An ERP measure of non-conscious memory reveals dissociable implicit processes in human recognition using an open-source automated analytic pipeline

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Abstract
Non-conscious processing of human memory has traditionally been difficult to objectively measure and thus understand. A prior study on a group of hippocampal amnesia (N = 3) patients and healthy controls (N = 6) used a novel procedure for capturing neural correlates of implicit memory using event-related potentials (ERPs): old and new items were equated for varying levels of memory awareness, with ERP differences observed from 400 to 800 ms in bilateral parietal regions that were hippocampal-dependent. The current investigation sought to address the limitations of that study by increasing the sample of healthy subjects (N = 54), applying new controls for construct validity, and developing an improved, open-source tool for automated analysis of the procedure used for equating levels of memory awareness. Results faithfully reproduced prior ERP findings of parietal effects that a series of systematic control analyses validated were not contributed to nor contaminated by explicit memory. Implicit memory effects extended from 600 to 1000 ms, localized to right parietal sites. These ERP effects were found to be behaviorally relevant and specific in predicting implicit memory response times, and were topographically dissociable from other traditional ERP measures of implicit memory (miss vs. correct rejections) that instead occurred in left parietal regions. Results suggest first that equating for reported awareness of memory strength is a valid, powerful new method for revealing neural correlates of non-conscious human memory, and second, behavioral correlations suggest that these implicit effects reflect a pure form of priming, whereas misses represent fluency leading to the subjective experience of familiarity.

KEYWORDS
analysis/statistical methods, ERPs, hippocampus, implicit memory, reproducibility
1 | INTRODUCTION

Non-conscious processing of human memory has traditionally been difficult to objectively measure, characterize, and thus understand (Perry & Lawrence, 1984; Schacter, 1987; Tulving & Schacter, 1990). Whereas conscious memory experiences can be directly reported and declared by people explicitly (i.e., ‘explicit memory’), memory that is unavailable to conscious awareness can typically only be inferred through passive observations of behavioral changes in performance or response times that are implicitly observed by others in the absence of the person’s own recognition (i.e., ‘implicit memory’). While modern psychological science now views implicit memory as a core element of human cognition, it still wrestles with the difficulties of objectively measuring it (Paller et al., 2012; Voss et al., 2012).

One core difficulty of empirical approaches to measuring implicit memory is controlling for the potential of contamination by components of explicit memory processing, as they may operate on a continuum (see below for further detail and discussion; for Review, see Berry et al., 2012; Perruchet & Baveux, 1989; Richardson-Klavehn & Bjork, 1988; Voss et al., 2012). That is: how can we be sure we are capturing memory outside of mental awareness and that no conscious memory trace could be contributing (MacLeod, 1998; Richardson-Klavehn & Bjork, 1988)? With the introduction of neuroimaging technologies such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), behavioral measures were no longer the only tool available in the experimenter’s repertoire because the physiological measures provide excellent covert indicators of memory (i.e., brain activity) that people are not overtly aware of (Luck, 2005, 2014). For instance, fMRI has been routinely used to successfully measure implicit memory effects of priming (Schacter et al., 2007; Wig et al., 2005), repetition suppression (Martin & Gotts, 2005), masked priming (Henke, 2010; Reber et al., 2012), and associative recognition (for Review see Hannula & Greene, 2012), while event-related potentials (ERPs) have provided researchers with sensitive physiological markers that can dissociate implicit and explicit forms of memory (Ozubko et al., 2021; Paller et al., 2003; Rugg et al., 1998; Schacter et al., 2007; Woollams et al., 2008). But simply using neuroscience tools by itself does not necessarily solve the problem of isolating implicit memory from conflation by explicit memory (Hutzler, 2014; McCabe & Castel, 2008; Michael et al., 2013; Poldrack, 2006, 2011)—for that, convergence of neuroscience tools and more sophisticated behavioral paradigms are needed.

As researchers used ERPs to study explicit memory processes of recollection and familiarity, their studies also revealed key insights into implicit memory processing (Ozubko et al., 2021; Rugg et al., 1998) due to using increasingly complex behavioral paradigms. As a brief primer, in episodic memory, familiarity is a memory process characterized by a person’s ability to explicitly recognize items from the past but while lacking full confidence and without the specificity of retrieving associated details such as when or where it occurred (Yonelinas, 2001a, 2001b, 2002, Yonelinas et al., 2010). It is typically associated with ERPs indicating a mid-frontal effect whereby previously encountered ‘old’ item ERPs are more positive than ERPs for ‘new’ items and occurs between approximately 300–600 ms after a stimulus onset. This memory difference in ERPs is often referred to as the FN400 (the frontal negative-going ERPs peaks at approximately 400 ms) or mid-frontal old-new effect (for Review see Curran, 2000; Rugg & Curran, 2007; Voss & Paller, 2017), though can be variable in scalp location (Addante, Ranganath & Yonelinas, 2012; Friedman, 2013; Leynes et al., 2017; Mecklinger & Bader, 2020). As researchers had been debating the relative contributions of implicit and explicit memory processing to a generally regarded ERP correlate of familiarity (the FN400), better ways to separately measure each process emerged (Wang et al., 2010, 2014; Wang & Yonelinas, 2012).

Some researchers pointed out that the experimental designs of many studies lacked the ability to isolate explicit familiarity from co-active forms of implicit conceptual priming and questioned—with vigorous debate—how much of the FN400 effect represented familiarity versus priming (for views of conceptual priming see: Hou et al., 2013; Lucas et al., 2010, 2012; Paller et al., 2003, 2007, 2012; Taylor & Henson, 2012; Voss et al., 2010, 2012, 2008; Voss & Paller, 2007, 2008, 2010; vs. views on familiarity-based interpretations see: Bader & Mecklinger, 2017; Bridger et al., 2012, 2014; Grob-Bordin et al., 2005, 2006; Mecklinger & Bader, 2020; Mecklinger et al., 2012; Stenberg et al., 2009, 2010). This vibrant debate led to the emergence of progressively more sophisticated methods and techniques for addressing the issue of possible conflation among implicit and explicit memory processes, which drove the field forward towards improved construct validity, and ultimately, led to novel discoveries.

1.1 | Emergence of a novel measure of implicit memory: Equating old and new conditions for levels of memory awareness

In ERP studies of recognition memory, implicit memory was traditionally measured by contrasting ERPs for memory misses (old items incorrectly endorsed as new) versus ‘correct rejections’ of new items endorsed as new (Ozubko et al., 2021; Rugg et al., 1998; Woollams et al., 2008). This
contrast used the logic that each condition shared the similar variable of having no consciously reported recognition yet varying on the dimension of having been experienced before. Thus, it served to reason that any differences in ERPs were attributable to differences in implicit processes since the explicit subjective reports of the participants were held constant (Kandel, 2013, pp. 1382–1383, figure 61-9).

Nevertheless, some researchers pointed out that it remained theoretically possible that misses may potentially be contributed to by some weak forms of explicit memory, since awareness may not be entirely absent (Berry et al., 2012; Poldrack & Rodriguez, 2003). As noted by both Kumaran and Wagner (2009) and Squire and Dede (2015): “awareness is continuous, so a low amount of awareness is not the same as a complete lack of awareness; thus it would be instructive to obtain confidence ratings for memory judgments and ask if there is any detectable awareness of which items are correct.” The idea was that as familiarity is modeled to operate on a continuum of memory strength across confidence levels (Yonelinas, 2001a, 2001b, 2002; Yonelinas et al., 2010), then it was possible that misses might have had some weak forms of familiarity included sub-threshold to a subject's decision criterion, such that those differences in ERP effects could potentially reflect differences in explicit memory strength instead of implicit memory processes, based on theoretical models of recognition as a continuous variable (Richardson-Klavehn & Bjork, 1988; Slotnick & Dodson, 2005; Wais et al., 2006; Wixted, 2007; Wixted & Squire, 2004; Wixted & Stretch, 2004).

That possibility was preliminarily tested by a unique analysis in a study by Woodruff et al. (2006), which had used a modified “Remember-Know” procedure to collect people's reports of familiarity confidence on a scale of 1 (sure new) to 4 (sure old). To account for discrepancies in trial counts among each of the various levels of familiarity, they devised a clever method that also measured implicit memory processing. Woodruff et al. ensured that an equivalent number of randomly selected trials of both old and new items were included for each level of memory confidence (for updated procedure, see Figure 1 below, and Method), which would have the effect of equating across old/new conditions for the subjective reports of memory awareness. Then, these awareness-equated-conditions could then be separately averaged within the old and new categories, respectively, and contrasted against each other (old vs. new) to identify differences of any physiological effects where they may vary (see Method, Figure 1); that is: providing a neural measure of repetition without awareness.

