AN EEG ANALYSIS: TEMPORAL DYNAMICS OF EPISODIC MEMORY IN THE PARIETAL CORTEX

by

ARIEL BACK

A THESIS

Presented to the Department of Psychology
and the Robert D. Clark Honors College
in partial fulfillment of the requirements for the degree of
Bachelor of Arts

May 2019

An Abstract of the Thesis of

Ariel Back for the degree of Bachelor of Arts
in the Department of Psychology to be taken May 2019

Title: An EEG Analysis: Temporal Dynamics of Episodic Memory in the Parietal Cortex

Approved: ______________________________________

Brice Kuhl

Recently fMRI studies by Kuhl and Chun (2014) demonstrated that the lateral parietal cortex (LPC) is implicated in content reactivation through recall-related activity patterns. The LPC signals that memories have been successfully recalled and it actively represents the content that is being remembered. However, given that fMRI reports data spatially, there is a lack of information regarding the temporal nature of recognition during memory retrieval. By conducting a test of episodic memory via EEG and examining the time course of memory retrieval, this project used decoding classification to investigate when in time the brain processes information for different tasks. We trained a classifier to distinguish between old (familiar) and new (unfamiliar) images, as well as images of faces and scenes, to define distinct neural processes that allow for classification into the two distinct categories. We found that the memory classifier peaks over a time course similar to the Old vs New ERP literature. Additionally, we found that across tasks in the parietal region and the frontal regions, these regions are generally not task dependent, but rather are relatively automatic.

Acknowledgements

I would like to thank Dr. Brice Kuhl for being my primary thesis advisor and for providing me with the opportunity to work in such an excellent laboratory facility with a great network of individuals. I would also like to extend my gratitude to my second reader, Maxwell Drascher for his mentorship, inclusivity, expertise and willingness to let me be a part of his study, to teach me data analysis through R, and act as a constant resource. Finally, thanks to my CHC representative, Dr. Dare Baldwin for being a great resource in both the field of Psychology and a reference to me within the Honors College, and for her support and commitment to my success over the past few years. These individuals have provided invaluable guidance, support, and mentorship in this exciting scientific undertaking. I would like to express my gratitude to be able to work with such excellent professors and faculty members as well as with a lab that is highly innovative and supportive.

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Introduction

The human memory system remains one of the mysteries of modern cognitive neuroscience. Researchers have postulated how memories are stored, what leads us to retrieve or fail to retrieve memories, and the nature of the process. Episodic memory, which comprises a large facet of our declarative, or explicit, memory system, allows individuals to directly and actively recall their knowledge and abilities. This form of memory is distinct from other forms of memory largely in part because episodic memory is fast-learning and tied to a specific spatiotemporal learning context. These factors make it an accessible and reliable form of memory to study. Episodic memory tests will directly recall memories from the past on a conscious level which have allowed for a robust foundation of literature.

Remembering is a controlled, goal-directed process by which one can construct a representation experienced as an episode from the past. This perception includes content details of the earlier encounter with the stimuli and is accompanied by a distinct perception that the information was old (Wheeler and Buckner, 2003). Past research has determined that certain regions of the brain such as the hippocampus and the medial temporal lobe are evidently and widely accepted as the cornerstones of memory. However, more recently other less-studied regions of the brain have been found to provide useful insight into this the mysterious process. Twenty years ago, the field of cognitive neuroscience had neither touched on nor anticipated the parietal cortex as playing a pivotal role in the process of episodic memory, given that parietal lesions did not present with severe episodic memory defects. However, within the last two decades researchers have realized that the parietal cortex may plays important roles in episodic memory.

Through recent investigation it has become evident that the parietal cortex is involved in the processing or representation of content from the memory system (Wagner et al., 2005, Cabeza 2008, Cabeza et al., 2008, Ciaramelli et al., 2008, Vilberg and Rugg 2008, Olson and Berryhill 2009). However, the functional significance of the parietal cortex, in particular the lateral region, during memory retrieval is a subject of debate. Several theories consider if the LPC actively represents the retrieved information or if the activity in the LPC functions with content reactivation elsewhere (Kuhl and Chun 2014). It is clear that the parietal lobe plays a significant role in the interplay of memory processes alongside other involved neuroanatomical regions, but the exact functioning of this region of interest (ROI) has been unclear. This thesis will expound upon past scientific literature to investigate the significance of this brain region via a temporal EEG analysis.

Background

Electroencephalography (EEG) is a form of brain imaging that involves the placement of multitude of electrodes across the scalp to depict and measure the electrical activity occurring on the surface of the brain. Through EEG, cognitive neuroscience research is able to explore the temporal dynamics of episodic memory, which is a region of the literature that has not been adequately investigated. EEG power, on a physiological level, is reflective of the number of neurons that discharge synchronously (Klimesch 1998). Electrodes placed on the scalp are able to measure the summed activity of large populations of synchronously firing neurons. A gel administered to the scalp helps increase the conductivity before an amplifier is used to amplify the neural signals. The neural activity is represented by waveforms of varying frequencies (Hz), and amplitudes which are measured in voltage. This method can reveal a plethora of neutrally generated signals related to human cognitive processing detected at the scalp and as well as intracranially (Morton et al., 2013). EEG provides unique access to brain activity, and when used in conjunction with other brain imaging techniques, provides a multimodal understanding of the neural corelates of episodic memory.

The parietal cortex, in particular the left lateralized portion, is of particular interest for recognition research due to the increased activation in this region when viewing previously seen items as compared to novel items (Wagner et al., 2005). The parietal lobe has been found to modulate activity when information is perceived as old (Wheeler and Buckner, 2003). The left lateral parietal region near BA 40/39, (Brodmann Areas 39 and 40, the angular gyrus and supramarginal gyrus respectively) increases in activity during correct recognition for episodic memory tests (Wheeler and Buckner, 2003). This fMRI study found a significant increase in blood oxygen level dependent (BOLD) responses in BA 40/39 in response to each of the old trials that subjects were presented with, as opposed to the new trials. These findings suggest that the parietal lobe contributes to processes associated with identification and recovery of content that had been previously encountered. These findings are similar to the influential work of Konishi et al., 2000 who compared hit trials, which were able to correctly recognize old items, to correctly rejected items, which were correctly rejected new items, and found a direct comparison between the trials to reveal a mostly left-lateralized set of brain regions. Differential activation was shown to be most robust in the LPC and the results from Konishi et al., 2000 suggest that left frontal and parietal regions modulate activity based on the successful retrieval of information from episodic memory. This demonstrates a significant role for the LPC in the recognition of familiar content and suggests a role that it may play in memory retrieval and recognition.

To further understand memory retrieval Rugg and Curran (2007) examined the role of event related potentials (ERPs) for familiarity and recollection during the retrieval process, which has provided a useful time course that defines when the brain is attending to different recognizable information. ERPs are voltage changes that are stimulated within the brain in response to different sensory, cognitive, and motor processes (Friedman and Johnson, 2000). Familiarity and recollections are components of the dual-process model which Rugg and Curran (2007) find to be valid based on their ERP findings. The concept of familiarity reflects an assessment of the general similarities between studied content and tested content (Curran, 2000). Familiarity plays an important role in recognition decisions based on the sense that an item was previously encountered (item memory). The other component, recollection, reflects the conscious retrieval of contextual information about a specific previously encountered episode (source memory) (Kahn et al., 2004). Both facets are instrumental to episodic memory. Recollection is context-dependent, as opposed to familiarity which refers to a context-independent contextual feeling of knowing. Both recollection and familiarity are related to two spatiotemporally different ERP effects, namely the early mid-frontal Old/New effect (familiarity) and the late parietal old new effect (recollection) (Hoppstäder et al., 2015).

Rugg and Curran (2007) explain that previous research by Düzel, E. et al., 1997, and Rugg, M.D. et al., (1998) had identified the old/new effect as correctly recognized old items which elicited an effect in the mid-frontal region 300-500 ms after the given stimulus. This is linked to a familiarity-driven recognition. Curran (2000) and Paller et al., (2007) referred to this 300-500 ms component as the FN400 old/new effect. The parietal effect which is linked to the recollection of specific information demonstrates an effect at 400-800 ms. Guillem et al., (2000) also found similar results while using ERPs to study face recognition with learned and unlearned faces. This study demonstrated a parietal and a fronto-central activation for previously learned faces compared to unknown faces. Similar results were found with old and new items during verbal recognition memory tasks in functional imaging studies with stronger activity in the left frontal and parietal areas (Rugg et al. 2002). Such studies encouraged the present study to investigate recognition of new faces, and scenes, in a context-dependent setting with EEG.

