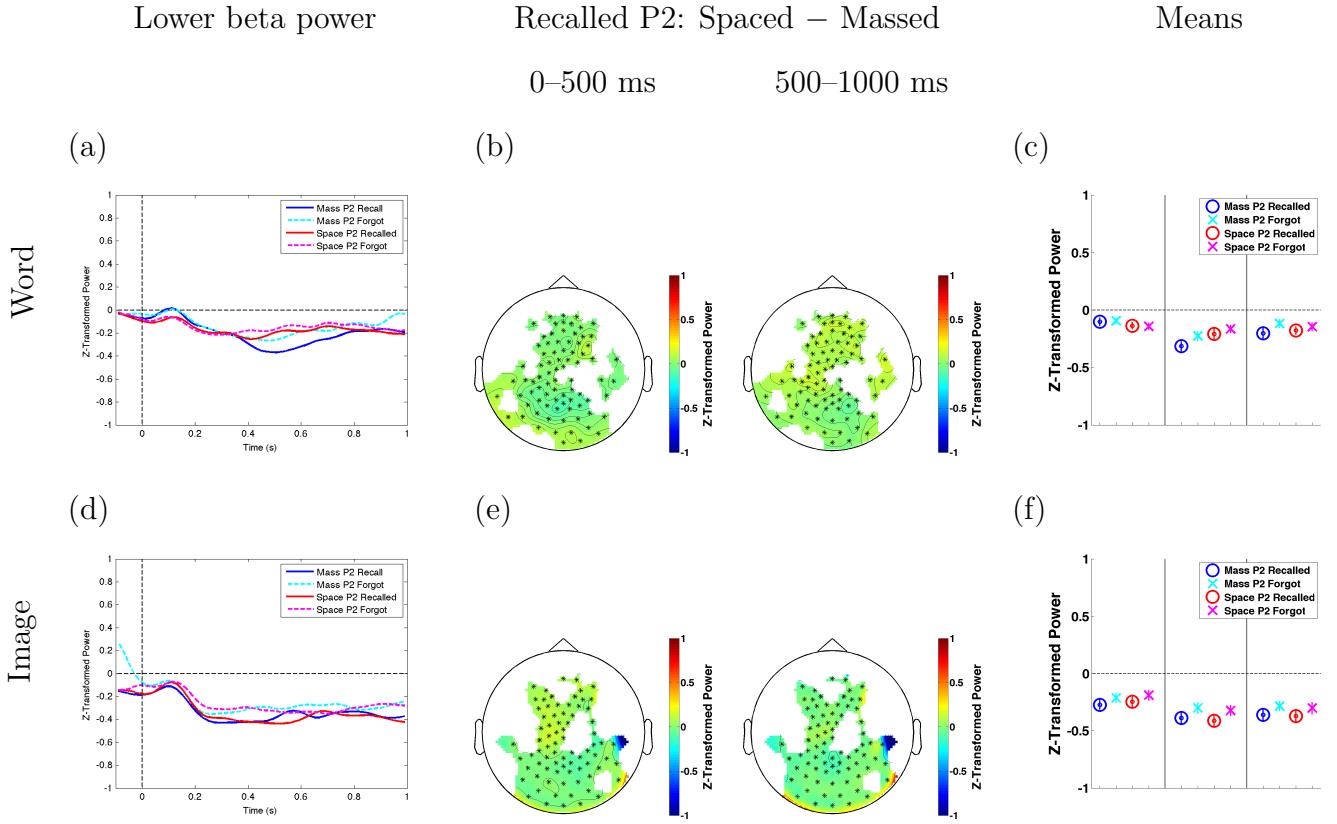


Figure 9. Lower beta power to words and images. (a) and (d) Grand averages; (b) and (e) contrast topographic plot between spaced and massed subsequently recalled trials displaying only the analyzed electrodes (*); (c) and (f) mean values for the three time windows (error bars are SEM).

Word, lower beta: Since lower beta oscillations showed a similar dip-and-rise pattern to upper alpha, we also used three time windows in these ANOVA. Across 81 electrodes (Figure 9, top), lower beta showed a spacing \times time interaction [$F(2, 44) = 9.89, p = .000453$]; massed decreased most in the middle time window [$p < .01$] but spaced showed no differences across time. There was also a marginal memory \times time interaction [$F(2, 44) = 2.91, p = .0725$]; power for both recalled and forgotten stimuli was lowest in the middle time window [$p < .05$], but was most negative for recalled [$p < .01$]. A main effect of time [$F(2, 44) = 12.9, p = 5.28e^{-05}$] and a marginal main effect of

subsequent memory that followed the same patterns [$F(1, 22) = 4.16, p = .0536$].

Image, lower beta: Across 78 electrodes (Figure 9, bottom), lower beta showed main effects of memory [$F(1, 22) = 20.2, p = .00018$] (recalled had a power decrease) and time [$F(2, 44) = 29.3, p = 1.14e^{-08}$] (less power in the middle time window).

Time-frequency discussion. Overall, there was higher theta power for spaced than massed repetitions during both words (late) and images (early). Under study-phase retrieval, spaced repetitions will naturally require retrieval from long-term memory, thereby needing to engage processes related to episodic memory. Since massed items are still primed and in working memory we would not expect these processes to engage. Greater theta power for spaced repetitions than massed items denotes that recollection processes are engaged, and this supports study-phase retrieval. Contextual variability does not necessarily require this retrieval, but both theories would posit that spaced items will be re-encoded with the evolved contextual state, and so theta should continue into the image presentation during processes that involve word–image binding (since participants were asked to link the stimuli). Thus, it seems that associative retrieval engages during words and the re-encoding of word–image associations (binding) engages during images, and this combination supports study-phase retrieval. The negative SME for images, driven by massed items, is interesting. Both positive and negative SME have been seen previously. Staudigl and Hanslmayr (2013) changed the direction of the effect by varying context: same context showed a positive SME, different context showed a negative SME. The present results only show the latter, but perhaps there is some type of contextual difference for massed repetitions.

The lower alpha band should correlate negatively with general attentional processes and should be widespread over the scalp. Deficient processing would predict increased alpha power for massed repetitions. We would also expect an effect of memory such that decreased power should be associated with better subsequent memory. Lower alpha showed a sharp decrease during massed words that continued through images compared to spaced

(going against the deficient processing prediction), as well as a main effect of memory. This result indicates that more attention gets allocated to massed items and to subsequently recalled items overall. In contrast to the visual N1 ERP component reported earlier, which is also related to attention, lower alpha does not show that massed repetitions are put at an attentional disadvantage; however, the timing difference between these effects implies that they are likely related to different mechanisms. Nonetheless, lower alpha shows a different pattern from our deficient processing predictions. Perhaps these effects follow the LPC and reflect attentional mechanisms accessing prior presentations of massed items more easily than spaced repetitions.

Effects in the upper alpha band and lower beta band should occur late during the word and into the image presentation while semantic processes are engaged (associating the word and the image). Because the semantic representation of massed items is still active, accessing this information may occur faster than for spaced items (like the LPC effect) but may not be processed as deeply. We would also expect an effect of subsequent memory such that trials with more semantic processing (decreased power) are remembered better. However, deficient processing would predict increased power, leading to decreased semantic processing of massed repetitions.

For upper alpha, we found a spacing \times time interaction after dividing power for words into three time windows (massed word repetitions desynchronized sooner and to a greater extent than spaced). This supports the idea that semantic information for massed repetitions is accessed more quickly than for spaced. Perhaps semantic information is quickly sought and retrieved for massed repetitions. Upper alpha for words quickly returns to near-baseline levels (meaning it is inhibited because it no longer needs to be accessed) and spaced repetitions decreased in power (desynchronize) more during the image, supporting a deeper semantic processing of spaced word–image pairs overall. Importantly, when considering three time windows for images the overall pattern in the three-way interaction showed that recalled spaced image repetitions were the most negative, denoting

that increased semantic processing leads to better subsequent memory for spaced trials.

Lower beta showed power decreases for massed words (mostly driven by the recalled trials), and a general subsequent memory effect for images (power decrease is associated with better memory). It seems that increased semantic processing (denoted by decreased power) helps memory overall, and massed trials get a quick semantic processing boost during word presentations but spaced are equally processed during the images. Upper alpha and lower beta power decreases therefore seem to be related to processing semantic information after retrieval, with alpha showing an advantage for spaced and beta correlating more with overall subsequent memory performance.

Across this range of frequency bands, our results show that spaced repetitions involve (a) more retrieval and encoding (theta) starting in the latter half of the word presentation, possibly reflecting the retrieval and encoding of word–image associations, as well as (b) more semantic processing (upper alpha) for remembered spaced repetitions during the image presentation, possibly reflecting the semantic link being made between the word and image.

Similarity results. While the ERP and time–frequency results reveal that massed representations are accessed more quickly but perhaps to a lesser extent semantically than spaced representations, the nature of this representation is still unclear. Are spaced repetitions remembered better due to essentially a repetition effect (in line with study-phase retrieval), or does temporocontextual drift play a role in encoding the repetition in a more variable manner (in line with contextual variability)?

EEG voltages during study image presentations were used to compute the neural similarity between each initial study presentation and its repetition. This same process was done separately for time–frequency oscillations using the following bands: theta, alpha, lower beta, upper beta, lower gamma, upper gamma. Images were used because this is when word–image binding should occur. Neural similarity between study repetitions was assessed using the method from Manning et al. (2011). All analyzed trials were subsequent

hits (correctly recognized as being old), and were divided by the factors of spacing at study (spaced or massed) and subsequent recall at test (correctly recalled or not). The analyzed electrodes were influenced by the regions where Manning et al. (2011) found context-related activity, but as this is a novel analysis the data were manually inspected and regions were chosen by hand (usually over occipital, temporal, and/or parietal regions). Each trial was split into five 200 ms windows (processed and analyzed separately) under the idea that different cognitive mechanisms may occur at different points in time and that these mechanisms may affect the similarity measurement.

Principal Components Analysis (PCA) was used for dimensionality reduction; for each subject, a three-dimensional matrix of voltage measurements (trials by electrodes by time samples) was reshaped into a two-dimensional matrix by unrolling electrodes and time within a trial. Similarly, a matrix with the additional dimension of frequency band was used when analyzing these data. For each time window, PCA was run on this two-dimensional matrix and the Kaiser criterion was used to choose the components that explained a substantial portion of the variance (eigenvalues > 1 ; Kaiser, 1960). Each retained component is a linear combination of the neural activity (voltage or power for each frequency band) across electrodes and time samples. Each trial then has a weight from each principal component, and together these weights yield the trial's feature vector. The similarity measurement is computed using the normalized dot product of a given item's repetitions (the cosine of the angle between the feature vectors). Finally, the between-trial similarity values for each participant (comparing each event with every other analyzed event, not just its repetition pair) are z-scored so they are in standard deviation units. Thus, a similarity value of zero means the representation is of average similarity compared to all events, and a positive or negative deviation from there means similarity increases or decreases relative to all events.

A three-way repeated measures ANOVA was run on the average voltage similarity values from left and right temporal regions with factors of spacing (spaced and massed),

subsequent memory (recalled and not recalled), and time (successive time bins). A main effect of spacing was found [$F(1, 27) = 29.8, p = 8.91e^{-06}$] such that spaced presentations ($M = 0.0777$) were more similar than massed ($M = -0.0886$), and a main effect of time was found [$F(4, 108) = 6.76, p = 8.68e^{-05}$] such that neural similarity decreased over time. This latter effect is explained by an interaction between spacing and time [$F(4, 108) = 9.58, p = 2.36e^{-06}$]. Here, spaced items kept a relatively consistent level of similarity across the time windows whereas massed items become dramatically dissimilar as time progressed. The three-way interaction was not significant [$F(4, 108) = 1.18, p = .323$] but the data are plotted in Figure 10.