The value in this analytic procedure was that it successfully measured neural effects of repetition without awareness: by holding constant the factor of subjectively reported memory awareness, then any difference in the ERP physiology for old versus new conditions could be attributed to the fact that one condition (old) had been repeated while the other had not (new). A core strength of this approach is that it satisfied the earlier calls from Kumaran and Wagner (2009) and Squire and Dede (2015) to assess for any detectable awareness levels using confidence ratings. By virtue of the shared reported strength of memory responses comprising both the old and new ERP conditions, this procedure eliminated the possible confound discussed above for memory misses: that they might reflect differential amounts of memory strength, or be contaminated by sub-threshold explicit memory difference among old and new conditions. This new method of measuring ERPs of implicit memory was thus stronger and more precise than methods used in prior studies (i.e., generic measures of miss vs. correct rejections), and was presumed (though not tested) to be free of conflation with other variables such as explicit memory.

Results from Woodruff et al. did not identify any reliable ERP effects for that contrast. This null finding was subsequently (and appropriately) criticized by Paller et al. (2007) for having low sample size (N = 16), which led to a follow up study being conducted by Yu and Rugg (2010) with a greater sample size (N = 23). In Yu and Rugg (2010), the same contrast this time elicited clear, statistically significant effects in the posterior region during the same time window as the mid-frontal FN400 (300–500 ms). These posterior parietal effects were assumed to reflect repetition priming and were topographically dissociable from the FN400 effects of familiarity, similar to earlier dissociation of implicit ERPs for misses by Rugg et al. (1998). Importantly, while there were not yet efforts made to empirically validate that this awareness-equating procedure excluded contributions from explicit memory (the logic of the contrast was reasonably deemed sufficient), these findings nevertheless presented the field with a new way to measure implicit memory in ERPs during ratings of memory confidence, which afforded better control of confounding variables, and inspired subsequent work exploring the subcortical brain regions that may be involved.

1.2 | Clinical application and validation of the implicit memory procedure

In 2015, an ERP data set of hippocampal amnesia patients and healthy controls applied the same procedure developed by Woodruff et al. (2006) and used by Yu and Rugg (2010), in order to assess what role the hippocampus might play
The explicit episodic memory task involved rating old and new items for recognition confidence on a scale of 1 through 5 instead of the modified “remember-know” scale used by Yu and Rugg (2010). For this task, a score of 1 meant “sure new” and a 5 indicated “sure old” (Figure 1), and it had been established that all patients exhibited intact mid-frontal FN400 effects related to familiarity-based memory from 400 to 600 ms (Addante, Ranganath, Olichney, et al., 2012). Results from healthy control subjects (N = 6 age-matched middle-aged controls and N = 25 younger adult controls) replicated the prior findings of Yu and Rugg (2010): identifying implicit repetition effects in broad posterior scalp regions that were dissociated from the frontal FN400, and found to be occurring from 400 to 800 ms (Figure 2, top panel). In contrast, the hippocampal patients exhibited a pronounced deficit in implicit memory effects as evidenced by a significant condition × group interaction, which post hoc tests revealed were due to hippocampal patients exhibiting a significant negative-going ERP effect instead of the positive one exhibited by healthy controls. Such findings of impairment in the patients were thus based not on absence of or null effects, but rather upon the presence of multiple significant effects. After a series of rigorous control analyses to rule out contributory factors such as sample size and which systematically validated that the awareness-equating procedure was not conflated with explicit memory response activity, it was concluded that the hippocampus provides a critical role in implicit memory processing.

The implication of a hippocampal-dependent implicit memory for single-item recognition effect thus questions the core dogma in the field derived from famous amnesic Patient HM (i.e., that a broad form of “non-declarative [implicit] memory does not depend upon the medial temporal lobe structures,” e.g.: Kandel, 2013, pp. 1452–1453, p. 1459; see also Corkin, 2002; Gazzaniga et al., 2013; Kandel, 2013; Kandel et al., 2016; Scoville & Milner, 1957;
Squire, 2009; Squire et al., 2004; Squire & Zola, 1997; Suthana & Fried, 2012), and added to burgeoning findings in the field suggesting that many areas of the brain—including the hippocampus—are involved in implicit memory processes beyond those particular kinds tested in Patient HM (for Reviews see Hannula et al., 2017; Hannula & Greene, 2012; Henke, 2010). Nevertheless, certain limitations remained to be addressed, which are particularly important given the broader implications of the prior work. For instance, the results were found in relatively small sample sizes ranging from \( N = 3 \) hippocampal (patients) to \( N = 6 \) (middle-aged matched controls) to \( N = 25 \) (young adult controls). The simulations performed to rule out sample size issues and to infer a hippocampal-dependent effect could have also been nuanced by control data and remain to be independently verified. Additionally, the three studies using the awareness-equating procedure to isolate ERP effects of implicit memory (Addante, 2015; Woodruff et al., 2006; Yu & Rugg, 2010) all relied upon a manual procedure for identifying randomly selected trials for ERP averaging. Such manual procedures are more prone to human error than automated functions while limiting wider adoption and testing in the field. Finally, the effect's functional significance remained an open question, such as what it means and how it relates to other neural and behavioral measures of implicit memory.

1 Note that sample size concerns in that study (Addante, 2015) were largely mitigated by a having performed a permutation analysis that created its own null r-distribution of patients' impairments from a simulation using control data iterating 1000 times to confirm that varying small samples of intact control participants did not reliably exhibit the same deficits observed in the hippocampal patients (see figure 3 of Addante [2015] and Figure 2 in current Results section for comparable findings from a larger independent sample).

1.3 | Current investigation

The current investigation sought to address these issues and further extend available knowledge of neural memory without awareness by applying an automated process for performing the same procedure that had been done manually in the prior studies (here called **IMAP: implicit**
memory analysis procedure, see Section 2 for detailed description). It makes use of a much larger sample (N = 54) of healthy young adults from a recent study published in the domain of explicit memory and metacognition involving the Dunning–Kruger Effect (Muller et al., 2021). We sought to pursue three main goals: (a) assess if the implicit memory effects are reproducible in the larger data set using the newer automated analysis, (b) assess if the effects persist under an expanded set of rigorous controls for construct validity to ensure the procedure is not contaminated by explicit memory, and (c) explore the functional significance of the implicit memory effects as compared to the more traditional measure of misses versus correct rejections, so as to identify the extent to which they may be measuring the same or different kinds of implicit processing in memory.

We predicted our findings would replicate the previously reported ERP effects of implicit memory in posterior parietal regions from 400 to 800 ms (Addante, 2015). We also predicted that the effects of implicit memory would persist when subjected to a series of control analyses that systematically varied the inclusion/exclusion of each explicit memory response from the aggregated confidence ratings of the old-new IMAP effects. To do this, we examined the IMAP effects after systematically removing individual explicit memory responses from the conditions analyzed, to identify if any individual level of explicit memory response affected the results. This was done for each combination of explicit memory response possibilities: by first assessing ERPs in the IMAP conditions with removal of recollection-related trials (confidence ratings of 5’s; Yonelinas et al., 2010; Yonelinas, 2001a, 2001b), next assessing the IMAP effects when removing just the familiarity-based trials (4’s, which was not examined in the 2015 validations; Yonelinas, 2002; Addante, Ranganath, & Yonelinas, 2012), and then more generally when removing both levels of explicit memory processing together (4’s + 5’s, hits). Furthermore, this approach also added an even more rigorous test of the hypothesis by including the explicit memory responses in the new condition while excluding them from the old condition. This approach was hypothesized to eliminate or reverse the implicit memory effects if they were driven by explicit memory responses.

We further hypothesized that the implicit ERP effects would be spatiotemporally differentiated from the ERP measures of miss versus correct rejections, because of the propensity for misses to include potential differences in memory strength whereas the IMAP procedure isolates implicit memory effects when the factor of memory strength is held constant (see prior discussion above, Method, Figure 1). To preface the more detailed results, the IMAP function was successful: it identified ERP effects that faithfully reproduced prior findings and which were then validated with systematic control analyses to confirm that it was measuring activity for memory without conscious awareness. From this, the results also revealed that the IMAP effects were functionally distinguishable from other forms of implicit memory (miss vs. correct rejections), as evidenced by both spatial and temporal dissociations, and were then found to be behaviorally relevant: as the size of the ERP effect was reliably correlated with response time measures of implicit memory. Together these findings revealed dual forms of implicit processing operating concurrently to support human recognition memory.

