

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

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Abstract

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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, 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 EEG (Manns, Howard, & Eichenbaum, 2007; 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 retrieves 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. 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). (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 others models as well (e.g., Howard & Kahana, 2002; Polyn, Norman, & Kahana, 2009).

Assuming that a study repetition brings to mind its prior occurrence(s), study-phase retrieval theory predicts the reinstatement of neural context (Lohnas & Kahana, 2014). Specifically, the neural activity during a repetition A' will be more similar to its initial presentation A (due to study-phase retrieval) than to the items just prior to the repetition A', given a spaced trial. This is different than what would be expected under the contextual variability theory where context should simply drift (A' would be more similar to the items just prior to it than to presentation A). Along these lines, Turk-Browne, Simon, and Sederberg (2012) showed that during visual scene processing, an identical 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 (supporting study-phase retrieval).

Contextual reinstatement is also thought to occur during a memory test. Some models assume that the current contextual state is used as a cue for 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).

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 as described above 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 previous 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 like continuous recognition, which does not seem ideal to base new 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

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.

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.

(Probably need to explain power and desynchronization.)

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). Voltage for a repetition becomes more negative as lag increases (Kim, Kim, & Kwon, 2001); this shows that spaced repetitions elicit semantic activation processes (AH asked: how does this show it?) 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.

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.

If massed repetitions are perceived as having stronger memory strengths compared to spaced repetitions (due to being primed and/or in working memory), retrieval mechanisms do not need to engage (Greene, 1989; Van Strien et al., 2007). The FN400 ERP effect (negative frontal peak similar to but different from the N400) indexes familiarity (Curran, 2000; Mecklinger, 2006; Rugg & Curran, 2007) and should attenuate more for massed repetitions than spaced because massed will feel more familiar. The FN400 is unlikely to be affected by attentional fluctuations during encoding (Curran, 2004) and should simply differentiate old/new recognition.

In contrast, the parietal old/new effect (late positive peak, also sometimes called the late positive component or LPC) is a recognition memory ERP component that indexes 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 effects (Olichney et al., 2000; Van Strien et al., 2007), and is linked to successful 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.

Therefore, given that the effect indexes retrieval, study-phase retrieval might predict a

larger effect for spaced repetitions than for massed, as spaced need to be retrieved from long-term memory but massed do not. However, based on prior repetition research we do not expect this to be the case.

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

have a bearing 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 will be recruited for each of two experiments. In EEG sessions, participants will either be given course credit (AH: How many? Were there credit subjects for SPACE EEG?) or paid \$15 per hour, and all experiments will last approximately 2 hours. All research will be conducted under the guidelines for human studies research at the University of Colorado Boulder. The method for the proposed studies will generally follow Experiment 1 (random stimulus assignment, hand counterbalancing, EEG recording, processing, and analysis, etc.); two sessions were used in Experiment 2.

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 will be 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 a monospaced 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 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

¹<http://memory.psych.upenn.edu>

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

were included at test).

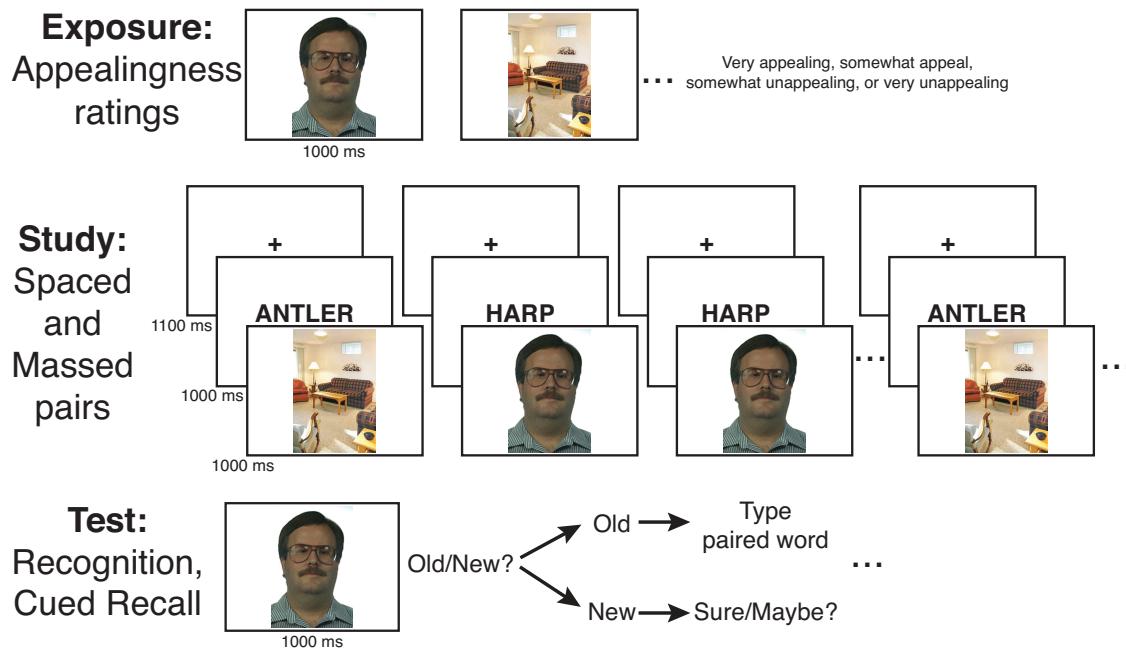


Figure 1. Experiment 1: Exposure, study, and test phases

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 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. The face and house presentations can be used for training classifiers.

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 pairs 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.

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

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

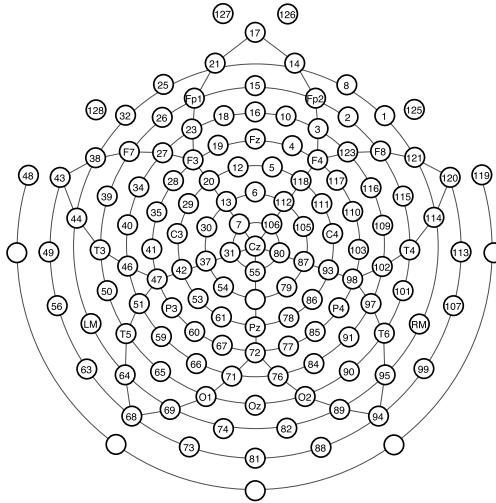


Figure 2. The 128-channel HydroCel Geodesic Sensor NetTM used to measure the EEG. In this top-down schematic the participant's nose is toward the front.

at 0.1 Hz, low-pass filter at 100 Hz, and a notch filter from 59–61 Hz were applied to the 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.

Since the N400 and LPC have precedent in the repetition literature we will analyze these components for semantic processing and memory effects, along with the visual N1 for attentional effects. We chose data for most analyses by finding the peak electrode and latency for each ERP component, and used a ± 50 ms window for the N400 and N1 and a ± 100 ms window for the LPC, as late effects tend to spread out more than earlier effects.

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.

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 also 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.

We would not expect differences 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 include these single and initial presentations in analyses as a baseline, but time–frequency analyses will focus on the second presentation (the repetition) and show the single-presentation stimuli in data plots.

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.

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. Again, during studied words the visual N1 peaked at 172 ms (Figure 3), the N400 peaked at 372 ms (Figure 4), and the LPC peaked at 596 ms (Figure 5). Significant results are reported.

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 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.

If attention is modulated by spacing, early ERP components may show effects. The visual N1 typically shows effects of selective attention. This is particularly relevant to deficient processing.

For the visual N1 voltage, a three-way ANOVA with factors of spacing, presentation, and subsequent memory was performed. A crossover pattern was borne out in the

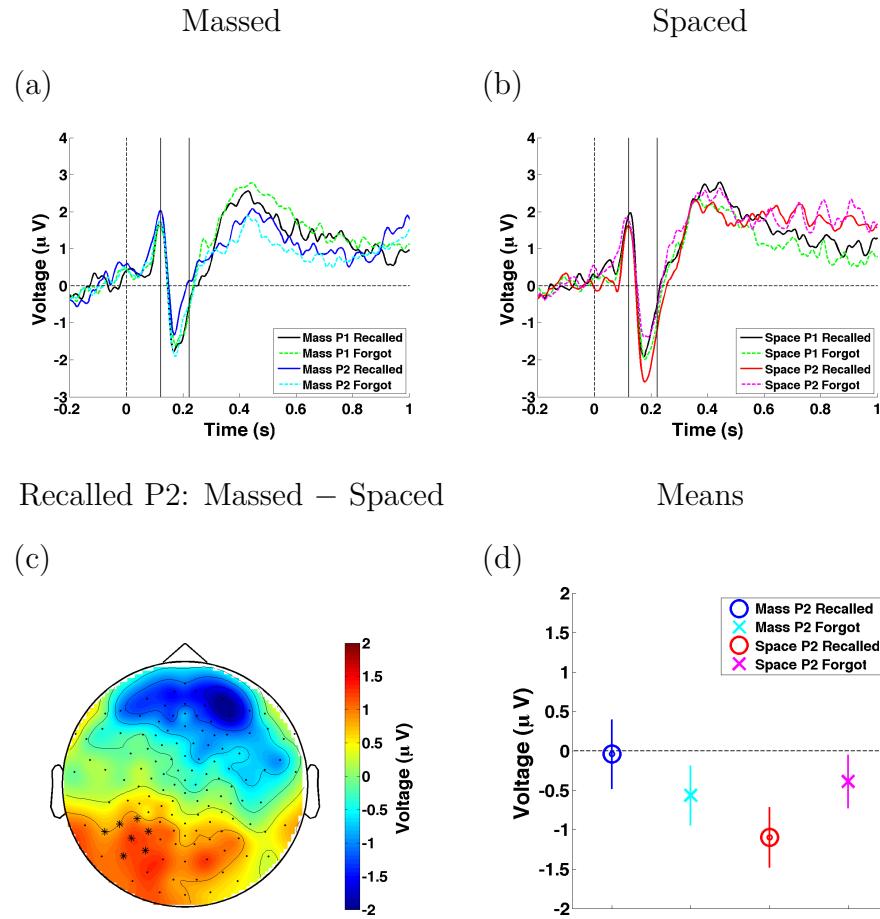


Figure 3. N1 to words at electrode 58 (T5) and neighbors, analyzed window 122–222 ms: (a) Massed ERPs; (b) spaced ERPs; (c) contrast between subsequently recalled massed *vs.* spaced Presentation 2 (P2) across time and electrodes (*); (d) analyzed means (error bars are SEM). The early negative peak is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