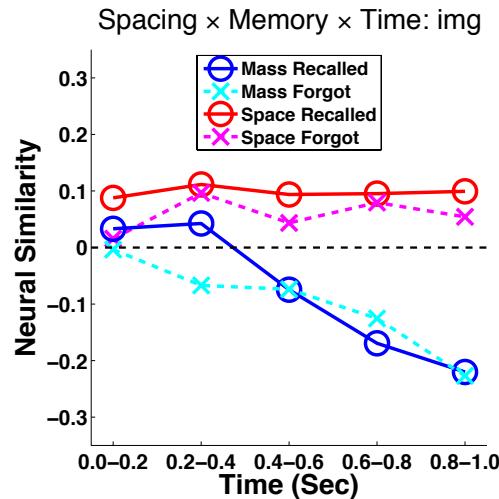


Figure 10. Similarity for voltage at left and right temporal sites during image repetitions: Interaction between spacing, memory, and time [n.s.].

The same three-way ANOVA was performed for time–frequency data over left and right parietal regions across all frequency bands. A significant effect of spacing was found [$F(1, 27) = 7.44, p = .0111$], but in the opposite direction of the voltage results: massed ($M = 0.318$) were more similar than spaced ($M = 0.243$). There was also a main effect of time [$F(4, 108) = 3.42, p = .0116$], which was driven by an interaction with subsequent memory [$F(4, 108) = 6.3, p = .000206$] such that recalled images showed an increase in similarity at the last time window ($M = 0.37$) compared to forgotten images ($M = 0.26$)

$[t(27) = 2.7614, p = .0102]$. Finally, the three-way interaction was marginal $[F(4, 108) = 2.42, p = .0535]$ and is plotted in Figure 11. The pattern shows that remembered items tend to increase in similarity in the second half of the trial while forgotten items tend to decrease; this increase is steeper for spaced compared to massed, though massed seem to receive a similarity boost earlier.

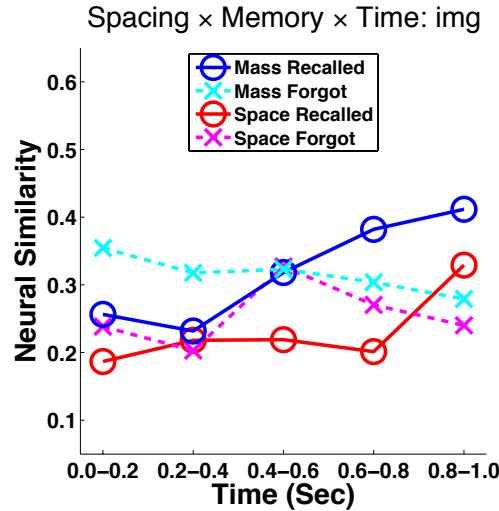


Figure 11. Similarity for oscillatory power at left and right parietal sites during image repetitions: Interaction between spacing, memory, and time [$p = .0535$].

Similarity discussion. It is clear that the way massed and spaced stimuli are processed and represented across their repetitions is different. Surprisingly, the patterns are different for voltage and time–frequency data. It is difficult to know exactly what a decrease in similarity means; perhaps it indicates a decrease in processing, or perhaps it indicates more variable processing. For voltage, it seems that spaced repetitions tend to induce a consistent representation across time (which might support the study-phase retrieval account) while massed repetitions become much more variable either because noise is added to the system (a possible explanation supporting deficient processing), they tend to induce a more variable representation (supporting contextual variability), or different neural/cognitive processes are engaged. The early attentional ERP results would seem to corroborate support for the deficient processing hypothesis, but only if ERPs to

words affect processing of the rest of the trial (including images).

For the time–frequency analysis, the increase in similarity leading to the subsequent memory effects supports study-phase retrieval (or the engagement of the same processes) for both massed and spaced repetitions, especially toward the end of the trial. No other spacing effect accounts seem to be supported with this analysis.

Experiment 1 Discussion

Behaviorally, participants showed a clear spacing effect for both recognition and recall, even using relatively short lags (compared to real-world learning).

It seems possible that memory effects might be relatively weak because subsequent memory is only contrasting subsequently recalled *vs.* forgotten; because every trial was a recognition hit, we can assume that at least the images were encoded at a reasonable level. It would be ideal to analyze the data for miss trials, but recognition accuracy was so good that there are very few trials.

Neural activity related to subsequent memory for spaced and massed repetitions is a critical factor to analyze in relation to the spacing effect. The three-way interactions between spacing, repetition, and memory were significant for N1 voltage and upper alpha power, and marginal for time–frequency similarity. Overall, this leads to the idea that increased attention for spaced items (as indexed by the N1) and semantic processing during word–image binding for spaced items (as indexed by upper alpha) benefits subsequent memory. Integration across the neural effects is discussed below. (TODO: Delete the last sentence and integrate these paragraphs more naturally.)

Early attentional mechanisms orient more to spaced repetitions than massed (N1 more negative for spaced), especially for those that are subsequently recalled. The N1 may be a signal to the system for when stimuli should receive additional processing (related to the N400 and upper alpha). In fact, using source localization, Proverbio and Adorni (2009) found that the N170 has neural generators in regions that support semantic processing

(BA10). This N1 difference supports deficient processing.

A more negative N400 has been found to correlate with both semantic processing and subsequent memory, though there is not always a memory effect (reviewed in Friedman & Johnson, 2000). We simply found that voltage was more negative for spaced repetitions compared to massed, and was most negative for initial presentations. This reflects that semantic processing decreases for massed repetitions, and also supports deficient processing. The main effect of memory for the N400 shows that subsequent memory is better when semantic processing is engaged to a greater extent during encoding. Matching these results overall, upper alpha showed the important interaction with memory such that remembered spaced repetitions had the largest power decrease. This is another sign that there is more semantic processing for remembered spaced items.

Our results support the idea that massed representations are accessed more quickly and to a greater extent on repetition trials than for spaced repetitions (LPC more positive for massed). Here, massed items are easily accessible because they are still in working memory, whereas spaced items need to be retrieved from long-term memory; this latter point is evident in the theta spacing main effect and interactions with time. However, because massed repetitions feel more familiar due to having greater memory strength, it seems that they are not subjected to additional semantic processing, as mentioned above.

In relation to the neural similarity of massed and spaced presentations (Figure 10), massed items decreased in similarity while spaced items maintained a consistent amount. Contextual variability predicts that context has not drifted between massed presentations, but this is not the effect we see. Deficient processing does predict this decrease in similarity. Another possibility for this pattern of results is the differential activation of neural processes across repetitions (e.g., the same noun is interpreted two different ways), but combined with the attention (N1) and semantic processing (N400) results, deficient processing seems more likely. For spaced items maintaining similar neural patterns, either the same memory representation is retrieved at the second presentations, the same

processes are engaged, or both of these occur. This can support study-phase retrieval, and deeply challenges contextual variability.

The combination of effects for spaced repetitions, from word–image binding (theta oscillation effects) to stable voltage similarity to increased power similarity, seems to support study-phase retrieval for these items that need to be retrieved from long-term memory, and does not yield support for contextual variability. This is because increased theta has been associated with increased episodic retrieval. Massed items, on the other hand, tend to be more variable; these EEG effects seem more in line with deficient processing than contextual variability.

Experiment 2: Additional Study Lags

The goal of Experiment 2 is to replicate and extend Experiment 1 in an attempt to answer some remaining questions about the spacing effect. We will examine patterns of effects across short, medium, and long lags to determine whether these spacing effects are modulated by these parameters. For example, deficient processing may still be present at shorter lags (this is important to scrutinize due to its status as an “impostor effect”; Delaney et al., 2010), there may be differences in reinstatement (study-phase retrieval) at longer lags, or we may see other effects change in a graded fashion. The presence of these gradations would allow us to better interpret data patterns that fit multiple theories. Experiment 1 used lags of 0 and 12; this experiment keeps these lags and adds repetitions at lags of 2 and 32, which are within the range of lags from behavioral spacing studies.

We expect that memory performance will show a lag effect: subsequent memory will correlate positively with lag. The most informative EEG effects regarding the spacing effect in Experiment 1 were for the N1, upper alpha, and time–frequency similarity, though the latter were difficult to interpret. Overall, they implicate differences in attention and semantic processing between spaced and massed repetitions that led to interactions with subsequent memory. It will be important to examine whether these effects modulate with

additional lags.

We are also including the single-presentation stimuli at test, which will allow us to get a baseline measurement of memory performance for comparison of subsequently remembered and forgotten massed and spaced items. We would always expect a repetition effect (repeated items will be remembered better than single presentation items), but perhaps if massed repetitions do involve deficient processing then they will be recalled no better than single presentation items.

Method

Participants. Forty University of Colorado Boulder undergraduates participated in the experiment for payment of \$15 per hour (ages 18–29, $M = 21.3$; 19 female). All participants were right-handed native-English speakers and had normal or corrected-to-normal vision. Informed consent was obtained from each participant, and the study conformed to the Institutional Review Board guidelines.

Materials. The stimuli and experiment presentation software were the same as for Experiment 1.

Design. Experiment 2 consisted of two sessions, each of which had nine blocks of three experimental phases: study, distractor, test. Two sessions were used to gather enough trials across the additional conditions. The phases were similar to Experiment 1 (Figure 1, page 22), but the exposure phase was not used to keep the experiment length reasonable. The sessions, including application of the electrode net and running in the task, lasted approximately 2.5 hours. Stimuli were randomly shuffled prior to creating the list for each phase at the beginning of the first session. The study phase contained the conditions that were manipulated within subjects, namely the viewing of spaced and massed paired associates.

Procedure. An electrode net was applied to each participant’s head, and the first session began with a shortened practice version of the experiment to familiarize

participants with the study and test procedures.

In each study phase block, participants viewed word–image pairs and were asked to think of a relationship between them or to make up a story pairing them. They were told that a subsequent test would require them to remember the word associated with each picture, but they were not told that some pairs will repeat. Spaced items were presented at a lag of either 2, 12, or 32, and massed items were presented at a lag of zero. For each of the two image categories there were three two-presentation spaced pairs per lag, three two-presentation massed pairs, three pairs presented only once, and four additional single-presentation buffers (two at the beginning of the list and two at the end). Buffer pairs did not appear on the test list. Thus, there were 58 word–image presentations in each block. On each trial, a fixation cross appeared for 1.0–1.2 s (jittered), then the word was presented first for 1.0 s followed immediately by the image for 1.0 s. No more than three images from the same category could occur in a row, and no more than two trials with the same lag (including single-presentation pairs) could occur in a row. Each study phase lasted approximately **5 min**.

In the distractor phase, participants answered simple math problems of the format $A+B+C=?$ for 2 min. They typed their responses with the keyboard. Different tones occurred for correct and incorrect answers, and mean accuracy and response time was reported to the participant at the end of the phase.

Finally, in the test phase, participants performed a cued recall task. Thirty images (nine spaced, three massed, and three single presentation images from each category) were mixed together and presented one at a time. Participants saw ?????? below each image and had to type the word previously paired with the image; they could pass if they could not remember the word. On each trial, a fixation cross appeared for 1.0–1.2 s (jittered) and the image was shown for 1.0 s, at which point the question marks appeared and participants were asked to make their response. Importantly, test images were presented in a sequence similar to the study order. To construct the test list, the positions of the second

presentations of study stimuli were divided into fifteen contiguous groups and each group was shuffled internally. This was done to approximately preserve a similar amount of time between the second presentation and the test across all “old” stimuli. Each test phase lasted approximately 4 to 5 min.