2 | METHOD

The current study performed a re-analysis of previously published ERP data (Muller et al., 2021), but which used the identical experimental conditions and recognition memory paradigm as that used to measure implicit memory by Addante (2015). The participants consisted of 61 right-handed students free from neurological disorder and memory problems, as was reported previously (Muller et al., 2021). Data was not used for four participants due to noncompliance issues (i.e., pressed only one button throughout the task or ignored experimenter’s instructions), data lost due to experimenter error (N = 1), or unusable EEG data (N = 2) due to excess motion artifacts/noise that resulted in an exclusion of the majority of EEG trials. This presented a working data set of N = 54 for the current study.

2.1 | Participants

As described by Muller et al. (2021): the majority of participants were women (N = 48); 57% were Hispanic, 23% Caucasian, 11% Asian, and 10% identified as more than one ethnicity. The average age was 23.5 years old (SD = 4.82). None of the participants reported any visual, medical, or physical issues that would interfere with the experiment. Most participants spoke English as their first language (N = 47) and those who had indicated speaking a different first-language had been speaking English for an average of 16.73 years (SD = 4.74). Written informed consent was obtained for participation in the experiment, approved via the Institutional Review Board of California State University—San Bernardino, and data analyses observed the privacy rights of human subjects, consistent with the Declaration of Helsinki.
2.2 | Paradigm

The paradigm used was the same item- and source-memory confidence paradigm that has been routinely used in our prior reports to characterize various facets of memory (Addante, 2015; Addante et al., 2011; Addante, Ranganath, Olichney, et al., 2012; Addante, Ranganath, & Yonelinas, 2012; Addante et al., 2021; Muller et al., 2021; Roberts et al., 2018), with slight modifications as noted below and in Muller et al. This paradigm consisted of an encoding phase containing four sequential study sessions, in which participants studied 54 words in each session, that was later followed by a retrieval phase that contained six test sessions in which the participant’s memory was tested for 54 words in each session. During the encoding phase, participants were given instructions to make a simple decision about the word presented. The participants were either asked to judge if the item was man-made or if the item was alive. The instructions were presented in one of two counterbalanced orders: ABBA or BAAB. The participants viewed four lists of 54 words during the encoding phase. After the encoding phase was complete, the EEG cap was applied to the scalp of participants. During the memory test, participants viewed a total of 324 words, 216 of which were presented in the encoding phase and 116 of which were unstudied items (new items). All stimuli words presented during study and test were presented in white font on black background screen.

During the memory retrieval phase, the participants were read instructions asking them to judge if the stimulus word presented was old (studied during the encoding phase) or new (not studied before in the encoding phase) (Figure 1). To begin a trial, a screen with a small white cross at the center was presented for one of three randomly chosen times: 1 s, 2.5 s, or 3 s. Then the participants were presented with a word in the middle of the screen, the numbers “1,” “2,” “3,” “4,” and “5” evenly spaced beneath the word, the word “New” on the left by the number “1,” and the word “Old” on the right under the number “5.” Participants pressed any number between “1” and “5” evenly spaced beneath the word, the word “New” on the left by the number “1,” and the word “Old” on the right under the number “5.” Participants pressed any number between “1” and “5” to indicate if they confidently believed the word was old (“5”), believe the word was old but was not confident (“4”), did not know if the word was old or new (“3”), believe the word was new but was not confident (“2”), or confidently believed the word was new (“1”). Participants were told to choose the response that gave the most accurate reflection of their memory.

Immediately after the decision on item memory confidence, participants were asked to answer a source memory question about if the word came from the animacy decision task or the man-made decision task. Measures of source memory were previously reported by Muller et al. (2021) and were not relevant for the IMAP procedure’s use of item judgments. Since the IMAP procedure relies on equating awareness levels of recognition confidence judgments for old and new on equivalent scales, and because our source memory confidence scale was different for old than it was for new items, IMAP would not be applicable to source memory responses in the paradigm of the current study. The retrieval phase of the paradigm also included a simple metacognitive question to participants for estimating their performance, which occurred once every 10 trials and for which the data has been previously reported elsewhere for metacognition effects (Muller et al., 2021). The current investigation focused instead upon the memory related responses, as the metacognitive response data has been reported previously. Each session consisted of a list of 54 words; overall, six lists of 54 words were presented during the retrieval phase.

2.2.1 | Implicit memory analysis procedure

The analysis procedure for implicit memory was the same that was reported previously (Addante, 2015; Woodruff et al., 2006; Yu & Rugg, 2010; here abbreviated as “IMAP”): requiring a random selection of an equated number of trials from old and new status items in each of the five recognition confidence categories during a memory retrieval task, in order to equate for memory strength across the confidence levels, aggregated then into general conditions of “old” and “new” (Figure 1). This procedure holds the subjective conscious reports of participants constant across variables by including the same levels of subjective reports in both the old and new conditions being compared with ERPs. The null hypothesis from this approach assumes that there should be no differences across ERPs for old and new conditions in any electrode or latency if the conditions were only tracking neural activity of conscious memory processing, similar to the logic used in previous traditional ERP measures of misses as implicit memory (Rugg et al., 1998; Woollams et al., 2008). This procedure also provided the alternate hypothesis that any difference that the ERPs for conditions of old and new exhibit either temporally or spatially across the scalp would necessarily be attributable to neural activity sensitive to information from the past that was unavailable to conscious awareness (e.g., implicit memory) (Addante, 2015; Rugg et al., 1998; Schacter, 1987; Woodruff et al., 2006; Woollams et al., 2008).

2.2.2 | Using the IMAP functions

The automated processing pipeline developed for the current project is freely available under the terms of
the GNU General Public License at https://github.com/IMAP-Lab/IMAP-Lab-IMAP-Implicit-Memory-Automated-Pipeline and is accompanied by additional optional scripts and sample datasets for creating figures for data visualization. It was developed to be compatible with ERPLAB and EEGLab toolboxes. In order to effectively use the IMAP pipeline, the user needs to merely adjust the information at the top lines of the MATLAB scripts and follow their commented instructions; for example: changing file names and path directories to the user’s particular settings and then follow the series of instructions in the associated readme file. It is designed to operate on bin-based epoched EEG data that has already been subjected to any artifact correction (ICA), detection or rejection that may have been needed in a preprocessing step.

The IMAP pipeline is built upon the premise of having multiple response categories (e.g., 1–5 confidence ratings) across multiple response conditions (e.g., old, new), and requires that event codes in the epoched EEG data are numerics. The provided exemplary scripts are coded for five levels of awareness for recognition confidence and two statuses (old and new items), but they are easily adjustable for other levels if needed for different experimental designs. Data analyses can be performed for an individual subject or for whole-group batch scripting. If users do not have their EEG data coded as numeric event codes, then they can use one of our scripts to remap their event codes using ERPLAB’s functions (Lopez-Calderon & Luck, 2014) (for instance, ‘target’ can be re-named as “615” by using the option “Create Events List Advanced”). The IMAP pipeline randomly selects trials in an unbiased way across the two encoding task conditions, and in cases where there are not data in one particular encoding condition/code (e.g., if an experiment or participant did not have a second encoding condition and lacked a certain event code such as 61) then the procedure would still work by bypassing that particular parameter in the analyses.

2.3 | Electrophysiological acquisition

Each subject was tested individually inside a private chamber. Stimulus presentation and behavioral response monitoring were controlled using Presentation software on a Windows PC. EEG was recorded using the actiCHamp EEG Recording System with a 32-channel electrode cap and other artifacts. The EEG cap was placed on the participant's head and prepared for electrical recording. Gel was applied to each cap site and impedances were lowered below 15 KΩ via gentle abrasion to allow the electrodes to obtain a clear electrical signal. Subjects were instructed to minimize jaw and muscle tension, eye movements, and blinking.