significant three-way interaction [$F(1, 22) = 10.5, p < .005$]. Pairwise comparisons showed that 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 ($M = -0.56 \mu\text{V}$) [$t(22) = 2.039, p = .053$].

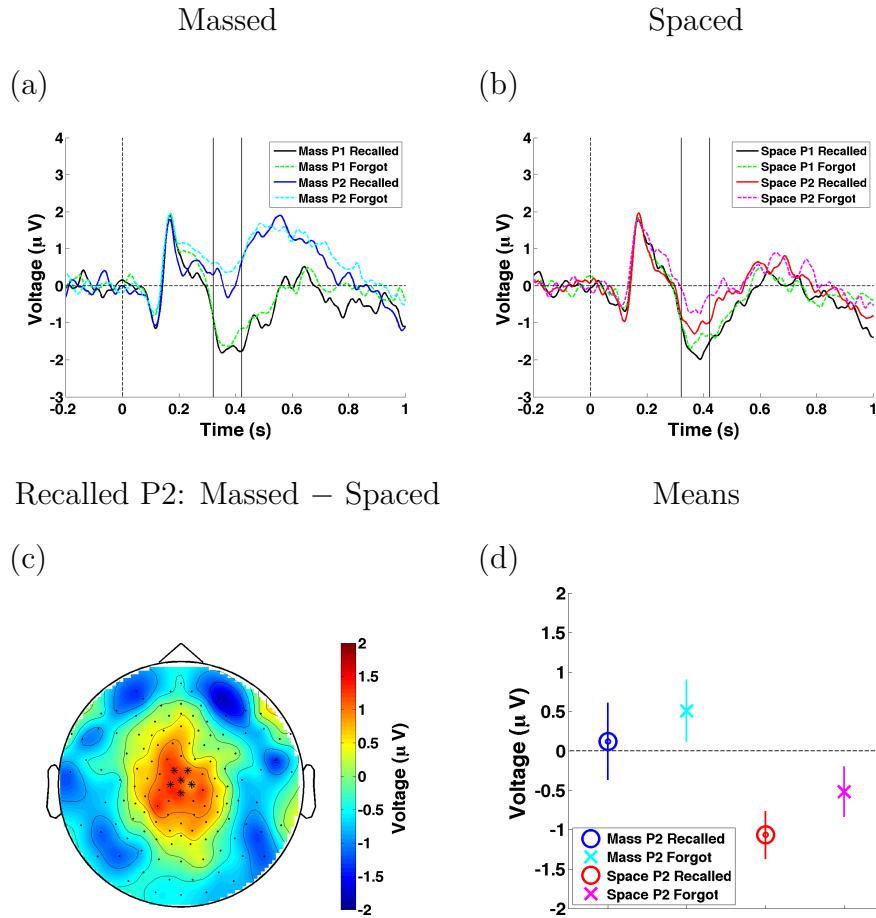


Figure 4. N400 to words at electrode Cz and neighbors, analyzed window 322–422 ms: (a) Massed ERPs; (b) spaced ERPs; (c) contrast between subsequently recalled massed *vs.* spaced Presentation 2 (P2) across time and electrodes (*); (d) analyzed means (error bars are SEM). The negative peak at 400 ms 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 N400 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 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 LPC 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 LPC latency there was a significant interaction of spacing \times presentation [$F(1, 22) = 7.5, p < .05$]. Massed repetitions ($M = 563 \text{ ms}$) peaked earlier than all other conditions (spaced repetition: $M = 605 \text{ ms}$; massed initial: $M = 589 \text{ ms}$; spaced initial: $M = 597 \text{ ms}$ [$p < .005$]).

ERP discussion. The N1 showed that recalled spaced word repetitions were more negative compared to the other conditions (repetitions of recalled massed words and forgotten spaced and massed words), indicating that more attention was paid to these

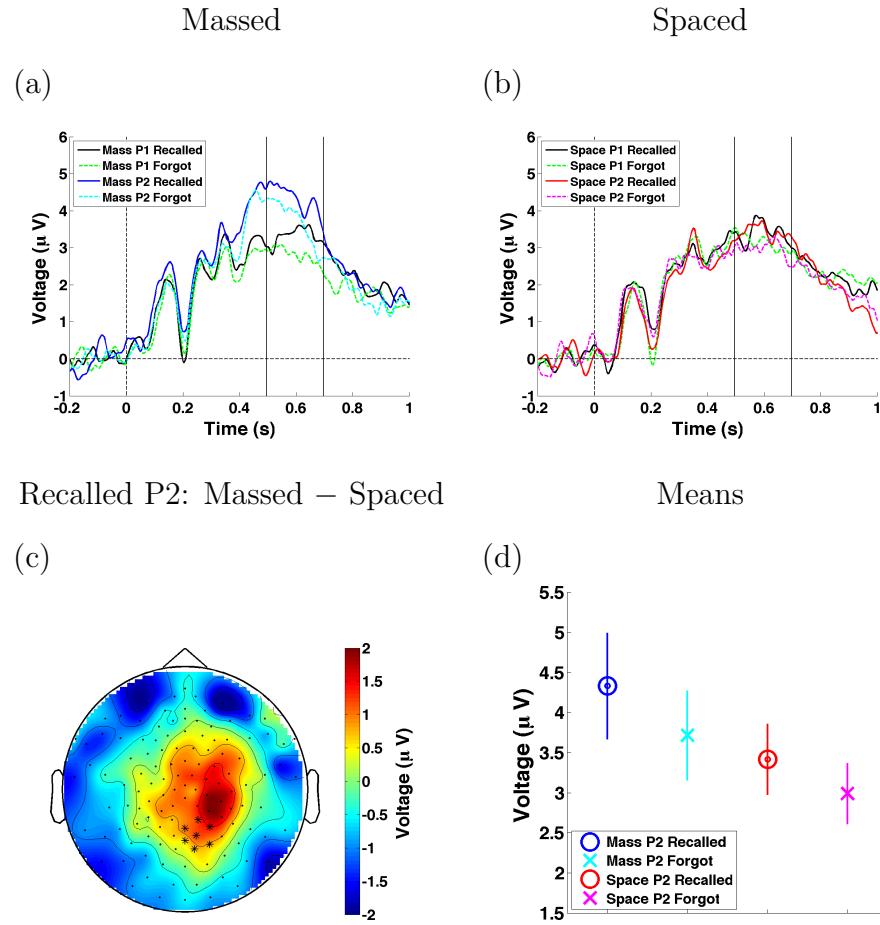


Figure 5. LPC to words at electrode 77 and neighbors, analyzed window 496–696 ms: (a) Massed ERPs; (b) spaced ERPs; (c) contrast between subsequently recalled massed *vs.* spaced Presentation 2 (P2) across time and electrodes (*); (d) analyzed means (error bars are SEM). The positive peak around 600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

items. This finding implies that attentional processing affects subsequent memory. If this is the case, massed items are at a disadvantage compared to remembered spaced items, supporting the deficient processing hypothesis. Because remembered massed items are the least negative 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 is engaged 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 finding also indicates that more semantic processing occurs for these items. Spaced items seem to have an overall processing advantage, or perhaps massed items have an overall disadvantage due 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 in repetition paradigms 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 our earlier results, 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 deficient processing to engage.

Time-frequency results. Since oscillatory effects can spread out over time (especially at low frequencies), we analyzed images in addition to words because there are no time-locked oscillatory “components” *per se* like with ERPs that would be perturbed by image stimuli immediately following words. Because word and image stimuli are presented

successively, we need to take into account 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 isolated by frequency band (theta, lower alpha, and upper alpha and lower beta, respectively).

Only repetition events were analyzed.

Three-way ANOVAs with factors of spacing (spaced and massed), subsequent memory (recalled and forgotten), and latency (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).