Electrophysiological recordings and data processing. All procedures for recording and processing electrophysiological data was the same as in Experiment 1, as was finding ERP component peaks and analyzing ERP and time–frequency data.

Results

Ten participants were excluded from all analyses either because they did not return for the required second session ($n = 8$) or their performance in important conditions was more than 2 standard deviations below the mean ($n = 2$). The remaining thirty participants were included in behavioral analyses. Three additional participants were excluded from ERP and time–frequency analyses either because they had extremely noisy EEG ($n = 2$) or had fewer than 10 artifact-free trials in any of the main trial conditions ($n = 1$), leaving twenty-seven participants in EEG analyses. Similarity analyses included the same participants, all of whom had six or more artifact-free pairs of initial presentation–repetition image trials.

All analyses contingent on subsequent memory are split by whether words were recalled or forgotten. There was no recognition test as in Experiment 1 (during cued recall, all test stimuli were “old”), so the “forgotten” trials category contained both images that were completely forgotten and those where participants were only unsure about the paired words.

Behavioral results. An ANOVA with factors of session (1 and 2), spacing (single presentation, massed/lag 0, short/lag 2, medium/lag 12, and long/lag 32 spaced), and image category, was run on cued recall hit rate. There was a main effect of spacing [$F(4, 116) = 174.2, p = 2.62e^{-36}$] in the expected order: long spaced words ($M = 56.9\%$)

were recalled better than medium spaced words ($M = 49.2\%$), and, in turn, performance for short spaced ($M = 45.8\%$), massed ($M = 35.7\%$), and single presentation words ($M = 23.0\%$) was better than the next. Words paired with faces and scenes were recalled at the same rate (faces: $M = 44.0\%$; scenes: $M = 40.2\%$). Thus, there are again clear spacing effects that scale with lag, as well as a simple repetition effect. These rates are comparable to Experiment 1.

There were also session \times image category [$F(1, 29) = 7.96, p < .01$] and spacing \times image category [$F(4, 116) = 7.52, p < .0005$] interactions such that recall was better for faces in session 1 compared to session 2, and performance increased at the longest lag for faces compared to scenes. However, these effects do not speak to our investigations of the spacing effect and will not be reported in detail.

Massed items were remembered significantly better than single-presentation items but less well than short (2) spaced items; this still leaves open the possibility that deficient processing occurs for massed items and decreases with lag. Only 9.3 sec elapsed between a short spaced item's initial presentation and repetition, whereas the delay was 3.1 sec for massed items. Neural effects can reveal how other processes contribute to the spacing effect.

ERP results. ERP component peaks in Experiment 2 were at the same electrodes as in the previous experiment, but were slightly earlier in time. The visual N1 peaked at electrode 58 (T5) at 144 ms (Figure 12; ± 50 ms window). The N400 peaked at Cz at 352 ms (Figure 13; ± 75 ms window used due a slight spreading of the peak voltage). The LPC peaked at electrode 77 at 536 ms (Figure 14; ± 100 ms window). Again, analyses use these peak electrodes and neighbors during study period words stimuli. After examining condition grand averages, it seems that voltages were overall slightly attenuated compared to Experiment 1; it is hard to give a reason for this, but it may be because Sessions 1 and 2 had the electrode cap placed in slightly different locations. Three-way ANOVAs with factors of spacing (massed and short, medium, and long spacing), presentation (1/new and 2/old), and subsequent memory (recalled and forgotten words) were performed on the

averaged window voltages for word presentations. Significant results are reported.

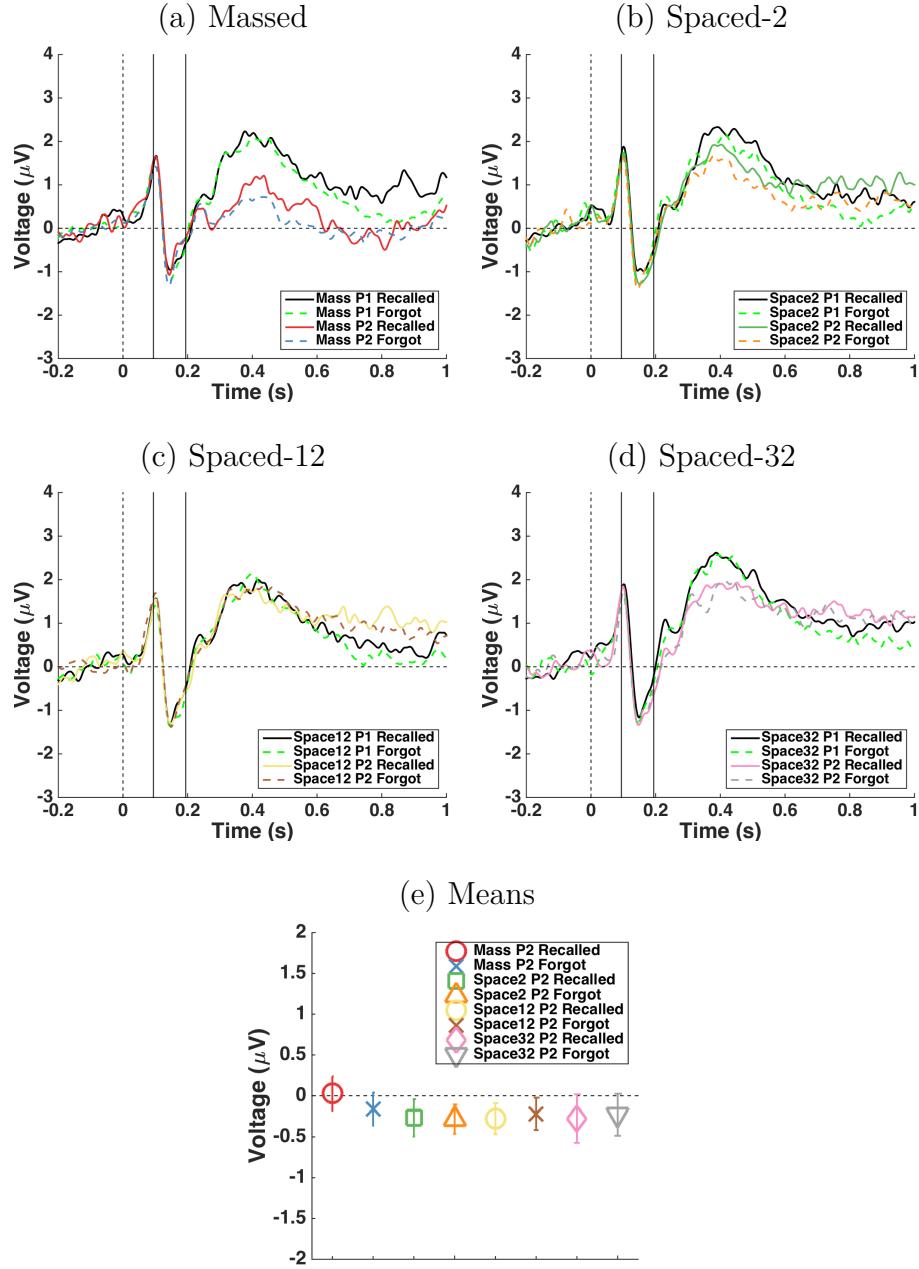


Figure 12. N1 to words at electrode 58 (T5) and neighbors, analyzed window 94–194 ms:
 (a) Massed ERPs; (b) short spaced ERPs; (c) medium spaced ERPs; (d) long spaced ERPs;
 (e) analyzed means (error bars are SEM). The early negative peak is not different
 across spaced and massed conditions.

If selective attention is modulated by spacing, early ERP components may show effects; this is relevant to deficient processing. However, there were no significant effects for N1 voltage. To dig deeper, we examined the pairwise comparisons in the three-way interaction, which was significant in Experiment 1). Here, recalled medium (12) spaced repetitions were marginally more negative ($M = -0.27 \mu\text{V}$) than recalled massed repetitions ($M = 0.03 \mu\text{V}$) [$t(26) = -1.99, p = .057$]. The pattern was similar for recalled short (2) ($M = -0.26 \mu\text{V}$) and long (32) ($M = -0.27 \mu\text{V}$) spaced items, and forgotten conditions were all slightly attenuated.

(I still don't feel like I know whether it is legit to look at the pairwise contrasts from an interaction...)

If differences in semantic priming and processing contribute to the spacing effect, the N400 should show effects. For N400 voltage there was a significant spacing \times presentation interaction [$F(3, 78) = 8.89, p = 6.36e^{-5}$] such that voltage became less negative from first presentations to spaced repetitions to massed repetitions [$p < .01$]. This is the same pattern as in Experiment 1. There were no quantitative differences between spaced conditions. There were also main effects of spacing (spaced items were more negative than massed [$F(3, 78) = 11.4, p = 2.85e^{-6}$]) and presentation (repetitions were less negative than initial presentations [$F(1, 26) = 53.2, p = 9.5e^{-8}$]). Finally, there was a three-way interaction [$F(3, 78) = 2.93, p < .05$]. There were no differences for the initial presentations. Rather, the effect seems to be driven by recalled medium (12) spaced repetitions showing a negative subsequent memory effect: medium recalled were more negative than forgotten (recalled: $M = -0.53 \mu\text{V}$, forgotten: $M = -0.19 \mu\text{V}$) [$t(26) = 2.45, p < .05$]. The medium SME and attenuation for massed compared to spaced trials are the same effects seen in Experiment 1.

The LPC is related to working memory and conscious access to information in memory in repetition paradigms, and may show subsequent memory effects. For LPC voltage, there were main effects for spacing [$F(3, 78) = 5.68, p < .005$], presentation

