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Mechanisms involved in the assessment of cumulative long-term familiarity of object concepts: An ERP study

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Abstract

We investigated the sensitivity of ERP components implicated in recognition memory to degree of experimentally controlled and lifetime cumulative exposures during explicit memory judgements. A parietally distributed ERP component spanning both the FN400/N400 and the LPC time windows tracked both types of judgements. This effect appears to be an LPC effect with an early onset, and differs from previously reported effects of repetition linked to implicit memory. Based on recent evidence, we interpreted it as response-related evidence accumulation processes that are in line with both single-process models and continuous dual-process models. We also observed more positive ERP in the left ROIs for frequency judgements as compared to lifetime familiarity judgements. This effect could be linked to encoding differences in the perirhinal cortex. Our findings provided new evidence concerning the memory of cumulative exposures, and demonstrated the possibility of studying certain aspects of lifetime cumulative familiarity in a laboratory environment.

Keywords

Memory, recognition, ERP, repetition, cumulative, familiarity, recollection.

Acknowledgments

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1 Introduction

1.1 General introduction

Recognition memory refers to the ability to distinguish previously encountered stimuli from new stimuli. It is a form of explicit (i.e. declarative) memory. Typically, recognition experiments adopt a study-test structure: participants first study a list of stimuli; then they make some form of old/new judgement on a list consisting studied stimuli and unstudied lures. Most theories of recognition memory fall into one of two broad classes: single-process and dual-process models. Single-process theories posit that a univariate memory strength underlies recognition judgements. Dual-process theories state that two separable processes, familiarity and recollection, contributes to recognition judgements. Although versions of the dual-process theories have substantial difference in their details, as a whole, they are more popular than their single-process competitors in cognitive neuroscience at present (Yonelinas, 2002).

One phenomenological experience captured by the dual-process view is the “butcher on the bus” phenomenon (Mandler, 1980): Imagine you were on a bus. You looked at a person next to you and felt a strong sense that you had met him before, but couldn’t recall his identity. This would be an example of familiarity. You might later realize that he was the butcher you met in a meat shop. At the same time, details about your past interactions would also come to mind, for instance, the way he looked in an apron. This contextually rich re-experience is an example of recollection. Familiarity has been generally theorized to support item-based recognition, while recollection supports associative or contextual recognition (Mayes et al., 2004; Holdstock, Mayes, Gong, Roberts, & Kapur, 2005; (Mayes, Montaldi, & Migo, 2007; but also see Quamme, Yonelinas, & Norman, 2007). The two processes are also thought to be largely independent (Yonelinas & Jacoby, 1995; Norman & O’Reilly, 2003; but also see Moran & Goshen-Gottstein, 2015). For a given trial in a recognition experiment, recollection is usually operationalized as successful recall of contextual details of the corresponding study episode. And familiarity is usually operationalized as correct recognition judgement (i.e. old/studied) without recollection. These can be either based on introspective self-reports, or objective measurements of the recalled details. Data from a variety of experiments involving different methodologies have also been interpreted to support the dual-process view, including human functional magnetic resonance imaging (fMRI) studies (Yonelinas, 2005; Davachi, Mitchell, & Wagner, 2003; but also see Wais, Squire, & Wixted, 2010), behavioral studies (Yonelinas, 1994; Onyper, Zhang, & Howard, 2010; Ingram, Mickes, & Wixted, 2012; but also see Hayes, Dunn, Joubert, & Taylor, 2016), neuropsychological studies on patients with medial temporal lobe (MTL) lesions (Aggleton et al., 2005; Bowles et al., 2007; Bowles et al., 2010; Mayes, Holdstock, Isaac, Hunkin, & Roberts, 2002; but also see Wais, Wixted, Hopkins, & Squire, 2006), and event-related potential (ERP) studies (Curran, 2000; Curran & Cleary, 2003; but also see Brezis, Bronfman, Yovel, & Goshen-Gottstein, 2016). The present study focused on the ERP components linked to recognition memory that have traditionally been interpreted under the dual-process framework. Specifically, we are interested in whether ERP markers identified in single-exposure recognition experiments also track cumulative exposures, resulted from either experimental repetitions or lifetime experience, when making explicit memory judgements.

1.2 ERP Components Related to Recognition Memory

In recognition-memory experiments that probe memory for items encountered in an experimental study phase, studied items usually evoke more positive ERPs than unstudied items. Two ERP components, the FN400 and the late positive complex (LPC), have been identified and distinguished based on their latencies and topographies. The FN400 is a frontally distributed negative going deflection peaking around 400 ms after stimulus presentation, and the LPC is a parietally distributed positive going deflection peaking around 600 ms after stimulus presentation. Note that the terms “positive going” and “negative going” only describe the shape of the peaks for each component. The actual voltage can be either positive or negative and is not very meaningful. It is the positivity or negativity resulted from contrasting one condition with another that most studies are concerned with.

It has been shown in several studies that behavioral measurements of familiarity and recollection modulate the two ERP components separately, leading to the classic dual-process interpretation that the FN400 is a marker of familiarity and the LPC is a marker of recollection (Rugg & Curran, 2007). The Remember/Know (RK) paradigm is widely used to separate recollection from familiarity. In such a paradigm, participants first study a list of items. Then in a test phase, they are asked to not only make old/new judgements, but also indicate whether they experience recollection for items judged old. If recollection is present (by introspection, that is), participants are asked to make a Remember (R) response. If recollection is not present, but the item is nonetheless judged to be old, they are asked to make a Know (K) response. Some versions also include a Guess (G) option when the source of recognition is unclear to reduce response biases (Gardiner, Ramponi, & Richardson-Klavehn, 1998). And finally, there is the New (N) option when participants judge a stimulus to be new. When paired with neural measurements, a contrast between R and K responses is thought to isolate the recollection signal, and a contrast between K and N responses would isolate the familiarity signal (Yonelinas & Jacoby, 1995).

Woodruff, Hayama, and Rugg, (2006) demonstrated a double dissociation between the FN400 and the LPC in a remember/know (RK) paradigm combined with confidence ratings, which is thought to reflect mnemonic strength (Brezis et al., 2016). In their experiment, different from the typical RK paradigm, participants were asked to provide confidence ratings along with the K and N responses. Woodruff et al. (2006) found a graded relationship between oldness ratings and the FN400 amplitude, with highly confident K responses eliciting the most positive FN400, followed by unconfident K responses, unconfident New responses, and confident New responses, which elicited the most negative FN400. Moreover, the effect disappeared when objective oldness of the stimuli was used instead of participants' responses, suggesting that the FN400 marks the consciously perceived familiarity. Critically, the LPC was insensitive to differences in confidence ratings for K responses. On the other hand, when contrasting ERPs corresponding to R responses and highly confident K responses, an LPC effect was observed, with more positive ERP associated with R responses. The FN400 was insensitive to this contrast. Thus, consistent with the dual-process account, Woodruff et al. interpreted the FN400 and the LPC as markers of familiarity and recollection, respectively. Although this interpretation has been challenged by the argument that R and

K responses do not simply map onto recollection and familiarity, respectively (Brezis et al., 2016; Dunn, 2004; Wixted & Stretch, 2004), a similar dissociation has been observed in studies using paradigms other than RK to separate familiarity from recollection, such as manipulating study-test item similarity (Curran, 2000; Curran & Cleary, 2003), or measuring source memory (Woroch & Gonsalves, 2010; Addante, Ranganath, & Yonelinas, 2012).

Interestingly, a posterior positivity was also observed in Woodruff et al. (2006) when contrasting confident responses with unconfident responses, collapsed between K and New responses. This confidence effect had a similar topography to the recollection LPC, but it was more rightly lateralized, and was smaller in amplitude compared to the recollection LPC. As will be discussed later, this effect may reflect a decisional process (Ratcliff, Sederberg, Smith, & Childers, 2016)

1.3 N400 and FN400

In contrast to the frontal distribution of the FN400, the N400 is a central parietally-distributed negative deflection peaking around 400 ms after stimulus presentation. It has been studied extensively in the semantic literature and is sensitive to a wide variety of manipulations (Kutas & Federmeier, 2011). Particularly relevant to recognition studies, the N400 is sensitive to repetition priming, which is thought to reflect implicit memory (Voss & Paller, 2008). Furthermore, the direction of the N400 repetition effect is the same as the FN400 old/new effect in a recognition experiment, with repeated stimuli eliciting more positive ERP. Due to similar time windows, topographies, and effect directions to the N400, some have challenged the classic interpretation of the FN400 as a distinct marker of familiarity in explicit memory, and argued that the FN400 may mark conceptual fluency (Paller, Voss, & Boehm, 2007; Wolk et al., 2004; but also see Bridger, Bader, Kriukova, Unger, & Mecklinger, 2012; Bader & Mecklinger, 2017).

Voss and Federmeier (2011) adopted a continuous RK paradigm, in which participants responded to a stream of words. Each target word was preceded by either a semantically related word or an unrelated one, with half the words being primed by the related words before the first presentations, and the other half being primed before the second presentations. A conceptual priming N400 effect was observed when contrasting the first presentations of targets words with their preceding related primes. An old/new familiarity FN400 effect was observed when comparing the second presentations of targets words following unrelated primes with the first presentations of targets words following unrelated primes. Critically, the topographies of the FN400 and the N400 effects were not significantly different in that study.

However, as Bader and Mecklinger (2017) have pointed out, the lack of a difference in topographies may be explained by the confounding of priming and study history. Specifically, the second presentations of any word would have been primed. Thus, the old/new FN400 effect obtained in Voss and Federmeier (2011) might reflect a priming effect. Bader and Mecklinger went on and demonstrated that the topographies of the old/new effect and the priming effect could be dissociated when the confound was removed.

Yet evidence from a human fMRI study has showed that familiarity and conceptual priming at least have partially overlapping neural substrate, as overlapping voxels in perirhinal cortex have been activated during both a free association task and a recognition task (Wang, Ranganath, & Yonelinas, 2014). Thus, at present, the relationship between the FN400 and the N400, and the interpretation that the FN400 is a unique marker of familiarity in study-test paradigms, remain contentious (Voss, Lucas, & Paller, 2009).

1.4 LPC and recollection

The link between the LPC and recollection has also been challenged in recent research. The dissociation between the FN400 and the LPC depends largely on behavioral dissociations of familiarity and recollection. For example, in the popular RK paradigm, a contrast between R and K trials is assumed to represent unique contribution of recollection. Brezis et al. (2016) refuted this assumption using a modified Remember/Know paradigm, in which participants provided confidence ratings along with old/new judgements before making Remember/Know/Guess (RKG) responses. Following the typical contrast between R and K, an LPC effect was observed. However, when they controlled for the proportion of RK responses using a bootstrapping procedure, an effect indistinguishable from the LPC was found to be modulated by response confidence. Moreover, a confidence effect in the LPC time window was observed when contrasting highly confident K responses with unconfident R response, while controlling for recognition accuracy. Brezis et al. thus concluded that the LPC is modulated by a univariate mnemonic strength signal and cannot be interpreted as a specific marker of a recollection process. Other researchers have argued that the LPC tracks the evidence guiding the decision process in memory decisions (Finnigan, Humphreys, Dennis, & Geffen, 2002). Ratcliff, Sederberg, Smith, and Childers (2016) performed a logistic regression analysis on single trial EEG data from a recognition paradigm and combined it with diffusion modeling. A diffusion model is a two-option decisional model of reaction time and accuracy, which models the accumulation of information that leads to the responses as a random walk procedure (Ratcliff, 1978). Ratcliff et al. (2016) found that signals around both 400 ms (i.e., the FN400 time window) and 600 ms (i.e. the LPC time window) after stimulus presentations contained information leading to significantly above chance classification performance. However, only the latter LPC signal predicted behavioral performance when fit to the diffusion model. These results were interpreted to suggest that the FN400 effect might be modulated by differences between old and new stimuli unrelated to the memory judgments performed, and that the LPC effect reflected explicit memory signals contributing to behavioral decisions.

1.5 Other types of familiarity

The majority of ERP experiments in the recognition memory literature contain only a single presentation (i.e., study episode) of each stimulus in the study phase, and recognition judgements are typically made with respect to that single study exposure. Familiarity measured in such paradigms is referred to as single-exposure familiarity in this paper. A relatively uncharted cognitive domain that also appears to be highly relevant to recognition memory, is cumulative (lifetime) familiarity. People encounter the same concepts hundreds or thousands of times throughout their lives, and certain concepts are more common than others in each culture. For instance, most Canadians will rate apple as a more familiar concept than mangosteen. Given the strong relation between cumulative lifetime familiarity and number of exposures (as measured, for example, in word frequencies in Cree & McRae, 2003), it is not surprising that people from the same cultural background also show strong agreement in their lifetime familiarity ratings on concrete concepts (Duke, Martin, Bowles, McRae, & Köhler, 2017). One way to probe cumulative familiarity in the laboratory is through variation of degree of experimental repetition (e.g. Xiang & Brown, 1998; Hölscher, Rolls, & Xiang, 2003). This approach provides objective control of the amount of prior exposure. Explicit memory of cumulative exposures can then be probed with frequency judgments. This experimental approach can be thought of as an intermediate point between assessment of single prior laboratory exposure and lifetime familiarity. Currently, it is unclear whether ERP components related to single-exposure recognition memory also track cumulative exposures in a graded manner, and whether they respond differently to experimental repetition and lifetime familiarity.