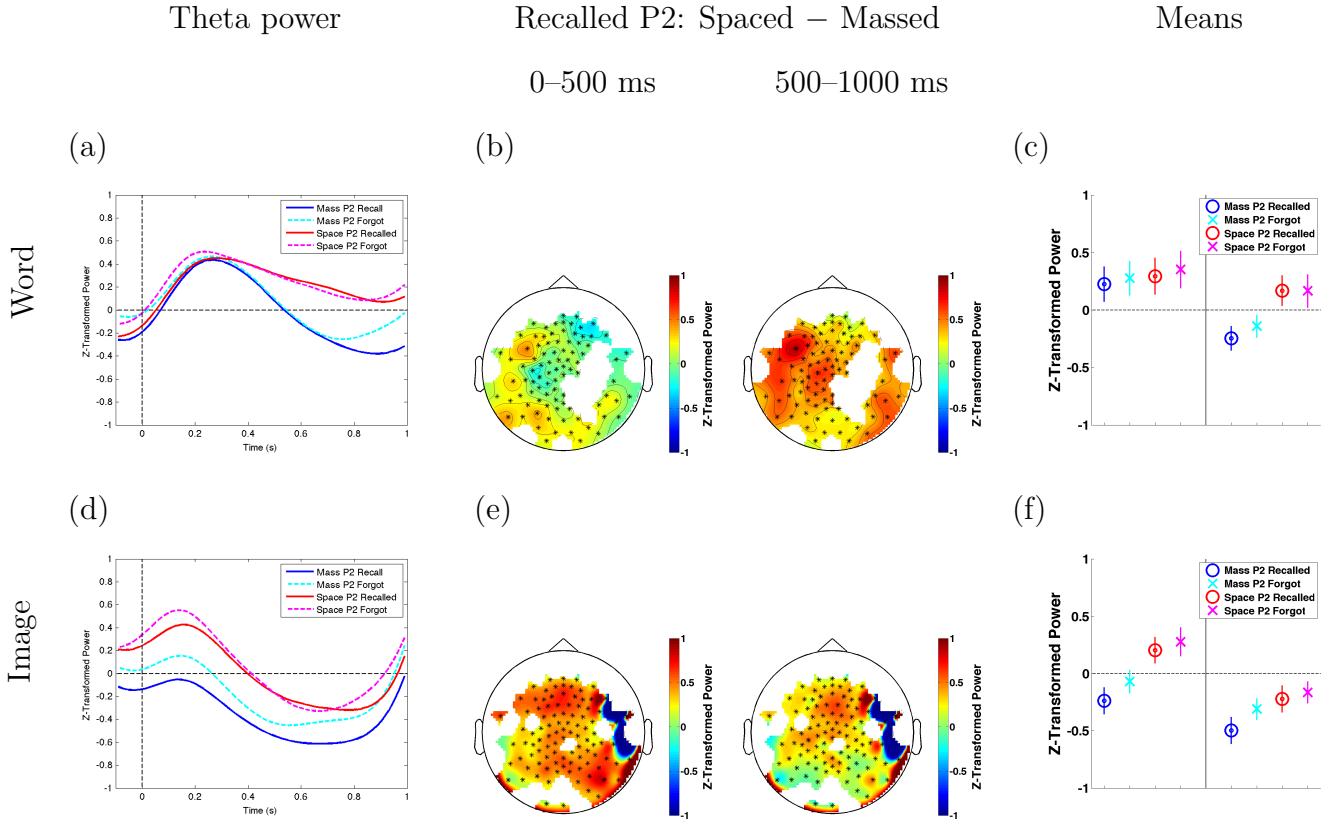


Figure 6. Theta power to words and images. (a) and (d) Grand averages; (b) and (e) contrast topographic plot between spaced and massed subsequently recalled trials displaying only the analyzed electrodes (*); (c) and (f) mean values for the two time windows (error bars are SEM).

Word, theta: Across 89 electrodes (Figure 6, top), theta showed a spacing × latency 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 latency [$F(1, 22) = 23.6, p = 7.4e^{-05}$] following the same patterns.

Image, theta: Across 99 electrodes (Figure 6, bottom), theta continued to show a spacing × latency 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 latency [$F(1, 22) = 30.6, p = 1.46e^{-05}$] 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. $M = -0.067$).

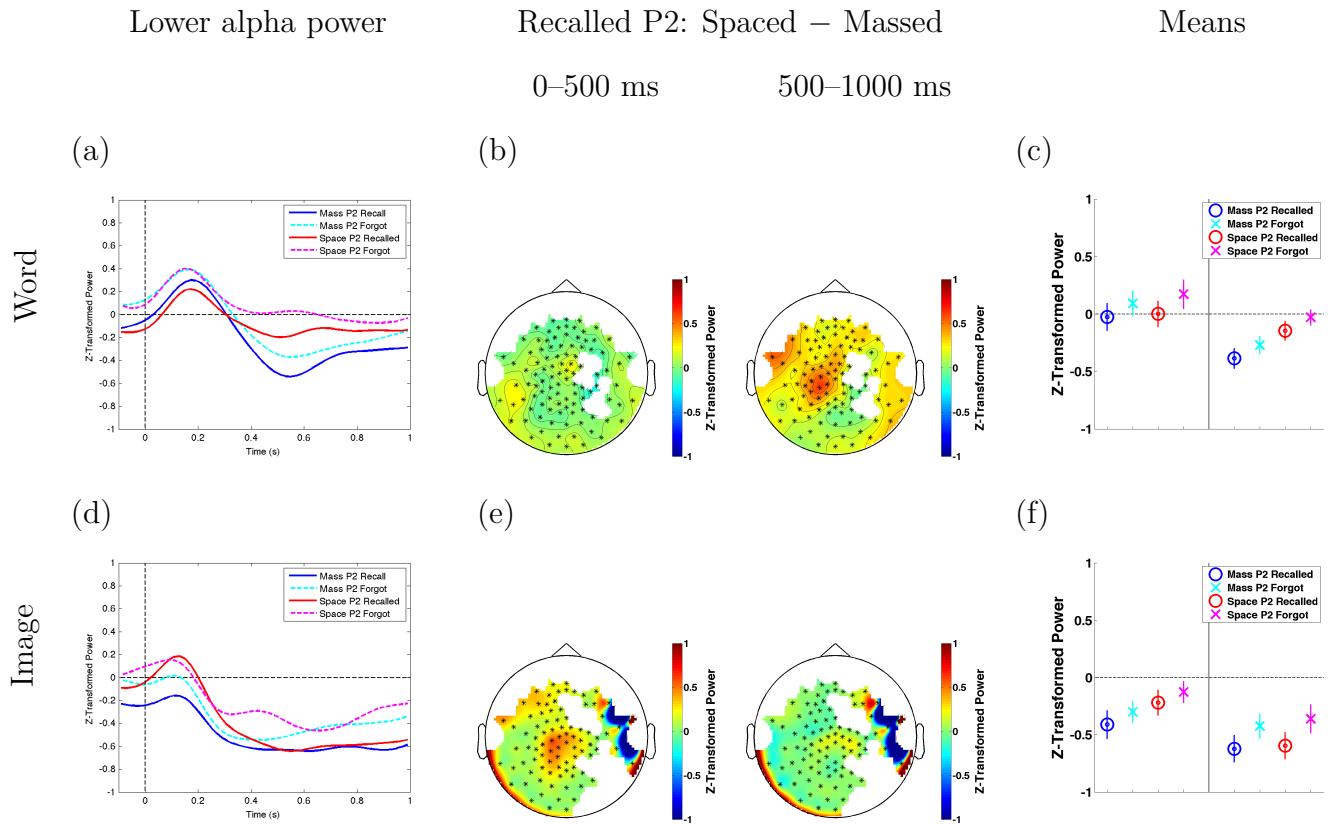


Figure 7. Lower alpha power to words and images. (a) and (d) Grand averages; (b) and (e) contrast topographic plot between spaced and massed subsequently recalled trials displaying only the analyzed electrodes (*); (c) and (f) mean values for the two time windows (error bars are SEM).

Word, lower alpha: Across 101 electrodes (Figure 7, top), lower alpha showed a

spacing \times latency 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 latency [$F(1, 22) = 15.3, p = .00074$] (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 latency 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 latency [$F(1, 22) = 21.4, p = .000131$] (less power in the later time window).