The neuroimaging literature has provided substantial findings in support of a critical role for the parietal lobe in episodic memory. Berryhill et al., (2007) and Olson and Berryhill (2009) investigated neuropsychological findings demonstrating the effects of parietal lobe lesions on working memory and episodic memory. Memory deficits are rarely associated directly to parietal lobe damage. However, two related finding derive from interesting cases involving aphasia and hemispatial neglect (Berryhill et al., 2007). From reports of aphasia, parietal lobe damage was linked to verbal short-term memory (STM) deficits. Damage to the right parietal lobe resulted in spatial STM impairments for patients with hemispatial neglect (Berryhill et al., 2007). Berryhill et al., (2007) found that the absence of hemispatial neglect in cases of patients with parietal lobe damage presented STM deficits for visual features such as color and shape, in addition to location. These findings indicate a relationship between parietal functioning and short-term forms of memory.

Two patients were studied with parietal damage which revealed deficits apparent only under certain retrieval conditions (Berryhill et al., 2007). For both working memory and long-term memory, recall performance was preserved while recognition performance was impaired. These two patients (patient EE555 and patient TQ591) sustained bilateral parietal lobe damage for various perception and neuropsychological tests. Patient EE555 was diagnosed with the bilateral lesions in the inferior parietal lobe after being hospitalized after her third stroke from three infarcts in the watershed between the posterior and middle cerebral arteries. Patient TQ591suffered bilateral parieto-occipital lesions as a result of CNS cerebral vasculitis (Berryhill et al., 2007). These patients were compared to control subjects when asked to recall autobiographical memory. Ultimately, the memories freely recalled by the patients with bilateral parietal lobe lesions were reported with fewer details than the control subjects. This shows a discrepancy in ability to retrieve memories with strength and detail based on the parietal lobe damage.

Berryhill et al., (2007) additionally specify that general deficits in visual imagery do not explain the memory deficit given that the patients were able to perform visual imagery tasks with accuracy. The patients were not amnesic and had not been diagnosed with any type of memory problem. The findings indicate a necessity for normal parietal functioning for natural recollection of detailed episodic memory. This study revealed that parietal lobe damage decreased the vividness and amount of detail freely recalled. Berryhill and Olson (2009) also tested the same patients via the Deese-McDermott Roediger (DRM) false memory paradigm. They found that the bilateral lesion patients exhibited normal false memory during recall tests and showed impaired results for tests of old/new recognition. These patients also presented abnormally low levels of “remember” responses compared to “know” response. Berryhill and Olson (2009) explain that, “Preserved memory on several episodic memory tasks indicate that memory retrieval per se is not diminished by parietal lobe damage, but what is damaged is a particular subprocess that tapped in certain retrieval tasks.” This conceptualization of the parietal lobe and its relation to memory and retrieval ability helps contextualize this region within the rest of the brain and concurrent literature.

In 1995 Hunkin and colleagues described a patient, referred to as DH, with parieto-occipital damage resulting from a closed head injury. DH retained his ability to recall semantic memory throughout his lifetime but felt that he lacked the more 'genuine' memories that constituted his life and experiences. He stated that it was as if he had not experienced the memories that he recalled. This case can be examined to highlight the relationship to context-dependent and self-attributed memories within these regions of the brain. The patient was unable to maintain the legitimacy of his episodic memories which he referred to as 'genuine memories,' given that he felt he did not feel he had experienced his own memories. This was described as if he had read a book describing his own life, but he lacked the feeling that he had experienced it. (Hunkin et al., 1995, cited in (Berryhill and Olson 2009). This study shows the value and potential involvement of the parietal region in terms of episodic memory and the vivid content-related details that were missing due to the lesion.

Transcranial magnetic stimulation (TMS), which can act as a was temporary brain "lesion" for healthy patients was used by Thakral, Madore, & Schacter, 2017 to investigate the role of the Angular Gyrus (AG), an interesting and informative structure within the parietal cortex. The AG is a region of particular significance given that directed disruption of this region impairs episodic memory. Thakral, Madore, & Schacter (2017) used magnetic resonance imaging (MRI)-guided transcranial magnetic simulation (TMS) to determine if the temporary disruption to the left angular gyrus would impair episodic simulation (for imagining future experiences) and episodic memory (for remembering past experiences). This expanded on research by Davidson et al., 2008 and Berryhill et al., 2009 examining lesions to the LPC which impaired the subjective experience associated with a variety of episodic memory judgments as well as the ability to recall information (Thakral, Madore, & Schacter, 2017). TMS has been shown to reduce accuracy in certain types of episodic memory judgments (Yazar et al., 2017), alter the biases of such judgements (Sestieri et al., 2013), and reduce the confidence with which those memories were reported (Yazar et al., 2017). This study by Thakral, Madore, & Schacter (2017) tested healthy non-lesioned patients and observed that administering TMS to the left angular gyrus caused a reduction in the retrieval of episodic details for both past and future events. It is postulated that the TMS altered the participants' retrieval orientation during the simulation and memory tasks. These results drew attention to the role of the lateral parietal cortex as a contender within the core network of brain memory regions (primarily composed of the hippocampus, medial prefrontal cortex, and left angular gyrus), given that the results support that the AG is critical for both episodic simulation and episodic memory.

The AG also shows stronger activation for items with greater familiarity. This consistent pattern of findings, defined earlier by the work of Rugg and Curran (2007), is known as the Old/New effect or the Retrieval Success Effect. This effect has been shown to be a useful tool of comparison to document and analyze memory during experimentation. The Old vs New model of recognition postulates that there is a greater neural activation for 'old', or previously seen, items that have been recognized and can be picked up by a signal, as opposed to ‘new’ items (Konishi et al. 2000). The activity in the parietal region has been found to be greater when a previously seen stimulus is correctly identified as old, compared to when a new item is correctly identified as new (Berryhill and Olson 2009).

Literature Review

Retrieved-context models of human memory suggest that retrieval cues are constructed while the given material is studied, allowing for the targeting of particular aspects of past experiences. Associated retrieved-context models support that integrative neural circuitry is involved in the construction and maintenance of the retrieval cue (Morton et al., 2013). To understand the retrieved-context model of memory, Morton et al., (2013) used EEG to characterize category-specific oscillatory activity during study and recall tasks. This study, titled, *Category-Specific neural oscillations predict recall organization during memory search,* examined category specific neural patterns and predictions to discern if category-specific patterns could predict if an item previously studied could be recalled, as well as how it would be recalled. Morton et al., 2013 reference the research of Paller and Wagner (2002) and the subsequent memory effect to explain how subsequently remembered items will elicit a stronger neural response in certain implicated brain regions as opposed to subsequently forgotten items. This shows the durability and strength of remembered items and how neural responses can provide explanation for behavioral responses.

In this study Morton et al., (2013) assessed participants' pre-experimental familiarity with the stimuli implicated in the study which included famous landmarks, celebrity faces, and common objects. The name of the stimulus was presented with each item for 3500 ms and for three sessions the participants were presented with 48 lists (either pure-category or mixed-category) to be tested on later. The participants were asked to make a category-specific semantic judgment on a four-point scale with questions such as, “How much to do hate/love (this celebrity)” and “How much would you like to visit this place?” (Morton et al. 2013). After the lists and judgments, the participants engaged in immediate free recall which was recorded before a final free recall at the end of the session. This illustrated the category clustering within the data and the order of the participants’ responses demonstrated the associative structure of the stored memories.

As the content was studied and encoded, retrieval cues were constructed, which made it more accessible for participants to target specific aspects of studied material. Participants used category-specific patterns with category-specific neural integration which demonstrated that individual differences during study predicted the degree to which a subject would use category information for memory search organization. Morton et al., (2013) found that category-specific patterns were stronger when the participants organized their responses according to the category of the studied material. This process was used to implicate particular brain regions or neural signals in memory related processes. ROIs were determined by grouping of electrodes and were analyzed via multivariate pattern analysis. The strength of the category-specific patterns elicited during the study was able to predict whether an item would be remembered in a later section of the study. The results aid in examining how people tend to create memories and navigate throughout their memory structures for retrieval.