2.4 | Electrophysiological analysis

Physiological measurements of brain activity were recorded using EEG equipment from Brain Vision LLC. All EEG data was processed en masse using the EEGLAB and ERPLAB toolboxes in Matlab (Delorme & Makeig, 2004; Lopez-Calderon & Luck, 2014). The EEG data was first re-referenced to the average of the mastoid electrodes, passed through a high-pass filter at 0.1 Hz as a linear de-trend of drift components, and then downsampled to 256 Hz. The EEG data was epoched from 200 ms prior to the onset of the stimulus to 1200 ms after the stimulus was presented. Independent components analysis (ICA) was performed using InfoMax techniques in EEGLab (Bell & Sejnowski, 1995) for artifact correction and the resulting data was individually inspected for artifacts, rejecting trials for eye blinks and other aberrant electrode activity. IMAP’s pipeline code uses the processed epoched EEGLab datasets as input. During ERP averaging, trials exceeding ERP amplitudes of ±250 mV were excluded, as described in Muller et al. (2021). A 30 Hz low pass filter was applied to each subject’s ERPs as a non-causal, infinite impulse response (IIR, Butterworth) filter, implemented through ERPLAB toolbox (Lopez-Calderon & Luck, 2014). Data is accessible upon request, as is code used to analyze the data. In order to maintain sufficient signal-to-noise ratio (SNR), all comparisons relied upon including only those subjects who met a criterion of having a minimum number of 12 artifact-free ERP trials per condition being contrasted (Addante, Ranganath, & Yonelinas, 2012; Boudewyn et al., 2018; Gruber & Otten, 2010; Kim et al., 2009; Luck, 2014; Otten et al., 2006; Ozubko et al., 2021). Participants were excluded from any particular analyses if they did not have responses in both/all of the comparisons for a given contrast.
2.5 | Statistical analysis

As the current investigation was based upon clear a priori-defined hypotheses derived from prior findings (Addante, 2015), initial analyses utilized planned paired t-tests to assess differences between the targeted conditions. In cases where exploratory analyses were conducted to explore unplanned comparisons, ANOVA was used to qualify potential differences that may exist and were corrected with Geisser–Greenhouse corrections when necessary. Because a non-significant p-value in conventional frequentist t-test methods is unable to inform whether there is actually evidence for the null hypothesis or if there is merely not sufficient evidence for any conclusion at all, analyses that revealed a null finding were subsequently quantified using Bayes factor analysis. Bayes factor analysis is a tool that allows researchers to quantify the relative strength of evidence for the null hypothesis (invariance) (Aczel et al., 2020; Bayes, 1958; Bayes & Price, 1763; Etz et al., 2018; Etz & Vandekerckhove, 2018; Jarosz & Wiley, 2014; Jeffreys, 1998; Morey & Rouder, 2011; Rouder et al., 2009; Wagenmakers et al., 2018). A resulting Bayes factor value can generally be considered as the ratio of how likely a hypothesis is as compared to the likelihood to another hypothesis (for specific details see Rouder et al., 2009; Jarosz & Wiley, 2014).

For interpreting Bayes factor result values, it is conventionally viewed that a Bayes factor (BF) of 1–3 typically represents “anecdotal/insensitive/uninformative” evidence, a BF of 3–10 represents “substantial evidence,” and a BF of 10–30 represents “strong” evidence for the given hypothesis (Jarosz & Wiley, 2014; Jeffreys, 1998). The Bayes factor analyses were computed for paired or one-sample t-test designs. As noted by Rouder et al. (2009), the results are calculated using the standard scale of r=.707 and the resulting outputs are provided as values in favor of the null hypothesis using the recommended Jeffrey–Zellner–Siow Prior (JZS, Cauchy distribution on effect size). Thus, results are reported as such for the pertinent analyses along with a noted indication of the relative strength of evidence for the null finding thereof.

3 | RESULTS

The main effect of interest was the IMAP effect (there was a mean of 44 trials selected per person for both old and new conditions; range: minimum of 14, maximum of 80), as produced by the pipeline described in Section 2 above (Figure 1). The initial interest was in assessing the extent to which the automated analysis tool may or may not replicate the prior IMAP effects reported as occurring from 400 to 800 ms at a posterior parietal electrode sites (figure S3 in Addante, 2015). Towards this end, we assessed ERPs at the same bilateral cluster of seven posterior electrode sites during the same latency as the previously reported findings (P3, P4, Pz, Cp1, Cp2, Po3, Po4; 400–800 ms), and found that old item ERPs were more positive-going than new items, t(53) = 3.53, p = .025, Cohen’s d = .190 (Old M = −1.14, SD = 2.19, SE = 0.298; New M = −1.55, SD = 2.12, SE = 0.288). This effect was maximal at right parietal site P4 (t(53) = 3.08, p = .003, Cohen’s d = .280; old M = −.512, SD = 2.31, SE = .32; new M = −1.15, SD = 2.24, SE = .30), effectively replicating the previous findings (Figure 2).

The IMAP effect was then explored further to characterize how it manifested through time beyond the 400–800 ms epoch of our a priori hypotheses. Inspection of the effect’s right parietal site revealed that the IMAP effect was evident throughout the 600–1000 ms epoch, with old items exhibiting significantly more positive ERPs than new items, t(53) = 3.53, p = .0008, Cohen’s d = .388 (Old M = 0.14, SD = 2.31, SE = 0.31; New M = −0.71, SD = 2.06, SE = 0.28) (Figure 3). Thus, the IMAP effects were found

![Graph](https://example.com/graph.png)

**FIGURE 3** Full characterization of the implicit memory effects. Topographic maps characterize the entire duration of the observed ERP effects occurring from 600 to 1000 ms post-stimulus onset. Representative ERPs are plotted from the representative right-parietal site of P4 that they were most pronounced at. Shaded areas represent the standard error of the mean for each plot throughout the time of the epoch.
to be evident across the right parietal region and occurred broadly throughout the epoch from 400 to 1000 ms post-stimulus. This was consistent with the previously reported bilateral effects from 400 to 800 ms (Figure 2) and relates them here to more specific right parietal regions where effects extended to later latencies of 600–1000 ms.

The original findings by Addante (2015) that motivated the current investigation also reported that the implicit memory ERP effects were hippocampal-dependent, by virtue of there having been a significant condition \( \times \) group interaction of the old-new effects among small groups of neuropsychological patients with damage to the hippocampus (\( N = 3 \)) and healthy control subjects matched for age, sex, and education (\( N = 6 \)). Since those were notably small sample sizes, their findings were bolstered by a simulation analysis using real data from a larger sample of healthy controls (\( N = 31 \)) to perform a permutation test on control data to examine how often one would expect to detect similar ERP effects between similarly sized groups of \( N = 3 \) and \( N = 6 \) after 1000 permutations (see Footnote 1 above). For computational simplicity, this used a between-groups \( t \)-test of the old-new difference wave for the implicit memory effect, as it is the computational equivalent as a condition \( \times \) group interaction. Those findings (2015) revealed a null \( t \)-distribution that indicated only one of the 1000 iterations fell above the actually observed \( t \)-value from the patients (Figure 2, top right panel), and was taken to indicate there was no difference between the two pseudo-groups and providing strong evidence that the observed impairment of implicit memory in patients was not attributable to small group size but rather to the factor that varied among the groups: the hippocampus.

Because the previously reported role of the hippocampus in the IMAP effect (Addante, 2015) had important implications towards updating traditional models of memory, and in the spirit of supporting the important role of reproducibility in science that has been widely heralded (Button et al., 2013; Ioannidis, 2005; Ioannidis et al., 2014; Moonesinghe et al., 2007), we thus considered it valuable to seek reproducibility of this core finding used for ruling out factors of sample size in the prior hippocampal study, by using the current independent sample of more than twice the original size (\( N = 54 \)). We thus performed the same permutation test but on the current data, whereby for each of the 1000 iterations of the permutation, data from nine subjects were randomly selected (without replacement) from the group of 54 subjects: six of these were randomly assigned as a pseudo-control group (\( N = 6 \)), the remaining were assigned as a pseudo-patient group (\( N = 3 \)), and a between-group \( t \)-value derived to represent a condition \( \times \) group interaction. The hypothesis is that if clinical impairments were due to low sample sizes, then there should be many similar instances in which groups of the same small sizes exhibit the same levels of observed \( t \)-values.

The resulting null distribution in the current data had a mean between-group \( t \)-value of \(-0.081\), with critical \( t \)-values of \(-2.69\) and \(2.21\), respectively, as estimated by the 95% confidence interval derived from the .025 and .975 quantiles (Figure 2, bottom right panel). Out of the 1000 iterations that we permuted here, only 25 times (a mere 2.5% of the time, .025) did the pseudo-patients group exhibit a significant impairment in the implicit memory effect as compared to the pseudo-control group, and thus statistically unlikely to be attributable to chance. Furthermore, none of those observed instances from the simulated outcomes were as large of between-group \( t \)-value as the one identified by the 2015 hippocampal patients (\( t = 6.10 \)), since the maximum between-group \( t \)-value identified in the simulation here was only 3.68 (Figure 2, bottom right). This finding in the current study nearly exactly replicated the prior analyses of 2015, using an independent sample that was doubled in size for statistical power and which was more demographically diverse. This finding here lends further credence to the conclusions in 2015 that the implicit memory effects of the IMAP method are dependent upon the only available factor that varied between groups (the hippocampus).