1.6 Cumulative familiarity and perirhinal cortex

One possibility is that the single-exposure familiarity and cumulative familiarity share overlapping neural substrates. The perirhinal cortex, situated in the medial temporal lobe, is one candidate, as it has been linked to single-exposure familiarity in several studies (for a review, see Eichenbaum, Yonelinas, & Ranganath, 2007). Henson, Cansino, Herron, Robb, and Rugg, (2003) demonstrated that a cluster of voxels in the anterior medial temporal lobe that included the perirhinal cortex consistently showed a reduced blood-oxygen-level-dependent (BOLD) signal for stimuli judged old compared to those judged new in recognition experiments. Critically, this effect was insensitive to source recollection, as trials with correct recollection of contextual information elicited similar responses with the incorrect ones. Similarly, Davachi et al. (2003) showed that activations in the perirhinal cortex during the study phase predicted later recognition performance, but not source recollection performance, indicating a selective involvement of the perirhinal cortex in familiarity based judgements.

Research on non-human primates has linked both cumulative familiarity and single-exposure familiarity to the perirhinal cortex (Xiang & Brown, 1998). Hölscher, Rolls, and Xiang (2003) trained Macaque monkeys to watch a series of images on a monitor and lick a tube when detecting a repetition. Half of the images were introduced to the monkeys before the experimental sessions of interest, and thus being familiar. The other half were introduced at the beginning of the sessions of interest, and thus being novel. While performing the task, their perirhinal neural activities were recorded using depth electrodes. Hölscher et al. discovered that perirhinal neurons initially fired only about half as frequently to the novel set as to the familiar set of images. Throughout the course of the experiment, these neurons gradually increased their firing rate to the novel images. And by the end of the experiment, the firing rates were indistinguishable between the novel and the familiar set. Converging evidence has also been reported in human fMRI research recently. In Duke et al. (2017), participants studied a list of words, some of which were repeated for different numbers of times. Later, they were exposed to a list of those old words mixed with some new words. They were asked to judge how frequently they saw each old word in the study phase, or how familiar they were, based on their life experiences, with words denoting object concepts (not presented at study). The activities of a cluster of voxels in the left perirhinal cortex was found to follow both the frequency judgements about degree of prior experimental exposure and the perceived cumulative lifetime familiarity. Furthermore, lesioning of the anterior temporal cortex with inclusion of left perirhinal cortex but sparing of the hippocampus has been found to lead to impairments in both frequency and cumulative lifetime familiarity judgements on object concepts (Bowles, Duke, Rosenbaum, McRae, & Köhler, 2016). Interestingly, the same patient (NB) also had single-exposure familiarity deficit, which had been shown in an earlier study (Bowles et al., 2007). However, it is unclear how these results map onto any ERP effect, given that the neural generators of the FN400 and the LPC remain largely unknown.

1.7 ERP studies on experimental repetition

A few ERP studies have directly investigated the effect of multiple repetitions in study-test paradigms and provided mixed results. Finnigan et al. (2002) manipulated the presentation frequencies of words (i.e. presented once or three times) in a recognition experiment that asked participants to make old/new judgements. When comparing the ERPs in the test phase for words with different presentation frequencies, a graded N400 effect was found such that words presented three times elicited the most positive ERP.

Yet the analysis for the LPC effect only approached significance and did not show the graded pattern. By contrast, Van Strien, Hagenbeek, Stam, Rombouts, & Barkhof (2005)https://paperpile.com/c/8Ruglr/tnxru found the opposite pattern. They used a continuous recognition paradigm, in which each word was presented 10 times throughout the whole experiment and participants were asked to indicate if a word was repeated. Van Strien et al. found that the N400 was only sensitive to the comparison between the second and the first presentation, while the LPC showed a graded response through the second to the tenth presentations, but was insensitive to the contrast between the second and the first presentations. The pattern is peculiar since it suggests that the first repetition is somehow qualitatively different from further repetitions. This can be explained in part by the behavioral responses. Van Strien et al. (2005) reported that participants typically performed the worst on the second presentation, with the lowest accuracy and the highest reaction time. After the second presentation, the accuracy quickly approached ceiling while the reaction time continuously decreased with more repetitions. The graded LPC effect is consistent with a strength account. The N400 effect, on the other hand, is harder to interpret. Given the strongly posterior topography and the longer reaction time for the second presentations, this effect is unlikely to reflect an FN400 marker of familiarity, or a priming effect. Overall, effects of experimentally induced cumulative familiarity on the FN400, the N400, and the LPC appeared to be quite complex and poorly understood at present.

1.8 ERP studies on lifetime familiarity

Although not concerned with concepts, Nessler, Mecklinger, and Penney (2005) compared ERPs elicited by famous faces and nonfamous faces in as a measurement of "semantic familiarity". This comparison yielded an FN400 effect and an LPC effect, with famous faces eliciting more positive ERPs in both time windows. The topography for the FN400 effect was significantly different from the an N400 perceptual fluency effect, which was acquired by comparing the first and second presentations of nonfamous faces. Interestingly, the topographies of the "semantic familiarity" effect in the FN400 time window seemed to depend on whether explicit judgements on semantic familiarity was made (i.e. whether a face is famous), although a statistical comparison of the topographies between the explicit and the implicit tasks only yielded a marginally significant effect. Consistent with Nessler et al. (2005), Bruett and Leynes (2015) found both the FN400 and the LPC were modulated by pre-experimental familiarity when comparing ERPs evoked by pictures of name-brand products with off-brand products. These results are markedly different from those of the experimental repetition. However, caution is needed when comparing results obtained with different types of stimuli, as some evidence has suggested that ERPs elicited by human faces differ significantly from those elicited by words (MacKenzie & Donaldson, 2007).

1.9 Objective

The present study thus focused on the sensitivity of ERP components previously implicated in recognition memory to degree of experimentally controlled and cumulative lifetime exposure during memory judgments. To our knowledge, no ERP study has directly compared cumulative exposures experienced in an experimental condition with lifetime familiarity. We adopted the paradigm from an fMRI study conducted by Duke et al. (2017), which incorporated both frequency judgments of experimentally controlled cumulative prior exposures and judgments of cumulative lifetime familiarity of concepts in the same experiment. Due to intimate links between the FN400/N400 and semantic processes, we selected our stimuli from a Canadian normative database on object concepts (McRae, Cree, Seidenberg, & Mcnorgan, 2005), and matched them on several semantic variables. The database also provided normative lifetime familiarity ratings, enabling us to select stimuli over a wide portion of the lifetime familiarity spectrum. We hypothesized that judgements of frequency and lifetime familiarity would involve similar mechanisms as classic recognition judgements. Although the exact processes underlying the LPC is still debated, it has been consistently observed in recognition ERP studies, sometimes even in paradigms without explicit memory judgements (Bermúdez-Margaretto, Beltrán, Domínguez, & Cuetos, 2015). Thus, we expect that both types of cumulative exposure should modulate the LPC in our experiment in the test phase. Under the assumption that the FN400 marks explicit familiarity signals, we expect it to track participants' explicit judgements of cumulative exposure in both tasks in the test phase, but not in the study phase where no explicit memory judgements were made. In contrast, repetition in the study phase should modulate the N400, given the documented repetition and semantic priming effects for concepts in the N400 and in the broader literature on semantic memory.

2 Method

2.1 Participants

65 participants (38 females) were recruited through posters or an online recruitment tool ("Psychology Research Participation Pool," n.d.). All participants were 18 to 35 years old, right handed, native English speakers who had lived in Canada since childhood. None of them reported presence of any known psychiatric or neurological disorder. 7 participants were excluded from final analyses due to various technical problems with EEG equipment. One more participant was excluded due to failure in following experimental instructions. Other analysis-specific exclusions based on EEG data quality (i.e. trial count) are reported below in the Result sections for which they apply. The study was approved by Western University Non-Medical Research Ethics Board. Informed consent was acquired for each participant before the experiment. Participants were given course credits or monetary compensation upon completion of the experiment.

2.2 Material

Stimuli were 250 concrete English nouns selected from a Canadian normative database (McRae et al., 2005). They were allocated into 10 bins of 25 words. 5 bins were randomly selected to be used for the frequency task, and the other 5 were used for the lifetime familiarity task. The assignment of bins to tasks was counterbalanced across participants to create two versions. Word length, number of phonemes, number of syllables, word frequency, and normative lifetime familiarity ratings were matched across bins. Stimuli were selected in a way that they covered a wide range of lifetime familiarity ratings in the database. On a 9-point scale of lifetime familiarity, version 1 had a mean rating of 5.44 and a range of 7.00. Version 2 had a mean rating of 5.52 and a range of 6.90.

2.3 Procedure

After acquiring informed consent, participants were seated in front of a monitor in a soundproof booth. They were told to relax while the experimenter equipped them with the EEG system. Before starting the experiment, an oral instruction was given to participants about the general structure of the study phase. Participants were also instructed to minimize movements and remain vigilant throughout the experiment. A written instruction about specific response key-mappings was also displayed on the monitor for participants to read at their own pace. E-prime (Psychology Software Tools, n.d.) was used to present the stimuli and log the behavioral responses. For the study phase, a list of 125 concrete nouns (i.e. 5 bins) appeared on the monitor one at a time following a fixation cross (Figure 1). Participants were asked to judge the animacy of each stimulus by pressing one of two keys. They were not told about the memory test in the second phase. The stimuli were presented at different frequencies (repetitions) across bins, such that items (i) in bin 1 were presented once, (ii) in bin 2 were presented three times, (iii) in bin 3 were presented five times, (iv) in bin 4 were presented seven times, and (v) in bin 5 were presented nine times. In sum, this resulted in a total of 625 trials. The presentation order was randomized. Within each trial, a fixation cross was first presented for 1000 milliseconds, which would become bolded for 1000 milliseconds to indicate the imminent presentation of a stimulus. Then a stimulus and the response options were presented for 1000 milliseconds, during which participants' responses were registered.

Immediately after the study phase, participants were given oral instructions about the structure of the test phase. A written instruction about specific response key-mappings was also displayed on the monitor for participants to read at their own paces. The test phase consisted of two types of trials: frequency judgements and lifetime familiarity judgements. For the frequency judgement tasks, participants saw studied stimuli, and were asked to judge their relative presentation frequency in the study phase on a 5-point scale. For the lifetime familiarity tasks, participants saw unstudied stimuli (i.e. the other 5 bins), and were asked to judge how familiar each corresponding concept was based on their lifetime experiences, on a 5-point scale. There was a total of 250 trials presented at test, with 125 trials per task. The two tasks alternated in blocks every 5 trials. A message indicating the task for the next 5 trials was shown for 2000 milliseconds prior to any alternation. The presentation order of items in each block and across blocks in a given task was randomized. Each trial of either type of tasks started with a fixation cross, which was presented for 1000 milliseconds and was subsequently bolded for 1000 milliseconds to indicate the imminent presentation of a stimulus. Then a stimulus and the response options were presented for 2500 milliseconds during which participants' responses were registered. Participants were asked to use all 5 keys and both hands. The mapping of the keys was counterbalanced across participants such that for approximately half of the participants, "5" appeared on the left of the monitor and the keyboard, while for the other half, "5" appeared on the right.

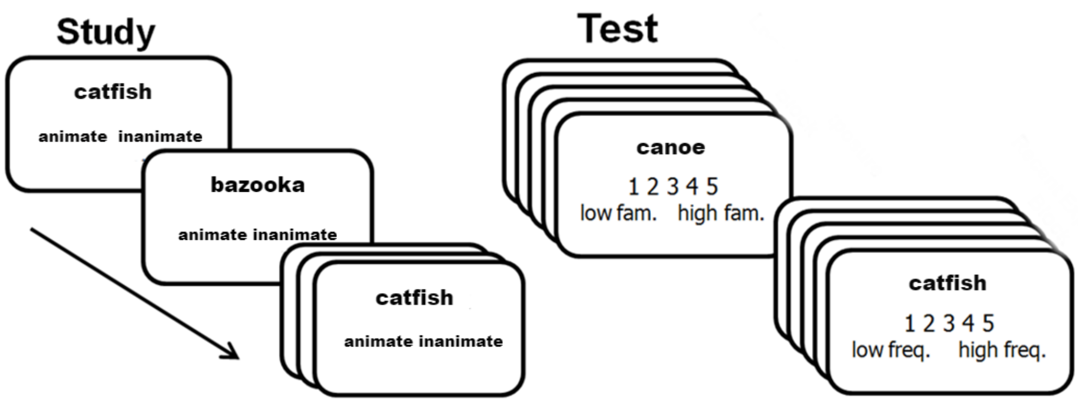

Figure 1. Experimental procedure. Note that the text below the scale in the test phase is only for illustrative purposes, they were not shown to participants in the actual experiment.