In another foundational experiment for the current study, Jafarpour et al. (2014) illustrates with magnetoencephalography (MEG) how brain activity patterns elicited during the early encoding process (180 ms) are implicated via a neural representation during recollection. This study, titled *Replay of very early encoding representations* *during recollection,* examined which patterns of brain activity elicited during an encoding task were present at a later recollection. By using stimuli comprised of faces and scenes, Jafarpour et al., 2014 utilized human and non-human representations throughout the study to determine that long term memories involve representations formed during early stages of encoding. These neural representations are formulated during the early stages of encoding (180ms) and are rapidly replayed during recollection about 500ms after the recollection-prompting cue. This illustrates that early representational information is stored in the memory engram and can consequently be rapidly reinstated for later retrieval usage.

Cortical representations of event-content such as faces emerge rapidly at 200ms. They occur while encoding processes are initiated in implicated brain regions (e.g. hippocampus and medial temporal areas), which begin at 200 ms and subsequently unfold in the next several hundred milliseconds. This questions whether the cortical event representations formed at early encoding stages could be held within long term memory (LTM) and later reinstated for retrieval. To investigate this, Jafarpour et al. (2014) utilized a study (encoding) phase and a test (retrieval) phase which were issued six times with a 5-minute arithmetic distractor task in between the two phases (Jafarpour et al. 2014). The participants were instructed to memorize a set of 20 unique images which were either faces or scenes and a unique corresponding word which was denoted by either a living or non-living object. The words were later used to encourage image recollection. After studying the content, the participants were required to make confidence judgments regarding if the content in the retrieval phase was familiar or novel by responding “not sure,” “sure” or “remember.” The findings from the data expand upon past fMRI studies to temporally investigate the neural patterns to suggest that very early representation of information is able to be effectively and successfully stored in the memory engram for reinstatement during recollection (Jafarpour et al. 2014). The category-specific neural representations of faces and scenes were elicited selectively during the early stages of encoding which aids in the understanding of which types of representations are able to be recollected.

Jafarpour et al. (2014) used multivariate pattern classifiers (MVPCs) to decode oscillatory brain activity while participants responded to images of faces and scenes. This was initiated every 66ms to capture the evolution of neural representations over time. Classifiers were used to classify faces and scenes from oscillatory activity for the purpose of detecting the timing of the replay of that neural activity pattern during retrieval. This was prompted with the word that was paired with the original image (Jafarpour et al., 2014). The reinstatement occurred ~500ms after the onset of the memory cue, detailing that the memory stored in the hippocampus must be sufficiently precise in order to enable the effective conservation of cortical event representations from the early stages of encoding.

The study which provided the foundational work for the present analysis by Kuhl and Chun (2014) administered a test of visual memory which involved a recall (source memory) test and a recognition (familiarity-based) test via a functional magnetic resonance imaging (fMRI) scanner. This type of imaging allows for a spatial understanding of the site(s) of increased activation during the recall of visual images. Kuhl and Chun (2014) examined the lateral parietal cortex (LPC) and the ventral temporal cortex (VTC) which are both implicated in memory. The LPC is associated with the subjective visual experience that occurs in this region which is thought to generalize across content types. The VTC is a high perceptual region that elicits a content-specific pattern of neural activity upon recall of a past event (Kuhl and Chun 2014). The study used multivoxel pattern analysis to compare and test for content reactivation within these two regions. The images employed in the study consisted of famous faces or famous scenes which were elicited in a test of recognition of both old and new images to discern how the brain reacted to familiar and novel stimuli. When an event is successfully recalled in memory it is associated with a reactivation of the content-specific patterns of neural activity which can be seen in the VTC when a person recalls a face or scene. This reactivates category-selective regions which are associated with behavioral measures of recall success and reaction time. Kuhl and Chun (2014) predicted that cued recall of pictures would elicit reactivation of category information (face vs scene), in the LPC as well as the VTC. Additionally, Kuhl and Chun (2014) predicted reactivation within the angular gyrus (AG) due to the fact that the AG is associated with recall success and vivid remembering.

The results from this study found a spatial overlap between the location of the previous memory signal and where the content signals were located. The left lateralized portion of the parietal cortex tended to become significantly more activated in response to familiar items as opposed to novel items. This is consistent with the Old/New effect. Kuhl and Chun (2014) found that the parietal cortex is involved in representing or processing the content of items retrieved from memory. Kuhl and Chun (2014) expected that the information signals found would likely overlap temporally with the spatial localization. Hoppstäder et al., (2015) utilized both fMRI and EEG methods in tandem to combine and multiply the values and advantages of each approach. This demonstrates the value between the two complementary methods since their combination is able to provide precise temporal information and spatial localization. This examination via multiple approaches is beneficial because it is assumed that both the EEG signal and metabolic fMRI signal emerge from overlapping brain structures (Hoppstäder et al. 2015). Based on the fMRI components that Kuhl and Chun (2014) developed in the literature, the present study will provide the elements and value of EEG to add the temporal component for further examination of episodic memory retrieval in the parietal cortex.

Present study

The present thesis project will examine questions similar to those studied by Kuhl and Chun (2014), but through EEG instead of fMRI. The electrophysical correlates of EEG paired with the hemodynamic correlates of fMRI clarify the link between their link with familiarity and recollection. Kuhl and Chun (2014) spatially defined the role of parietal regions and the use of EEG in this current study will further define the temporal dynamics of these memory processes. This EEG approach is reflective of natural neural processes happening in real time that create subject experiences of recollection. We predicted that we would see a peak in the accuracy of the decoding classifiers when the parietal lobe processed the familiar content information in that particular region. Parietal investigation was paired with a frontal ROI due to the co-involvement and similarities of these two regions as well as for a point of comparison. Through this investigation of the parietal region we can learn more about how memories are stored and the time course that this involves. Additionally, this investigation will lead to further understanding of how the strengths of memories are categorized, visualized, and utilized within the human memory system.

Methods

Subjects

26 (22 female) students recruited from the University of Oregon participated in this EEG study for the monetary compensation of $10/hour. Students were recruited via the Psychology Department human subjects pool and flyers placed around campus. Selected participants were between age 18 and 30, with a mean age of 21.8, right-handed, native English-speakers, and possessed normal-sighted or corrected-to-normal vison. 6 participants were excluded from data analysis due to poor data quality owing to scanner error (n=4), or unalignment of systems (n=2). This yielded a final data set of 20 participants for the experiment (3 males). Participants provided informed consent in accordance with the University of Oregon Institutional Review Board.

Stimuli

Word stimuli were nouns comprised of 128 nouns selected from the Medical Research Council Psycholinguistic Database to cue participants. The cue words spanned between 3 and 9 letters and assigned randomly to each participant. Image stimuli consisted of 128 face images and 128 scene images. Images were shown in color and 225x225 pixels. The face images were comprised of famous people of multiple races and genders (e.g. Heidi Klum and Bruno Mars). The scene images were comprised of famous locations, both manmade and natural, (e.g. the Taj Mahal and the Grand Canyon). Famous images were selected to help maximize the participants' ability to retrieve from memory. For each participant, 64 randomly-selected words were paired with 64 randomly-selected face images and the other 64 words were paired with randomly-selected scene images. These word-image pairs were used for the associative learning task. Famous and recognizable images were selected to make it easier for participants to learn the associations. The remaining 64 faces and 64 images were used as lures for a memory recognition task.

Procedure

The experiment was comprised of eight blocks with each block divided into 3 phases: a study phase, a recall phase, and a recognition phase. Each study phase presented new information for the participant to encode and be tested on for that specific block's subsequent recall and recognition phases. Every two blocks the participant was given a break with a total of three breaks issued throughout the experiment. During such times, if necessary, the investigator could fix any noisy electrodes that may have occurred. The participants were issued a practice phase before the start of the experiment to become accustomed to the testing and ask any pertinent questions.

<u>Study phase</u>. During the study phase, participants encoded 128 word-image pairs which were presented in 8 lists of 16 pairs each During the study phase the participant was asked to study word-image pairs, with each pair presented one at a time and present on the screen for 4000 ms. The participant was asked to remember the pairs for later retrieval. In between each word-image pair a fixation cross appeared on the screen to provide a visible break between the pairs. This brief break existed as a boundary in between each word-image pair and provided a chance for successful encoding. Of the 16 word-image pairs in each study phase, half contained face images and half contained scene images. During the study phase, each of the 16 word-image pairs was repeated a

second time in a randomized order to promote a higher recognition rate during the next successive phases. Thus, each study phase consisted of a total of 32 trials.