### 3.1 Validating that the implicit memory effects are not contaminated by explicit memory responses

One common misconception of the current measure of implicit memory (IMAP) is that it may be contaminated by or conflated with explicit memory responses that are inherently included in its conditions (e.g., recognition confidence responses of “4” and/or “5”). A primary basis to refute this possibility is the core logic that the procedure used holds constant the factor of explicit memory responses (Figure 1). This is achieved by including the same explicit memory response levels equated across both conditions of old and new, so it is difficult to attribute the findings to factors held constant. A secondary reason that conflation with explicit memory activity is unlikely is because the prior report of these effects have already performed rigorous control analyses that systematically withheld most explicit memory ratings from the conditions and found that the implicit memory effects remained unaffected by exclusion of those trials (Addante, 2015), effectively ruling out that possibility. Nevertheless, since those findings have yet to be independently corroborated or reproduced, the current investigation represented a novel analysis of an independent data set so it remained both (a) viable that such possibilities could potentially
exist and (b) valuable to re-address the issue again here to ensure construct validity.

Therefore, as an additional effort to ensure the validation of the implicit effects in the current dataset, we conducted a further-improved control analysis performed to both mirror and extend the validation originally provided by Addante (2015). The goal here was to provide another rigorous standard that would verify if the observed effects of implicit memory could be attributed to any contamination by explicit memory responses. As done in the prior work (2015), this analysis assessed the IMAP contrast but using an approach of systematic exclusion of explicit memory responses, focusing on the right parietal site of P4 from 600 to 1000 ms identified above for the present effect. It was expected that these manipulations of explicit response conditions would change the pattern of IMAP results if they were in fact driven in any meaningful way by the explicitly declared memory responses.

When removing the trials of high-confidence responses from the IMAP contrast (“5” responses), ERPs for old items remained reliably more positive than ERPs for new items (Figure 4b), \( t(48) = 2.29, p = 0.026 \), Cohen’s \( d = .288 \) (old \( M = 0.11, SD = 2.37, SE = 0.34 \); new \( M = -0.56, SD = 2.29, SE = 0.33 \)). When removing the high confident memory responses (“5”s) from old items but leaving them still included in the condition for new items, implicit memory effects still remained (Figure 4c), \( t(48) = 2.93, p = .005 \), Cohen’s \( d = .332 \) (old \( M = 0.11, SD = 2.37, SE = 0.34 \); New \( M = -0.64, SD = 2.14, SE = 0.31 \)). The same effects persisted when instead removing just the low confident explicit memory responses (“4”) from the old items but retaining them in the new items (Figure 4d), \( t(49) = 3.43, p = 0.001 \), Cohen’s \( d = .431 \) (old \( M = 0.216, SD = 2.44, SE = 0.35 \); new \( M = -0.760, SD = 2.08, SE = 0.29 \)), and also when excluding them from the new items, too (Figure 4e), which is a new finding that was not assessed in the preceding 2015 paper’s validations (\( t(48) = 2.29, p = 0.027 \); Cohen’s \( d = .288 \); old \( M = 0.107, SD = 2.37, SE = 0.34 \); new \( M = -0.566, SD = 2.39, SE = 0.33 \)). When removing both high and low confidence memory responses from old items but leaving them included in new items, the implicit memory results persisted at marginal levels that maintained a small-to-moderate effect size (Figure 4f) \( t(41) = 2.01, p = 0.051 \), Cohen’s \( d = .252 \) (old \( M = -0.10, SD = 2.6, SE = 0.4 \); new \( M = -0.71, SD = 2.21, SE = 0.34 \)).

Taken together, these findings further validate the IMAP procedure as identifying ERP effects of implicit memory, independently reproducing the findings from Addante (2015) with a sample size that is nearly doubled from the original findings and extending them with further rigor. The results from the validation show that the ERP effects remained largely unchanged when manipulating explicit memory responses, and are thus not being driven by explicit, declarative memory processes such as recollection (high confident hits [old “5”]) or familiarity (low confident hits, “4”) (Addante, Ranganath, & Yonelinas, 2012; Yonelinas, 2002). Therefore, the positive-going ERP differences observed for the IMAP procedure cannot be explained as reflecting differences attributable to factors of explicit memory, but instead leaves only the processes of implicit memory for which to attribute results.

As a final measure, similar to the previously reported findings of Addante (2015), removing the high and low confidence trials (“4” and “5”) from both old and new conditions did not identify any significant differences across the epoch, \( t(41) = 0.93, p = .36 \), Bayes Factor = 4.02 indicating substantial evidence for the null (Old \( M = -0.10, SD = 2.60, SE = 0.40 \); New \( M = -0.44, SD = 2.44, SE = 0.38 \)). This was presumably due to having effectively reduced the comparison to a weakened contrast of misses versus correct rejections that only included some-but-not-all of the trials for each condition and thus substantially reduced the power to detect differences (i.e., lowered signal-to-noise ratio, SNR). This observation spurred the next steps of investigations into first identifying what the normal comparison of all miss versus correction rejection trials would reveal, and second, determining both if and how the ERP effects of misses versus correct rejections may differ from the IMAP effects.

### 3.2 Comparing implicit memory measures

The technique used in the current investigation to measure implicit memory remains a relatively new procedure that is now being employed with an automated pipeline instead of the manual process used previously for all three extant studies. It remains unclear how IMAP effects relate to traditionally reported ERP correlates of implicit memory (comparing misses versus correct rejections: which we will abbreviate in subsequent sections as “Misses” or “ERP effects of misses”; Kandel, 2013; Rugg et al., 1998). In recognition paradigms, the traditional measure of implicit memory comes from comparing misses to correct rejections, which usually reveals ERP activity manifesting in posterior parietal regions of the scalp occurring relatively early in the epoch (e.g., 300–500, 400–600 ms, etc.) (Ozubko et al., 2021; Rugg et al., 1998; Woollams et al., 2008). Thus, we next examined how the relatively novel IMAP effects may relate to the more well-studied physiological correlates of implicit memory: ERP effects of miss [old item responses of “1” and “2”] minus correct rejections [new item responses of “1” and “2”].

We conducted a \( 2 \times 2 \times 2 \) ANOVA with factors of Region (left parietal [P7, P3, Cp5, Cp1], right parietal [P4, P2, Cp6, Cp2]) and Type (old item responses of “1” and “2”) and Time (epochs of 300–500 ms, 400–600 ms, etc.). The results indicated significant main effects of Region (P4 > P2, Cp6 > Cp2) and Time (400–600 ms > 300–500 ms), as well as a significant interaction of Region × Time (P4 > P2, Cp6 > Cp2) and Type × Time (old item responses of “1” and “2”). Further post-hoc comparisons using Bonferroni correction indicated that the P4 site showed significantly larger ERP effects of misses versus correct rejections than the P2 site, and the Cp6 site showed significantly larger effects than the Cp2 site. Additionally, the ERP effects of misses versus correct rejections were significantly larger in the 400–600 ms epoch compared to the 300–500 ms epoch for both P4 and Cp6 sites, but not for P2 and Cp2 sites. These findings suggest that the IMAP procedure may provide a novel measure of implicit memory that is distinct from traditional ERP correlates of implicit memory.
FIGURE 4 Validating that implicit memory effects are not due to explicit memory responses. Topographic maps indicate the memory effects of old–new differences, with warm colors indicating positive differences, and cool colors indicating negative differences; the underscore mark in the contrast title indicates the removed confidence level(s) from the contrast being depicted in each panel. Bottom row displays ERPs from the representative right parietal site of P4 for each condition of old and new that is contrasted in the topographic map above it. Shaded areas on the ERPs represent the standard error of the mean for each plot throughout the time of the epoch. Panel (a) is shown for comparison purposes and is the same as the main effect shown in Figure 3, where both the “old” and “new” items included the same confidence bins of matched memory awareness levels (ranging from 1 to 5, with 1 meaning “sure new” and 5 meaning “sure old”). Panel (b) excluded high confidence recognition responses (5’s) from both old and new conditions. Panel (c) removed explicit high confidence hits from the old condition but retained them in the new condition. Panel (d) excluded low confidence hits but retained all explicit new trials; Panel (e) removed low confidence recognition responses from both old and new conditions. Panel (f) removed all explicitly remembered responses (both high and low confidence) from but included all trials in the new condition. The main effect of implicit memory remained unaffected by these manipulations of explicit memory responses.