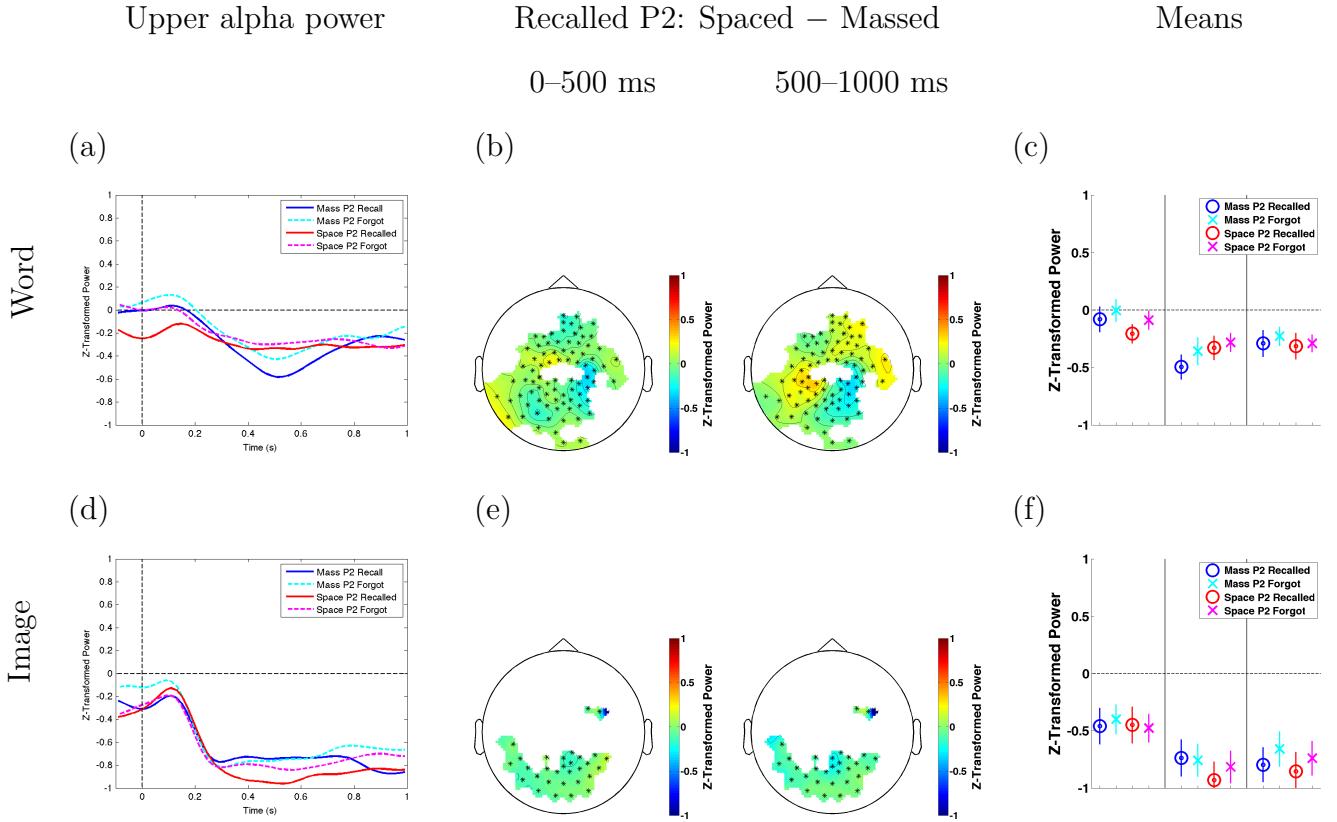


Figure 8. Upper alpha power to words and images. (a) and (d) Grand averages; (b) and (e) contrast topographic plot between spaced and massed subsequently recalled trials displaying only the analyzed electrodes (*); (c) and (f) mean values for the three time windows (error bars are SEM).

Word, upper alpha: Across 82 electrodes (Figure 8, top), upper alpha only showed a main effect of latency 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 latency interaction [$F(2, 44) = 7.46, p = .00377$, Greenhouse-Geisser corrected]. Massed were more negative in the middle time window than in neighboring time windows [$ps < .05$], and were more negative than spaced in the first and second time windows [$ps < .05$].

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 latency [$F(1, 22) = 21.2, p = .000138$] (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 [$p < .05$].

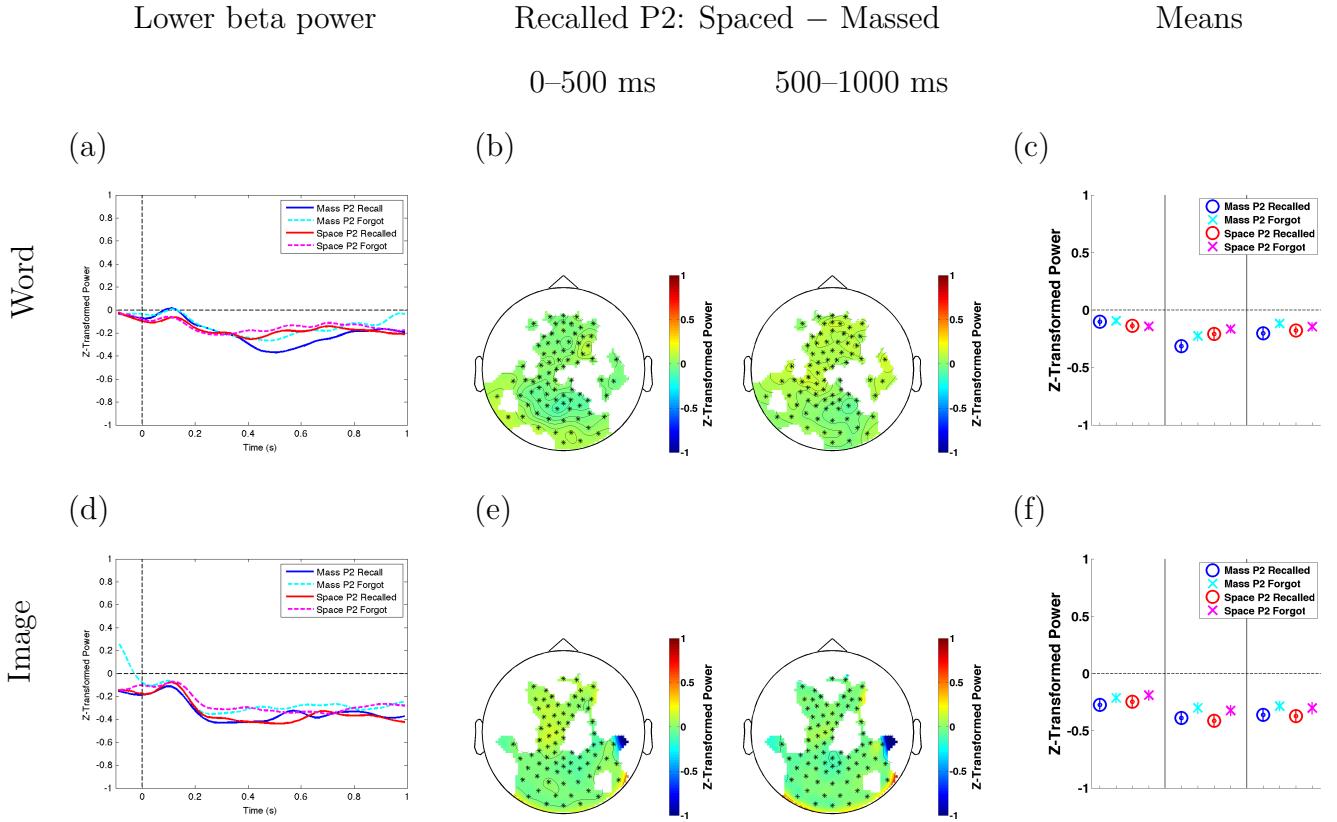


Figure 9. Lower beta power to words and images. (a) and (d) Grand averages; (b) and (e) contrast topographic plot between spaced and massed subsequently recalled trials displaying only the analyzed electrodes (*); (c) and (f) mean values for the three time windows (error bars are SEM).

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 latency 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 latency 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 latency [$F(2, 44) = 12.9, p = 5.28e^{-05}$] 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 latency [$F(2, 44) = 29.3, p = 1.14e^{-08}$] (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 subsequent memory effect for images remains to be explored (c.f., Staudigl & Hanslmayr, 2013).

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, 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. This band remains to be characterized better (Klimesch et al., 2007).

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 latency interaction after dividing power for words into three time windows. 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 item–context 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 power 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. Images were used because this is when word–image binding (an item–context association) 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. 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 voltage 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 similarity values from left and right temporal regions with factors of spacing (spaced and massed), subsequent memory (recalled and not recalled), and latency (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 latency 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.

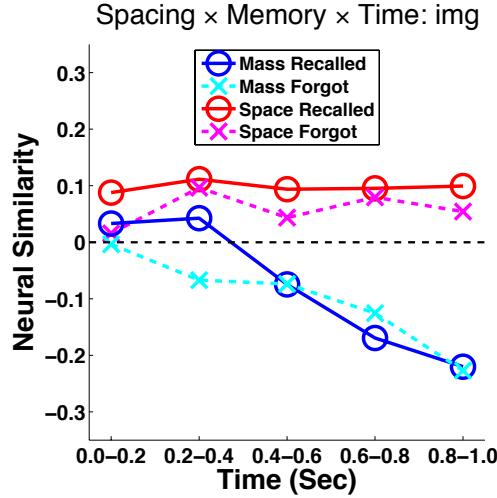


Figure 10. Similarity for voltage at left and right temporal sites during image repetitions: Interaction between spacing, memory, and time [n.s.].

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 latency [$F(4, 108) = 3.42, p = .0116$], 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.

Similarity discussion. It is clear that the way massed and spaced stimuli are processed and represented across their repetitions is different. Surprisingly, the patterns

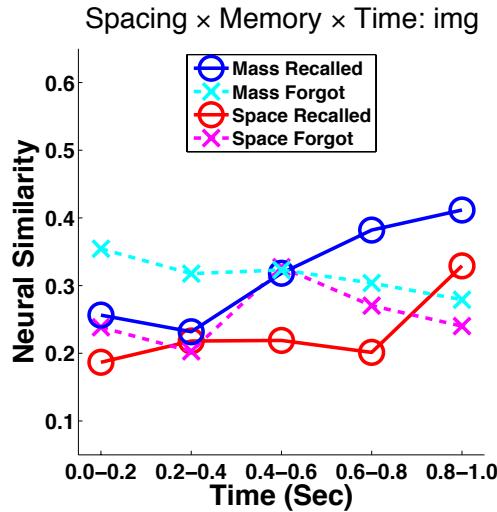


Figure 11. Similarity for oscillatory power at left and right parietal sites during image repetitions: Interaction between spacing, memory, and time [$p = .0535$].