2.4 Behavioral analyses

To quantify participants' behavioral performance, their ratings in the frequency task and the lifetime familiarity task were correlated with the actual presentation frequencies in the study phase and the normative lifetime familiarity ratings, respectively. Reaction time in the study phase was also analyzed to provide a behavioral measurement of repetition priming. In order to perform behavioral and ERP analyses his/her averaged response for the corresponding type (i.e. frequency/lifetime familiarity) was introduced for trials in which a participant failed to respond.

2.5 ERP data collection and preprocessing

EEG data were collected using a Biosemi ActiveTwo 64-channel system. Electrode placements followed the international 10-20 system (“Biosemi Headcaps”). Two extra electrodes were applied on bilateral mastoids to be used in offline re-referencing. Another four extra electrodes were applied to the lateral corners of both eyes, above and below the left eye, to capture eye movements. Electrode offsets were kept below 20 mV. The data were originally sampled at 2048 Hz, and were downsampled to 512 Hz to be read into EEGLAB (Delorme & Makeig, 2004), a free toolbox for MATLAB (MATLAB-R2015a, The MathWorks, Inc.). Data for malfunctioning electrodes were interpolated from neighboring electrodes using the spherical interpolation algorithm provided in EEGlab. Data were bandpass filtered between 0.1 to 30 Hz. An independent component analysis (ICA) was applied to identify and remove for ocular artifacts (Jung et al., 1998). The data were then re-referenced to linked mastoids. Epochs were extracted from -199 ms to 998 ms with reference to stimulus onsets. A moving window with a width of 200 ms, a step size of 100 ms, and a threshold of 100 μV was used to mark remaining artifacts in the epoched data. Data were then averaged with respect to trial types (i.e., experimental task and response selected) to extract ERPs. All marked epochs were excluded from the averaging process.

Six regions of interest (ROI) were selected (Figure 2). They were left frontal (F1, F3, F5), right frontal (F2, F4, F6), left mid (C1, C3, C5), right mid (C2, C4, C6), left parietal (P1, P3, P5), and right parietal (P2, P4, P6). These electrodes are commonly used in recognition ERP studies (e.g. Brezis et al., 2016). ERPs were averaged across electrodes within each ROI before submitted to statistical analyses. The omnibus ANOVAs were carried out separately for mean amplitudes between 300 ms and 500 ms, and between 500 ms and 800 ms, representing the FN400/N400 time window and the LPC time window, respectively. The time windows were selected as in Woodruff et al. (2006). Violations of the sphericity assumption were corrected by the Greenhouse-Geisser procedure unless otherwise specified. Multiple comparisons were corrected using the Bonferroni procedure. Effect sizes were reported using generalized eta squared (Bakeman, 2005) and Cohen’s d for F-tests and t-tests, respectively.

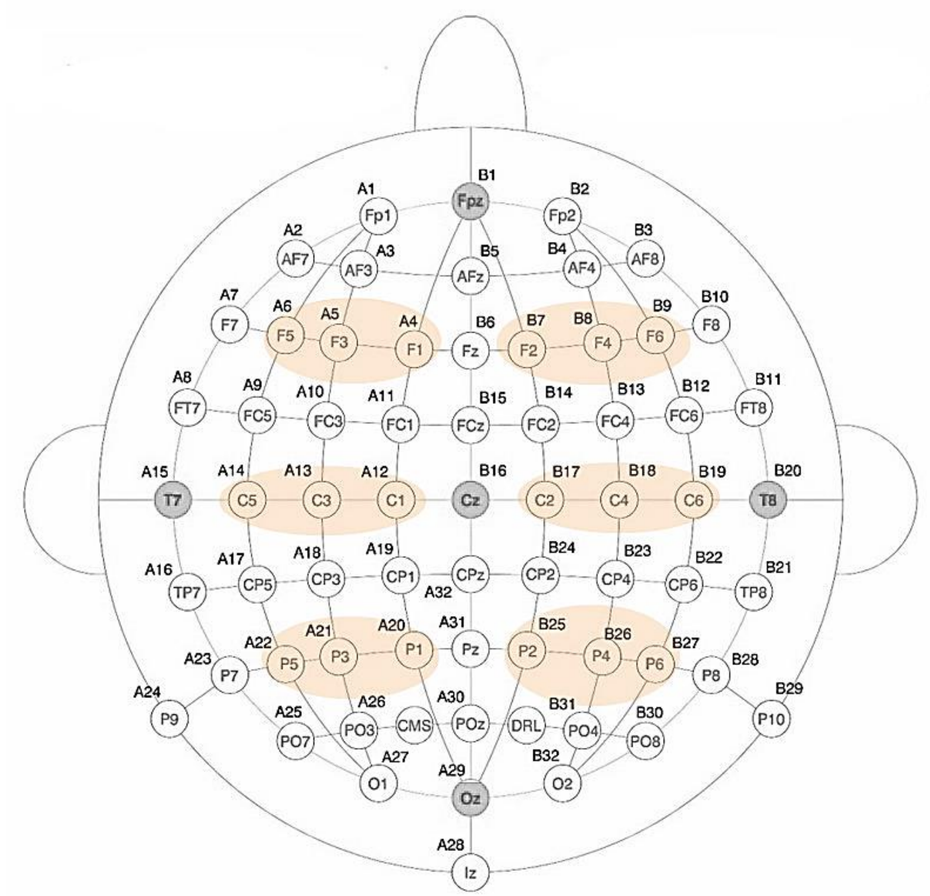

Figure 2. Regions of interest (ROIs) used in statistical analyses. Signals were averaged within each ROI

3 Results

3.1 Behavioral results

The overall rating distribution of the frequency judgement task is roughly symmetric, with most responses around the center ratings, as shown in Figure 3. The overall rating distribution of the lifetime familiarity task is skewed to the left, with most responses around the higher ratings, as shown in Figure 5. Due to the lack of objective measurements of response accuracy, to quantify participants' performance, we first correlated participants' frequency judgements in the test phase with the actual number of repetitions in the study phase across individual stimuli. Significant positive correlations were observed in 54 out of 57 participants, mean $r(123) = .41$, $p < .001$. Figure 4 shows the mean ratings of each frequency bin. We applied the same correlation procedure for participants' lifetime familiarity ratings with normative ratings. Again, significant positive correlations were observed in 54 out of 57 participants, mean $r(123) = .51$, $p < .001$. Figure 5Figure 6 shows the mean ratings of five normative familiarity ranks.

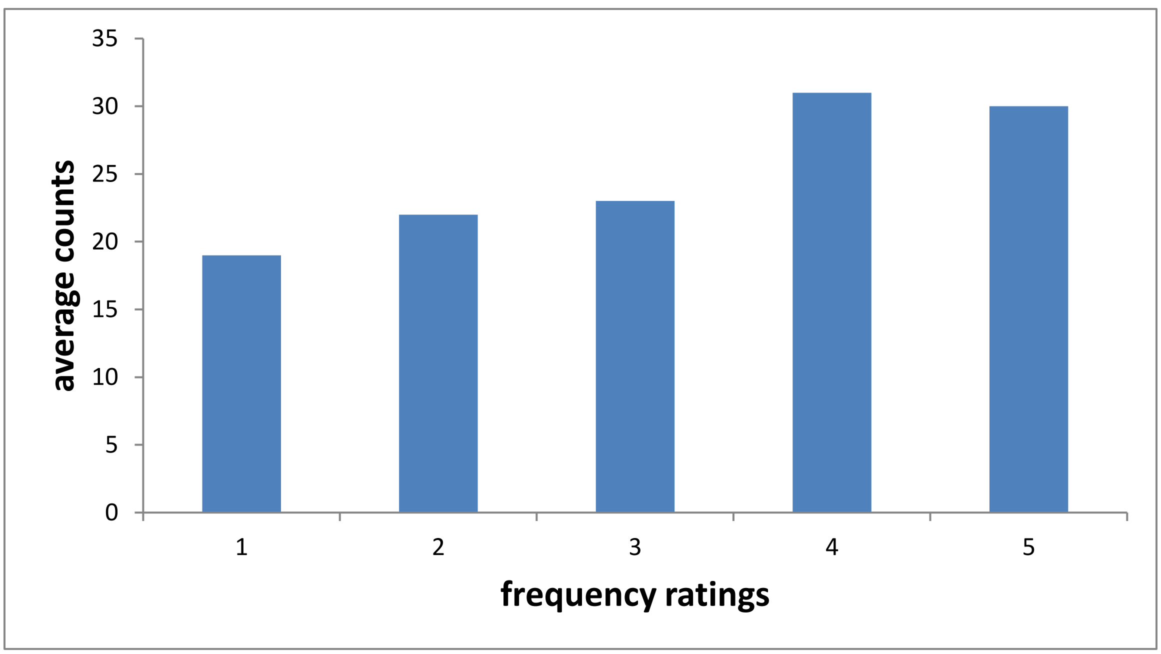

Figure 3. Average numbers of responses made in each rating option for the frequency task in the test phase. Error bars represent standard errors of the means

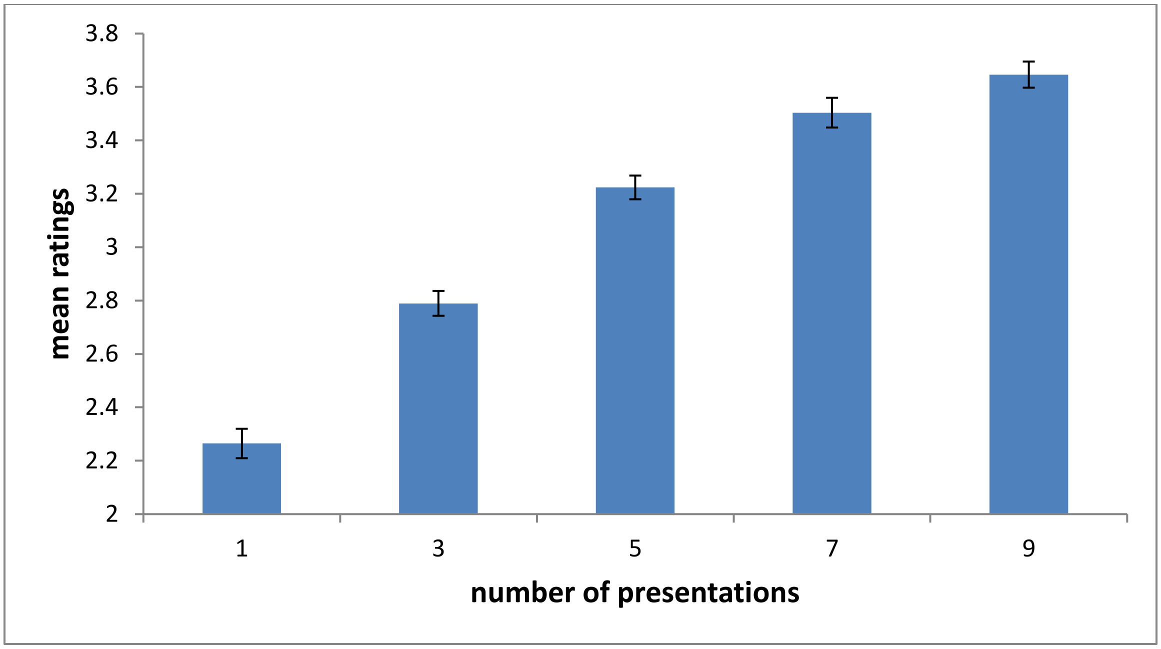

Figure 4. Mean ratings given to each frequency bin in the test phase. Error bars represent standard errors of the means

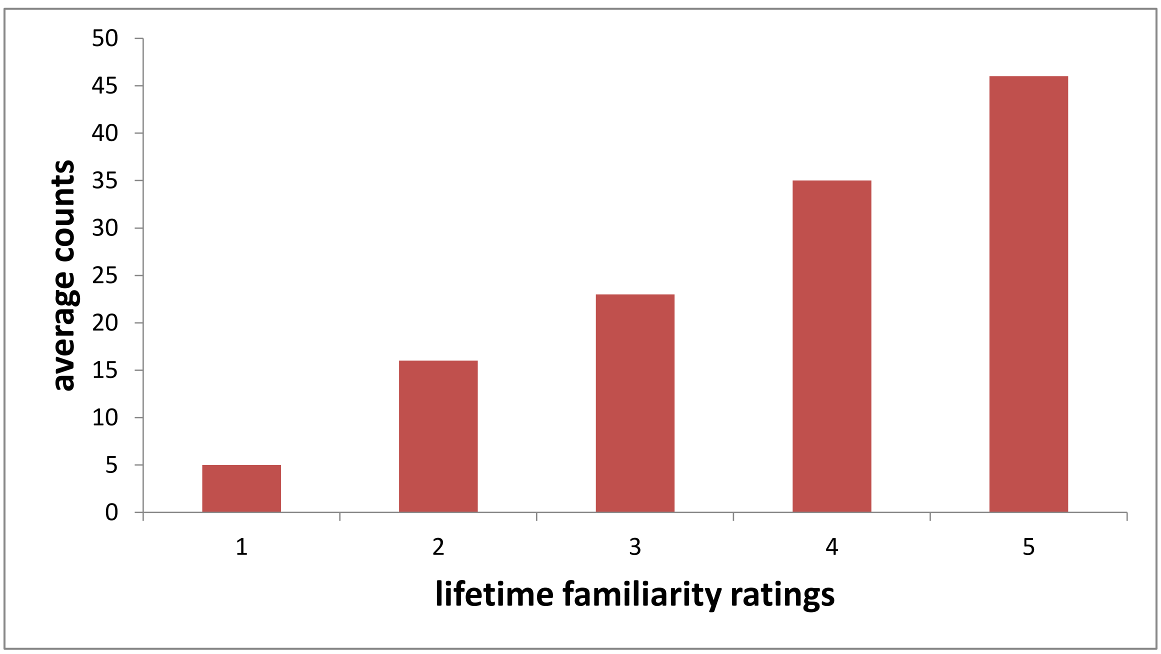

Figure 5. Average numbers of responses made in each rating option for the lifetime familiarity task in the test phase. Error bars represent standard errors of the means