[P8, P4, Cp6, Cp2]), Time (400–600 ms, 600–1000 ms), and Measure (Miss, IMAP), using a sample of 42 participants that met the inclusion criteria of having a minimum of 12 trials/observations per each condition being assessed (see Method). Results revealed no main effects of region ($F(1,41)=1.20$, $p=.280$), Measure ($F<1$), or time
(F(1,41) = 1.54, p = .222), but a significant region × measure interaction (F(1,41) = 6.52, p = .014, η² = .137) and a significant measure × time interaction (F(1,41) = 4.18, p = .047, η² = .093) (Figure 5). This indicated that there were reliable differences between the implicit memory measures across both region and time.

The interactions of factors were next explored via planned t-tests, which revealed that misses were more positive than correct rejections at left parietal sites (P3, P7, Cp1, Cp5) from 400 to 600 ms (t(41) = 2.49, p = .016, Cohen’s d = .229; M = −1.03, SD = 2.24, SE = .35; M = −1.55, SD = 2.31, SE = .36), but not at right parietal sites (t(41) = .992, p = .326, Bayes Factor = 3.79 indicating substantial evidence for the null; M = −.865, SD = 1.93, SE = .28; M = −1.04, SD = 1.73, SE = .27) (Figure 5). In the later latency of 600–1000 ms, neither the left nor right parietal regions exhibited any reliable differences in ERPs for misses and corrections, (t(41) = .957, p = .343, Bayes Factor = 3.91; t(41) = 1.20, p = .904, Bayes Factor = 5.95, respectively, each BF providing substantial evidence for the null).

Conversely, in the same subjects, old items equated for conscious awareness (IMAP) were more positive than new items at right parietal sites beginning from 400 to 600 ms, (41) (4.1) = .29, p = .03, Cohen’s d = .20; 600–1000 ms Old M = −.053, SD = 1.35, SE = .21, New M = −.421, SD = .127, SE = 1.97, respectively), but not at left parietal sites in either latency (t(41) = 1.44, p = .158, Bayes Factor = 2.32 (t(41) = 1.37, p = .177, Bayes Factor = 2.51 indicating being insensitive to differentiating either the null or alternative hypotheses for either latency). Overall, these findings indicate that these two measures of memory were capturing different activity patterns of ERPs throughout the scalp during these latencies.

3.3 Topographic analysis of implicit memory effects

The previous analyses identified that the two different implicit memory effects (IMAP, Misses) were spatially dissociable in their topographic distribution across the scalp, as well as temporally dissociable in their manifested latencies. Spatial–temporal dissociations of physiological effects have traditionally been taken as providing strong evidence that there are dissociable cognitive processes represented by them. However, since the spatial dissociations were evident in raw ERP amplitudes, it remains technically possible that those findings could instead be due in whole or in part to magnitude differences in the ERP signals, for example, scaling artifacts (Haig et al., 1997; McCarthy & Wood, 1985; Urbach & Kutas, 2006; Wilding, 2006). So, to verify that

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**FIGURE 5** Comparison of two different approaches to measuring physiology of implicit memory. Left panels: Topographic maps indicate the implicit memory effects of the difference waves for miss versus correct rejection (top) and the IMAP contrast (old–new) (bottom), with warm colors indicating positive differences, and cool colors indicating negative differences. Middle panel: ERPs show the activity time course from the right and left parietal regions of each effect, respectively, as indicated by the white box on the topographic maps. Shaded areas on ERP plots represent the standard error of the mean for each plot throughout the time of the epoch. Right panel: topographic maps of each implicit memory effect from the time course of 400–800 ms, with voltage scales range-normalized to account for potential scaling artifacts in topographic analyses. Topographic scales of each effect are shown in minimum-maximum values (μV) below each map (−.3 to 5 and .15 to .65 μV, respectively).
the observed effects of a spatial dissociation were not being driven by scaling artifacts of ERP magnitude differences, we performed a formal topographic analysis on the posterior parietal sites’ effects during the latencies of 400–600 ms and 600–1000 ms, respectively, as well as upon the primary 400–800 ms time window in which the original effects were observed to occur in (Figure 2). For this analysis, we followed conventional techniques for topographic analyses and used range-normalized values of each effect, similar to prior studies (Rugg et al., 1998; Yu & Rugg, 2010; for further detail and discussion, see footnote 6 in Addante et al. (2015) and broader discussions in main and supplemental sections of Ozubko et al., 2021).

Range normalized amplitudes at posterior parietal scalp sites were subjected to a 2 × 2 ANOVA with factors of hemisphere (left, right) and memory effect (miss minus correct rejections, equated-old minus new). Beginning with the original main effects during the 400–800 ms latency shared by both of the implicit memory effects, there was a significant interaction of memory effect and parietal region (F(1,41) = 7.30, p = .009, ηp² = .151) (Figure 5), but no effects of either factor independently (both Fs < 1). This identified that the different implicit memory effects were occurring at different places on the scalp during the same time, and thus providing clear evidence that they are composed of different neural generators and thereby represent at least partially non-overlapping cognitive processes (Rugg & Coles, 1995; Rugg et al., 1998). This pattern of topographic findings remained consistent across more specific analyses of each effect’s respective latency: from 400 to 600 ms, results revealed evidence for a region × effect interaction (F(1,41) = 3.89, p = .055, ηp² = .087) but no indication of main effects for either factor of region or effect (both Fs < 1), while in the 600–1000 ms latency results revealed similar, but even stronger, findings of a region × effect interaction (F(1,41) = 9.1064, p = .004, ηp² = .182), with no other evidence of either main effect of region or effect (both Fs < 1). Overall, the topographic results indicated that these two approaches of measuring implicit memory represent two spatial-temporally different patterns of neural activity for implicit memory, which prior work has established is evidence for distinct neurocognitive processes (Rugg & Coles, 1995; Rugg et al., 1998; Wilding, 2006).

3.4 | Relationship of IMAP physiology to behavior

An open question about IMAP effects from both the prior studies and the preceding analyses here concerns the functional significance: what do they mean? Are IMAP effects behaviorally meaningful to memory, or perhaps just epiphenomena at the scalp? Our next approach sought to inform those open questions via probing the relationship between behavioral and physiological measures: first by assessing ERP effects and general overall processing speeds overall, then progressing to more focused analyses correlating ERP effects to response time differences for specific memory conditions.

When assessing behavioral measures of implicit memory in basic old/new recognition paradigms, one common strategy is to identify a significant difference between response times of missed old items and new items correctly rejected, which is taken as a behavioral manifestation that demonstrates implicit memory (Ozubko et al., 2021; Schacter, 1987), under the rationale that the person’s behavior has reliably changed as a function of prior experience but without their awareness of it. In the current study, misses were responded to significantly more slowly than correct rejections (t(53) = 3.36, p = .002, Cohen’s d = .41; M = 2982, SD = 924, SE = 126; M = 2627, SD = 800, SE = 109), while successful explicit memory hits were alternatively responded to more quickly than both correct rejections and misses (t(53) = 4.09, p < .001, Cohen’s d = .505; M = 7.04, p < .001, Cohen’s d = .923; M = 2280, SD = 550, SE = 75), indicating evidence that there were reliable behavioral measures of implicit memory performance.

First, we began with a general inquiry to determine if there was any behavioral relevance of the IMAP effects overall, beginning with the original IMAP effect reported at right parietal site P4 from 400 to 800 ms (Figure 3) and assessing if there was a correspondence with overall response times during memory judgments. The IMAP effects were reliably predictive of overall response time (r = −.333, p = .014, Figure 6a), as was the ERP effects of misses (r = −.407, p = .008), such that the larger one’s magnitude of the implicit memory physiology, the faster they responded on all trials. This pattern is consistent with mnemonic information being enhanced by fluent processing that facilitates faster responding (Bader & Mecklinger, 2017; Bruett & Leynes, 2015; Mecklinger & Bader, 2020; Nessler et al., 2005; Whittlesea & Leboe, 2000, 2003; Whittlesea & Williams, 2000). Broadly, this finding revealed that the IMAP effects were behaviorally relevant and not merely a physiological epiphenomenon. Accordingly, this motivated several follow-up explorations into understanding the nature of the relationship of the implicit ERP effects to actual memory behavior. We next sought to determine how they might relate to behavior, in hopes of gaining leverage towards understanding their more precise significance to memory processes.