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 power analysis, the increase in similarity leading to the subsequent memory effects support 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).

In relation to the experiment, 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, as indexed by the N1, and semantic processing, as indexed by upper alpha, benefits subsequent memory. Further work needs to be done to investigate the nature of neural representations across repeated study episodes. Integration across the neural effects is discussed below.

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. This 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.

Both contextual variability and deficient processing predict a decrease in similarity for massed items over time. However, contextual variability predicts that context has not drifted between massed presentations, and so we would not expect a difference due to contextual variability. However, this result cannot completely support deficient processing because differential activation of neural processes across repetitions (not due to memory trace differences) would also support a decrease in similarity. Spaced, on the other hand, maintain a consistent amount of similarity between repetitions over time. Here, either the same memory representation is retrieved at the second presentations, the same processes are engaged, or both of these occur. This might 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 (2a in the proposal) 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 short 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 long lags, or we may see other effects change in a graded fashion.

Design and Predictions

Again, the purpose of this experiment is to look for gradations in EEG effects so we can 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; that is, 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 ?–?, $M = ?$; ? 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 nine blocks of three experimental phases: study, distractor, test. These phases were similar to Experiment 1 (Figure 1, page 21), but there was no exposure phase. 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 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 are repeated. 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). 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. The procedure for recording and processing electrophysiological data was the same as in Experiment 1.

The same methodology was used to find peak electrodes and latencies for analyzing ERP effects. Peaks in Experiment 2 were at the same electrodes as in the previous experiment, but were slightly earlier in time. (Comment/question for Tim: I think latency difference is because for Exp 1 we didn't know about the EGI's A/D DIN delay so the correct offset (8 ms @ 250 Hz) was not used. Also, I used the average photocell offset for Exp 2 (17 ms) because tclab didn't want to deal with the photocell for every session, but I segmented to the actual photocell DINs for Exp 1. What should I do about this? The "correct" thing would be to redo Exp 1 analysis...) 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, though it is hard to give a reason for this.

Time-frequency processing and analyses also followed the same procedures as in Experiment 1.

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.

Behavioral results. An ANOVA with factors of session (1 and 2), spacing (single presentation, massed, short, medium, and long spaced), and image category, was run on cued recall hit rate. There was a main effect of spacing [$F(1, 29) = 174.2, p = 0$] 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 spacing, as well as a simple repetition effect. These rates are comparable to Experiment 1.

There were also session \times image category [$F(1, 29) = 7.96, p = .0086$] and spacing \times image category [$F(4, 116) = 7.52, p = 4.47e^{-5}$] 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 elapses between a short spaced item 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. Again, during studied words the visual N1 peaked at 144 ms (Figure 12), the N400 peaked at 352 ms (Figure 13), and the LPC peaked at 536 ms (Figure 14). 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.

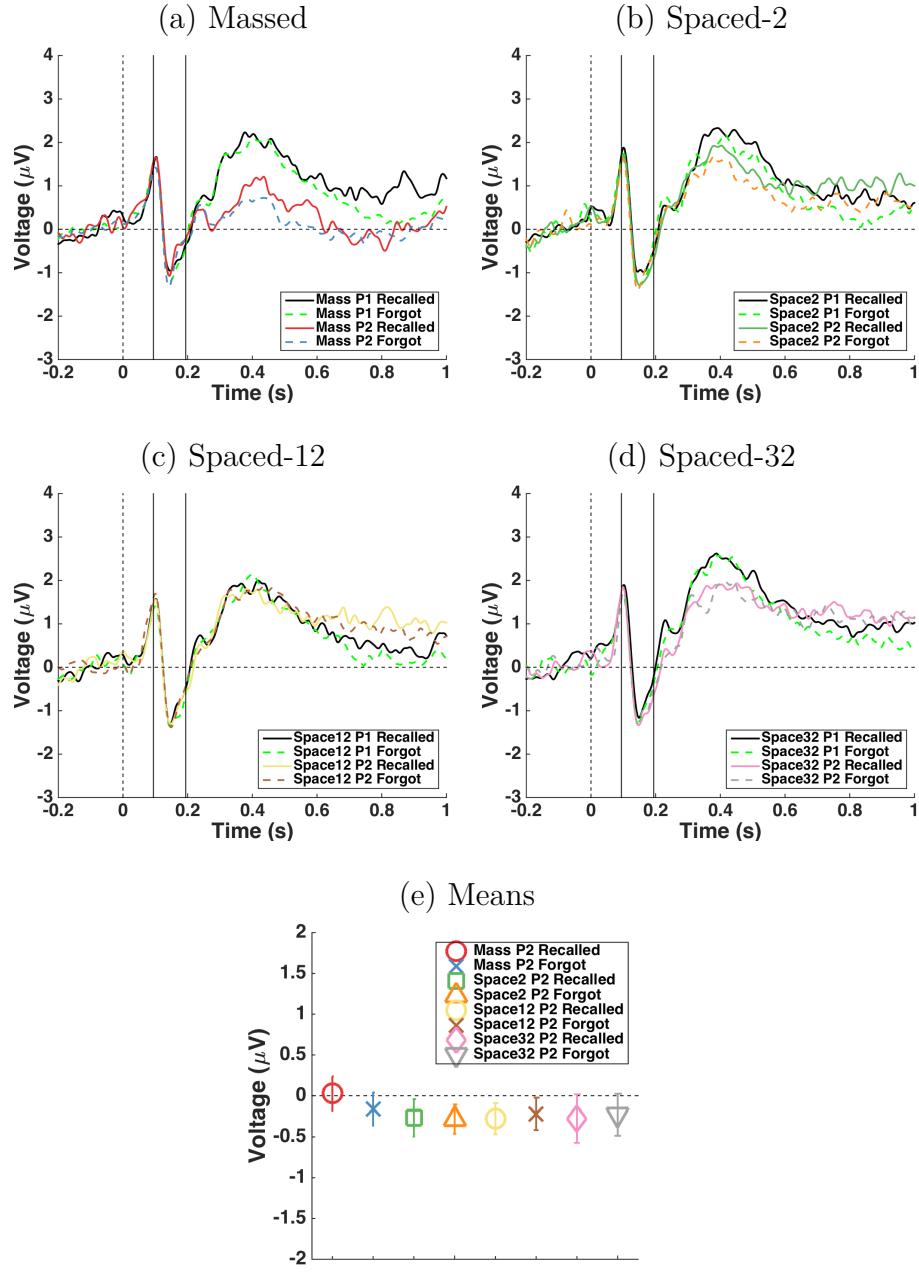


Figure 12. N1 to words at electrode 58 (T5) and neighbors, analyzed window 94–194 ms: (a) Massed ERPs; (b) short spaced ERPs; (c) medium spaced ERPs; (d) long spaced ERPs; (e) analyzed means (error bars are SEM). The early negative peak is not different across spaced and massed conditions.

If selective attention is modulated by spacing, early ERP components may show effects; this is relevant to deficient processing. However, there were no significant differences for N1 voltage.

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 [$F(3, 78) = 2.93, p < .05$], perhaps driven by remembered medium (12) spaced repetitions being more negative than forgotten ones [$t(26) = 2.45, p < .05$], while remembered massed repetitions were marginally more positive than forgotten ones [$t(26) = -1.78, p = .087$].

The LPC is related to working memory in repetition paradigms, and may show subsequent memory effects.

For LPC voltage, there were main effects for spacing, presentation, and memory. Massed words were more positive than all spaced conditions [$F(3, 78) = 5.68, p < .005$], repetitions were more positive than initial presentations [$F(1, 26) = 31.6, p = 6.52e^{-6}$], and subsequently recalled words ($M = 2.81 \mu\text{V}$) were more positive than forgotten ($M = 2.28 \mu\text{V}$) [$F(1, 26) = 22.4, p = 6.88e^{-5}$].