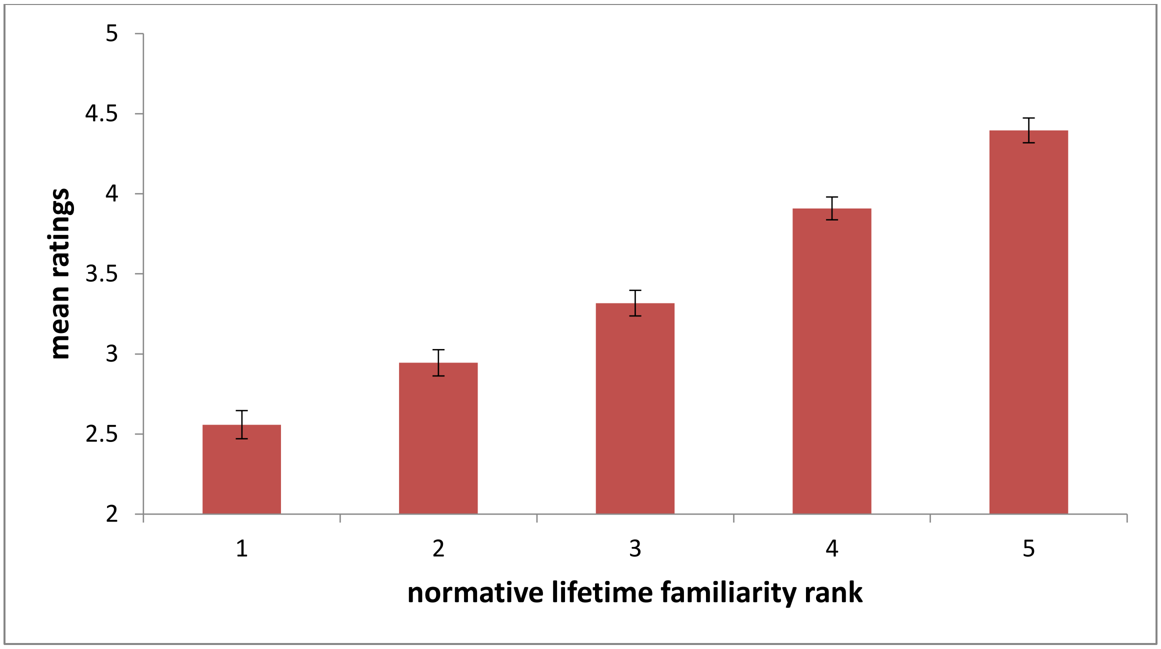

Figure 6. Mean ratings given to each normative familiarity rank in the test phase. Ranks are defined based on normative data for lifetime familiarity reported by (McRae et al., 2005). Error bars represent standard errors of the means

To test for behavioral repetition priming effect, we analyzed participants' reaction time data in the study phase. 125 words were used in the study phase. They were divided into 5 matched bins of 25 (see Material). The 5 bins were presented for 1, 3, 5, 7, and 9 times respectively, giving 25 unique combinations of bin presentations (i.e. 1+3+5+7+9). 2 out of 57 participants who made less than 5 responses in one of the 25 combinations were excluded. To test for the classic repetition priming effect, we compared reaction time between the first and the second presentations, averaged across stimuli. A one-tailed paired t-test showed that the average reaction time for the second presentations ($M = 646.65$ ms, $SD = 62.40$ ms) was significantly shorter than that for the first presentations ($M = 683.31$ ms, $SD = 61.38$ ms); $t(54) = 10.28$, $p < .001$, $d = 1.36$. To show that the priming effect was not specific to a given bin, we performed linear regressions of repetition both within and across bins. For the within-bin regression, reaction time was modeled as a linear function of repetition in bin 5, which was presented nine times in total. Repetitions significantly predicted the response time, $\beta = -8.11$, $t(219) = -12.39$, $p < .001$. To compare the results with the across-bin regression, we only included the odd numbers of presentations (i.e. 1st, 3rd, 5th, 7th, and 9th) for the within-bin regression. For the across-bin regression, reaction time was modeled as a linear function of the total number of presentations for all five bins (i.e. 1, 3, 5, 7, and 9 presentations in total, respectively). Again, a significant linear relationship was found, $\beta = -7.79$, $t(219) = -12.76$, $p < .001$. Figure 7 shows the reaction time for each category.

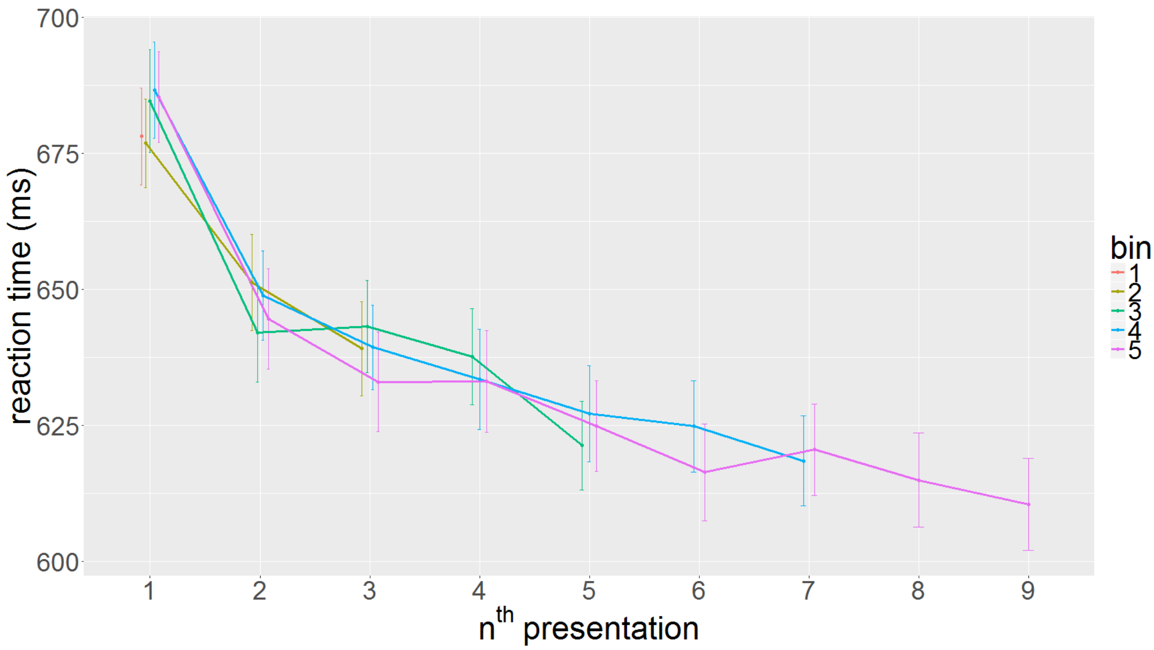

Figure 7. Mean reaction time for each presentation. Each bin was plotted in a separate curve. Error bars represent standard errors of the means

3.2 ERP effects for test phase

Due to the uneven distribution of observed behavioral responses, we computed weighted averages of ERPs for the upper two response categories (i.e. 4 and 5, coded "high"), and the lower two response categories (i.e. 1 and 2, coded "low") for each task, in order to maximize stability of waveforms. Ten participants with less than 10 trials in one of the combined categories were excluded. After exclusion, the average numbers of trials in each combined category were 43 for high frequency judgements, 38 for low frequency judgements, 53 for high lifetime familiarity judgements, and 35 for low lifetime familiarity judgements. The repeated measurement ANOVAs included factors anteriority (3 levels), laterality (2 levels), task (2 levels), and response (2 levels).

3.2.1 300-500 ms time window

The omnibus ANOVA revealed significant main effects of anteriority F (3.45, 158.62) = 62.82, p < .001, $\hat{\eta}_G^2$ = .26; laterality F (1, 46) = 12.79, p < .001, $\hat{\eta}_G^2$ = .009; and task F (1, 46) = 6.22, p = .02, $\hat{\eta}_G^2$ = .007. Significant two-way interactions of anteriority x laterality F (3.03, 139.39) = 7.20, p = .005, $\hat{\eta}_G^2$ = .003; and laterality x task F (1, 46) = 6.20), p = .02, $\hat{\eta}_G^2$ = .0004 were also observed. Two other effects were marginally significant after the Greenhouse-Geisser correction: A two-way anteriority x response interaction F (3.39, 155.93) = 3.25, p = .07, $\hat{\eta}_G^2$ = .0008; and a three-way anteriority x laterality x task interaction F (2.11, 96.84) = 2.84, p = .07, $\hat{\eta}_G^2$ = .0001. Other effects were non-significant, F < 2.35, p > .1 $\hat{\eta}_G^2$ < .002.

Because we were primarily interested in effects related to perceived prior exposure as reflected in memory judgements, all interactions involving the factor "response" were followed up with post hoc tests. Post hoc tests on the anteriority x response interaction showed that the ERPs corresponding to the high response category were significantly more positive than those of the low response category, but only in the parietal ROI, t (46) = 2.18, p = .05, d = 0.32, two-tailed.

To test for potential task differences, post hoc tests on the anteriority x laterality x task interaction were also performed. They revealed that the ERPs for the frequency task were more positive than those of the lifetime familiarity task in the left ROIs t (46) = 3.00, p = .008, d = 0.44, two-tailed. However, no significant anteriority x task interaction was found F (2.74, 126.03) = 0.15, p = .80, $\hat{\eta}_G^2$ = .00004.

In summary, ERPs associated with both high frequency responses and high lifetime familiarity judgements were more positive than those associated with low responses in the parietal ROIs. The direction and the topography of this effect were more consistent with an interpretation as an N400 than as an FN400 component (Figure 8 & Figure 10). Frequency judgement task also evoked more positive ERPs than lifetime familiarity judgments in left-sided ROIs. Relatively speaking, frequency judgements on concepts are more episodic than lifetime familiarity judgements on concepts, since the former still make references to the previous laboratory exposures. This effect may reflect this difference in episodic content.

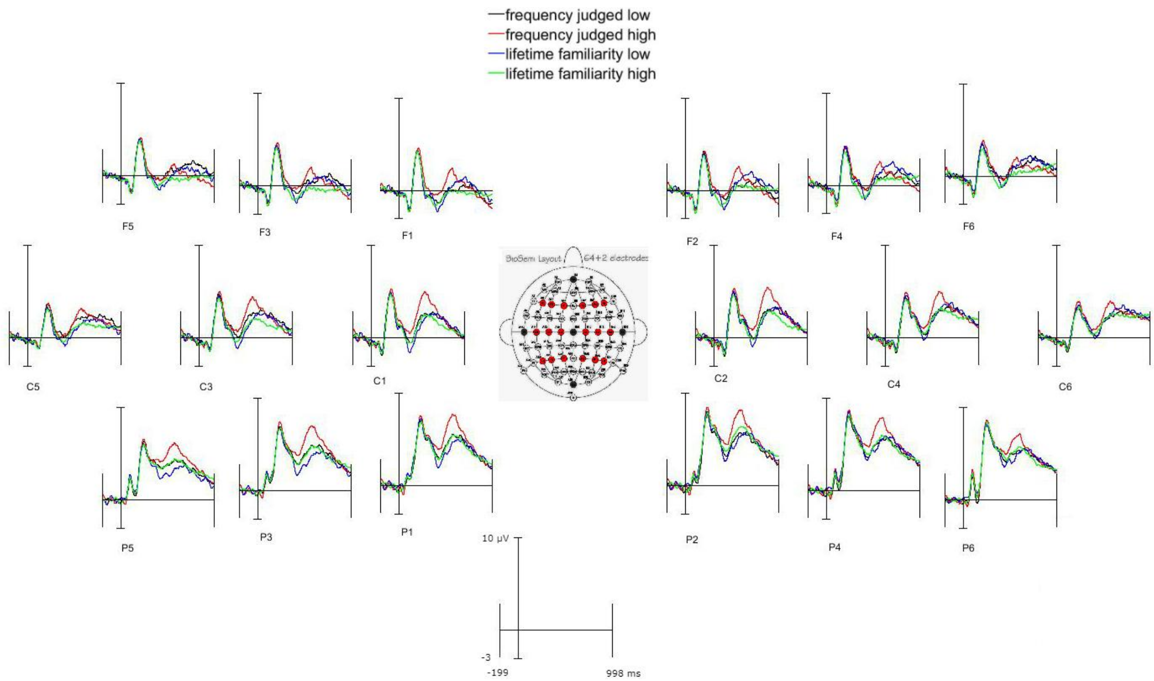

Figure 8. Grand average ERP trace plots on the 18 electrodes included in the statistical analyses, for the high and low responses in each task in the test phase.