Recall phase. In the second phase of the sequence, referred to as the recall phase, the participants were presented with cue words from the previous study phase and were asked to recall the word-image pair's corresponding image as vividly as possible. The given cue word appeared on the screen for 4000 ms, followed by a blank outline of a square where the corresponding image had originally been located. The participant was then prompted to make a judgment regarding how vividly they were able to remember the corresponding image from the previously learned word-image pair. Specifically, subjects responded via a 3-point vividness scale using keys on a keyboard in the testing chamber. To indicate a "vivid" recollection, the participant selected 'J' with their index finger; to indicate a "weak" recollection the participant selected 'K' key with their middle finger; and to indicate a "don't know" response, the participant selected the 'L' key with their fourth digit. To avoid unnecessary artifacts from eye movement, the participant was instructed to place their fingers on the provided keyboard before the start of the experiment. This recall phase of the experiment also included a fixation cross for 1000 ms in between each trial to create a visual break. The 16 trials in this phase were presented in a random order and then repeated again in a randomized order. Since the recall phase asked the participant to recall the information from the trials provided in the study phase, it also consisted of 32 trials.

Recognition phase. The final phase of the sequence, the recognition phase, was comprised either of an old vs new task to assess familiarity or a face vs scene task. These tasks were assessed via face/scene classification or old/new classification so in a

2x2 type fashion so that a face vs scene task could be analyzed with either face/scene classification or old/new classification. This also meant that an old vs new task could be analyzed with either a face/scene classification or an old/new classification. These two types of task, face vs scene or old vs new, were randomly switched between throughout each recognition phase of the experiment. For each of these two tasks the participants were shown an image (either face or scene) followed by a visual mask. Each image was presented in the center of the screen for 200 ms and was followed by a visual mask for 400 ms. After the visual mask, an outline of a square, which had previously housed the image appeared. If no response was given in the subsequent 4000 ms the trial ended and the next trial began. If the recognition phase consisted of an old vs new task, the participant was instructed to make a judgment indicating whether the image was "old" (previously studied) or "new" (not previously studied). This was quantified on a 2-point scale, in which the participants selected the 'J' key with their index finger if the image was old, or the participant selected the 'K' key with their middle finger if the image was new.

If the recognition phase consisted of a face vs scene task, the participants were shown images of faces or scenes and were instructed to select the 'J' key with their index finger if the image was a face, or a 'K' key with their middle finger if the image was a scene. Each recognition phase, regardless of task type included the original 16 images from the block's study phase in addition to 16 novel images which were presented in randomized order. In total, the number of images in the recognition phase remained at 32 trials.

EEG acquisition and analysis

Participants were fitted with an EEG cap whose size was determined from a measurement in centimeters around the subject's head circumference. The cap size was rounded down to the nearest centimeter when a measurement was in-between sizes. Two sets of 32 electrodes were clipped into the cap to comprise a 64-electrode cap. The cap was placed on the participant's head, attached to an amplifier, and the electrodes were filled with high viscosity electrolyte gel. The subjects were tested individually with noise interference counteracted by the use of a sound-attenuating chamber. Inside the chamber, the subjects were monitored for stimulus presentation and behavior responses. Subjects were asked to avoid eye and body movement as well as to be conscious of jaw and muscle tension (Addante et al. 2012). Behavioral responses and stimulus presentation were monitored using Presentation software on a Windows PC. EEG was sampled at a rate of 1000 HZ.

EEG Methods

EEG was recorded using a BrainVision actiCHamp recording system. All channels were digitized at a sampling rate of 1000 Hz and amplified with the BrainVision actiCHamp amplifier. Recordings were referenced to an average reference electrode (FCz REF/32).

Preprocessing

EEG data was continuously recorded from 63 sites and one reference electrode. The data was then referenced based on the average activity of all electrodes. For the ROIs, specific electrodes were analyzed. The classifications were performed on the data collected from 20 electrodes from the parietal region. Two other ROIs were identified to use as comparison, the frontal region which was comprised of 24 electrodes, and the occipital region which included 8 electrodes.

The EEG data was digitized at a rate of 1kHz with a 58-62 Hz Butterworth filter to reduce electrical line noise (Roach, B. J., & Mathalon, D. H., 2008). Given that 60 Hz is the frequency of the electrical wiring, it is preferable to detect a signal at or near this frequency which is more likely to be coming from the electrical equipment as opposed to the brain. Preprocessing was performed in Matlab via the EEGLAB library.

Oscillatory Analysis

Spectral power was computed via a morlet wavelet transform as a function of time and frequency coded for in Matlab. A 1000 ms buffer was included on both sides in order to minimize edge artifact. Frequencies were sampled logarithmically at intervals between 2 and 100 Hz. Power values were down-sampled into 100 ms time windows.

Multivariate Pattern Analysis.

Multi-Variate Pattern Analysis (MVPA) was used to measure when specific content was represented in the left parietal cortex by classifying the category type of a retrieved memory into one of two the categories. The classification analyses were all performed using a L2 regularized logistic regression with a penalty parameter of 1 from the LIBLINEAR library (Fan et al., 2008). The analysis was repeated separately for the two different classifications for old vs new and face vs scene content. Time bins were trained to identify when an image was old/new, or face/scene for all recognition trials.

The time bins were tested to determine how well they could predict the content type based on the EEG data. This analysis reported the accuracy as the percentage that the classifier was able to determine correctly. Time points from 0 (when stimulus was first presented) to 2000 ms after the stimulus was presented were assessed with a sliding scale of 100 ms to measure the timeline of participants' recognition. While the timing of memory signals for the old vs new content could have been analyzed via ERP, MVPA was selected to distinguish between the categories for the sake of fair comparison. This memory classifier was anticipated to peak temporally for Old/New similar to the current ERP literature. As the parietal cortex processes the content of retrieved memories, it is predicted that the classifier will pick up on distinct neural processes allowing for classification into the two distinct categories. A peak in classifier performance at a specific time point would indicate when content information was processed in the parietal region. The performance of the classifier was evaluated in relation to chance via a series of one-sample t-tests to determine significant classifier results. T-tests were run for discrete time bins for statistically independent tests and were assessed at the $p < 0.05$ level. Classifier accuracy was assessed for each outcome and averaged together to ensure that the results were not due to bias or noise.

Results

Behavioral

Overall as anticipated, participants were highly successful at remembering the studied content. During the recognition task participants correctly identified items 95.7% of the time. Participants had a mean reaction time (rt) of 0.79 seconds with a standard deviation of 0.38 for recognition trials. For Face/Scene trials of the recognition phase the participants tended to respond at a faster rate (μ=0.71s, sd=0.37) than Old/New trials (μ=0.87 sd=0.36). In the recall task 75.6% of subjects reported that they could vividly recall the studied image, 13.6% of subjects reported a weak recollection of the image, 9.9% of subjects reported they were unable to recall the studied image, and 0.78% failed to indicate a response. The mean reaction time of recall trials was 1.34 seconds with a standard deviation of 0.59. Items recalled vividly tended to be recalled more quickly (μ=1.16, sd=0.42) than items recalled weakly (μ=1.75, sd= 0.58). Face and scene content appeared to be recalled more quickly *(Face* rt μ=0.68, sd=0.29; *Scene* rt μ=0.71, sd=0.32) than old and new content with smaller reactions times (*Old* rt μ=0.86, sd=0.29; *New* rt μ=0.86, sd=0.29), meaning it took less time to identify.

Memory Decoding during the Recognition Phase

The decoding classifier was trained and tested on the same 100ms time window to establish a time course with which to analyze the interaction between the recognition task and the point in time. The time course spans from 0ms to 2000 ms after the stimulus was presented. A heightened point in the decoding classifier would indicate when the content information was being processed in that particular region. A series of one sample t-tests were used to identify the time points on this spectrum when the classifier reported significant results above chance (50%). The parietal region was selected as the main region of interest, however, coding for the frontal ROI was also employed for comparison and additional insight. The results for the Old/New classifier performance in the parietal region are consistent with the Old vs New effect detailed in the literature which illustrate a peak in performance starting around 400ms after presentation of the stimulus and lasting until about 800 ms (Rugg and Curran, 2007). The present study found that this peak in Old/New performance is at its highest at around 500ms and graphically can be seen to float above the chance indicator for about 300ms (see Figure 1). This is indicative of when the participant retrieved the familiar content after the presentation of the stimulus. The t-tests were significant for the Old/New time course at 500-600ms (t (19) = 4.26, p =4.2e-4 < 0.05) which is typical for this retrieval success effect. However, the other points in this peak from about 400-800 ms which can be visualized on the graph figure 1, were in not significant by t-tests results. The only other significant time point, which demonstrated a significant result was toward the end of the time course at around 1900ms after the stimulus was presented (t (19) = 2.32, p = 0.032 < 0.05). This would be an interesting finding given that the peak of the Old/New classifier generally tends to span the 400-800ms range. However, upon reevaluation of results with corrected p-values, this point has been deemed erroneous.