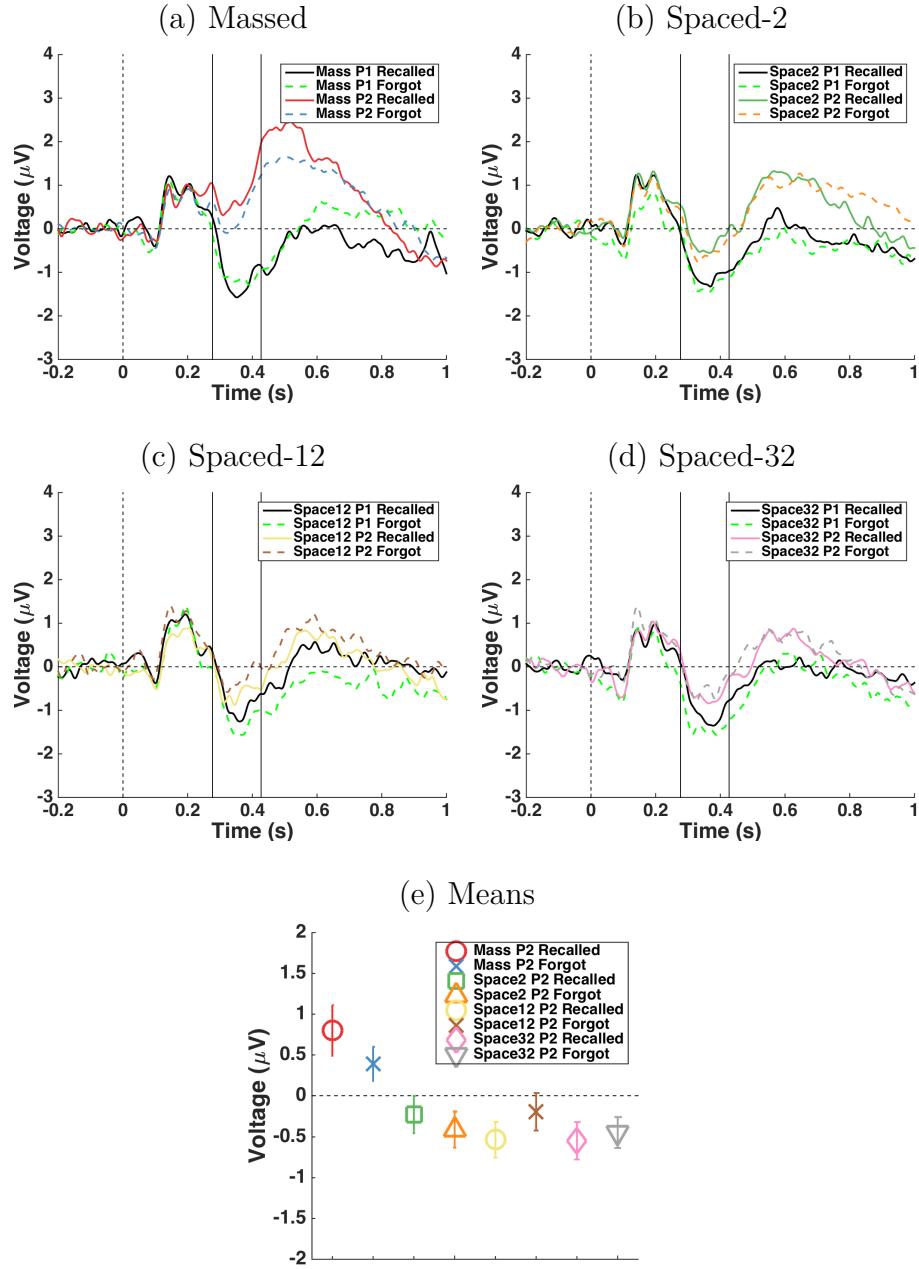


Figure 13. N400 to words at electrode Cz and neighbors, analyzed window 227–427 ms: (a) Massed ERPs; (b) short spaced ERPs; (c) medium spaced ERPs; (d) long spaced ERPs; (e) analyzed means (error bars are SEM). The negative peak at 400 ms is significantly smaller for massed repetitions compared to any spaced repetition condition.

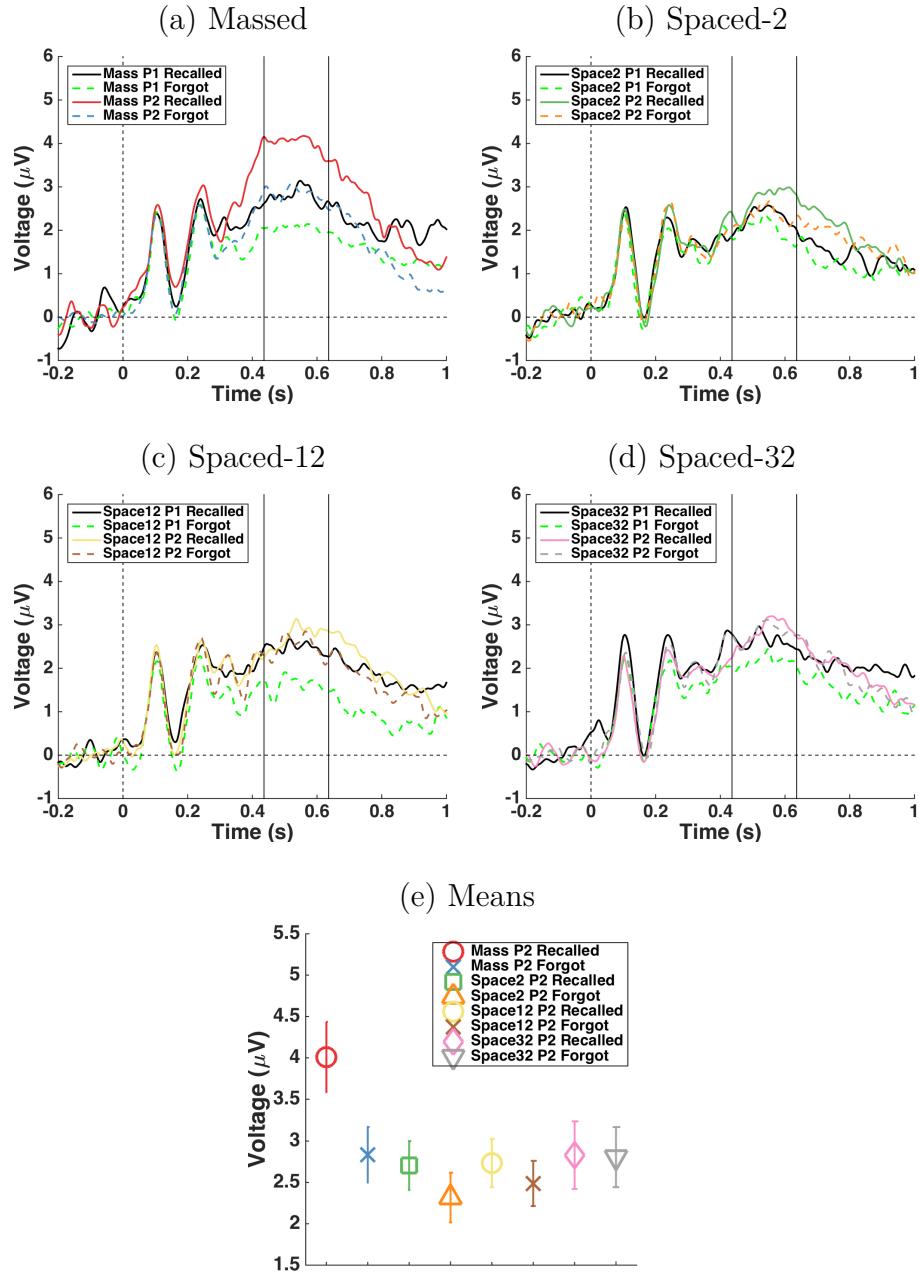


Figure 14. LPC to words at electrode 77 and neighbors, analyzed window 436–636 ms: (a) Massed ERPs; (b) short spaced ERPs; (c) medium spaced ERPs; (d) long spaced ERPs; (e) analyzed means (error bars are SEM). The positive peak around 600 ms is significantly larger for massed compared to spaced repetitions.

[$F(1, 26) = 31.6, p = 6.52e^{-6}$], and memory [$F(1, 26) = 22.4, p = 6.88e^{-5}$]. Massed words ($M = 2.92 \mu\text{V}$) were more positive than short ($M = 2.33 \mu\text{V}$) and medium ($M = 2.33 \mu\text{V}$) spaced words, but only marginally more than long spaced words ($M = 2.6 \mu\text{V}$) [$t(26) = 1.871, p = .073$]; long spaced words were also marginally more positive than short and medium trials [$p < .1$]. On average, repetitions ($M = 2.4 \mu\text{V}$) were more positive than initial presentations ($M = 2.25 \mu\text{V}$), and subsequently recalled words ($M = 2.81 \mu\text{V}$) were more positive than forgotten ($M = 2.28 \mu\text{V}$) .

There was no three-way voltage interaction, but when examining only repetitions using a two-way ANOVA (factors of spacing and memory), there was a significant interaction [$F(3, 78) = 3.53, p < .05$] showing that massed was the only category with a subsequent memory effect; the actual voltage difference between recalled and forgotten words decreased with lag.

For LPC latency effects, which illuminate how quickly information is consciously accessed, there was the same spacing \times presentation interaction [$F(3, 78) = 2.86, p < .05$] as in Experiment 1: medium (544 ms) and long (550 ms) spaced repetitions peaked later than massed repetitions (529 ms) [$p < .05$] and their respective the initial presentations (long: 529 ms [$t(26) = 3.98, p < .0005$], medium: 532 ms [$t(26) = 1.96, p = 0.061$] marginal).

ERP discussion. We expected the N1 to become more negative for repetitions as lag increases because early attentional processes tend to vary with this parameter. For example, a repetition at lag 2 would have a voltage in between a massed item and a repetition at lag 12. However, for N1 voltage there were no significant effects, though examining the pairwise comparisons of the three-way interaction revealed qualitatively similar patterns to Experiment 1: Spaced items seem to get more attentional processing than massed items, albeit weakly here.

Since there were no significant N1 effects here leads to the idea that attention is not the critical factor for why the spacing effect occurs, at least when defining attention as an early involuntary mechanism. Perhaps an experiment difference such as removing the

exposure phase made a difference for the N1 (e.g., having an existing representation of a stimulus before needing to learn stimulus pairings changes attentional mechanisms).

Regardless, the lack of an exposure phase made no difference behaviorally, as there was a strong spacing effect in Experiment 2. We cannot make any strong claims in the face of null results, but overall this is less evidence to support deficient processing.

An interesting question to consider regarding the lack of N1 effects is how short term the repetition effects are. Henson, Rylands, Ross, Vuilleumeir, and Rugg (2004) investigated ERP effects for repetitions of pictures of objects at different lags and saw an N1 repetition effect after an unfilled 4-second delay (N1 amplitude decreased for repetition), but not when the four seconds was occupied by another stimulus or at a much longer lag (96 seconds). Thus, deficient processing may be eliminated at a relatively short delay if it is filled with other stimuli. Regardless, based on the results from Experiment 1 we still expected an N1 attenuation for massed items.

We expected the N400 to show graded effects, considering its tie to semantic processing: the component would get more negative as lag increases because more semantic processing is needed during retrieval. The N400 showed similar results to Experiment 1, but there were no graded effects within spaced conditions, only a difference between massed and spaced items in the expected direction: massed items were strongly attenuated compared to spaced. The voltage averages (Figure 13e) show an overall voltage decrease for remembered items at longer lags, but the only significant effect of memory was for recalled medium spaced repetitions (there were no SMEs in Experiment 1).

Based on the N400, it seems that a similar amount of semantic processing is engaged when there have been at least two intervening stimulus pairs between repetitions. These results imply that spaced repetitions (regardless of lag) receive more semantic processing, or conversely that semantic processing disengages more for massed repetitions. This still supports the Challis (1993) semantic activation hypothesis (less semantic activation for items in working memory), but only one that posits deficient processing for immediate

repetitions, and graded behavioral performance does not mimic this pattern. Therefore these results do not seem to support deficient processing.

Finally, we expected working memory effects (LPC) to be graded across lags. This could occur for two reasons, in opposite directions. First, in terms of memory retrieval (posited under study-phase retrieval), we might see a subsequent memory effect. Reinstatement should be more difficult as lag increases (as described in the models of Pavlik & Anderson, 2005 and Mozer et al., 2009) but also more beneficial to long-term memory if it is successful. Second, the gradation might go in the other direction: effects for working memory should be stronger for massed items and decrease with lag; this larger difference for subsequent memory of massed items is what we see. As in Experiment 1, it again seems that the LPC indexes the information that is in working memory, and again, the result does not seem to directly support any of the theories unless the match to working memory for massed items is an indicator of deficient processing.

The pattern of latency effects for the LPC implies that it takes longer to access existing medium and long spaced representations compared to the massed and short spaced conditions, also supporting the idea of the LPC indexing conscious access to information in working memory.

We still have not found a defining neural signature for why performance is best for long (32) spaced repetitions.

Time–frequency results. We again analyzed images in addition to words for time–frequency data. Three-way ANOVAs with factors of spacing (spaced and massed), subsequent memory (recalled and forgotten), and time (0–500 ms and 500–1000 ms) were performed for word and image repetitions on power in the theta, lower alpha, upper alpha, and lower beta bands (eight ANOVAs).