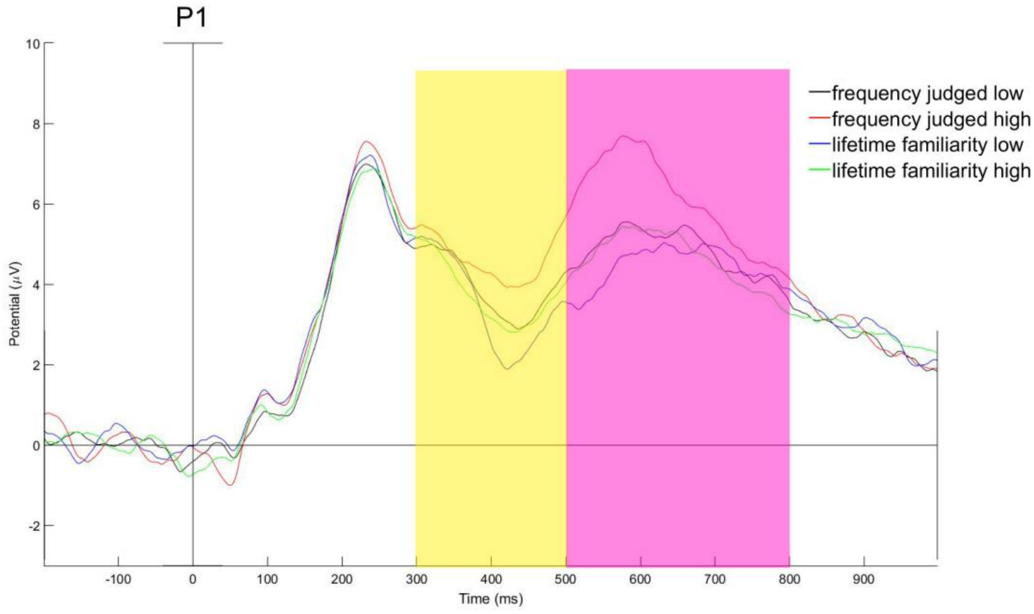

Figure 9. Grand average ERP traces on electrode P1 for high and low responses in the test phase. The yellow box represents the FN400/N400 time window, and the pink box represents the LPC time window

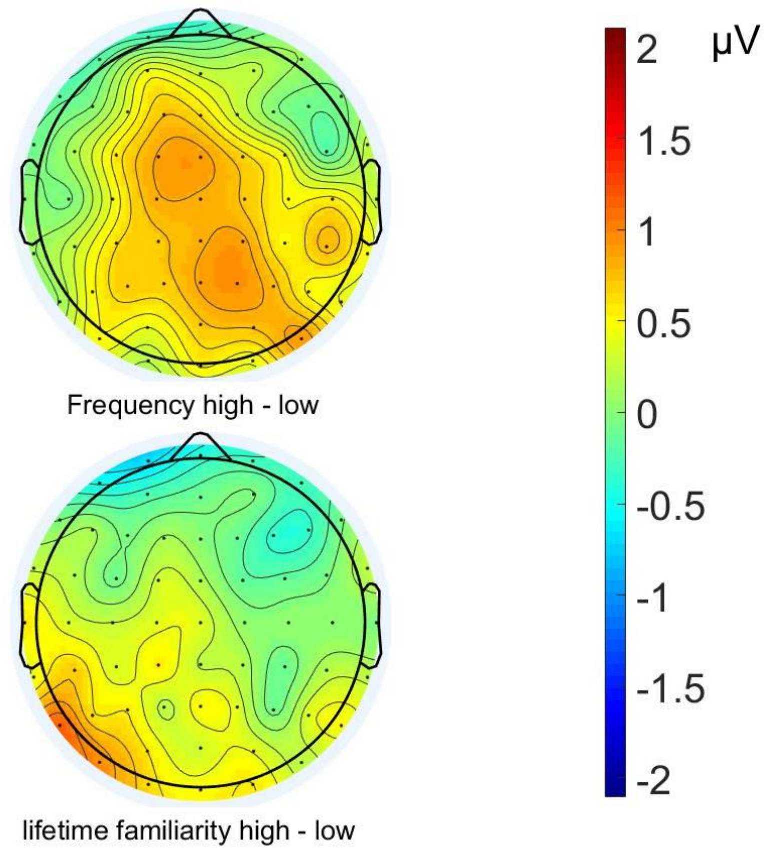

Figure 10. Grand average topographies for the 300-500 ms time window, contrasted between high and low responses.

3.2.2 500-800 ms time window

The omnibus test yielded significant main effects of anteriority, F (3.46, 159.28) = 67.12, $p < .001$; $\hat{\eta}_G^2 = 0.18$; and laterality, F (1, 46) = 15.53, $p < .001$, $\hat{\eta}_G^2 = .01$. The main effect of task was marginally significant, F (1, 46) = 3.58, p = .065, $\hat{\eta}_G^2 = .007$. Significant two-way interactions of anteriority x response, F (3.30, 151.69) = 18.60, $p < .001$, $\hat{\eta}_G^2 = .004$; task x response, F (1, 46) = 4.10, p = .049, $\hat{\eta}_G^2 = .005$; and laterality x task, F (1, 46) = 9.25, p = .004, $\hat{\eta}_G^2 = .0007$ were also observed. All other effects were non-significant, F < 2.07, p > .13, $\hat{\eta}_G^2 < .005$.

Again, because of our primary interest in effects related to perceived prior exposure reflected in judgements, all interactions involving the factor “response” were followed up with post hoc tests. Post hoc tests on the anteriority x response interaction revealed that ERPs corresponding to both high frequency judgements and high lifetime familiarity judgements were significantly more positive than those of low frequency and lifetime familiarity judgements, but only in the parietal ROI, $t(46) = 2.75$, $p = .01$, $d = 0.40$, one-tailed.

To test for potential task differences, post hoc tests on interactions involving the factor “task” were also performed. Post hoc tests on the task x response interaction failed to reach significance, all $t < 1.52$, $p > .27$, $d < .23$. On the other hand, post hoc tests on the laterality x task interaction revealed that ERPs in the frequency task were more positive than that of the lifetime familiarity task, but only in the left ROIs $t(46) = 2.42$, $p = .04$, $d = 0.44$, two-tailed.

In summary, ERPs associated with both high frequency responses and lifetime familiarity judgements were more positive than those associated with low responses in the parietal ROIs. The direction and the topography of this effect were largely consistent with the LPC component previously described in the literature on recognition memory (Figure 8 & Figure 11). Similar to the 300-500 ms time window, frequency judgements also evoked more positive ERPs than lifetime familiarity judgments in left-sided ROIs.

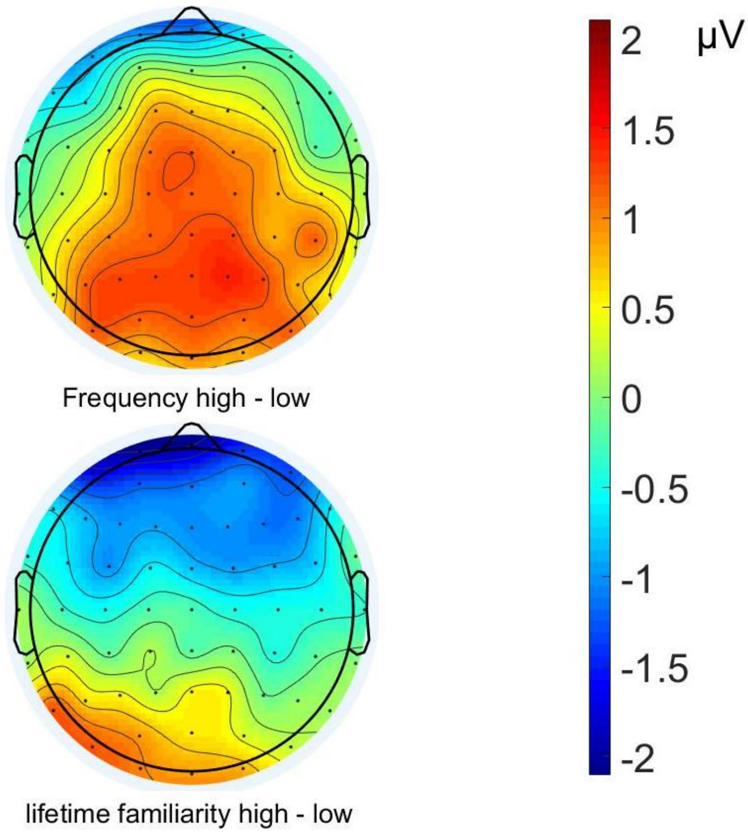

Figure 11. Grand average topographies for the 500-800 ms time window, contrasted between high and low responses.

3.2.3 Correlation between the parietal effects in the two time windows

Due to the observed similar topographies, we also examined whether the 300-500 ms effect was statistically related to the 500-800 ms effect that was observed in the parietal ROIs. In each time window, for each participant, we calculated the difference ERP between high and low responses, collapsed across tasks, and correlated the difference ERPs for the two time windows. A significant positive correlation was observed between the two ERP components, $r(45) = .55$, $p < .001$ (Figure 12).

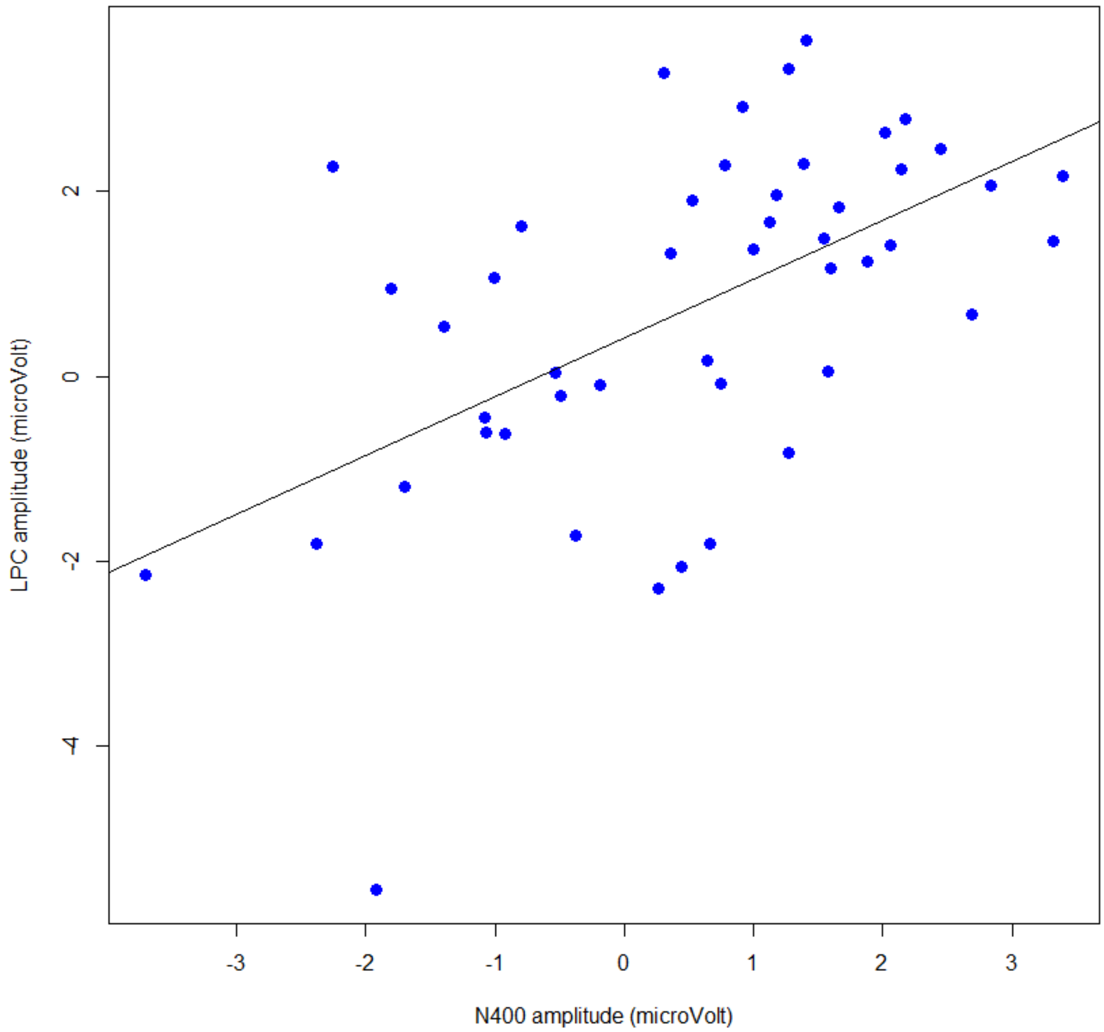

Figure 12. Scatter plot of the N400 amplitude difference between high and low responses as a function of the LPC amplitude difference between high and low responses, collapsed across tasks. Data were taken from the parietal ROIs where the two effects were significant. The straight line is the best fit.