The results for the Face/Scene classifier demonstrated a different time course with an earlier peak in the classifier results. The peak begins to climb immediately after the presentation of the stimulus, with a steep peak around 100ms-200ms, which lasts about 400ms before returning to chance accuracy at around 700ms (Fig. 1). This figure shows the differential time courses and illustrates that the Face/Scene content is processed faster than Old/New content. A two-way ANOVA was calculated to assess the significance of this interaction and the validity of these differential plots in the parietal ROI. The ANOVA found a main effect of time ($F(19, 361)$, $p = 3.29e\text{-}34 < .05$) with a significant Generalized Eta-Squared measure of effect size ($\eta_G^2=0.26$), as well as trial type ($p=4.53e\text{-}05 < 0.05$, $\eta_G^2 = 0.12$). This ANOVA looked across recognition versions of Old/New and Face/Scene to examine across the two versions of recognition analyzed. The interaction between recognition trial type and time was also significant ($F(19, 361)$, $p = 1.36e\text{-}46$, $\eta_G^2 = 0.28$) The following figure depicts the classification results for the Old vs New recognition tasks for the parietal ROI.

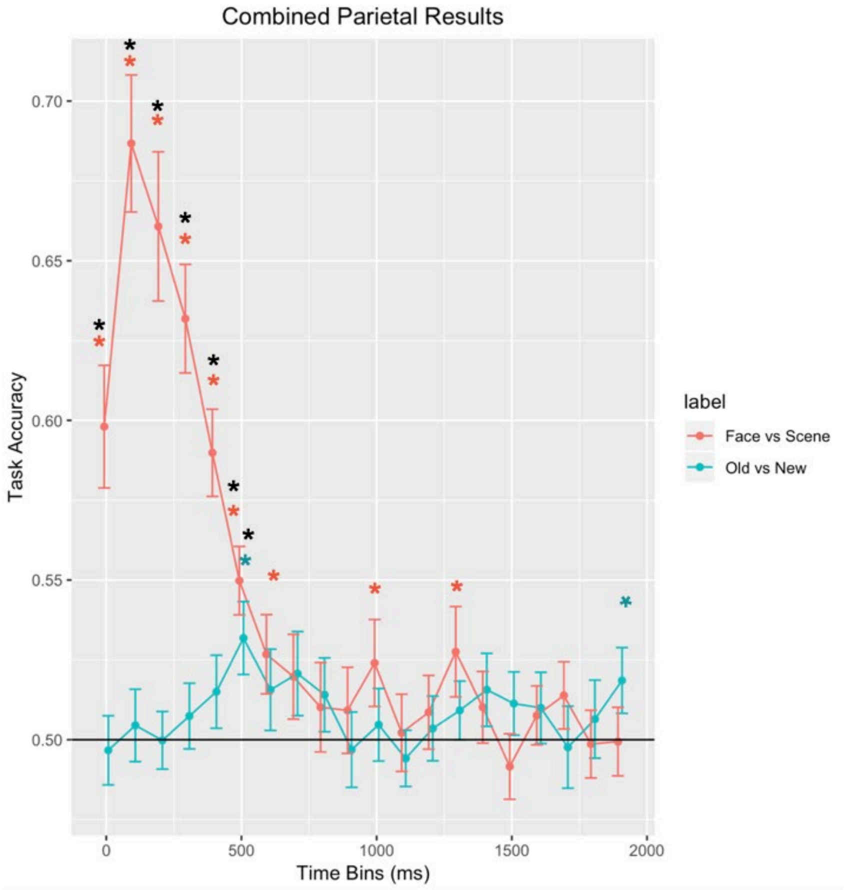

Figure 1. Classification accuracy for the combined Face vs Scene and Old vs New classification results in the parietal region. Time is plotted starting when the image first appeared on the screen. Black asterisks signify corrected p-values. The solid black line represents chance (50% accuracy).

Once we were able to justify that the Face/Scene decoding precedes the Old/New decoding we ran t-tests to determine the significant time points for the Face/Scene recognition. From 0-700ms the t-tests presented significant values, significant at the p <.001 value. (0-100ms: *t* (19) = 5.36, p = 3.56e-05< .05), (100-200ms: *t* (19)= 9.12, *p*= 2.279e-08 < .05), (200-300ms: *t* (19)= 7.19, *p*= 7.89e-07< .05), (300-400ms: *t* (19) = 8.46, *p*= 7.198e-08 < .05), (400-500ms: *t* (19)= 7.73, *p*= 2.77e-07

< .05), (500-600ms: t (19) = 6.31, p = 4.68e-06 <.05), (600-700ms: t (19) = 2.535, p = 0.021 < .05). After this significant peak, two much smaller peaks can be seen which produced significant t-tests. These points deviate above the rate of chance with the first point at the 1000-1100ms time window (t (19) = 2.2614, p = 0.036 < .05) and the second point at the 1300-1400ms (t (19) = 2.4178, p= 0.026 < .05). While there was postulation that these points could be representative of content processing and a consideration after the initial judgment, however, it is likely that these points are due to noise given that they deviate around the chance indicator (50%).

A two-way ANOVA calculated for the frontal ROI combined across trial types also found significant effects for the time (F(19, 361), p=1.25e-05, η_G^2 =.071), recognition trial type (F(1, 19), p= 4.38e-02, η_G^2=.013) and their interaction (F(19, 361), p=2.41e-07, η_G^2 =.083). As per Figure 2, the Face/Scene decoding is drastically less heightened in terms of classifier accuracy in this region compared to the parietal region seen in Figure 1. The Old/New decoding in the frontal region, while barely significant above chance, may indicate a prolonged time course of this effect in this region. The significant number of points in this region was rather unexpected. However, based on the literature of the presence of the old/new effect in the mid-frontal region as well as the parietal, this is not entirely surprising (Rugg and Curran, 2007). This relationship between Old/New and Face/Scene recognition task classification decoding for the frontal ROI is featured in the following figure.