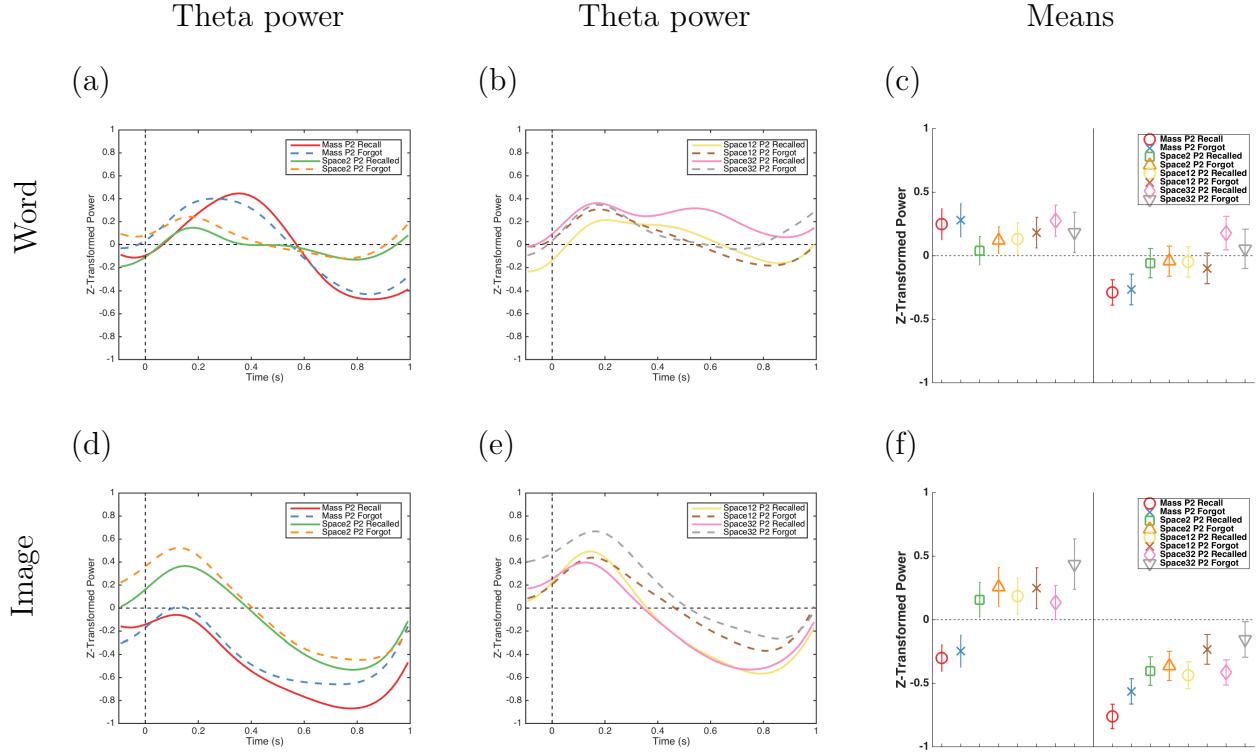


Figure 15. Theta power to words and images. (a), (b), (d), and (e) Grand averages; (c) and (f) mean values for the two time windows (error bars are SEM).

Word, theta: Across 73 electrodes (Figure 15, top), there were main effects of spacing [$F(3, 78) = 4.0, p < .05$] and time [$F(1, 26) = 33, p = 4.81e^{-6}$]. Long (32) spaced word repetitions showed more theta power than all other conditions [$p < .05$], and there was a decrease in power across time. There was also a spacing \times time interaction [$F(3, 78) = 16, p = 5.33e^{-8}$] such that all conditions decreased across time [$p < .05$] except long spaced words. There was no three-way interaction, but pairwise comparisons for recalled words between massed and spaced conditions in the later time window showed that long (32) spaced words had significantly higher theta power than all other conditions.

Image, theta: Across 90 electrodes (Figure 15, bottom), there were main effects of spacing [$F(3, 78) = 27.2, p = 1.17e^{-10}$], memory [$F(1, 26) = 8.76, p < .01$], and time [$F(1, 26) = 91.1, p = 5.57e^{-10}$]. Massed items desynchronized more overall than the other

conditions, subsequently recalled items desynchronized more than forgotten ones, and power decreased across time. A spacing \times time interaction [$F(3, 78) = 5.14, p < .01$] showed that the decrease in power across time for massed items was less than short and medium spaced repetitions.

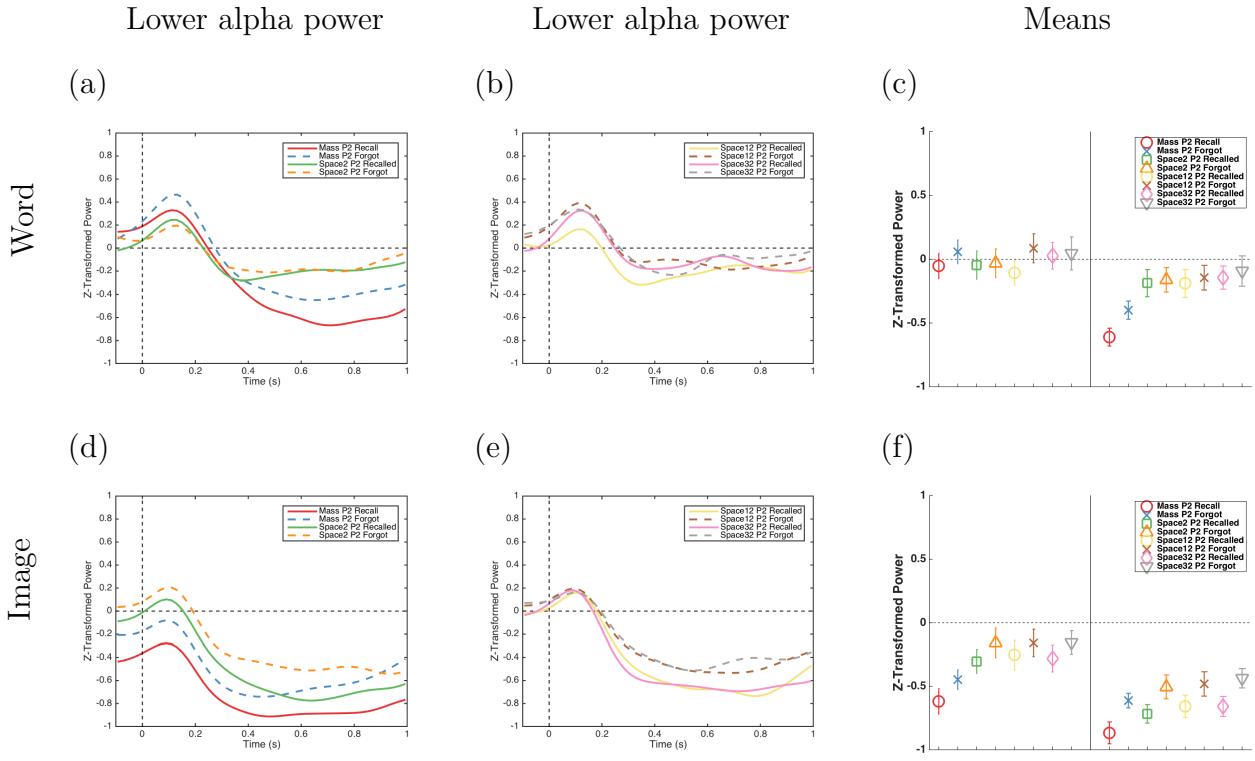


Figure 16. Lower alpha power to words and images. (a), (b), (d), and (e) Grand averages; (c) and (f) mean values for the two time windows (error bars are SEM).

Word, lower alpha: Across 49 electrodes (Figure 16, top), we saw the same spacing \times time interaction [$F(3, 78) = 15.1, p = 2.15e^{-7}$] as in Experiment 1. Lower alpha desynchronized more (power was more negative) across time windows for massed compared to spaced words. There were also significant main effects of spacing [$F(3, 78) = 9.78, p = 2.22e^{-5}$], memory [$F(1, 26) = 5.89, p < .05$], and time [$F(1, 26) = 9.71, p < .005$]. Massed word repetitions showed more lower alpha desynchronization than the other conditions, there was more desynchronization for recalled

images, and there was more desynchronization in the second time window; these effects were the same as in Experiment 1 and seem to be driven by massed recalled items.

Image, lower alpha: Across 94 electrodes (Figure 16, bottom), lower alpha for images showed the same pattern of effects as for words; these are also the same effects as from Experiment 1. There was a spacing \times time interaction [$F(3, 78) = 6.23, p < .005$] that showed a larger decrease for spaced items across time compared to massed. There were main effects of spacing [$F(3, 78) = 14.3, p = 2.65e^{-7}$] (massed desynchronized more than spaced), memory [$F(1, 26) = 24.7, p = 3.67e^{-5}$] (remembered desynchronized more than forgotten), and time [$F(1, 26) = 33.6, p = 4.19e^{-6}$] (desynchronization decreased over time). Additionally, there was a memory \times time interaction [$F(1, 26) = 5.37, p < .05$]; SMEs were stronger in the later time window.

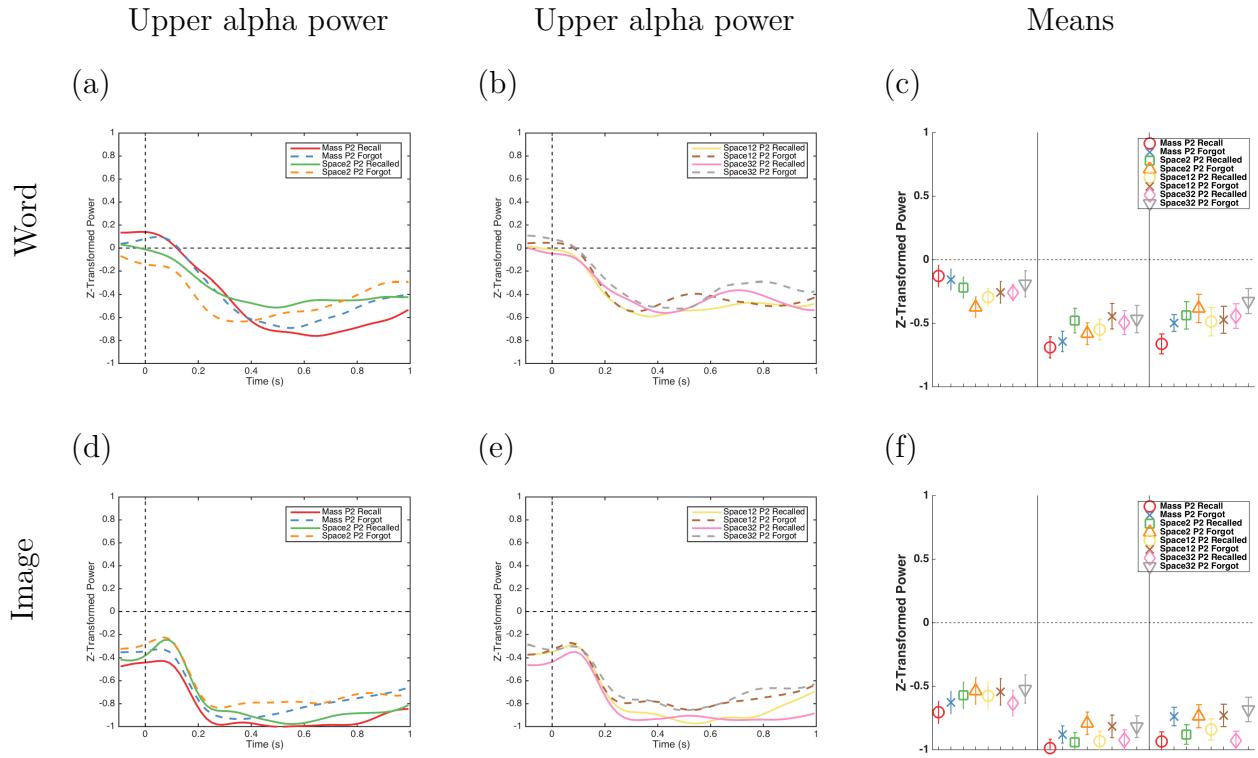


Figure 17. Upper alpha to words and images. (a), (b), (d), and (e) Grand averages; (c) and (f) mean values for the three time windows (error bars are SEM).