3.3 ERP effects for study repetition

3.3.1 Repetition priming

To help interpret the ERP effects we observed in the test phase, we also examined effects of repetition in the study phase, which correspond to the behavioral priming effect we mentioned. First, we tested for the classic repetition priming effect in ERPs between the first and the second presentations for all items that were presented more than once in the study phase. A repeated measurement ANOVA with factors anteriority (3 levels), laterality (2 levels), and presentation (2 levels) was conducted on the mean ERP amplitude between 300 ms to 500 ms after stimulus onsets. It revealed significant main effects of anteriority, F (3.23, 151.61) = 129.92, p < .001, $\hat{\eta}_G^2$ = .36; and presentation, F (1, 47) = 9.72, p = .003, $\hat{\eta}_G^2$ = .02. Significant two-way interactions were also observed: anteriority x laterality, F (3.39, 159.32) = 6.15, p = .012, $\hat{\eta}_G^2$ = .003; and anteriority x presentation, F (3.23, 151.61) = 7.42, p = .005, $\hat{\eta}_G^2$ = .002.

We then followed up on the anteriority x presentation interaction examining whether it might reflect an N400 repetition effect. Post hoc one-tailed t-tests on the effect of presentation in each level of anteriority showed that the second presentations evoked more positive ERPs than the first presentations only in the central, t (47) = 3.52, p = .001, d = 0.51; and the parietal ROIs, t (47) = 3.49, p = .002, d = 0.50, consistent with a typical N400 repetition priming effect.

In summary, compared to the first presentations, the second presentations in the study phase elicited more positive ERPs in the central and parietal regions, revealing the N400 repetition priming effect reported in many prior studies (Figure 13 & Figure 15).

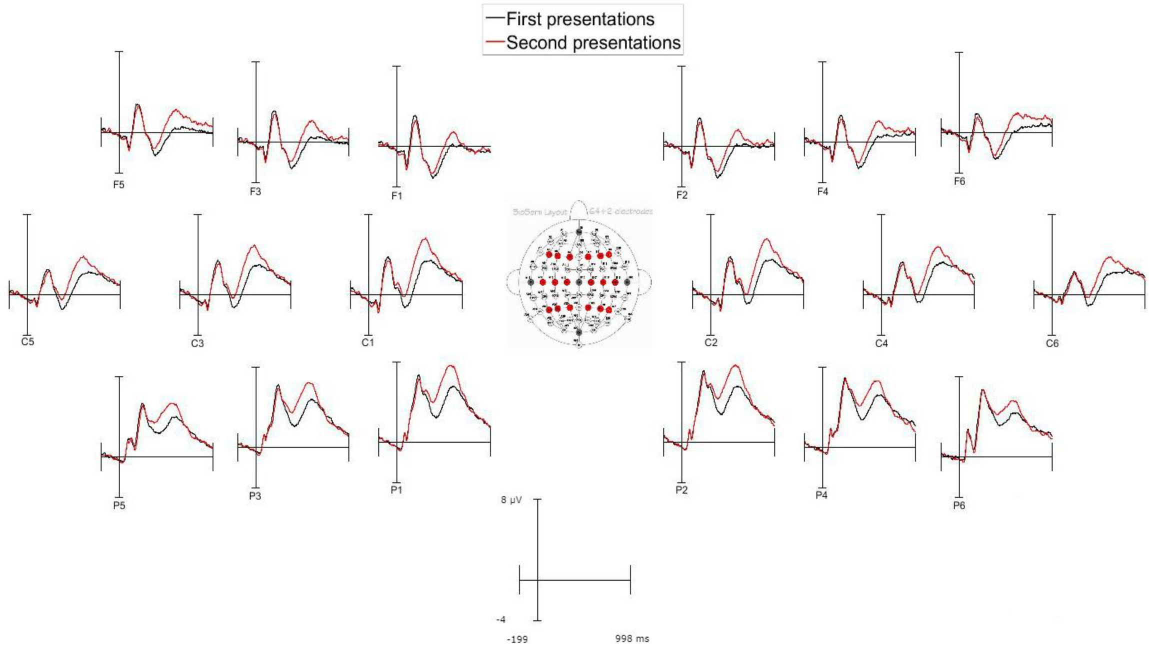

Figure 13. Grand average ERP trace plots on the 18 electrodes included in the statistical analyses, for the first and second presentations in the study phase.

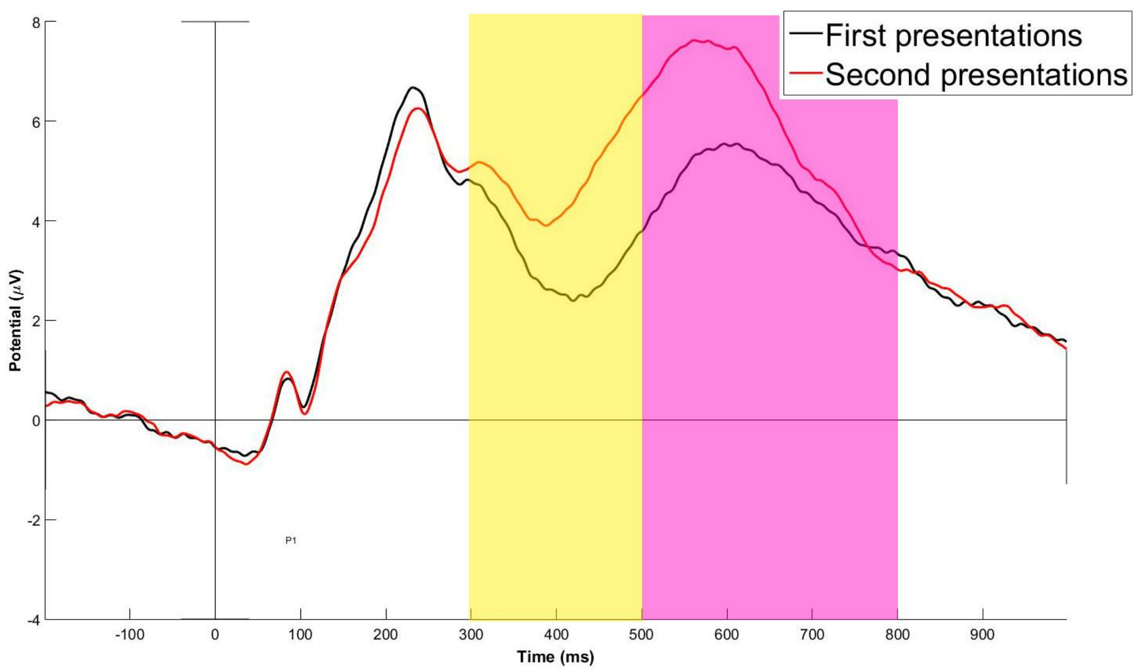

Figure 14. Grand average ERP traces on electrode P1 for the first and second presentations in the study phase. The yellow box represents the FN400/N400 time window, and the pink box represents the LPC time window

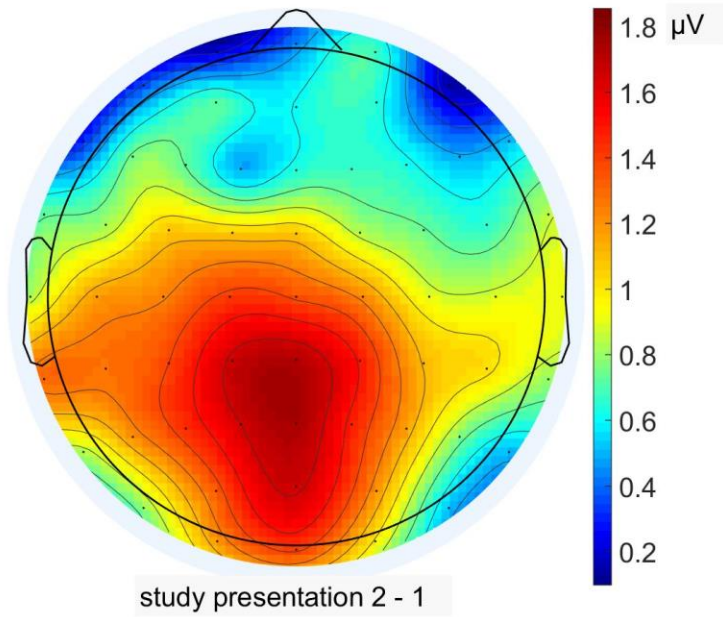

Figure 15. Grand average topography showing the contrast between the second and the first presentations in the study phase, in the 300-500 ms time window.

3.3.2 Linear regression of repetition

To compare our results with the graded effect of repetition seen in Finnigan et al. (2002) and Van Strien et al. (2005), for each participant, study phase EEG for the last presentations of all the stimuli in each bin was averaged together to form one ERP. This means that for each participant, 5 ERP measurements were formed from stimuli that have been presented 1, 3, 5, 7, and 9 times. They were compared with the ERPs elicited by the same stimuli in the test phase, which were used in the frequency judgement task. Note that in this case, the test phase ERPs were extracted based on their objective presentation frequencies, instead of participants' ratings. We modelled presentation frequency as a continuous factor and study/test phase as a categorical factor. Nine participants with less than 10 trials in any of the ERPs were excluded. Data were fitted to a linear mixed effect model, and ANOVAs were performed separately for the two time windows of interest (i.e. 300 ms to 500 ms, and 500 ms to 800 ms), with factors anteriority (3 levels), laterality (2 levels), phase (2 levels), and frequency (numeric). Note that the sphericity correction was not available for this model.

3.3.2.1 300-500 ms time window

For the 300-500 ms time window, significant main effects of anteriority, F (2, 94) = 112.38, p < .001, $\hat{\eta}_G^2 = .43$; laterality, F (1, 47) = 15.21, p < .001, $\hat{\eta}_G^2$ = .11; and phase, F (1, 47) = 3.91, p = .029, $\hat{\eta}_G^2$ = .03 were found. The main effect of frequency was marginally significant, F (1, 47) = 3.91, p = .054, $\hat{\eta}_G^2$ = .01. A significant two-way interaction of anteriority x frequency was also significant, F (2,94) = 6.35, p = .003, $\hat{\eta}_G^2$ = .001. Critically, there was no significant interaction between frequency and phase F (1, 47) = 2.22, p = .14, $\hat{\eta}_G^2$ = .005, indicating the frequency effect was not different between the study and the test phase. Other interactions were either not significant or irrelevant to our research questions. Post hoc analysis on the significant anteriority x frequency interaction revealed that the linear effect of frequency was only significant in the parietal ROIs, β = 0.13, t (191) = 2.69, p = .02.

In summary, ERPs in the parietal regions became increasingly positive with more repetitions in the study phase. Critically, this effect was preserved in the test phase. The distribution and the direction of this effect were largely consistent with the N400 component. For illustrative purposes, the topographies of the contrasts between the ninth and the first presentations for each phase are plotted in Figure 16.

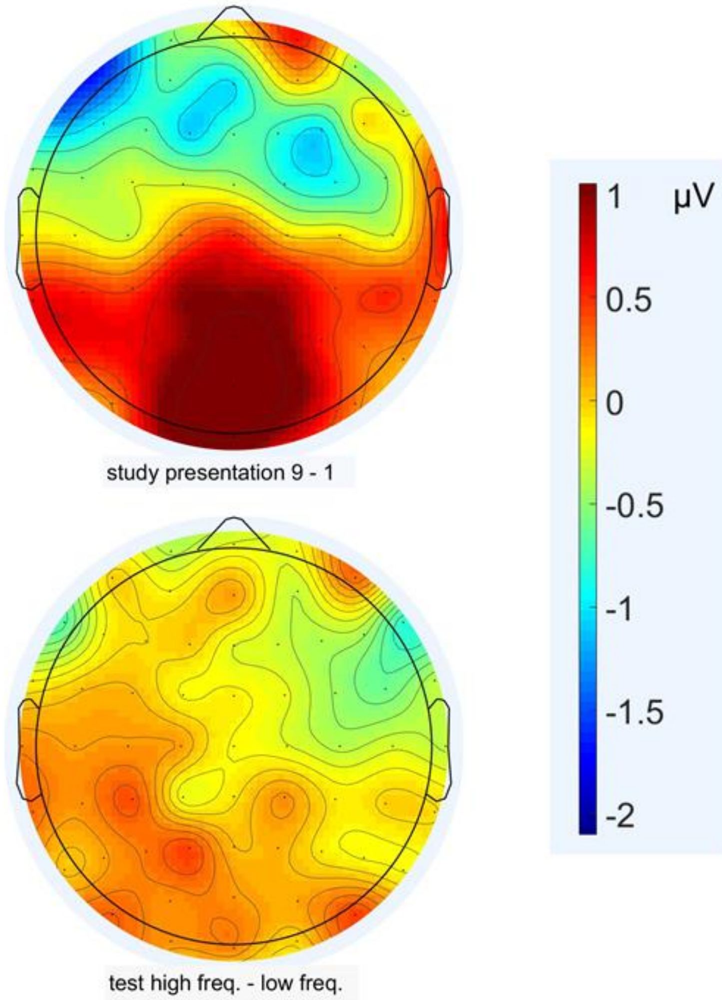

Figure 16. Grand average topographies of the contrast between stimuli with the highest and the lowest presentation frequencies in the 300-500 ms time window, plotted separately for the study and the test phase.

