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# Detecting the neural correlates of episodic memory with mobile EEG: Recollecting objects in the real world

Joanne L. Park [*], David I. Donaldson

*Psychology, Faculty of Natural Sciences, University of Stirling, Stirling, Scotland, UK*

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ABSTRACT

Episodic memory supports recognition of the details of complex real world experiences, providing a continuous record of events embedded within spatial and temporal context. Despite the inherently dynamic nature of real events, the bulk of neuroscientific research to date examines recognition in absence of the detailed contextual information that is known to be a defining characteristic. Given the importance of environmental context for episodic memory, examining ERP correlates of memory in more naturalistic settings is vital for progress in understanding how retrieval operates in daily life. The current study capitalized on recent advances in mobile EEG technology to address this issue and is the first to investigate ERP correlates of episodic retrieval in real world contexts. Participants were guided around a pre-defined route inside a building on campus, while performing a recognition memory task, which paired images of objects with actual physical locations in the building to provide context. Importantly, the findings clearly demonstrate that it is possible to observe reliable neural correlates of memory in real world contexts. Replicating two well established ERP correlates of episodic retrieval reported in prior laboratory based studies, we detected FN400 old/new effects traditionally associated with familiarity between 300 and 500 ms, and a late posterior negativity (LPN) often linked to reconstructive processing or evaluation of retrieval outcomes between 500 and 800 ms. Moreover, the FN400 effect was found to be sensitive to retrieval of context, with more sustained effects for objects encountered in a different context at study and test. Overall, the current work highlights the power of mobile EEG technology for examining complex cognitive functions in more naturalistic real world settings.

## 1. Introduction

Episodic memory supports recognition of the details of complex real world experience, providing a continuous record of events embedded within spatial and temporal context.

Dual-process models of recognition are dominant in the episodic memory literature, proposing that separate familiarity and recollection processes support retrieval (see Yonelinas, 2002, for an extensive review). Familiarity is traditionally characterized as a relatively automatic process that supports item memory, whereas recollection is characterized as a controlled process that supports retrieval of contextual information. Crucially, EEG techniques have been prominent in advancing our understanding of episodic memory, providing one of the strongest sources of support for dual process models (Donaldson and Curran, 2007). In particular, Event-Related Potentials (ERPs) recorded during laboratory based episodic memory tests have linked familiarity with an early mid-frontal old/new effect (FN400) onsetting between 300 and 500 ms post-stimulus and recollection with a left-parietal old/new effect evident between 500 and 800 ms (for reviews see Friedman and Johnson, 2000; Rugg and Curran, 2007). More broadly, ERPs have also been used to identify other processes linked to recognition memory. For example, a late onsetting posterior negativity (LPN) observed over parieto-occipital locations has been reported in a number of source memory tasks, linked to reconstructive processing or evaluation of retrieval outcomes (for a review see Mecklinger et al., 2016). Similarly, many studies report late onsetting right-frontal old/new effects, linked to post-retrieval evaluation and source monitoring (e.g., Wilding and Rugg, 1996; Schloerscheidt and Rugg, 2004; Woodruff et al., 2006; Hayama et al., 2008; Cruse and Wilding, 2009). While it is clear that significant progress has been made in elucidating neural correlates of recognition, to date neuroimaging research has principally examined recognition in relatively restricted settings that inherently limit the richness of episodic experience.

Limitations in prior ERP studies of recognition memory are driven, in

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[*] Corresponding author. Psychology, Faculty of Natural Sciences, University of Stirling, Stirling, FK9 4LA, Scotland, UK.
*E-mail address:* joanne.park3@stir.ac.uk (J.L. Park).