Word, upper alpha: As in Experiment 1, we used three time windows for upper alpha and lower beta. Across 46 electrodes (Figure 17, top), there was a main effect of time [$F(2, 52) = 18.3, p = 2.36e^{-5}$]: the second and third time windows showed more upper alpha desynchronization than the first. There was also a spacing \times time interaction [$F(6, 156) = 11.8, p = 9.2e^{-8}$]: each repetition decreased in power across time, but massed decreases more.

Image, upper alpha: Across 44 electrodes (Figure 17, bottom), there were main effects of memory [$F(1, 26) = 21.8, p = 8.08e^{-5}$] (recalled items desynchronized more than forgotten items) and time [$F(2, 52) = 25, p = 3.55e^{-6}$]: power was lowest in the middle time window. The spacing effect was marginally significant [$F(3, 78) = 2.74, p = .053$]: massed images desynchronized more than short and medium spaced items. There was also a memory \times time interaction [$F(2, 52) = 6.82, p < .005$] showing that the SME was strongest in the third time window.

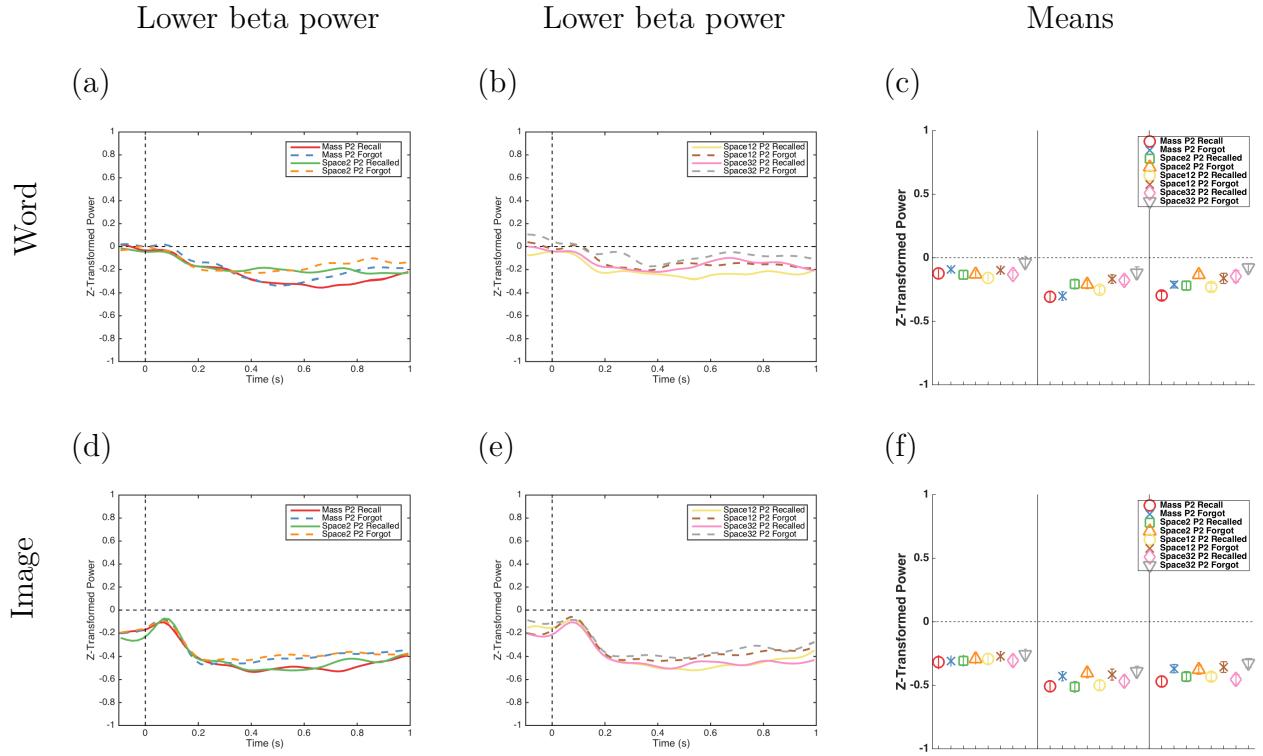


Figure 18. Lower beta power to words and images. (a), (b), (d), and (e) Grand averages; (c) and (f) mean values for the three time windows (error bars are SEM).

Word, lower beta: Across 66 electrodes (Figure 18, top), there were main effects of spacing [$F(3, 78) = 9.48, p = 7.16e^{-5}$], memory [$F(1, 26) = 8.36, p < .01$], time [$F(2, 52) = 25.5, p = 5.06e^{-8}$], a spacing \times time interaction [$F(6, 156) = 6.96, p = 3.79e^{-6}$]. Massed word repetitions desynchronized more than the spaced conditions, subsequently recalled words desynchronized more than forgotten ones, and there was more desynchronization during the second time window compared to the others (though the third was still lower than the first). Additionally, spacing effects across all spaced lags (short, medium, and long) were larger in the second and third time windows (massed were more negative).

Image, lower beta: Across 30 electrodes (Figure 18, bottom), there were main effects of memory [$F(1, 26) = 25.2, p = 3.22e^{-5}$] and time [$F(2, 52) = 53.7, p = 3.33e^{-12}$] which

followed the patterns of effects reported above for words: recalled had more desynchronization, and power was lowest in the second time window and increased in the third.

Time-frequency discussion. In addition to the LPC ERP voltage effect, theta is the other place where we might expect to see effects of study-phase retrieval, especially at longer lags where retrieval would be more difficult but also more beneficial to long-term memory if successful (Delaney et al., 2010; Pavlik & Anderson, 2005)). The sustained theta spacing effect for long (32) spaced word repetitions (including pairwise comparisons between recalled items only) is interesting because these trials had the highest behavioral performance; in fact, the pattern of theta power for recalled word repetitions in the second time window follows behavioral performance. Thus, theta effects support study-phase retrieval and are possibly a main indicator of the spacing effect.

The lower alpha band generally correlates negatively with attentional processes and shows a widespread scalp topography. Deficient processing would predict increased alpha power for massed repetitions, though the results for Experiment 1 were in the opposite direction (massed desynchronized more, or showed a decrease in power) and we expected these to be the same. We also expected to see decreased power (more desynchronization) for better subsequent memory, due to increased attentional processing. Lower alpha results followed Experiment 1: we see the memory effect just described, and the spacing effect again does not support deficient processing (more attention seems to get allocated to massed items).

For upper alpha, we expected semantic processing to show graded spacing effects: remembered items should desynchronize more as lag increases because items with longer lag are remembered better on average, and semantic processing should help memory. The results show that remembered items incur more semantic processing across the trial, but the spacing effect is opposite from what we predicted. Massed items showed more semantic processing (and showed this earlier than spaced), so perhaps the effect is driven by the

semantic representation being active in working memory. As in Experiment 1, these results do not support deficient processing because it would predict less semantic processing for massed items.

The lower beta effects for words and images almost exactly follow those of Experiment 1. This solidifies the idea that semantic processing (denoted by decreased power) helps memory overall. Massed trials get a semantic processing boost during word presentations (more desynchronization in time windows 2 and 3), perhaps because they are in working memory, but spaced are equally processed during the images.

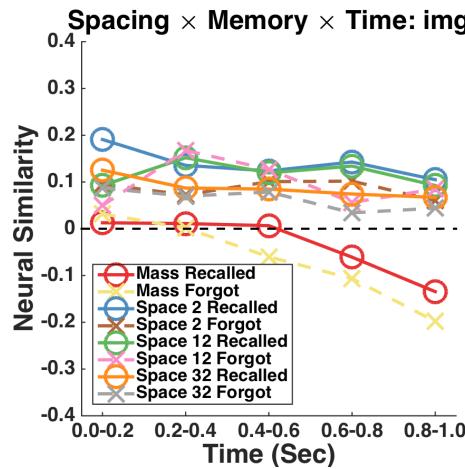


Figure 19. Similarity for voltage at left and right temporal sites during image repetitions: Interaction between spacing, memory, and time [n.s.].

Similarity results. None of our effects for Experiment 2 have supported contextual variability; to do so, we would need to see more variability in EEG at as lag increases, an effect of temporocontextual drift. Perhaps a clearer picture will emerge with more lags.

The same ROIs, latencies, and data processing methods were used to measure neural similarity between initial and repetition trials as in Experiment 1, including using images for analysis because this is when word–image (item–context) binding should occur.

For voltage (Figure 19), a three-way repeated measures ANOVA was run on the average similarity values from left and right temporal regions with factors of spacing (spaced and massed), subsequent memory (recalled and not recalled), and time (successive

200 ms time bins). There was a main effect of spacing [$F(3, 78) = 11.1, p = 5.19e^{-6}$], a marginal effect of memory [$F(1, 26) = 3.92, p = .058$], and a main effect of time [$F(4, 104) = 6.31, p < .0005$]. There was also a spacing \times time interaction [$F(12, 312) = 2.99, p = .005$]. Spaced items of all length lags were more similar than massed items, subsequently recalled items were marginally more similar than forgotten ones, and similarity decreased across time. The interaction explains the two significant main effects in that massed item similarity decreased across time whereas spaced items stayed consistent. These follow the results of Experiment 1, with the addition of the memory effect.

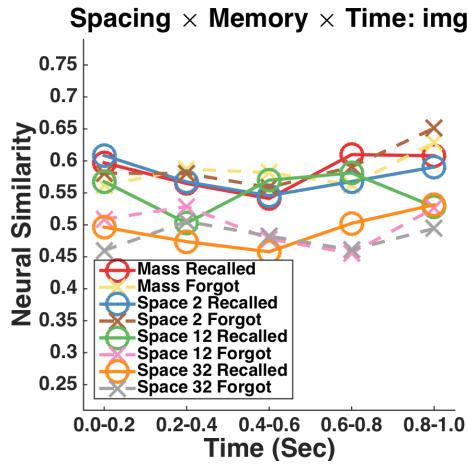


Figure 20. Similarity for oscillatory power at left and right parietal sites during image repetitions: Interaction between spacing, memory, and time [n.s.].

For time-frequency data (Figure 20), the same three-way ANOVA was performed over left and right parietal regions across all frequency bands. There was a main effect of spacing [$F(3, 78) = 8.92, p = 6.5e^{-5}$] (similarity decreased with lag), a main effect of time [$F(4, 104) = 2.9, p < .05$] (similarity increased across time), and a marginal memory \times time interaction [$F(4, 104) = 2.46, p = 0.051$] (without a clear pattern). These also follow the results of Experiment 1, though the interaction was less clear here.

Similarity discussion. The patterns for voltage and time-frequency data mimicked Experiment 1 in the same way. Repeating some of the discussion from the prior experiment, it seems that for voltage, spaced repetitions tend to induce a consistent

representation across time (possibly supporting study-phase retrieval) while massed repetitions become more variable. This could be attributed to noise being added to the system (supporting deficient processing), inducing a more variable representation (supporting contextual variability), or engaging different neural/cognitive processes. It does not seem like noise would be added to the system when a massed stimulus received semantic processing at the repetition (earlier upper alpha and lower beta results), and from a theoretical standpoint there is no good reason for massed repetitions to have more variable representations because context has not drifted. Study-phase retrieval seems like the most reasonable explanation for the advantage for spaced items (the spacing effect) at this point.