Specificity of the IMAP relationship to behavior was investigated by assessing the full IMAP effect from 600 to 1000 ms at P4 (Figure 3) for correspondence to specific response time measures of both implicit memory (Miss-CR)
and explicit memory (Hit-CR) established above. IMAP effects exhibited a significant relationship with implicit memory RT effects ($r = -.272, p = .046$, Figure 6b), but not explicit memory measures (Hit-CR) ($r = -.160, p = .248$, Bayes Factor = .327). This pattern was specific for the IMAP effects, as it was not evident for the ERP effect of misses (implicit: $r = -.077, p = .627$, Bayes Factor = .215; explicit: $r = -.167, p = .291$, Bayes Factor = .331). Thus, there was specificity to the IMAP effects’ relationship to meaningful memory behavior, as it was predictive of implicit but not explicit behaviors. This specificity of the IMAP effect to implicit memory behaviors is consistent with what other work has referred to as late right parietal activity for “pure” priming (Bader & Mecklinger, 2017), and also begged the question of what, alternatively, the ERP effects of misses may be representing since these two ERP effects had already been dissociated in the preceding topographical analysis (Figure 5).

Previous findings in the literature have suggested that early ERP effects for misses between approximately 300–600 ms represent forms of implicit fluency that can lead to the subjective cognitive experience of familiarity (for Review see Mecklinger & Bader, 2020). We thus hypothesized that the ERP effects for misses would exhibit a meaningful relationship to behavioral measures of familiarity, and moreover, that such relationships would be specific, such that they would alternatively not be evident for the IMAP effects if the IMAP effects were indeed related to “pure priming” as the preceding analyses suggested. For this analysis, we used response times for familiarity-based judgments as defined by item hits (collapsed across high and low recognition confidence) that were not accompanied by any source memory (i.e., “source unknown” responses) (Addante et al., 2011; Yonelinas, 2002) and verified results by a secondary approach instead defining item familiarity as response times for false alarms (Addante et al., 2015; Jones & Jacoby, 2001, 2005).
Jones & Jacoby, 2001, 2005; Lucas et al., 2012; Wang et al., 2015, 2019). Both approaches found that the response times for familiarity-based responding was significantly predicted by the ERP effect of misses ($r = -.368, p = .042$, Figure 6c; $r = -.313, p = .044$, Figure 6d, respectively), such that the larger the ERP magnitude of misses was then the faster the person would provide familiarity-based responses, but the response times exhibited no discernable relationship to the IMAP effects ($r = -.196, p = .164$, Bayes Factor $= .443; r = -.110, p = .428$, Bayes Factor $= .231$, respectively).

4 | DISCUSSION

4.1 | Overview

The current investigation used ERPs to assess a relatively novel neural measure of implicit memory in healthy young adults on a test of recognition confidence. We substantially increased the sample size from the previously reported clinical study ($N = 6$) to the current size of $N = 54$ using a more diverse cohort to both confirm and extend the few extant prior findings. This adds to the preceding reports of similar findings using the IMAP measure of nonconscious memory activity (Yu & Rugg, 2010 ($N = 23$); Addante, 2015 ($N = 6$, $N = 25$), and demonstrates its convergent validity and replicability across both cohorts and paradigms. Building upon the initial results we obtained reproducing prior findings, we then explored IMAP effect in new ways and discovered behavioral relevance of the neural activity to memory performance, as discussed with detail further below.

Instead of the manual selection of trials that has been used to perform this delicate procedure in prior electrophysiological studies, we created an automated approach for assessing implicit memory in humans (IMAP, see Method), and have made it open source for others to adopt, test, and improve upon. The automated analysis procedure adds value to the field for scientists interested in investigation and applying this approach in the future. This analytic approach to measure implicit memory in human EEG is now available open source to students, researchers, and clinicians via a MATLAB automated pipeline, fully compatible with EEGLAB and ERPLAB toolboxes, and includes scripts for data visualization. This tool provides quality assurance against manual errors, allows researchers to explore larger population samples while dramatically reducing data processing time, and since it is freely available, it can be easily adopted and adapted by the cognitive neuroscience community for use in a range of future studies. In addition to supporting broad industry efforts at reproducibility in science (Button et al., 2013; Ioannidis, 2005; Ioannidis et al., 2014; Moonesinghe et al., 2007), the current results also extend the prior findings in several valuable ways, as noted below.

From these methodological innovations, we first reproduced prior IMAP findings (Addante, 2015), such that ERPs for old items were more positive than new items equated for conscious awareness at posterior scalp sites from 400 to 800 ms. Results also showed that the IMAP effects are behaviorally meaningful as they were related to facilitated response speed on memory trials, but also that the magnitude of physiological signals of implicit memory measured by the IMAP procedure reliably predicted the speed of implicit memory responses, too. Thus, the implicit memory ERP effect had specificity in predicting implicit memory behaviors that left explicit memory measures unaffected (Figure 6). These findings were then tested, and extended, in several ways that informed a better understanding of the functional significance, which is discussed in further detail in the sections below.

4.2 | Characterization of IMAP effects

The IMAP procedure is still a very new development for studying non-conscious memory that has remained under-explored in the field of cognitive neuroscience and has thus been poorly understood due this novelty and the previously complex procedure needed to study them. The current work provided the first comprehensive characterization of the implicit IMAP ERP effects, which were found to occur from 600 to 1000 ms post-stimulus onset and characterized the specific scalp topography as manifesting in right parietal sites. This broad temporal window extends substantially beyond the previously known time windows of 400–800 ms reported by Addante (2015) and 300–500 ms in Yu and Rugg (2010), to the present time window of ~600–1000 ms identified here. The IMAP effects were additionally characterized as being both temporally and topographically dissociable from other well-studied ERP effects of implicit memory (Miss–Correct Rejections), which occurred instead in the left parietal region and earlier in time (400–600 ms). Since spatial resolution is a relatively poor capability of the EEG/ERP technique (as opposed to its relative strength of high temporal resolution), the topographic dissociation of effects observed here overcomes inherent challenges for identifying localization of different neural processing; however, for the same reasons of inherent limitations we would also expect that future studies might observe variability in topographic distributions as has been found for other original topographic findings (Rugg et al., 1998) that later were observed to occasionally vary in scalp location (Addante, Ranganath, & Yonelinas, 2012; for Reviews see Leynes et al., 2017; Mecklinger & Bader, 2020).
4.3 | Construct validity of IMAP as a measure of implicit memory

Because the IMAP procedure and its respective effects have only been reported twice before\(^2\) (Yu & Rugg, 2010; and validated only once prior by Addante, 2015), and because the clinical findings of the IMAP impairments in hippocampal amnesia patients had substantial implications to most models of memory organization in the medial temporal lobes, it was essential to independently verify construct validity. The current investigation engaged in a series of rigorous control analyses that tested the validity that the procedure was measuring implicit memory and was not reflecting contamination by any contributions of explicit memory by examining the effects while systematically removing from it each independent level of explicit memory response (Figure 4). Some of these control analyses provided vital reproducibility to validation results reported in Addante (2015), but other present analyses provided additional new tests that were not performed then, such as the exclusive removal of low-confidence recognition judgments of “4” from the analysis (Figure 4e). The results confirmed that the IMAP effect remained intact and unaffected by the manipulation and removal of any explicit memory responses, and thus provided evidence that IMAP effects were not contaminated, confounded, nor conflated by the potential contributions of explicit memory responses.

Together, these results ruled out key alternative explanations of the main findings here and in the preceding hippocampal patients as being driven by explicit memory. Results also validated the IMAP procedure as an accurate measure of implicit memory, similar to what has been called “pure” priming in other ERP studies (Bader & Mecklinger, 2017). The implicit memory effects produced by the IMAP procedure are thus arguably a more precise measure for unconscious memory activity than other traditional measures such as misses, which have been criticized for being potentially contaminated by conscious memory activity and/or explicit memory processes (Kumaran & Wagner, 2009; Lucas et al., 2012; Paller et al., 2007; Squire & Dede, 2015; Voss et al., 2012). From the current results (and in convergence with the previously reported studies), it thus appears clear that the awareness-equating approach in IMAP is a reliable neural measure of memory outside of conscious awareness.