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part, by restrictions in the recording setup. In a typical recognition memory study, participants view stimuli whilst seated in a darkened, electrically shielded testing chamber, and movement is heavily discouraged to avoid contamination of the signal. As such, despite changes in spatial and temporal context being central to definitions of episodic memory, in traditional experiments the environmental context of study episodes is routinely held constant for the duration of the experiment. To be clear, even in these conditions context is often examined explicitly, e.g., using local manipulations such as changes in word colour or screen position, rather than examining more global contextual factors that form rich episodic experiences. Importantly, recent work demonstrates that it is now possible to capture reliable EEG data using mobile technology, opening the door to investigations of episodic memory in more naturalistic settings (Gramann et al., 2014; Park et al., 2015; Ladouce et al., 2017). Initial contrasts between wireless mobile and laboratory-based EEG amplifiers report a high degree of correlation across systems (Debener et al., 2012; De Vos et al., 2014; Cruz-Garza et al., 2017). Moreover, in the last few years there has been a steady growth in the number of studies successfully employing mobile EEG to query aspects of cognitive function in real world contexts (e.g., Gramann et al., 2010; Wascher et al., 2014, 2016; Jungnickel and Gramann, 2016), including ERPs associated with attention (Debener et al., 2012; De Vos et al., 2014; Zink et al., 2016). Most relevant here, mobile EEG has been employed to investigate the influence of real world environments on the formation of episodic memories (Griffiths et al., 2016), providing a clear demonstration that memory-related EEG data can be reliably obtained in naturalistic settings.

Here, our aim is to demonstrate that ERP signatures associated with episodic memory in prior lab-based work can be detected in real word contexts, and to establish how these neural correlates of memory are affected. Given the importance of environmental context for episodic recollection, and the limitations of laboratory based studies outlined above, our view is that investigating neural correlates of remembering in more naturalistic settings is vital for progress in understanding how retrieval operates in daily life. To date, results from lab-based ERP studies are mixed, with some demonstrating strong links between recollection related left-parietal old/new effects and the retrieval of contextual detail, as predicted by traditional dual-process models (e.g., Wilding et al., 1995; Wilding, 2000), and others demonstrating contextual influences on FN400 effects associated with familiarity (e.g., Graham and Cabeza, 2001). Importantly, results from laboratory based ERP studies suggest that the neural correlates of retrieval may vary depending on the way in which context is examined. Key factors that may influence the results obtained are the type of stimulus employed and the specifics of the task. In the following sections we provide a brief overview of factors potentially driving differences observed in ERP components associated with retrieval of context, which highlight the importance of adopting a real world approach.

### *1.1. Stimulus parameters*

The complexity of the materials used to examine retrieval of context influences ERP correlates of memory - the functional role appears to differ depending on the content of the episode to be retrieved. Evidence linking recollection to the left-parietal old/new effect comes from studies examining stimulus-related context, such as the gender of the speaker for words presented auditorily at study, or paired associations between studied items (e.g., Wilding and Rugg, 1996; Wilding, 1999; Vilberg et al., 2006). Strong links between contextual retrieval and the left-parietal old/new effect have predominately been found by studies using words. By contrast, studies examining episodic memory using visual images have reported contextual influences on FN400 effects associated with familiarity (e.g., Ecker et al., 2007; Diana et al., 2011). Moreover, studies examining memory for faces (with names as context) and objects (with verbal locations as context) show that recollection of some kinds of contextual information is associated with frontally distributed old/new effects (e.g., MacKenzie and Donaldson, 2009; Galli and Otten, 2011; Yick and Wilding, 2014), suggesting that the neural correlates of recollection could be material specific. However, taken together the findings also point to an alternative conclusion – that the difference in findings is not linked to the specific modality in which stimuli are presented *per se*, but to a difference in the depth and realism of episodic details being represented.

Attempts to strongly manipulate more realistic context have been carried out in a number of laboratory based ERP studies, by pairing images of everyday objects with background scenes. In one such study, which influenced the design of the current experiment, Tsivilis et al. (2001) manipulated the old/new status and the combination of object images and landscape scenes, to produce five pairings at test: old objects/same background (SAME), old object/different background (REARRANGED), old object/new background (OLD/NEW), new object/old background (NEW/OLD) and new object/new background (NEW/NEW). Results revealed that FN400 old/new effects for correctly classified old objects were only present when paired with a studied context, while left-parietal old/new differences were present for correctly classified objects irrespective of the study status of the context. These findings suggest that using more complex and ecologically valid stimuli to test recognition memory produces a different pattern of results than would be predicted on the basis of traditional dual-process models. In this case, context influences FN400 effects associated with familiarity rather than left parietal effects associated with recollection. However, there is also evidence that the specific parameters of the memory task itself can impact whether contextual retrieval is associated with FN400 or left-parietal old/new differences.