Experiment 2 Discussion

The purpose of this experiment was to look for gradations in neural effects to better interpret data patterns in the context of the three theories. Behaviorally, we saw exactly what was expected: performance increased significantly as lag increased. The EEG effects mostly followed the patterns of Experiment 1. Across the ERP results, it seems like information that is already in working memory and does not need to be retrieved (massed) does not gain the repetition advantage of information that needs to be retrieved (spaced).

For many effects there was no difference between spaced condition lags, which was not what we were hoping for. However, increased theta power is associated with memory retrieval, and it varied positively with repetition lag (as spacing increased). Additionally, in the voltage similarity analysis, a more similar neural state during the repetition (compared to the initial presentation) leads to better subsequent memory. Overall, the spacing effect seems to be more consistently driven by retrieval of a prior occurrence than by any other process, and therefore it seems that study-phase retrieval is a key part of the spacing effect.

General Discussion

The results of the two experiments followed the same overall pattern. Based on the behavioral results of Experiment 2, we hoped that the additional spaced study lags would have provided more graded neural effects, but the analyses undertaken here do provide additional insights. To reiterate at a high level, it seems like information that is no longer in working memory shows evidence of retrieval during a study repetition, and this benefits performance on a subsequent test.

Plenty of previous research has shown theta to be important for memory processing. Fuentemilla, Penny, Cashdollar, Bunzeck, and Düzel (2010) showed that memory reactivation involves increased theta power, coupled with activity in the beta and gamma bands. The tasks in the present experiments have not been working memory tasks requiring the maintenance and manipulation of information over short periods of time, but the reactivation of memory representations during stimulus repetitions correlates with lag (and with behavioral performance); longer lags showed more theta power. Theta synchrony along the visual ventral stream (occipitotemporal region) is important for maintaining cortical representations (Düzel, Penny, & Burgess, 2010), which is one reason why elevated levels of theta in the medial temporal lobes prior to stimulus presentation can lead to better memory encoding.

Future Directions

For future analyses, comparing the similarity of each during test to its study presentations would be another way to examine study-phase retrieval and contextual variability. Contextual variability would be supported if a spaced test image is similar to only one study image, whereas study-phase retrieval would be supported if the test image was similar to both study images. This analysis would benefit from separating item and context features in neural patterns.

For future experiments, it would still be enlightening to get away from a paradigm that involves immediate repetition so that deficient processing could be eliminated as a

possible theory. An interesting way to take this would be to use an established spacing effect paradigm from the literature (e.g., Cepeda et al., 2009, Experiment 1) and add EEG recordings. This would involve a multi-session experiment and have the added benefit of being more applicable to real-world learning. It may also simplify the possibilities for why the spacing effect occurs (deficient processing should essentially be eliminated).

References

- Bjork, R. A. (1988). Retrieval practice and the maintenance of knowledge. In M. M. Gruneberg, P. E. Morris, & R. N. Skyes (Eds.), *Practical aspects of memory: Current research and issues* (Vol. 1: Memory in everyday life, pp. 396–401). Oxford, England: Wiley & Sons.
- Bower, G. H. (1972). Stimulus-sampling theory of encoding variability. In A. W. Melton & E. Martin (Eds.), *Coding processes in human memory* (pp. 85–123). John Wiley & Sons.
- Brainard, D. H. (1997). The psychophysics toolbox. *Spat Vis*, 10(4), 433–436.
- Braun, K., & Rubin, D. C. (1998). The spacing effect depends on an encoding deficit, retrieval, and time in working memory: evidence from once-presented words. *Memory*, 6(1), 37–65. doi: 10.1080/741941599
- Callan, D. E., & Schweighofer, N. (2010). Neural correlates of the spacing effect in explicit verbal semantic encoding support the deficient-processing theory. *Hum Brain Mapp*, 31(4), 645–659. doi: 10.1002/hbm.20894
- Carpenter, S. K., Cepeda, N. J., Rohrer, D., Kang, S. H., & Pashler, H. (2012). Using spacing to enhance diverse forms of learning: Review of recent research and implications for instruction. *Educational Psychology Review*, 24(3), 369–378.
- Cepeda, N. J., Coburn, N., Rohrer, D., Wixted, J. T., Mozer, M. C., & Pashler, H. (2009). Optimizing distributed practice: Theoretical analysis and practical implications. *Exp Psychol*, 56(4), 236–246. doi: 10.1027/1618-3169.56.4.236
- Cepeda, N. J., Pashler, H., Vul, E., Wixted, J. T., & Rohrer, D. (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychol Bull*, 132(3), 354–380. doi: 10.1037/0033-2909.132.3.354
- Challis, B. H. (1993). Spacing effects on cued-memory tests depend on level of processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 19(2), 389–396.

- Curran, T. (2000). Brain potentials of recollection and familiarity. *Memory and Cognition*, 28(6), 923–938.
- Curran, T. (2004). Effects of attention and confidence on the hypothesized ERP correlates of recollection and familiarity. *Neuropsychologia*, 42(8), 1088–1106. doi: 10.1016/j.neuropsychologia.2003.12.011
- Curran, T., Tanaka, J. W., & Weiskopf, D. M. (2002). An electrophysiological comparison of visual categorization and recognition memory. *Cogn Affect Behav Neurosci*, 2(1), 1–18.
- Delaney, P. F., Verkoeijen, P. P., & Spiegel, A. (2010). Spacing and testing effects: A deeply critical, lengthy, and at times discursive review of the literature. In B. H. Ross (Ed.), *Psychology of learning and motivation* (Vol. 53, pp. 63–147). Burlington: Elsevier.
- Dempster, F. N. (1988). The spacing effect: A case study in the failure to apply the results of psychological research. *American Psychologist*, 43(8), 627–634.
- Duarte, A., Ranganath, C., Trujillo, C., & Knight, R. T. (2006). Intact recollection memory in high-performing older adults: ERP and behavioral evidence. *J Cogn Neurosci*, 18(1), 33–47. doi: 10.1162/089892906775249988
- Duarte, A., Ranganath, C., Winward, L., Hayward, D., & Knight, R. T. (2004). Dissociable neural correlates for familiarity and recollection during the encoding and retrieval of pictures. *Brain Research. Cognitive Brain Research*, 18(3), 255–272.
- Dunlosky, J., Rawson, K. A., Marsh, E. J., Nathan, M. J., & Willingham, D. T. (2013). Improving students' learning with effective learning techniques: Promising directions from cognitive and educational psychology. *Psychological Science in the Public Interest*, 14(1), 4—58. doi: 10.1177/1529100612453266
- Düzel, E., Penny, W. D., & Burgess, N. (2010). Brain oscillations and memory. *Current Opinion in Neurobiology*, 20(2), 143–149. doi: 10.1016/j.conb.2010.01.004
- Ebbinghaus, H. (1885/1913). *Memory: A contribution to experimental psychology*. New

- York: Teachers College, Columbia University.
- Estes, W. K. (1955). Statistical theory of spontaneous recovery and regression. *Psychol Rev*, 62(3), 145–154.
- Fellner, M.-C., Bäuml, K.-H. T., & Hanslmayr, S. (2013). Brain oscillatory subsequent memory effects differ in power and long-range synchronization between semantic and survival processing. *Neuroimage*, 79, 361–370. doi: 10.1016/j.neuroimage.2013.04.121
- Friedman, D., & Johnson, R., Jr. (2000). Event-related potential (ERP) studies of memory encoding and retrieval: A selective review. *Microsc Res Tech*, 51(1), 6–28.
- Fuentemilla, L., Penny, W. D., Cashdollar, N., Bunzeck, N., & Düzel, E. (2010). Theta-coupled periodic replay in working memory. *Curr Biol*, 20(7), 606–612. doi: 10.1016/j.cub.2010.01.057
- Glanzer, M., & Duarte, A. (1971). Repetition between and within languages in free recall. *Journal of Verbal Learning and Verbal Behavior*, 10(6), 625–630.
- Glenberg, A. M. (1976). Monotonic and nonmonotonic lag effects in paired-associate and recognition memory paradigms. *Journal of Verbal Learning and Verbal Behavior*, 15(1), 1–16.
- Glenberg, A. M. (1979). Component-levels theory of the effects of spacing of repetitions on recall and recognition. *Mem Cognit*, 7(2), 95–112.
- Greene, R. L. (1989). Spacing effects in memory: Evidence for a two-process account. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15(3), 371–377.
- Greenhouse, S., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika*, 24(2), 95–112.
- Groen, I. I. A., Ghebreaab, S., Lamme, V. A. F., & Scholte, H. S. (2012). Spatially pooled contrast responses predict neural and perceptual similarity of naturalistic image categories. *PLoS Comput Biol*, 8(10), e1002726. doi: 10.1371/journal.pcbi.1002726

- Hanslmayr, S., Spitzer, B., & Bäuml, K.-H. (2009). Brain oscillations dissociate between semantic and nonsemantic encoding of episodic memories. *Cereb Cortex, 19*(7), 1631–1640. doi: 10.1093/cercor/bhn197
- Hanslmayr, S., & Staudigl, T. (2014). How brain oscillations form memories—a processing based perspective on oscillatory subsequent memory effects. *Neuroimage, 85 Pt 2*, 648–655. doi: 10.1016/j.neuroimage.2013.05.121
- Hanslmayr, S., Staudigl, T., & Fellner, M.-C. (2012). Oscillatory power decreases and long-term memory: the information via desynchronization hypothesis. *Front Hum Neurosci.*
- Hanslmayr, S., Volberg, G., Wimber, M., Raabe, M., Greenlee, M. W., & Bäuml, K.-H. T. (2011). The relationship between brain oscillations and BOLD signal during memory formation: a combined EEG-fMRI study. *J Neurosci, 31*(44), 15674–15680. doi: 10.1523/JNEUROSCI.3140-11.2011
- Henson, R. N., Rylands, A., Ross, E., Vuilleumeir, P., & Rugg, M. D. (2004). The effect of repetition lag on electrophysiological and haemodynamic correlates of visual object priming. *Neuroimage, 21*(4), 1674–1689. doi: 10.1016/j.neuroimage.2003.12.020
- Hintzman, D. L. (1974). Theoretical implications of the spacing effect. In R. L. Solso (Ed.), *Theories in Cognitive Psychology: The Loyola Symposium* (pp. 77–97). Lawrence Erlbaum Associates.
- Hintzman, D. L., & Block, R. A. (1973). Memory for the spacing of repetitions. *Journal of Experimental Psychology, 99*(1), 70–74.
- Hintzman, D. L., Summers, J. J., & Block, R. A. (1975). Spacing judgments as an index of study-phase retrieval. *Journal of Experimental Psychology: Human Learning and Memory, 1*(1), 31.
- Howard, M., & Kahana, M. (2002). A distributed representation of temporal context. *Journal of Mathematical Psychology, 46*(3), 269–299.
- Johnston, W. A., & Uhl, C. N. (1976). The contributions of encoding effort and variability