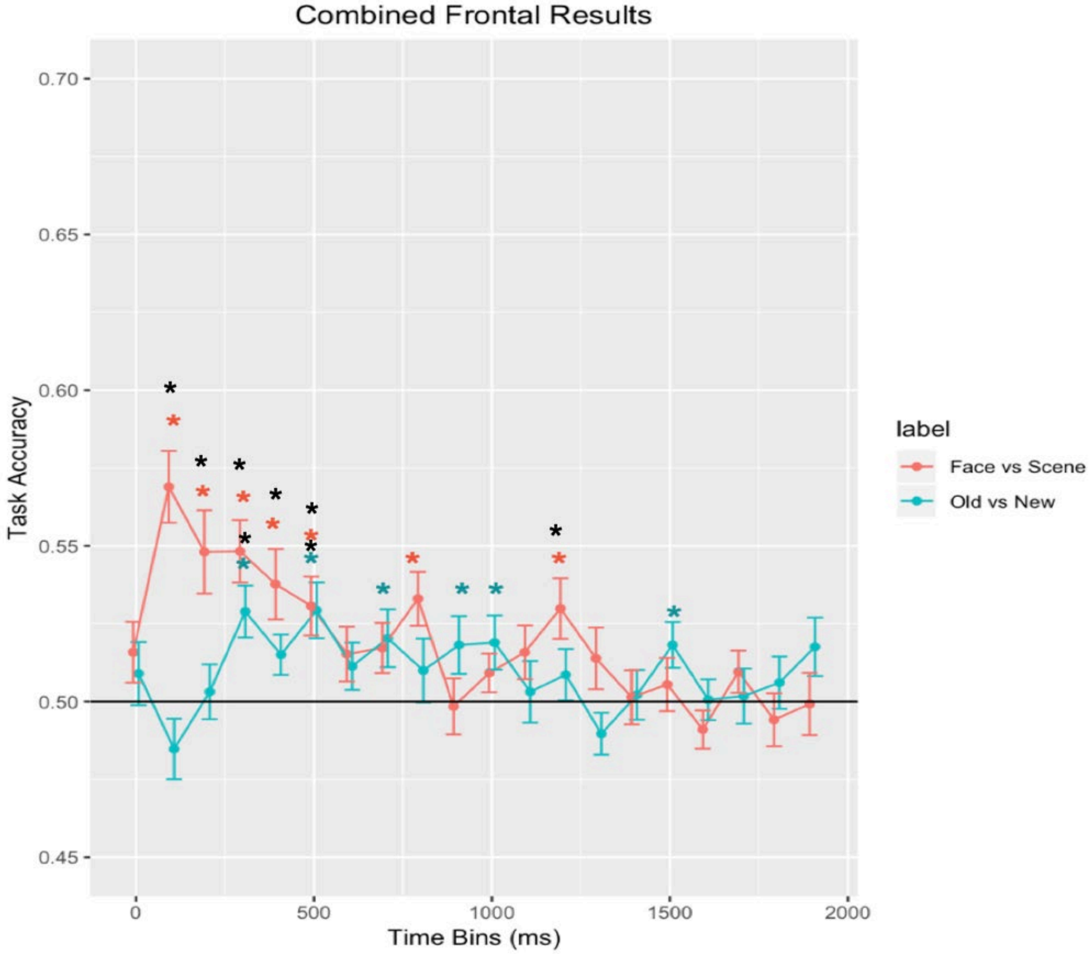

Figure 2. Classification accuracy for the combined Face vs Scene and Old vs New classification results in the frontal region. Time is plotted starting when the image first appeared on the screen. Black asterisks signify corrected p-values. The solid black line represents chance (50% accuracy).

Recognition Task-Specific Results Upon analysis of the recognition task for the parietal region during the Face vs Scene recognition trial, a two-way ANOVA demonstrated no main effect of task and no interaction between task and time. Time was found to be significant ($F(19, 361)$ $p = 1.61e\text{-}56 < .05$, $\eta_G^2 = .49$), but neither task ($F(1, 19)$, $p = 0.80 > 0.05$) nor time-task interaction ($F(19, 361)$, $p = 0.18 > 0.05$) was significant at the 0.05 level. The lack of significant differentiation between task suggests that memory effects were relatively automatic, meaning that they did not depend on task. This is depicted in in the following figure with the recognition task (recogTask) illustrating lines that mirror each other without deviating significantly in path.

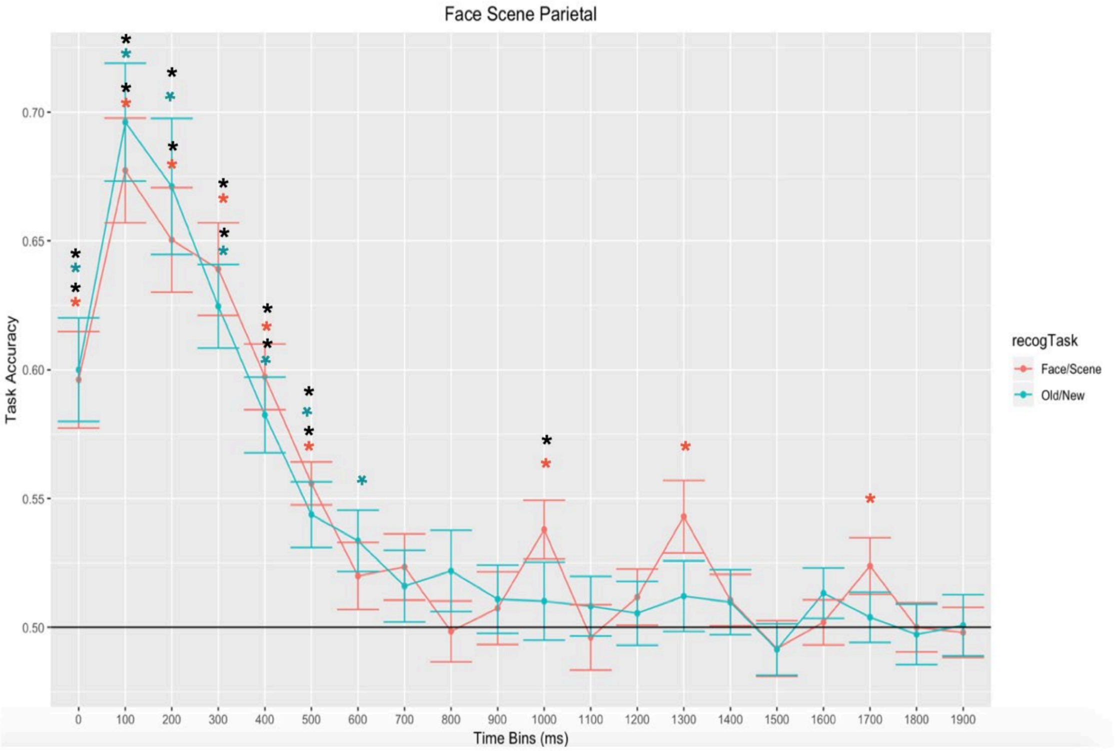

Figure 3. Face/Scene and Old/New classification accuracies for the Face vs Scene task in the parietal region during the recognition phase. Time is plotted starting when the image first appeared on the screen. Black asterisks signify corrected p-values. The solid black line represents chance (50% accuracy).

Similar results were also found in the frontal region for this Face vs. Scene version of the recognition phase which presented no main effects of task ($F(1, 19)$ $p = 0.09 > .05$) or interaction between time and recognition task, ($F(19, 361)$, $p = 0.74 > .05$) There was however an effect of time ($F(19, 361)$, $p= 1.98\text{e-}10 < 0.05$, $\eta_G^2=.15$). The following figure for this task of Face/Scene in the frontal ROI also demonstrates lines that tend to mirror one another by running in a parallel trend which shows a lack of differentiation between the two tasks in this particular region. This lack of significant differentiation between the two tasks presents that findings within the two Face vs Scene trials in the frontal region were relatively automatic and not dependent on the given task.

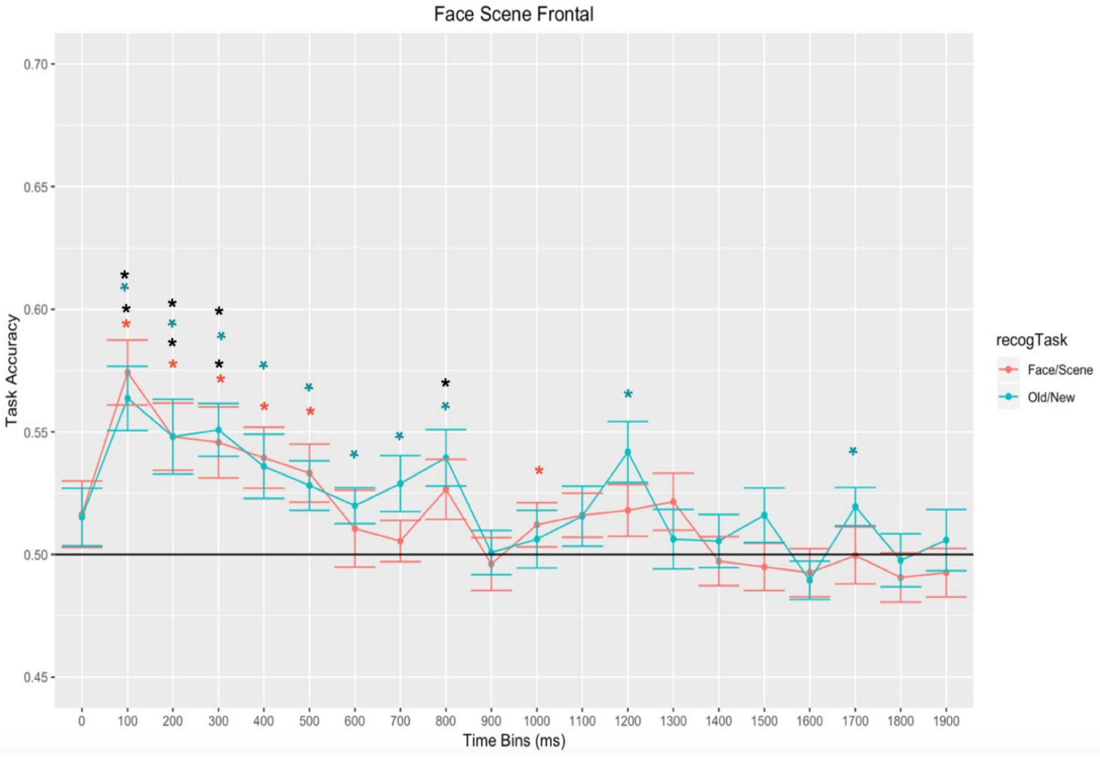

Figure 4. Face/Scene and Old/New classification accuracies for the Face vs Scene task in the frontal region during the recognition phase. Time is plotted starting when the image first appeared on the screen. Black asterisks signify corrected p-values. The solid black line represents chance (50% accuracy).