3.3.2.2 500-800 ms time window

For the 500-800 ms time window, significant main effects of anteriority, F (2, 94) = 83.92, p < .001, $\hat{\eta}_G^2$ = .22; laterality F (1, 47) = 8.52, p = .005, $\hat{\eta}_G^2$ = .006; and frequency, F (1, 47) = 7.01, p = .011, $\hat{\eta}_G^2$ = .011 were observed. The main effect of phase was nonsignificant F (1, 47) = 0.85, p = .36, $\hat{\eta}_G^2$ = .0082. A significant two-way interaction of anteriority x frequency was also found, F (2, 94) = 6.13, p = .003, $\hat{\eta}_G^2$ = .002. Again, the interaction between frequency and phase was nonsignificant, F (1, 47) = 0.53, p = .47, $\hat{\eta}_G^2$

= .002, indicating the frequency effect was not different between the study and the test phase. Other interactions were either not significant or irrelevant to our research questions. Post hoc analysis on the significant anteriority x frequency interaction revealed that the linear effect of frequency was only significant in the frontal ROIs, $\beta = 0.16$, $t(191) = 2.54$, $p = .04$.

In summary, ERPs in the frontal regions became increasingly positive with more repetitions in the study phase. And this effect was preserved in the test phase. The direction of this effect was largely consistent with the LPC component, although the distribution was different from this component as typically reported in prior research on recognition memory. For illustrative purposes, the topographies of the contrasts between the ninth and the first presentations for each phase are plotted in Figure 17.

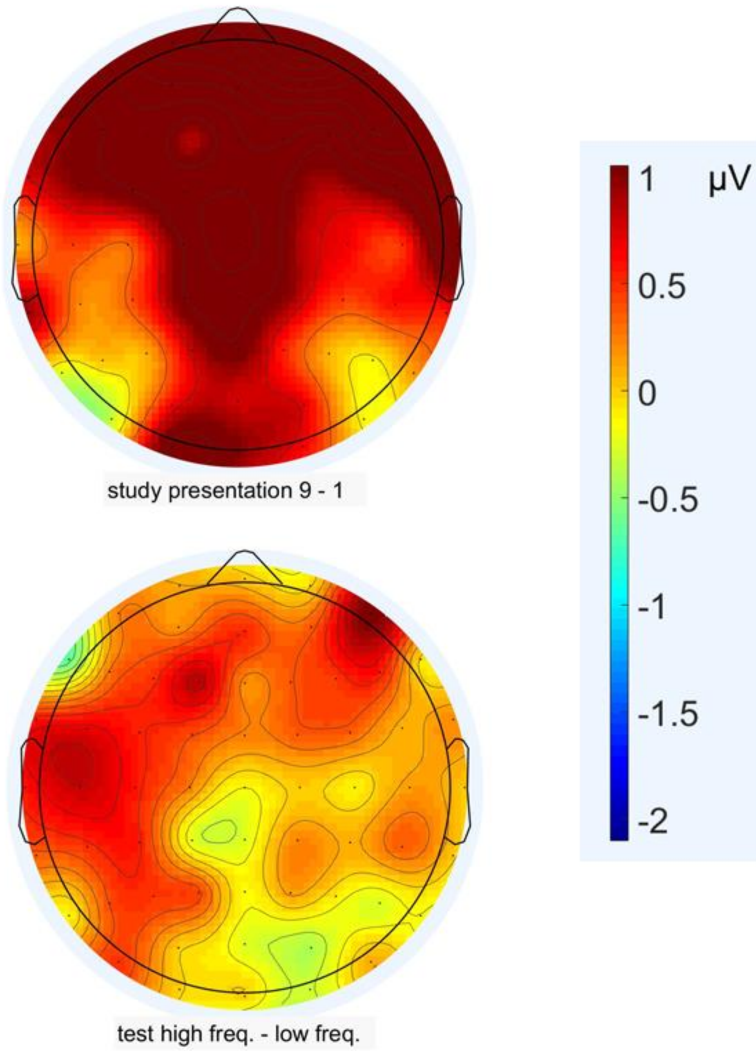

Figure 17. Grand average topographies of the contrast between stimuli with the highest and the lowest presentation frequencies in the 500-800 ms time window, plotted separately for the study and the test phase.

3.4 Correlation between the N400 effect on objective repetition and the N400 effect on subjective judgements

Due to similar distributions, we also examined whether the N400 repetition effect in the study phase reported above was related to the N400 effect of subjective frequency judgements at test. Given the significant positive correlation between participants' subjective frequency judgements and the objective presentation frequency, the two N400s may reflect the same set of underlying mechanism. To explore this possibility, we correlated the N400 amplitude difference between the high and low frequency judgements in the test phase with the N400 amplitude difference between the high and low presentation frequencies in the study phase. The N400 amplitude of low presentation frequencies were defined as the weight average of the last presentations of bin 1 and 2 (i.e. 1 and 3 presentations, respectively). Similarly, the N400 amplitude of high presentation frequencies were defined as the weighted average of the last presentations of bin 4 and 5 (i.e. 7 and 9 presentations, respectively). The test phase N400 amplitudes of high and low frequency judgements were defined as they were in the test phase analyses (3.2). Notably, we did not find evidence for any statistically significant relationship, $r(43) = -.17$, $p = .26$.

4 Discussion

In the present study, we investigated the sensitivity of ERP markers previously implicated in single-exposure recognition-memory paradigms to degree of experimentally controlled and cumulative lifetime experience with object concepts during memory judgements. At the behavioral level, participants showed significant positive correlations between perceived experimental presentation frequencies and the actual presentation frequencies at study, as well as significant positive correlations between their lifetime familiarity ratings and the normative ratings, indicative of their ability to complete the tasks. ERP data from the test phase of the present study revealed that the perceived degree of cumulative exposure, both at study in the laboratory and based on lifetime experience, modulated the LPC. An ERP component that resembled the N400 was also modulated by degree of perceived cumulative exposures in both types of judgements, although this effect was only marginally significant. Critically, this marginal effect in the N400 time window was significantly correlated with the LPC. Linear effects of objective repetition frequency in the laboratory were observed in the N400 and were consistent between the study and the test phase. Lastly, in a direct comparison between the two types of judgments in the test phase, frequency judgements elicited more positive ERPs in the left-side ROIs in both time windows.

4.1 The LPC time window

Under the dual-process framework, the LPC has long been implicated as a marker of retrieval of episodic contextual detail about prior stimulus encounters. Supporting this view, the LPC has been shown to reflect participants' perceived recollection (Woodruff et al., 2006); differentiate stimuli that are highly similar (e.g. change of plurality as in Curran, 2000); and track correct source memory (Addante et al., 2012). However, to take it as evidence supporting the claim that familiarity and recollection contribute independently to recognition, the LPC's insensitivity to behavioral measurements of familiarity is also required. Since familiarity is often conceptualized as a continuous process, one way to approximate it is by measuring response confidence (Dunn, 2004). On the other hand, recollection has been theorized as a discrete threshold-based process by some researchers (Yonelinas, 1994). Hence, the LPC, as a marker of recollection, should not be sensitive to degrees of confidence. However, as discussed in the introduction, Brezis, Bronfman, Yovel, & Goshen-Gottstein (2016) recently demonstrated that the LPC tracked confidence when controlling for the behavioral measurements of recollection and familiarity (i.e. proportion of Remember and Know responses). Along with Ratcliff, Sederberg, Smith, & Childers, (2016), they suggested that the LPC instead tracks the response-related evidence accumulation process.

Data from research on study repetition also provide challenge for the interpretation of the LPC as a marker of a threshold-based recollection process, as multiple studies have shown a graded repetition effect on the LPC at retrieval and even when no explicit memory judgment was required (Bermúdez-Margaretto, Beltrán, Domínguez; Cuetos, 2015; Segalowitz, Van Roon, & Dywan, 1997; Van Strien, Hagenbeek, Stam, Rombouts, & Barkhof, 2005). In Bermúdez-Margaretto et al. (2015), participants were asked to distinguish words from pseudo-words. The pseudo-words were repeated while the real words were not. An LPC effect was observed to track the number of repetition, so that later presentations elicited a more positive LPC than the earlier ones. Although lacking an explicit memory task, such results are largely consistent with an evidence accumulation account of the LPC, in that item repetition could activate more task relevant information that may lead to a shortened accumulation process.

Previous work in an amnesic patient with severely impaired episodic recollection has demonstrated preserved abilities to make cumulative lifetime familiarity judgements, suggesting a dissociation between recollection and lifetime familiarity judgements (Bowles et al., 2016). Regarding frequency judgements, early research comparing frequency judgements and recognition paradigm suggested familiarity, which is often conceptualized as a continuous memory strength signal, is the primary source underlying frequency judgements (Hintzman & Curran, 1994). In the present study, the LPC was modulated by outcome of both lifetime familiarity judgements and frequency judgements. If we assume that both types of judgements are largely based on familiarity, then the data seem to support an alternative dual-process view of the LPC component, in which it acts as a marker of familiarity rather than recollection. Consequently, it is difficult to explain why the same component marks two independent memory processes (i.e., recollection and familiarity). Naturally, one way to resolve this conflict is to not assume absolute independence between recollection and familiarity. Indeed, a recent study has demonstrated that a dual-process model without the independence assumption provided better fit to the behavioral data in a Remember/Know paradigm compared to a dual-process model that assumes independence (Moran & Goshen-Gottstein, 2015). Indeed, Duke et al. (2017) showed that participants were also more likely to report perceived recollection to stimuli with high lifetime familiarity ratings, suggesting cumulative familiarity may not always be independent from recollection.

Although Brezis et al. (2016) and Ratcliff et al. (2016) suggested a more parsimonious single-process (i.e. strength) model of recognition memory. The evidence-accumulation account of the LPC is also consistent with the continuous dual-process model proposed by Wixted and Mickes (2010). Under the continuous dual-process account, memory strength is a combination of recollection and familiarity, which are both continuous and differentially emphasized by the memory task at hand. The combined signal leads to participants' judgements of cumulative exposure, and is reflected on the LPC amplitude. Whether the LPC observed in the current study does indeed reflect evidence accumulation is an issue that requires further investigation in future research, for instance, through plotting the average EEG epoch of single trials across participants in the order of reaction time (Delorme & Makeig, 2004). Based on the diffusion model (Ratcliff et al., 2016) of memory retrieval, trials with shorter reaction time should also elicit higher LPC amplitudes.

Similar to Van Strien et al. (2005), we also observed a frontally distributed linear effect in the LPC time window that is modulated by objective repetition. Critically, the LPC effect we observed in the test phase based on participants' responses shows a different scalp distribution from this objective repetition effect at study, when no explicit memory judgements were required. Importantly, the objective repetition effect does not conform to the LPC distribution typically reported. Thus, the LPC effect at test is more consistent with an interpretation that relates it to the outcome of the memory judgment rather than repetition as such.

4.2 The FN400/N400 time window

As hypothesized, we observed more positive ERPs in the 300 to 500 ms window for higher as compared to lower ratings in both frequency judgments and judgments of lifetime familiarity. However, this effect was only observed in the parietal ROIs, thus being more similar in distribution to an N400 than an FN400. A controversial issue about the distinction between the FN400 and the N400 in the current literature concerns whether they mark explicit and implicit memory signals, respectively. Explicit memory is always accompanied by awareness of access to memory, while implicit memory can operate without this conscious awareness (Voss & Paller, 2008). One way to probe implicit memory is through priming paradigms, in which effects of identical or conceptually related items are examined without any requirement to make explicit memory judgements. Behaviorally this often results in a decrease in response time. The N400 has been shown to be sensitive to primes that are either identical or semantically related stimuli (Kutas & Federmeier, 2011). Voss, Lucas, & Paller (2009) compared ERPs elicited by words rated meaningful or meaningless by participants; only words rated as meaningful elicited a conceptual priming effect and an FN400 effect in a recognition-memory test. Since the N400 is also sensitive to conceptual priming and occurs in the same time window as FN400, these results suggest that the FN400 and the N400 can be unified as a single component (Voss & Federmeier, 2011). However, the FN400 effect has also been reported in some other studies with meaningless stimuli (Groh-Bordin, Zimmer, & Ecker, 2006). Given the strong links between N400 and semantic processes, it is difficult to explain why it would be sensitive to stimuli without semantic meaning. Thus, the N400 may not be completely inseparable from the FN400.