There was no three-way interaction, but when examining 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

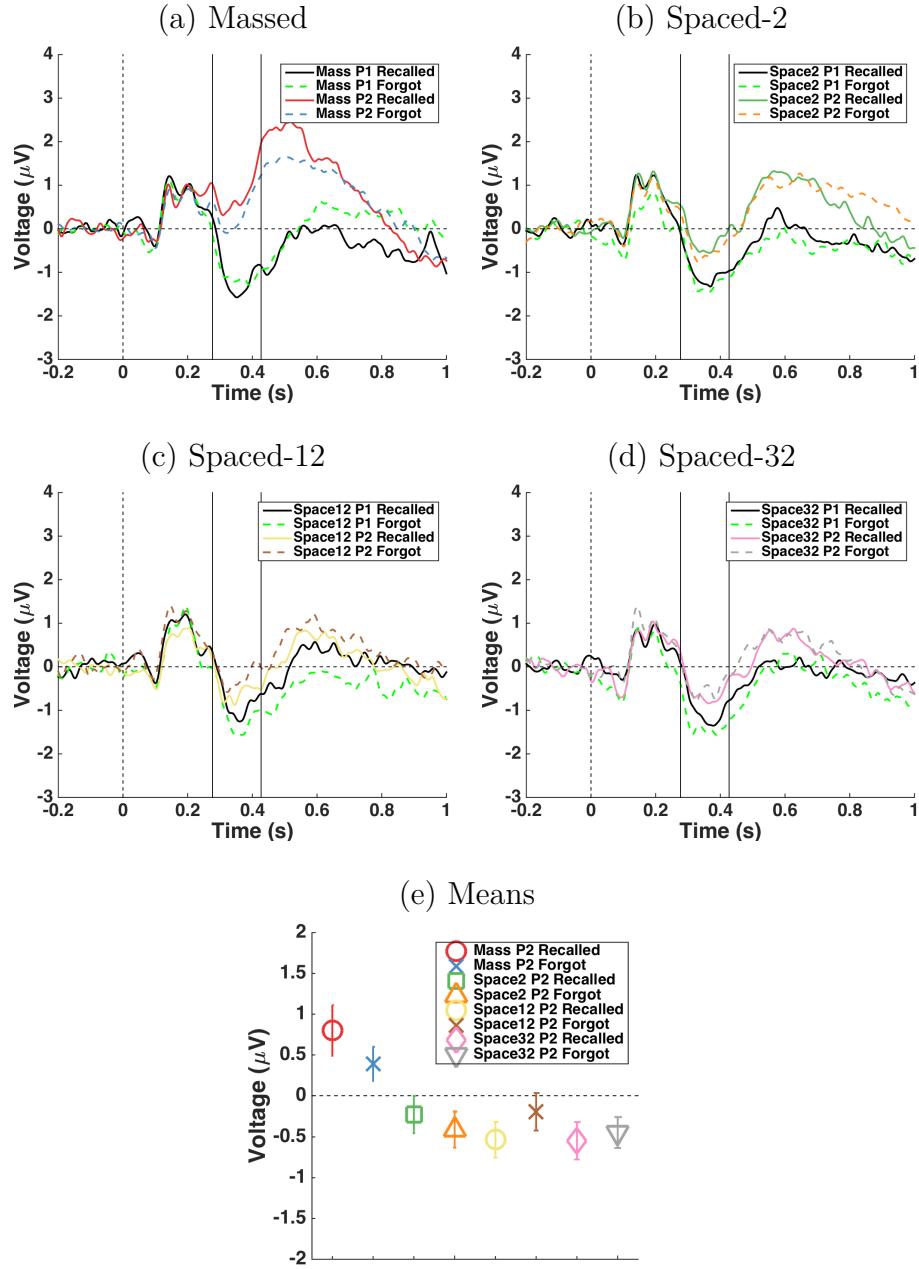


Figure 13. N400 to words at electrode Cz and neighbors, analyzed window 227–427 ms:
 (a) Massed ERPs; (b) short spaced ERPs; (c) medium spaced ERPs; (d) long spaced ERPs;
 (e) analyzed means (error bars are SEM). The negative peak at 400 ms is significantly smaller for massed repetitions compared to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

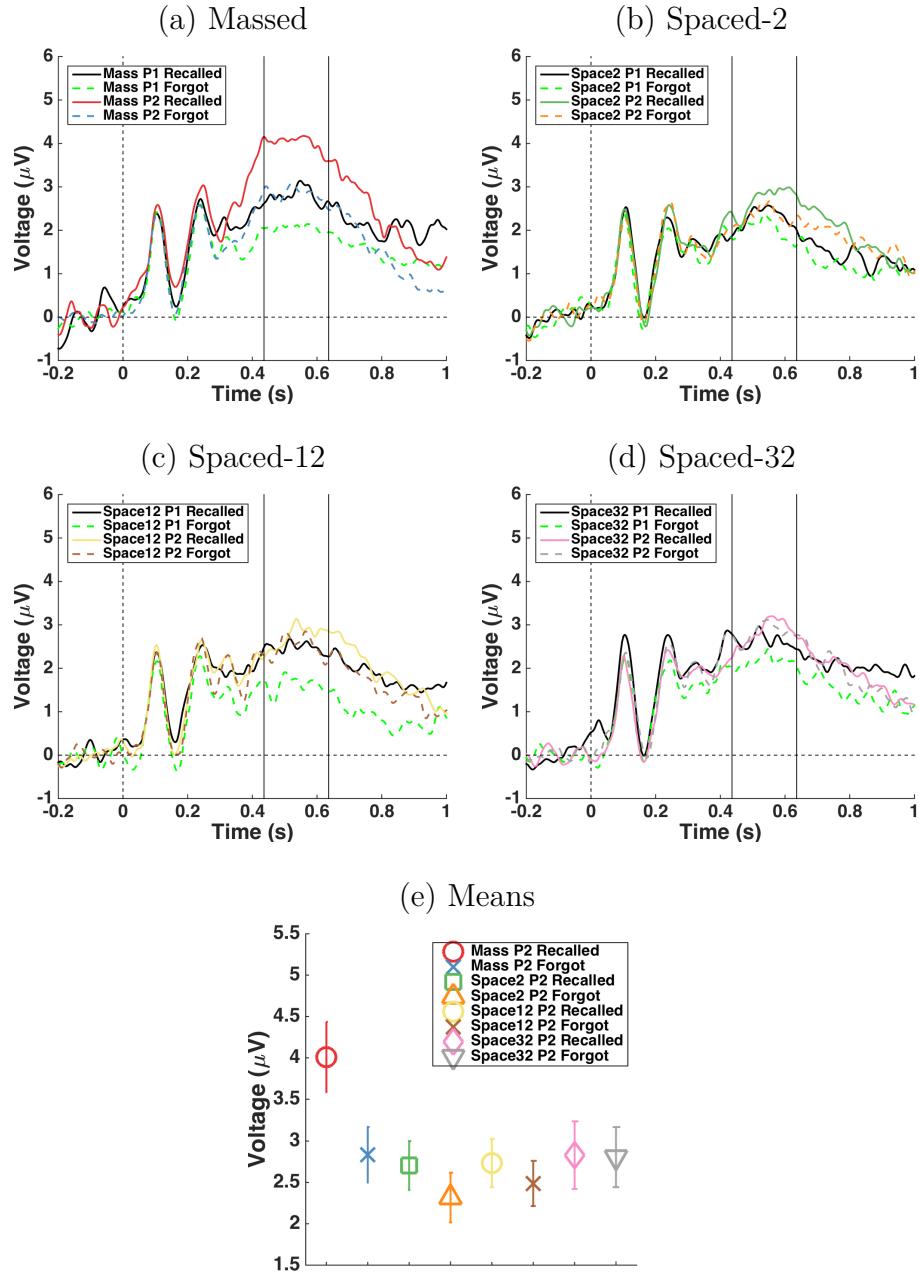


Figure 14. LPC to words at electrode 77 and neighbors, analyzed window 436–636 ms: (a) Massed ERPs; (b) short spaced ERPs; (c) medium spaced ERPs; (d) long spaced ERPs; (e) analyzed means (error bars are SEM). The positive peak around 600 ms is significantly larger for massed compared to spaced repetitions.

decreased with lag.

There were no LPC latency effects.

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 between a massed item and a repetition at lag 12. However, for N1 voltage there were no significant differences.

That there were no N1 effects at all is interesting because Experiment 1 did find effects where they were tied to an attentional component of the spacing effect. This leads to the idea that attention is not a critical factor for why the spacing effect occurs, at least when defining attention as an early involuntary mechanism. On the other hand, perhaps 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). However, 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 this is less evidence to support deficient processing.

An important 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. Based on the results from Experiment 1 we still expected an N1 attenuation for massed items, and it is unclear why this effect disappeared.

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. 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 there was no significant effect of memory (as in Experiment 1).

It seems that a similar amount of semantic processing is engaged when there have been at least two intervening stimulus pairs between repetitions. This would be in line with a deficient processing theory that only posits deficient processing for immediate repetitions; however, behavioral performance does not mimic this pattern. 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 behavioral performance does not mimic this pattern.

Finally, we would expect working memory effects (LPC) to be graded across lags. This could be for two reasons, in opposite directions. First, in terms of memory retrieval (posited under study-phase retrieval), which we might see as a subsequent memory effect. Reinforcement 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. The other idea is that for working memory, effects should be stronger for massed items and decrease with lag; this larger difference for subsequent memory of massed items is what we see.

As exhibited through behavioral performance, spaced items were obviously not forgotten even though they did not show an LPC memory effect, so this effect does not seem to be indexing recollection. This makes sense when comparing its topography (Experiment 1, Figure 5, page 31) to that of the parietal old/new effect, typically more left parietal. 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 for deficient processing to engage.

Thus, the LPC showed that information is being retrieved during repetitions (higher voltage), particularly for primed and/or still active massed items, as well as for subsequently recalled words overall. The two-way ANOVA for repetitions indicates that information is more easily retrieved from memory at shorter lags. Or, perhaps it shows that higher voltage matters more at shorter lags for subsequent memory performance. Since performance was best for the long (32) spaced repetitions, under the study-phase retrieval hypothesis we would expect a sign of retrieval. However, we did not find this.

We still have not found the 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 latency (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).