A two-way ANOVA of the Old vs. New version of the recognition phase for the parietal region revealed no significant effect for the specific recognition task (*F*(1,19) *p*=0.11 > 0.05) or the interaction between time and recognition task(*F*(19, 361), *p*=0.70 > 0.05) (Figure 3). This is consistent with the other ANOVA-based findings, which indicate that the tasks in the Old/New are not task dependent. Rather they are also relatively automatic. Compared to the Figures 2 and 3, Figure 5, which depicts the two tasks for Old vs New in the parietal region, does not appear to be as highly correlated to the same degree across tasks and has several significant result at the first significance level but not at the corrected level of p-values.

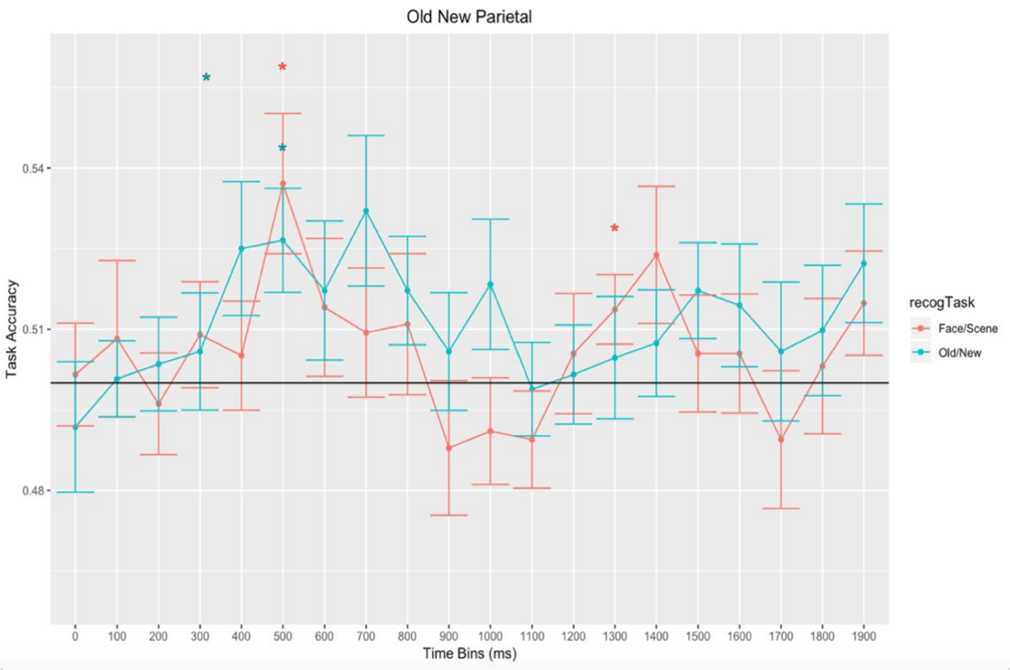

Figure 5. Face/Scene and Old/New classification accuracies for the Old vs New task in the parietal region during the recognition phase. Time is plotted starting when the image first appeared on the screen. This graph features no corrected p-values. The solid black line represents chance (50% accuracy).

This could be investigated further in a more selective region to understand if this is a place for potential distinction across tasks. However, as it stands the result present task dependent findings that are not statistically different. Alternatively, the frontal region analysis for the Old vs New recognition task did show a main effect for recognition task ($F(1,19)$ $p = 1.8e\text{-}04 < 0.05$, $\eta_G^2 = 0.02$), as well as an effect of time ($F(19, 361)$, $p = 0.02 < .05$, $\eta_G^2 = 0.05$). The interaction between time and recognition task revealed no main effect ($F(19, 361)$, $p = 0.26 > 0.05$). The following figure demonstrates a differentiation in this region for this task which is different than the previous analyses.

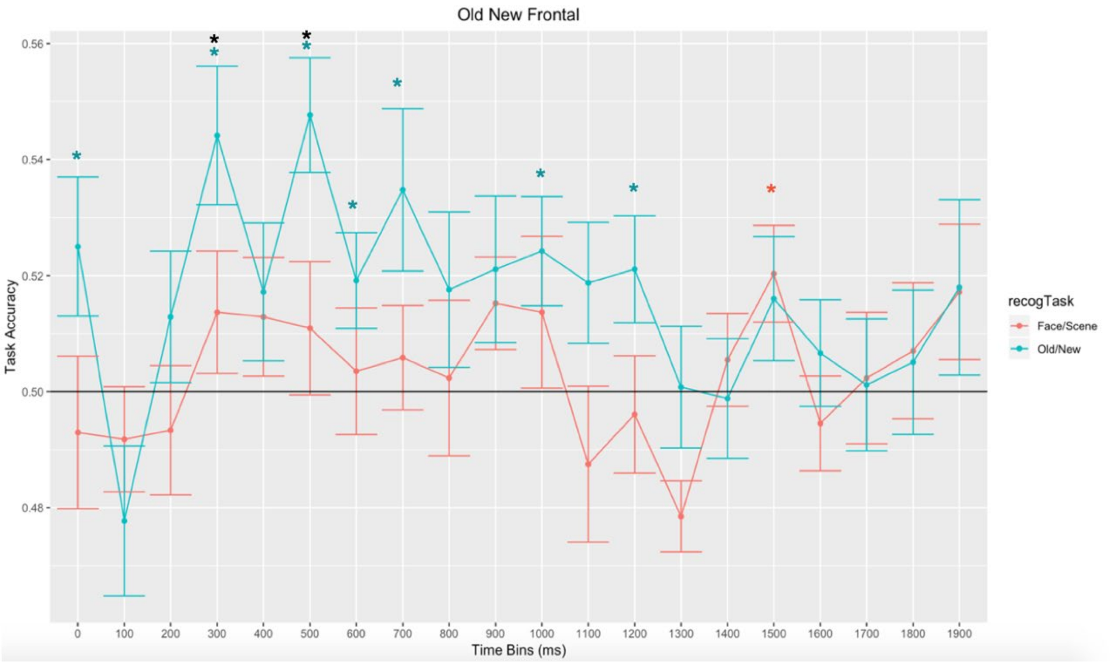

Figure 6. Face/Scene and Old/New classification accuracies for the Old vs New task in the frontal region during the recognition phase. Time is plotted starting when the image first appeared on the screen. Black asterisks signify corrected p-values. The solid black line represents chance (50% accuracy).

These findings depicted in Figure 6 shows a differential pattern of neural activity in response to the two tasks. This suggests that the memory effects in the frontal cortex were task dependent as compared to the parietal cortex which did not depend on task and were more automatic.

Discussion and Limitations

Based on the comparison of the results and the foundation of literature, there is reason to believe that the memory signal is originating from the parietal region. The temporal dynamics of the parietal classifier, which show consistencies with the ERP study's timing of the Old/New effect, suggests that the classifier is characterizing the content when a memory signal is being processed in this region (Friedman and Johnson, 2000). Given that the content signals generated from fMRI studies emerge from the same location, it is likely that the memory and content signals are both coming from the same area (Jafarpour et al., 2014). From the results, there is further support for the notion that the Old/New effect is reflective of a neural process that constructs the subjective recollection experience. While prior findings have postulated that the parietal region may be influenced by task-based demands, the results indicate that the memory effects in the parietal cortex did not depend on task and proved to be relatively automatic. This supports that regardless of the content type, either Face/Scene or Old/New, the parietal region did not provide any indication that the given task provided a noticeable main effect.