The effect that resembled the N400 in the test phase of the current study did not differ between the two types of judgements, as indicated by the nonsignificant task x response interaction. One possibility is that this effect was indeed an N400 and marked semantic implicit memory resulted from cumulative exposures in both types of judgements. Since participants' frequency judgements in the test phase were significantly correlated with actual numbers of repetitions in the study phase, a contrast between high and low frequency judgements could also be thought as a contrast between large and small number of repetitions, thus contained different implicit memory. Similarly, since lifetime familiarity ratings of concepts correlate with word frequencies (Cree & McRae, 2003), it is reasonable to assume that concepts with higher lifetime familiarity ratings are encountered more often and thus processed more fluently by participants. Such a difference in fluency can affect either or both implicit and explicit memory.

Ultimately, the two components are differentiated based on relative, instead of absolute scalp distributions. The Frontal Negative (i.e. "FN") 400, by its name, should be more frontally distributed than the N400. Bader & Mecklinger (2017) combined a conceptual priming paradigm with a recognition paradigm, and demonstrated that the ERP distribution associated with the priming contrast were significantly different from that associated with the recognition contrast, although the two effects share the same time window. They also noticed that when the priming and the recognition effect were confounded, the N400 priming effect was superimposed with the FN400 recognition effect, and resulted in a more posterior distribution. Similarly, De Chastelaine et al. (2009) presented unnamable symbols to participants in a remember/know paradigm. The study was divided into four sessions, each with the same set of old symbols and some new symbols unique to that session. A clear parietal shift with more repetitions was observed when the FN400 old/new effect was compared across sessions.

The primary source of implicit memory difference in frequency judgements should come from the different number of repetitions in the study phase, since word frequency and normative lifetime familiarity ratings were matched across bins. We reasoned that participants who showed a strong repetition priming effect in the study phase would also show a strong priming effect in the test phase on the stimuli used in the frequency judgement task. Data from the analysis on the ERP effects of objective number of repetitions supported this prediction, in that a linear trend consistent with the N400 tracked objective number of repetitions in both the study and the test phase. However, participants who showed a strong N400 effect of repetition priming did not necessarily show a strong N400 effect of frequency judgements. Thus, the N400 like effect in the test phase on participants' explicit memory judgements does not reflect implicit memory alone. As was in Bader and Mecklinger (2017), when explicit memory is mixed with conceptual implicit memory, due to the overlapping time window, the effect may show different scalp distribution from a typical FN400 effect. Thus, the N400 like effect we observed in the test phase is likely a combination of a distorted FN400 sensitive to explicit memory component, and an N400 repetition effect sensitive to implicit memory component.

4.3 Relationship between the two ERP components

Within classic dual-process models, the FN400 and the LPC has been interpreted as markers of familiarity and recollection, respectively. Although they can be dissociated in certain paradigms, it is not guaranteed that they are independent in all memory tasks. Indeed, a significant positive correlation is present between the LPC and the N400 like effect on participants' memory judgements in the test phase of our study. This correlation can be interpreted in several ways. One interpretation is that there are two processes, presumably familiarity and recollection, that are marked by the two ERP components respectively. But when making judgements about cumulative exposure, the two processes are not independent. Another possibility is that one ERP component tracks multiple underlying memory processes. Although the difference between the two interpretation is subtle, the latter one is more parsimonious and supported by research in cumulative exposure. For instance, Groh-Bordin, Busch, Herrmann, & Zimmer, (2007) asked participants to make old/new judgements on meaningless line drawings that were presented up to four times in a study phase. Consistent with our results, they found that the ERP from 430 ms to 600 ms after stimulus onsets increased positivity with repetitions. Note that this time window overlapped with the N400 and the LPC time windows in the present study. We chose our ERP time windows following a set of frequently cited studies of recognition memory to avoid the multiple implicit comparison problem (Luck, 2014). However, differences do exist across studies in terms of choosing ERP analyzing windows, especially for the later component (i.e. LPC). Thus, it is possible that our time window choices were not optimal in separately identify the FN400 and the LPC in cumulative memory task. If we are forced to choose one of the two components, the LPC describes our data better, due to the parietal distribution of the effect in both time windows.

4.4 Difference in the types of perceived cumulative exposure

We observed in both time windows and regardless of responses, more positive ERPs in the left ROIs for frequency judgements as compared to the lifetime familiarity judgements. Duke et al. (2017) showed that the left perirhinal cortex tracked both experimentally controlled and lifetime cumulative exposures. Interestingly, the BOLD responses for the two types of judgements were of opposite directions in the left perirhinal cortex. A key difference between the two types of judgements is the difference in the encoding context. Specifically, frequency judgements require more episodic encoding than lifetime familiarity judgements, since the former needs to refer to a previous laboratory session, while the latter does not. The perirhinal cortex has been implicated in encoding of object memories (Diana, Yonelinas, & Ranganath, 2007). More direct evidence comes from depth electrodes study on epileptic patients. Fernández et al., (1999) asked participants to memorize words and later tested their recall. They demonstrate that electrophysiological activities in the perirhinal cortex predicted later memory performance. Critically, this perirhinal memory effect was consistent in both the FN400/N400 time window and the LPC time window. Thus, it is possible that the ERP difference we observed between the two types of judgements is linked to encoding processes in the perirhinal cortex.

4.5 Limitations and future directions

Although presentation frequency judgements have been shown to rely on similar mechanisms as old/new recognition judgements (Hintzman & Curran, 1994), the lack of old/new judgements weakened, to some extent, the comparability of our results to previous literature. Future study would benefit from embedding old/new judgements or a remember/know paradigm in the test phase with the current design. For instance, participants may be asked to first make a remember/know judgement for each stimulus. Then if they judge the stimulus to be old, a presentation frequency estimation would follow. If they judge the stimulus to be new, a lifetime familiarity judgement would follow. Such a paradigm will enable us to directly compare ERPs elicited by classic recognition procedures with those elicited by cumulative exposures. Since the functional sensitivities, the spatial specificities and the temporal profiles of the ERPs of interest, namely the FN400/N400 and the LPC, have not been mapped out clearly, comparing ERPs associated with different behavioral tasks within a study would be much more interpretable than comparing across studies. Adding an old/new judgement task also has the added benefit of providing an objective measurement of correct responses, which we did not have in our current design. This would further increase the comparability with extant literature, since many studies only analyzed ERPs associated with correct responses. However, such a design would require a larger number of stimuli to get enough trials in each response category for stable ERPs. This would pose a serious challenge if stimuli also need to be matched on various measurements (e.g. normative lifetime familiarity ratings and word frequency) for the presentation frequency manipulation. A potential solution is to conduct online studies to collect large sets of normative data, and thus allowing more complex designs.

Expanding on Wixted and Mickes (2010)'s continuous dual-process model, we can also picture more than two processes. To this day, the "butcher on the bus" phenomenon (Mandler, 1980) is still used as one example to support the dual-process account. Since people typically can distinguish judgements about single-exposure familiarity (e.g. have you seen this word in the study phase?) from judgements about cumulative familiarity (e.g. how familiar are you with this word?), we can view cumulative familiarity, at least phenomenologically, as a separate process from the single-exposure familiarity. Taking it one step further, we can also view experimentally induced cumulative familiarity as a separate process from lifetime familiarity. These memory processes may each have a dimension of strength, and are unlikely to be independent. Nonetheless, they can be differentially emphasized by the requirements of the memory task at hand. Thus, they may still be dissociable in certain tasks. Then the question is that how many different dimensions can be conceptualized. Is the question "did you see this word today" different from the question "did you see this word in the past three days"? At some level, yes, since we perceive them as different questions. But that difference is likely to become more and more trivial as we shorten the difference in the time range of the judgements. Dual-process models emphasize the qualitative differences between familiarity and recollection, which are not merely reflected on the time scale of the judgements. For instance, familiarity is thought as item-based memory, while recollection is defined as retrieval of contextual details (Ranganath et al., 2004). The dichotomy of semantic and episodic memory captures the time dimension to some extent. However, it is sometimes treated as parallel to the familiarity/recollection distinction, so that the term "episodic recollection" is redundant. However, we have demonstrated that people can make familiarity judgements on different time scales. Moreover, it is not well defined how long an episode should be. Would the recollection of some details of an event lasting several days engage the same episodic processes as recollection of similar details of an event last several hours? Perhaps, we should treat the difference between semantic and episodic memory as quantitative instead of qualitative, and model it as a separate dimension from the familiarity/recollection distinction.

5 Conclusion

We investigated the sensitivity of ERP components previously implicated in recognition memory to degree of experimentally controlled as well as lifetime cumulative exposures. A parietally distributed ERP component spanning both the FN400/N400 and the LPC time windows was found to track participants' perceived degree of cumulative exposure for both types of judgements. This effect could be an LPC effect with an early onset. It appears to differ from previously reported effects of repetition linked to implicit memory, and likely represent response-related evidence accumulation processes that are consistent with both a single-process model and a continuous dual-process model. We also observed more positive ERP in the left ROIs for frequency judgements as compared to lifetime familiarity judgements. This effect does not interact with participants' responses, and is likely linked to encoding processes in the perirhinal cortex.

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Appendix I Oral instructions to participants

The following oral instructions were given to all subject before each phase of the experiment.

Study phase:

"The first section will take you about 40 minutes to complete. You will see one word appearing on the screen at a time. Your task is to judge whether that word represents animal or not animal, i.e. animate or inanimate, by pressing one of two keys. The key mappings will be shown to you in an written instruction before the experiment begins. Before each word appears, there will be a cross on the center of the screen. Please focus your eyes on that, and do not look down onto the keyboard when you make responses. Since it is an ERP experiment, it is very sensitive to movements. Please minimize movements throughout the experiment, and do not touch the electrodes or the cap. Do you have any questions? [after answering all questions] Now, please give me 10 seconds to close the door for you, then you can proceed."

Test phase

"You may have noticed that there were some repetitions in the first section. The second section will take you about 20 minutes. You have two tasks here. Again, you will see one word appearing on the screen at a time, following a cross. In one task, you will see words that you have seen in the previous section. For those words, please judge relatively how frequently you saw each one, on a scale of 1 to 5, with 5 being the most frequent. In the other task, you will see words that you have not seen in the previous section. For these new words, please judge how familiar you are with the concept that the word represents, based on your lifetime familiarity, again on a scale of 1 to 5, with 5 being the most familiar. For instance, if you see the word "dog", most Canadians will probably say that is a very familiar concept. But the concept "aardvark" will likely be less familiar to most Canadians. The two tasks alternate every five trials. Before they switch, there will be a message on the screen telling you what the next five trials will be. Please use both of your hands to make responses. And try to use all five keys to space out your responses. Just like in the previous section, please minimize movements and do not touch the electrodes or the cap. Do you have any questions? [after answering all questions] Now, please give me 10 seconds to close the door for you, then you can proceed."

Appendix II written instruction for participants

Welcome to the study phase of your experiment!

Your task in this phase is to judge wether the concept presented is inanimate or animate.

You will provide response by pressing one of two keys:

"Z" or "M"
with "Z" indicating inanimate," M" indicating animate

Type a key to continue...

Figure 18. Written instructions for the study phase

Welcome to the test phase of your experiment!

You have 2 tasks in this phase:

1) Judging how frequently you saw the concept in the study phase

2) Judging how familiar you are with the concept based on your lifetime experience with that concept

In both cases you will provide ratings on a 5-point scale, with 5 indicating high frequency/familiarity
1 2 3 4 5

Type a key to continue...

Figure 19. Written instructions for the test phase

Welcome to the test phase of your experiment!

You have 2 tasks in this phase:

1) Judging how frequently you saw the concept in the study phase

2) Judging how familiar you are with the concept based on your lifetime experience with that concept

In both cases you will provide ratings on a 5-point scale, with 5 indicating the highest frequency/familiarity
5 4 3 2 1

Type a key to continue...

Figure 20. Written instructions for the counter-balanced version of the test phase

Appendix III Ethics approval form

Western Research

Research Ethics

Western University Non-Medical Research Ethics Board
NMREB Annual Continuing Ethics Approval Notice

Date: December 23, 2016
Principal Investigator: Prof. Stefan Kohler
Department & Institution: Social Science\Psychology,Western University

NMREB File Number: 107492
Study Title: Mechanisms involved in judgements of object concepts: An ERP study
Sponsor: Natural Sciences and Engineering Research Council

NMREB Renewal Due Date & NMREB Expiry Date:
Renewal Due -2017/12/31
Expiry Date -2018/01/20

The Western University Non-Medical Research Ethics Board (NMREB) has reviewed the Continuing Ethics Review (CER) form and is re-issuing approval for the above noted study.

The Western University NMREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), Part 4 of the Natural Health Product Regulations, the Ontario Freedom of Information and Protection of Privacy Act (FIPPA, 1990), the Ontario Personal Health Information Protection Act (PHIPA, 2004), and the applicable laws and regulations of Ontario.

Members of the NMREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Ethics Officer, on behalf of Dr. Riley Hinson, NMREB Chair

Ethics Officer: Erika Basile ✓ Katelyn Harris__ Nicole Kaniki __ Grace Kelly__ Vikki Tran __ Karen Gopaul __

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Curriculum Vitae

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Post presentation:	LPC tracks recent as well as cumulative lifetime experiences with object concepts Lake Ontario Visionary Establishment February, 2017 Crowne Plaza Hotel, Niagara Falls