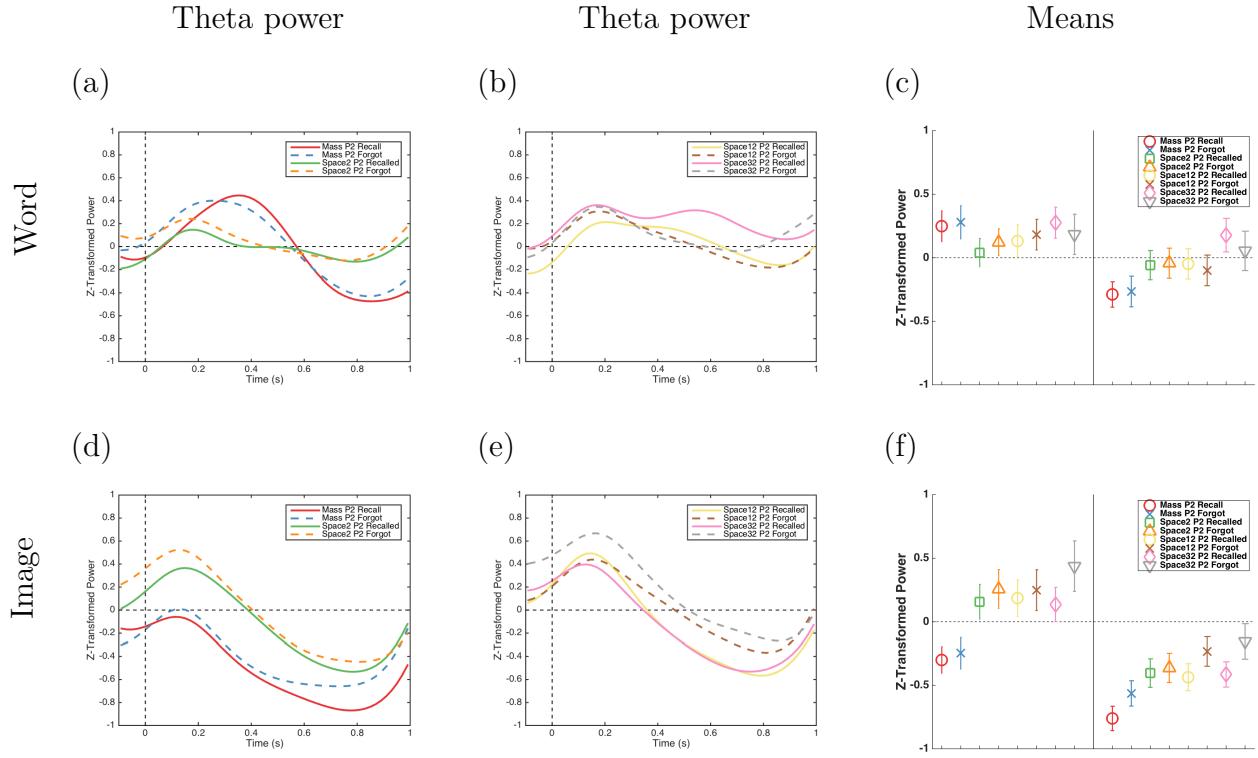


Figure 15. Theta power to words and images. (a), (b), (d), and (e) Grand averages; (c) and (f) mean values for the two time windows (error bars are SEM).

Word, theta: Across 73 electrodes (Figure 15, top), there were main effects of spacing [$F(3, 78) = 4.0, p < .05$] and latency [$F(1, 26) = 33, p = 4.81e^{-6}$]. 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 latency 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 latency [$F(1, 26) = 91.1, p = 5.57e^{-10}$]. Massed items desynchronized more than the other

conditions, subsequently recalled items desynchronized more than forgotten ones, and power decreased across time. A spacing \times latency interaction showed that the decrease in power across time for massed items was less than short and medium spaced repetitions.

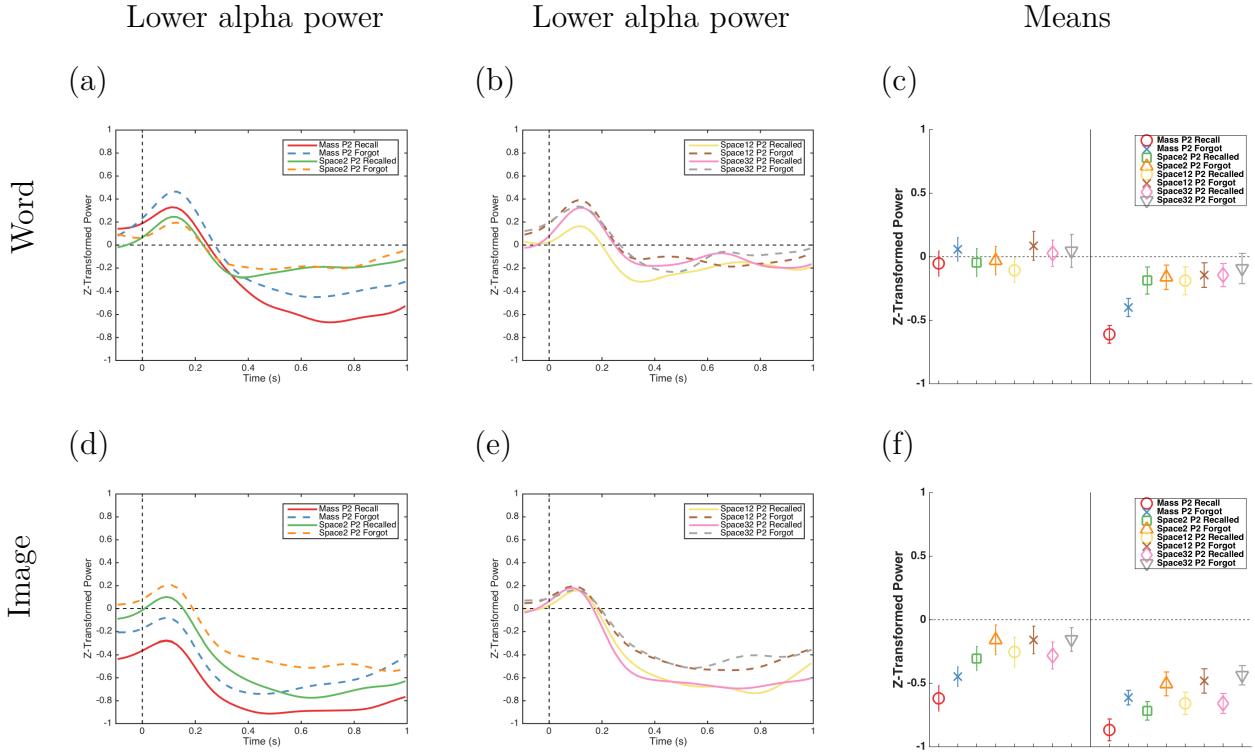


Figure 16. Lower alpha power to words and images. (a), (b), (d), and (e) Grand averages; (c) and (f) mean values for the two time windows (error bars are SEM).

Word, lower alpha: Across 49 electrodes (Figure 16, top), we saw the same spacing \times latency 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 latency [$F(1, 26) = 9.71, p < .005$]. 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 latency 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 latency [$F(1, 26) = 33.6, p = 4.19e^{-6}$] (desynchronization decreased over time). Additionally, there was a memory \times latency interaction [$F(1, 26) = 5.37, p < .05$]; recalled items desynchronized more across time than forgotten ones.

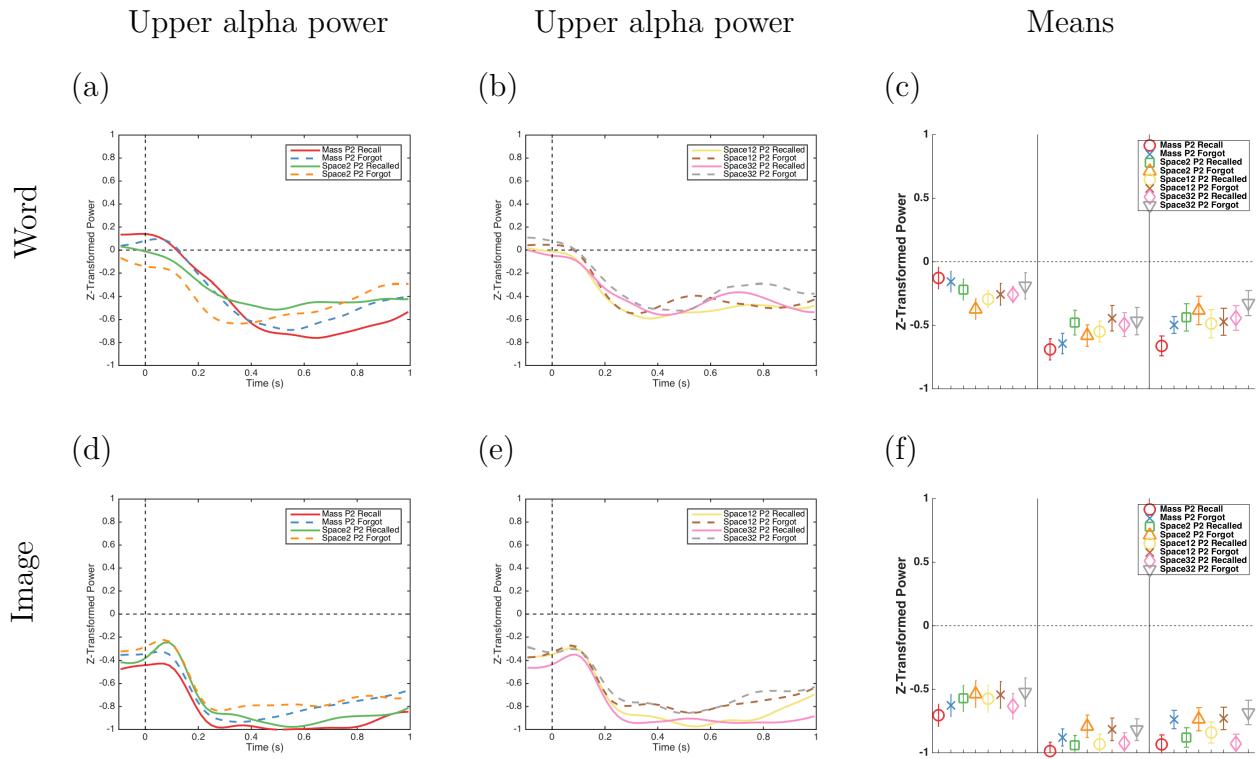


Figure 17. Upper alpha to words and images. (a), (b), (d), and (e) Grand averages; (c) and (f) mean values for the three time windows (error bars are SEM).