Based on some of the ERP literature, notably by Rugg and Curran (2007), there is evidence of the old/new effects in the midfrontal region as well as the parietal region. Thus, this result supports the connectivity and crossover between these two regions, consistent with the crossover in the different regions in the results. Leube et al. (2003) also discusses the involvement of a fronto-parietal network in successful episodic memory retrieval of newly learned faces. This study states that left frontal and parietal areas consistently exhibit stronger activity for old vs. new items which was assessed via verbal recognition memory tasks demonstrated in functional imaging studies (Leube et al., 2003). While the present study focused on familiar and generally recognizable faces, the fronto-parietal network and the two regions potentially working in tandem can be referenced to help explain the similarities found across the two regions. The frontal region, which was used in the present study as a point of comparison, has significant decoding accuracies above chance, which is to be expected given that the parietal region is not the sole neuroanatomical location to process the content information. The frontal region did not present the Old/New Effect to the same extent as the parietal region which showed a stronger occurrence of this retrieval success effect (Figure 2). Rugg, M.D. et al., (1998) demonstrated how the mid-frontal region demonstrated an Old/New effect 300-500 ms after the given stimulus while the parietal effect was a bit later at 400-800 ms, which shows the cross-connectivity and presence of the Old/New effect in both regions but with different time frames.

It is notable that the literature has focused not only on the parietal region but more specifically the left parietal region which contains the angular gyrus (Rugg & Curran, 2007). This region has been of particular interest given that direct disruption of this region has been shown to impair episodic memory (Thakral, Madore, & Schacter, 2017). This region of the brain demonstrates content processing as well as the retrieval successful effect for items with a higher degree of familiarity. Thus, in future studies, such research might investigate the left parietal ROI more specifically, ideally with a higher density EEG array. This would provide a more focused and specialized localization of the signals which may provide better definition of the distinct anatomical locations of these results.

In terms of the scope of the results, the findings are contingent on the sample in order to adequately assess the generalizability of the results. Twenty participants provide a reasonable sample size from which we can make predictions and ascertain viable results. However, this number is on the lower end of the spectrum. Including more participants in the analysis will only strengthen the results and future directions of this study. There are currently 38 participants who have been recorded via EEG, thus the next step would be to evaluate the current findings with the additional subjects to determine the complexity and strength of the results. Another potential limitation that is the number of males enrolled in the study. The number of females in the study was substantially higher than the number of males, which did not directly confound the results or analyses, but a more ideal sample would include an equal proportion of male and female subjects. It is noticeable that the participants of this study are primarily psychology students who heard about the opportunity to participate in the study from their department. The population distribution of students in the psychology major does have a higher concentration of female students, which may account for the disproportionate number of female students in the sample distribution. Given the tendency for females to sign up for the experiment at a higher rate than their male counterparts, future directions and versions of this study may look into methods of recruitment encouraging males to partake in the experiment.

Additionally, by conducting this study with a larger and more evenly distributed sample size, the peaks in the classifier performance will likely be more pronounced providing significant t-tests throughout the entirety of the Old/New peak as opposed to only the start and end points. There also may be some differentiation due to the fact that the nature of the current study is different than that of an ERP study. Interestingly, while there is evidently one main peak for the Face/Scene recognition trials, two much smaller yet statistically significant peaks emerge later on at 1000ms and 1300ms respectively (Figure 1). It is unclear if these two points are in fact two smaller peaks offset from the main peak since the distance between them is relatively small. The two smaller points seen in Figures 1, and 3 with red Face vs Scene decoding could in actuality exist as part of one separate point. The existence of a second peak could represent a form of response processing happening after the initial reaction and processing of the content. Another possibility is that that these points are a continuation of the first and significant main peak. This would indicate that the nature of the Face/Scene processing is more prolonged and distributed than we were led to believe with the current t-tests and graphic visualizations of the results. While these are possible predictions, it is also possible that the points are not in fact representative of the neural activity in the brain and could be due to chance given these points tend to deviate close to the chance line (50%).

The results combined across trials for the frontal ROI have a similar pattern of significance (Figure 2) compared to the parietal ROI (Figure 1), but the y-axis scale of the frontal ROI results is much smaller. Additionally, for the recognition-task specific results for Face/Scene tasks in the parietal ROI and the frontal ROI (Figures 3 and 4 respectively), the concurrent lines on the graphs tend to mirror each other which leads us to believe that the results here are not task dependent. The Old/New recognition-task specific results showed this lack of differentiation in the parietal ROI (Figure 5) but not the frontal ROI (Figure 6) which leads us to believe that the frontal ROI is processing tasks differently than the parietal ROI and that it is task-dependent.

Ultimately, research aims to reach a full understanding of the different sub-processes involved in the overall subjective recognition experience. This exploratory analysis has developed interesting connections across the literature and established new understandings of the task-related processes and their specific time courses. By being able to chart when the brain is processing and retrieving different familiarized content, we have acquired a stronger connection between the nature and interworking of the encoding and retrieval processes and their important similarities and patterns. Moving forward, further EEG studies can be used to analyze the temporal dynamics of the given sub-regions in conjunction with additional fMRI investigations of the particular sub-regions and their functions.

Appendix

Combined Parietal	
Face/Scene	*Old/New*
Time 21 (0 ms) p=3.56e-05	**Time 26 (500 ms) p=.00042**
Time 22 (100 ms) p=2.28e-08	Time 40 (1900 ms) p=.0319
Time 23 (200 ms) p=7.88e-07	
Time 24 (300 ms) p=7.20e-08	
Time 25 (400 ms) p=2.77e-07	
Time 26 (500 ms) p=4.684e-06	
Time 27 (600 ms) p=.0201	
Time 31 (1000 ms) p=.0357	
Time 34 (1300 ms) p=.0258	

Combined Frontal	
Face/Scene	*Old/New*
Time 21 (0 ms) p= 5.89e-05	**Time 21 (0 ms) p= 5.59e-05**
Time 22(100 ms) p = 4.43e-08	**Time 22(100 ms) p = 5.94e-08**
Time 23 (200 ms) p= 5.06e-07	**Time 23 (200 ms) p= 3.34e-06**
Time 24 (300 ms) p= 2.74 e-07	**Time 24 (300 ms) p= 3.08e-07**
Time 25 (400 ms) p= 3.39e-07	**Time 25 (400 ms) p= 1.99e-05**
Time 26 (500 ms) p= 2.09e-06	**Time 26 (500 ms) p= .0028**
Time 31 (1000 ms) p= .0036	Time 27 (600 ms) p=.0112
Time 34 (1300 ms) p=.0065	
Time 38 (1700 ms) p=.04317	

Frontal Face vs Scene	
Face/Scene	*Old/New*
Time 21 (0) p= 5.89e-05	**Time 21 (0) p= 5.59e-05**
Time 22(100) p = 4.43e-08	**Time 22(100) p = 5.94e-08**
Time 23 (200) p= 5.06e-07	**Time 23 (200) p= 3.34e-06**
Time 24 (300) p= 2.74 e-07	**Time 24 (300) p= 3.08e-07**
Time 25 (400) p= 3.39e-07	**Time 25 (400) p= 1.99e-05**
Time 26 (500) p= 2.09e-06	Time 26 (500) p= .0028
Time 31 (1000) p= .0036	Time 27 (600) p=.0112
Time 34 (1300) p=.0065	
Time 38 (1700) p=.0431	

Frontal Face vs Scene	
Face/Scene	*Old/New*
Time 22 (100 ms) p= 2.09e-05 **Time 23 (200 ms) p=.0023** Time 24 (300 ms) p= .0052 Time 25 (400 ms) p= .0051 Time 26 (500 ms) p= .0114 Time 29 (800 ms) p=.043	**Time 22 (100 ms) p= .0001** Time 23 (200 ms) p=.0053 **Time 24 (300 ms) p= .0002** Time 25 (400 ms) p= .0129 Time 26 (500 ms) p= .0119 Time 27 (600 ms) p=.0135 Time 28 (700 ms) p=.0204 **Time 29 (800 ms) p=.0028** **Time 33 (1200 ms) p=.0034** Time 28 (1700 ms) p=.0213

Parietal Old vs New	
Face/Scene	*Old/New*
Time 26 (500 ms) p= .0104 Time 34(1300 ms) p=.0484	Time 26 (500 ms) p=.0128 Time 28 (700 ms) p=.034

Frontal Old vs New	
Face/Scene	*Old/New*
Time 35 (1500ms) p=.0246	Time 21 (0 ms) p=.050 **Time 24 (300 ms) p=.0015** **Time 26 (500 ms) p=.00012** Time 27 (600 ms) p= .0318 Time 28 (700 ms) p=.0226 Time 31 (1000 ms) p=.0186 Time 33 (1200 ms) p=.0336

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