4.4 | Neuropsychological implications

Though the present study did not measure nor manipulate the hippocampus, the implicit memory signal that was characterized here has previously been found to be hippocampal-dependent (Addante, 2015), but that finding had not yet been independently verified for the measure’s construct validity nor corroborated for its interpretation ruling out the possibility of results being due to low sample sizes of clinical cohorts (N=6 vs. N=3). First, the present control analyses (Figure 4) validated that the same IMAP effects cannot be attributed to even minimal degrees of conscious awareness via two ways: (a) providing independent replications of the previous validations performed in the 2015 study (Figure 4a–d,f) and then (b) providing an additional new validation that was not available in 2015—which was the systematic removal of only the low confidence recognition responses (Figure 4e). Second, the permutation analysis performed in the current study of healthy participants (Figure 2, bottom right) adds support to those prior clinical findings by offering independent evidence corroborating that the same IMAP measure previously impaired in a cohort of patients cannot be attributed to alternative factors such as low sample size (Figure 2).

To that extent, the present findings support the prior conclusions about a form of implicit memory being dependent upon the hippocampus (Addante, 2015). Findings from other neuroimaging studies have also converged in identifying hippocampal activity associated with implicit memory processing (Daselaar et al., 2006; Degonda et al., 2005; Hannula & Ranganath, 2009; Hannula et al., 2017; Hannula et al., 2005; Kirwan et al., 2009; Moody et al., 2004; Reber et al., 2012; Schendan et al., 2003; for Reviews see Hannula & Greene, 2012; Henke, 2010), while behavioral deficits of implicit memory have been observed in other case studies of clinical amnesia patients (Chun & Phelps, 1999) and even in classic Patient HM (Postle & Corkin, 1998; Corkin, 2002; though see Annese et al., 2014 and Dittrich, 2016 for limiting factors). Future work replicating the IMAP deficits in patients after hippocampal damage, as well as studies exploring direct hippocampal activity for the IMAP effects using intracranial, neuro-modulatory (e.g., Inman et al., 2018, 2020), and neuroimaging modalities can provide valuable additional confirmation of the role of the hippocampus in these findings.

4.5 | Functional significance of IMAP effects

What do the IMAP effects mean, and what processes of memory might they represent? To address these questions we adopted two concurrent approaches: first, we directly contrasted the relatively novel IMAP effects to another
well-known ERP measure of implicit memory (miss–correct rejections), and second, we assessed the relationship between those two ERP measures of implicit memory to standard behavioral measures of implicit memory and related memory processes. Furthermore, the correlation approach allowed us to determine if, and then examine how, there might be behavioral relevance to the physiological effects, respectively. As discussed in the sections above, the IMAP effect (late, right parietal effects) was found to be both temporally and topographically distinct from the earlier, left parietal effects of misses. That is taken to mean that there are at least two different neurocognitive processes of non-conscious memory co-occurring in support of implicit recognition, and that whatever the IMAP effects are representing it is different than what the effects of recognition misses represent. What are those two different implicit processes? For this, we turned to examining their correspondence to behavioral measures, to determine what, if any, cognitive process they exhibit relationships to.

The theoretical framework for the correlation investigation was informed by the existing literature on ERP effects of implicit fluency,⁴ which will be briefly reviewed first as a foundation for discussing interpretations derived from it. Implicit memory judgments can be influenced by various different cognitive processes, including distinct forms of fluency (i.e., repetition, conceptual, perceptual, semantic, etc.) that research has shown can operate dissociably during recognition memory tasks (Andrew Leynes et al., 2023; Leynes & Addante, 2016; Leynes et al., 2017; Leynes & Zish, 2012; Li et al., 2017; Wang et al., 2018). Both perceptual and conceptual fluency ERP effects have been found to manifest earlier in the epoch (100–200 and 300–500 ms, respectively; Wang et al. (2018) than the IMAP effect that was found here (600–1000 ms]), making it unlikely that conceptual/perceptual fluency can be attributed as an account of what may be driving the IMAP effects observed here. Some studies have also found perceptual fluency to be associated with early negative-going ERP differences (Voss & Paller, 2010) similar to reports from Leynes and Zish (2012) alongside Bruett and Leynes (2015) that ERPs for repetition fluency were more negative than new items at parietal sites 225–400 ms, while Ozubko et al. (2021) attributed early centrally located negative ERP effects from 300 to 500ms to fluency in a cued recall task-findings which also weigh against interpretations of IMAP effects as representing perceptual or conceptual fluency.

However, Ozubko et al. (2021) also reported other positive parietal effects assumed to reflect semantic priming which were found later in the epoch (600–900 ms, Figure 3), and which corresponded much closer to the present findings of the IMAP effects, as well as with similar positive-going right parietal effects reported by Bader and Mecklinger (2017) for conditions they referred to as ‘pure priming’. Likewise, Lucas et al. (2012) found that ERPs for masked priming exhibited positive-going midline parietal activity albeit during earlier latencies (350–450 ms) than IMAP. Additionally, previous findings in the literature have suggested that early ERP effects for misses from 300 to 600ms (similar to those observed here) represent forms of implicit fluency that then lead to the subjective experience of familiarity in ensuing memory judgments (for Review see Mecklinger & Bader, 2020).

In the present study, the correlation analyses revealed that ERP effects of both IMAP and Misses were associated with increased fluency via faster overall response times, but that only the IMAP signal was found to exhibit a meaningful relationship to implicit memory behaviors (Figure 6b), whereas the effect of misses was instead found to correlate with faster memory judgments linked with familiarity-based processing (Figure 6c,d). Thus, the functional interpretation of the pattern of results we observed could view the ERP effects of IMAP as representing ‘pure’ implicit priming (Bader & Mecklinger, 2017) by virtue of their relationship to behavioral measures of priming and in convergence with the validation of their construct as an uncontaminated measure of implicit memory (Figure 4). On the other hand, by virtue of the ERP effects of misses demonstrating a relationship to response times for familiarity-based responding (Figure 6c,d), ERPs of misses could be seen as instead representing N400-related processing of conceptual implicit fluency (Figure 6a) that then gives rise to the cognitive experience of familiarity, just as is proposed in the fluency-to-recognition model by Mecklinger and Bader (2020). This interpretation is in line with originating proposals by Paller et al., about the contribution of fluency to familiarity that were discussed in the Introduction as having led through progressive steps to the development of the IMAP procedure and the current study (Lucas et al., 2010, 2012; Paller et al., 2003, 2007, 2012). Distinguishing between different kinds of fluency such as conceptual, perceptual, and repetition fluency in the present findings is beyond the scope of the current data, and is left for future studies to explore (for extensive Review, see Mecklinger & Bader, 2020).

4.6 Future applications & conclusions

There are several potential future applications of the current findings. Given the validation provided for the procedure’s measurement of relatively pure implicit memory. Future work may find it fruitful to extend.

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⁴ We thank an anonymous Reviewer for this suggestion.
these measures to various other clinical patient populations where subtle but profound deficits of cognition may exist. This would provide an improvement to coarser measures traditionally used to characterize patients’ capabilities as intact or impaired. Other directions that future research may benefit from exploring include examining the oscillatory correlates of these implicit memory effects, as well as exploring what role that pre-stimulus effects may contribute, since prior research has identified oscillatory activity to be influential during both pre- and post-stimulus times of memory (Addante et al., 2011; Axmacher et al., 2010; Clouter et al., 2017; Cohen et al., 2015; Griffiths et al., 2016; Guderian et al., 2009; Hanslmayr et al., 2019; Hanslmayr & Staudigl, 2014; Herweg et al., 2020; Hsieh & Ranganath, 2014; Kim et al., 2020; Watrous et al., 2015; Watrous & Ekstrom, 2014).

Therefore, the development and validation of these measures of implicit memory gives scientists and clinicians alike a new tool that is robust, automated, and rigorous from which to continue the next steps of exploration of the non-conscious mind. The contributions from the steps taken here inform a new functional significance of the ERP effects of misses and IMAP measures. Overall, the findings contribute towards a better understanding of the fundamental nature of human memory organization, and particularly the kinds of memory processing that the brain may be sensitive to outside of our subjective conscious awareness.

AUTHOR CONTRIBUTIONS
Richard J Addante: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing – original draft; writing – review and editing. Javier Lopez-Calderon: Methodology; software; writing – review and editing. Nathaniel Allen: Formal analysis; validation; writing – review and editing. Daniel L Drane: Funding acquisition; resources; writing – review and editing.

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DATA AVAILABILITY STATEMENT
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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