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 latency [$F(2, 52) = 18.3, p = 2.36e^{-5}$]: the second and third time windows showed more upper alpha desynchronization than the first. There was also a spacing \times latency 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 latency [$F(2, 52) = 25, p = 3.55e^{-6}$] (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 latency interaction [$F(2, 52) = 6.82, p < .005$] such that remembered items continued to stay desynchronized into the third time window, whereas forgotten items did not.

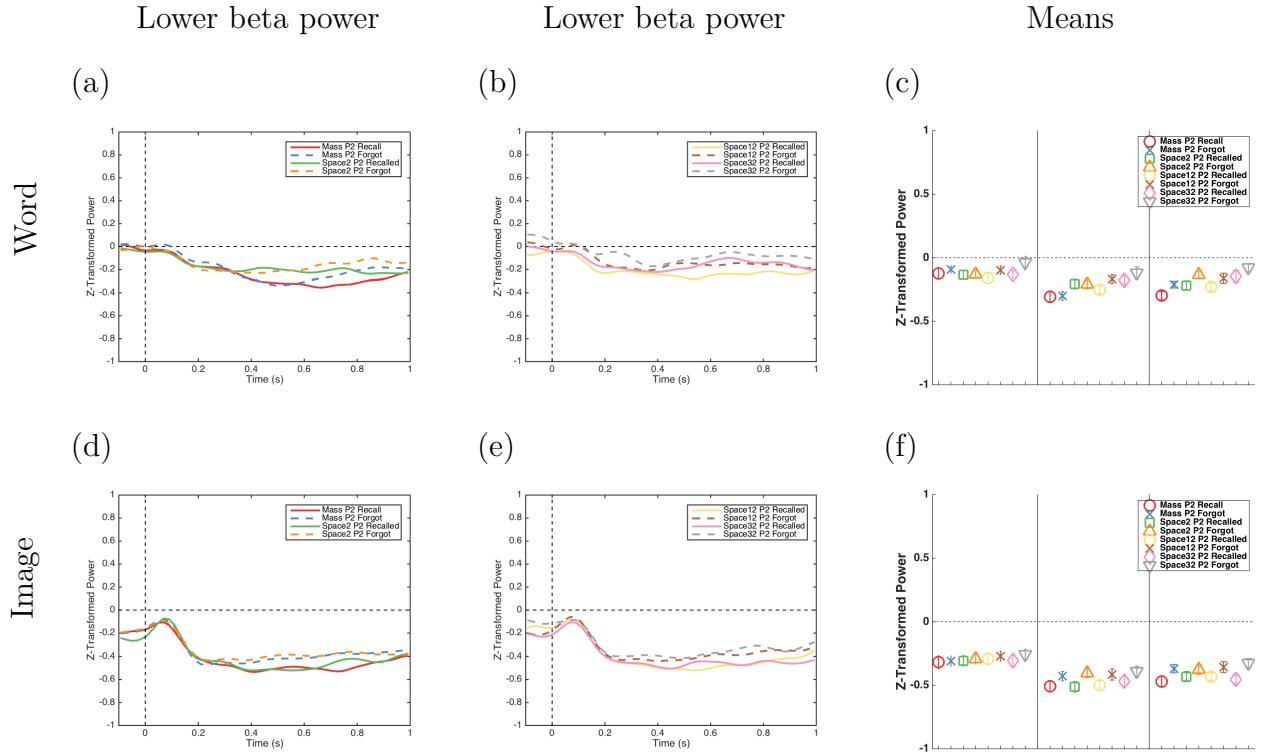


Figure 18. Lower beta power to words and images. (a), (b), (d), and (e) Grand averages; (c) and (f) mean values for the three time windows (error bars are SEM).

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 [$F(1, 26) = 8.36, p < .01$], latency [$F(2, 52) = 25.5, p = 5.06e^{-8}$], a spacing \times latency interaction [$F(6, 156) = 6.96, p = 3.79e^{-6}$] Massed 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, massed items decreased more across time and stayed decreased throughout the trial compared to spaced items.

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 latency [$F(2, 52) = 53.7, p = 3.33e^{-12}$] which followed the patterns of effects reported above: 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 effect, theta is the other place where we expected to see effects of reinstatement, 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 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.

As discussed previously for Experiment 1, lower alpha should correlate negatively with general attentional processes with a widespread scalp topography. Deficient processing would predict increased alpha power for massed repetitions. We also expected to see decreased power (more desynchronization) for better subsequent memory, due to increased attention. Lower alpha results followed Experiment 1: we see the memory effect just described but not the spacing effect in the expected direction. Again, more attention seems to get allocated to massed items. It is possible that these effects are related to orientation during working memory.

For upper alpha, we expected semantic processing to show graded spacing effects: upper alpha for 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 faster semantic processing boost during word presentations, and perhaps because they are in working memory, but spaced are equally processed during the images.

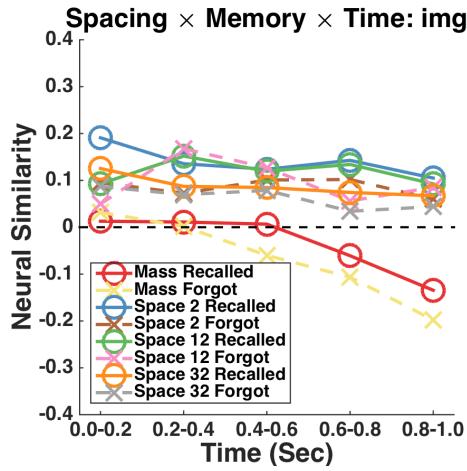


Figure 19. Similarity for voltage at left and right temporal sites during image repetitions: Interaction between spacing, memory, and time [n.s.].

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 (plotted in 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 latency (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 latency [$F(4, 104) = 6.31, p < .0005$]. There was also a spacing \times latency

interaction [$F(12, 312) = 2.99, p = .005$]. Spaced items of all lengths 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 more across time than spaced items. These follow the results of Experiment 1, with the addition of the memory effect.

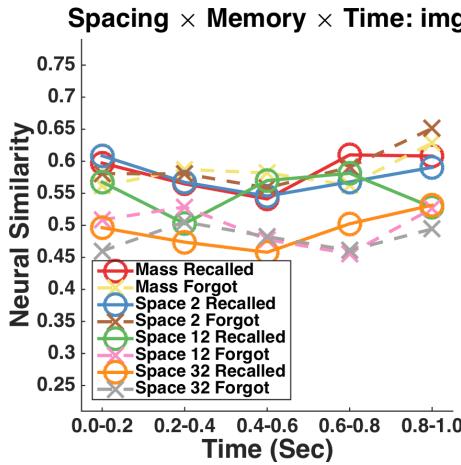


Figure 20. Similarity for oscillatory power at left and right parietal sites during image repetitions: Interaction between spacing, memory, and time [n.s.].

For time–frequency data (plotted in 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 latency [$F(4, 104) = 2.9, p < .05$] (similarity increased across time), and a marginal memory × latency interaction [$F(4, 104) = 2.46, p = 0.051$] (without a very 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 surprising 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 much more variable either because noise is added to the system (supporting deficient processing), they tend to induce a more variable representation

(supporting contextual variability), or different neural/cognitive processes are engaged.

Study-phase retrieval seems the most reasonable explanation; it does not seem like noise would be added to the system when a massed stimulus is being processed semantically, and from a theoretical standpoint there is no good reason for massed repetitions to have more variable representations.

Experiment 2 Discussion

The purpose of this experiment was to look for gradations in effects so we can better interpret data patterns in the context of three theories.

Behaviorally, we saw exactly what we expected: performance increased significantly as lag increased. The EEG effects are less clear, but overall, many of the effects described here are similar to Experiment 1. The only effect that differed across spaced repetitions was theta power: there was more theta at longer lags for repeated items.

General Discussion

The results of the two experiments presented here (were mostly the same) (diverged slightly). Why?

The present set of experiments failed to fully disambiguate the roles of XYZ in the spacing effect.

It would be enlightening to examine the effects that are related to the spacing effect. Theta power seems to play a large role here.

Future Directions

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 spacing effect experiment would be to take 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 and simplifying the possibilities for why the spacing effect occurs (deficient processing should essentially be eliminated). A “massed” condition could be added as either a between- or within-subjects manipulation in this way (look at proposal).

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