- to the spacing effect on free recall. *Journal of Experimental Psychology: Human Learning and Memory*, 2(2), 153–160.
- Kahana, M. J. (1996). Associative retrieval processes in free recall. *Mem Cognit*, 24(1), 103–109.
- Kaiser, H. F. (1960). The application of electronic computers to factor analysis. *Educational and psychological measurement*, 20, 141–151. doi: doi:10.1177/001316446002000116
- Karpicke, J. D., & Roediger, H. L., III. (2007). Expanding retrieval practice promotes short-term retention, but equally spaced retrieval enhances long-term retention. *J Exp Psychol Learn Mem Cogn*, 33(4), 704–719. doi: 10.1037/0278-7393.33.4.704
- Khajah, M. M., Lindsey, R. V., & Mozer, M. C. (2014). Maximizing students' retention via spaced review: Practical guidance from computational models of memory. *Top Cogn Sci*, 6(1), 157–169. doi: 10.1111/tops.12077
- Kim, M., Kim, J., & Kwon, J. S. (2001). The effect of immediate and delayed word repetition on event-related potential in a continuous recognition task. *Brain Res Cogn Brain Res*, 11(3), 387–396.
- Klimesch, W. (1999). Eeg alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res Brain Res Rev*, 29(2-3), 169-195.
- Klimesch, W., Doppelmayr, M., Russegger, H., & Pachinger, T. (1996). Theta band power in the human scalp EEG and the encoding of new information. *Neuroreport*, 7(7), 1235–1240.
- Klimesch, W., Hanslmayr, S., Sauseng, P., Gruber, W., Brozinsky, C. J., Kroll, N. E. A., ... Doppelmayr, M. (2006). Oscillatory eeg correlates of episodic trace decay. *Cereb Cortex*, 16(2), 280–290. doi: 10.1093/cercor/bhi107
- Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: the inhibition-timing hypothesis. *Brain Res Rev*, 53(1), 63–88. doi: 10.1016/j.brainresrev.2006.06.003

- Klimesch, W., Schack, B., & Sauseng, P. (2005). The functional significance of theta and upper alpha oscillations. *Exp Psychol*, 52(2), 99–108.
- Klimesch, W., Schack, B., Schabus, M., Doppelmayr, M., Gruber, W., & Sauseng, P. (2004). Phase-locked alpha and theta oscillations generate the p1-n1 complex and are related to memory performance. *Brain Res Cogn Brain Res*, 19(3), 302–316. doi: 10.1016/j.cogbrainres.2003.11.016
- Kriegeskorte, N., Mur, M., & Bandettini, P. (2008). Representational similarity analysis - connecting the branches of systems neuroscience. *Front Syst Neurosci*, 2, 4. doi: 10.3389/neuro.06.004.2008
- Lohnas, L. J., & Kahana, M. J. (2014). A retrieved context account of spacing and repetition effects in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.
- Lohnas, L. J., Polyn, S. M., & Kahana, M. J. (2011). Contextual variability in free recall. *J Mem Lang*, 64(3), 249–255. doi: 10.1016/j.jml.2010.11.003
- Long, N. M., Burke, J. F., & Kahana, M. J. (2013). Subsequent memory effect in intracranial and scalp eeg. *Neuroimage*, 84C, 488–494. doi: 10.1016/j.neuroimage.2013.08.052
- Luck, S. J., Woodman, G. F., & Vogel, E. K. (2000). Event-related potential studies of attention. *Trends Cogn Sci*, 4(11), 432–440.
- Malmberg, K. J., & Shiffrin, R. M. (2005). The “one-shot” hypothesis for context storage. *J Exp Psychol Learn Mem Cogn*, 31(2), 322–336. doi: 10.1037/0278-7393.31.2.322
- Mammarella, N., Russo, R., & Avons, S. E. (2002). Spacing effects in cued-memory tasks for unfamiliar faces and nonwords. *Mem Cognit*, 30(8), 1238–1251.
- Manning, J. R., Polyn, S. M., Baltuch, G. H., Litt, B., & Kahana, M. J. (2011). Oscillatory patterns in temporal lobe reveal context reinstatement during memory search. *Proc Natl Acad Sci U S A*, 108(31), 12893–12897. doi: 10.1073/pnas.1015174108
- Manns, J. R., Howard, M. W., & Eichenbaum, H. (2007). Gradual changes in hippocampal

- activity support remembering the order of events. *Neuron*, 56(3), 530–540. doi: 10.1016/j.neuron.2007.08.017
- Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, 164(1), 177–190. doi: 10.1016/j.jneumeth.2007.03.024
- Mecklinger, A. (2006). Electrophysiological measures of familiarity memory. *Clinical EEG and Neuroscience*, 37(4), 292–299.
- Melton, A. W. (1967). Repetition and retrieval from memory. *Science*, 158(3800), 532. doi: 10.1126/science.158.3800.532-b
- Melton, A. W. (1970). The situation with respect to the spacing of repetitions and memory. *Journal of Verbal Learning and Verbal Behavior*, 9(5), 596–606.
- Mensink, G.-J. M., & Raaijmakers, J. G. (1989). A model for contextual fluctuation. *Journal of Mathematical Psychology*, 33(2), 172–186.
- Mitchell, D. J., McNaughton, N., Flanagan, D., & Kirk, I. J. (2008). Frontal-midline theta from the perspective of hippocampal “theta”. *Prog Neurobiol*, 86(3), 156–185. doi: 10.1016/j.pneurobio.2008.09.005
- Mozer, M. C., Pashler, H., Cepeda, N., Lindsey, R., & Vul, E. (2009). Predicting the optimal spacing of study: A multiscale context model of memory. In *Advances in neural information processing systems* (pp. 1321–1329).
- Nyhus, E., & Curran, T. (2010). Functional role of gamma and theta oscillations in episodic memory. *Neuroscience and Biobehavioral Reviews*, 34(7), 1023–1035. doi: 10.1016/j.neubiorev.2009.12.014
- Olichney, J. M., Van Petten, C., Paller, K. A., Salmon, D. P., Iragui, V. J., & Kutas, M. (2000). Word repetition in amnesia: Electrophysiological measures of impaired and spared memory. *Brain*, 123 (Pt 9), 1948-1963.
- Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data.

- Computational Intelligence and Neuroscience*, 156869. doi: 10.1155/2011/156869
- Pashler, H., Rohrer, D., Cepeda, N. J., & Carpenter, S. K. (2007). Enhancing learning and retarding forgetting: choices and consequences. *Psychonomic Bulletin and Review*, 14(2), 187–193.
- Pavlik, P. I., Jr, & Anderson, J. R. (2005). Practice and forgetting effects on vocabulary memory: an activation-based model of the spacing effect. *Cogn Sci*, 29(4), 559–586. doi: 10.1207/s15516709cog0000_14
- Pfurtscheller, G., & Lopes da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clinical Neurophysiology*, 110(11), 1842–1857.
- Phillips, P. J., Moon, H., Rizvi, S. A., & Rauss, P. J. (2000). The FERET evaluation methodology for face-recognition algorithms. In *Pattern Analysis and Machine Intelligence, IEEE Transactions on* (Vol. 22, pp. 1090–1104). IEEE.
- Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences*, 10(2), 59–63. doi: 10.1016/j.tics.2005.12.004
- Poldrack, R. A., & Wagner, A. D. (2004). What can neuroimaging tell us about the mind? Insights from prefrontal cortex. *Current Directions in Psychological Science*, 13(5), 177–181.
- Polyn, S. M., & Kahana, M. J. (2008). Memory search and the neural representation of context. *Trends in Cognitive Sciences*, 12(1), 24–30. doi: 10.1016/j.tics.2007.10.010
- Polyn, S. M., Norman, K. A., & Kahana, M. J. (2009). A context maintenance and retrieval model of organizational processes in free recall. *Psychol Rev*, 116(1), 129–156. doi: 10.1037/a0014420
- Proverbio, A. M., & Adorni, R. (2009). C1 and P1 visual responses to words are enhanced by attention to orthographic vs. lexical properties. *Neurosci Lett*, 463(3), 228–233. doi: 10.1016/j.neulet.2009.08.001
- Raaijmakers, J. G. (2003). Spacing and repetition effects in human memory: Application

- of the SAM model. *Cognitive Science*, 27(3), 431–452.
- Rugg, M. D., & Curran, T. (2007). Event-related potentials and recognition memory. *Trends in Cognitive Sciences*, 11(6), 251–257. doi: 10.1016/j.tics.2007.04.004
- Russo, R., Parkin, A. J., Taylor, S. R., & Wilks, J. (1998). Revising current two-process accounts of spacing effects in memory. *J Exp Psychol Learn Mem Cogn*, 24(1), 161–172.
- Sederberg, P. B., Howard, M. W., & Kahana, M. J. (2008). A context-based theory of recency and contiguity in free recall. *Psychol Rev*, 115(4), 893–912. doi: 10.1037/a0013396
- Sederberg, P. B., Kahana, M. J., Howard, M. W., Donner, E. J., & Madsen, J. R. (2003). Theta and gamma oscillations during encoding predict subsequent recall. *J Neurosci*, 23(34), 10809–10814.
- Staudigl, T., & Hanslmayr, S. (2013). Theta oscillations at encoding mediate the context-dependent nature of human episodic memory. *Curr Biol*, 23(12), 1101–1106. doi: 10.1016/j.cub.2013.04.074
- Su, L., Fonteneau, E., Marslen-Wilson, W., & Kriegeskorte, N. (2012). Spatiotemporal searchlight representational similarity analysis in EMEG source space. In *Pattern recognition in neuroimaging (prni), 2012 international workshop on* (pp. 97–100).
- Summerfield, C., & Mangels, J. A. (2005). Coherent theta-band EEG activity predicts item-context binding during encoding. *NeuroImage*, 24(3), 692–703. doi: 10.1016/j.neuroimage.2004.09.012
- Thios, S. J., & D'Agostino, P. R. (1976). Effects of repetition as a function of study-phase retrieval. *Journal of Verbal Learning and Verbal Behavior*, 15(5), 529–536.
- Tucker, D. M. (1993). Spatial sampling of head electrical fields: the geodesic sensor net. *Electroencephalography and Clinical Neurophysiology*, 87(3), 154–163.
- Tulving, E., & Thomson, D. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological review*, 80(5), 352–373.

- Turk-Browne, N. B., Simon, M. G., & Sederberg, P. B. (2012). Scene representations in parahippocampal cortex depend on temporal context. *J Neurosci*, 32(21), 7202–7207. doi: 10.1523/JNEUROSCI.0942-12.2012
- Van Strien, J. W., Verkoeijen, P. P. J. L., Van der Meer, N., & Franken, I. H. A. (2007). Electrophysiological correlates of word repetition spacing: ERP and induced band power old/new effects with massed and spaced repetitions. *Int J Psychophysiol*, 66(3), 205–214. doi: 10.1016/j.ijpsycho.2007.07.003
- Vilberg, K. L., Moosavi, R. F., & Rugg, M. D. (2006). The relationship between electrophysiological correlates of recollection and amount of information retrieved. *Brain Research*, 1122(1), 161–170. doi: 10.1016/j.brainres.2006.09.023
- Vogel, E. K., & Luck, S. J. (2000). The visual n1 component as an index of a discrimination process. *Psychophysiology*, 37(2), 190–203.
- Wagner, A. D., Maril, A., & Schacter, D. L. (2000). Interactions between forms of memory: when priming hinders new episodic learning. *J Cogn Neurosci*, 12 Suppl 2, 52–60. doi: 10.1162/089892900564064
- Wilding, E. L. (2000). In what way does the parietal ERP old/new effect index recollection? *International Journal of Psychophysiology*, 35(1), 81–87.
- Wilding, E. L., & Rugg, M. D. (1996). An event-related potential study of recognition memory with and without retrieval of source. *Brain*, 119, 889–905.
- Xiao, J., Hays, J., Ehinger, K. A., Oliva, A., & Torralba, A. (2010). SUN database: Large-scale scene recognition from abbey to zoo. In *Computer vision and pattern recognition (CVPR), 2010 IEEE conference on* (pp. 3485–3492).
- Xue, G., Dong, Q., Chen, C., Lu, Z., Mumford, J. A., & Poldrack, R. A. (2010). Greater neural pattern similarity across repetitions is associated with better memory. *Science*, 330(6000), 97–101. doi: 10.1126/science.1193125
- Xue, G., Mei, L., Chen, C., Lu, Z.-L., Poldrack, R., & Dong, Q. (2011). Spaced learning enhances subsequent recognition memory by reducing neural repetition suppression.

J Cogn Neurosci, 23(7), 1624–1633. doi: 10.1162/jocn.2010.21532