### *1.2. Task parameters*

In line with findings demonstrating contextual influences on familiarity, a number of studies have shown that the FN400 can support associative recognition under certain circumstances: when separate items are unitized into a single representation at encoding (e.g., Rhodes and Donaldson, 2007, 2008; Bader et al., 2010; Diana et al., 2011). This explanation relies on the assumption that employing more realistic stimuli automatically makes them easier to unitize. However, this explanation cannot entirely account for the findings because unitization studies rely on specific encoding manipulations (e.g., invented definitions, interactive imagery) to form strong associations between unrelated stimuli, and encoding tasks in prior work demonstrating contextual influences on the FN400 did not employ a similar approach. Nonetheless, work on unitization highlights that the nature of the encoding task could be another factor influencing whether contextual influences are observed on neural correlates of familiarity or recollection. In line with this view, Ecker et al. (2007) have demonstrated that context effects on familiarity are reduced when contextual information does not automatically capture attention, by contrasting across groups where one group was cued to focus only on the target object, rendering the background scenes incidental to the task (although see MacLeod and Donaldson, 2017 for concerns about between group comparisons).

Overall, while EEG data provides strong evidence for dissociable neural correlates of episodic memory, variability in the way in which context is instantiated and examined experimentally clearly has an impact on the neural correlates of retrieval, impacting them in ways not predicted by dual-process models. To make further progress in elucidating how episodic memory works, recognition must be examined under more naturalistic conditions, where to-be-remembered stimuli are encountered embedded in rich environmental context.

### *1.3. The current study*

This study is the first attempt to measure neural correlates of episodic retrieval in a real world setting, by employing mobile EEG during an associative recognition task that pairs images of objects with unique indoor locations. We designed the task as an initial step outside of the laboratory, introducing greater ecological validity by having participants study objects in physically-distinct environmental contexts, but maintaining an acceptable level of experimental control by presenting objects on a tablet (with the aim of making the findings of the current study as comparable as possible with prior laboratory based studies). The real world feature of the current study was the physical context in which objects were encountered, the specifics of the recognition memory task itself were similar to laboratory based tasks. Moreover, it is important to distinguish between spatial memory tasks, which include an active navigation component, and our episodic memory task, where no navigation demands were placed on participants. To be clear, our task was not designed to examine processes associated with navigating through space. The current study had two specific goals 1) to demonstrate that ERP signatures associated with episodic memory in prior lab-based work can be detected in real word settings using mobile EEG, and 2) to assess the impact of real world contextual retrieval on the neural correlates of recognition memory.

In practice our real world experiment was straightforward. At study, participants were guided around a pre-defined route, encoding objects to be associated with their current location in the building. At test, participants repeated the route and were presented with three different item/context combinations: old objects presented in the same location as at study, old objects presented in a different location and new objects presented in a previously encountered location. Participants were required to discriminate between same location old, different location old and new objects. Based on prior behavioural evidence of changes in memory for items where the study context is reinstated at test (e.g., Hayes et al., 2007; for review and meta-analysis see Smith and Vela, 2001), we predicted that objects presented in the same context at test would be better remembered (i.e., with increases in performance/decreases in reaction time). At issue is whether the ERP correlates of familiarity and recollection can be detected during real world remembering, and if so, whether changes in the environmental context really matter.

## 2. Methods

### 2.1. Participants

27 University of Stirling students (18–36, 8 males) were recruited through an in-house online booking system. Participants were compensated at a rate of £7.50 per hour for taking part and had the option of receiving payment for the first hour in course credits. All participants were right-handed, native English speakers, with no known neurological problems and normal or corrected-to-normal vision. Five participants were excluded from the sample due to issues with recording equipment resulting in insufficient trials (<16 per condition), and a further five were excluded from analyses due to excessive EEG artifacts which resulted in insufficient ERP trials for critical contrasts. The remaining 17 participants comprised of 13 females and 4 males with a mean age of 21 (range = 18–36; SD = 4.37). Ethical approval was granted by the General University Ethics Panel (GUEP) at the University of Stirling.

### 2.2. Materials and design

Critical stimuli consisted of 160 unique everyday objects sampled from the BOSS database (Brodeur et al., 2010), and 60 unique locations distributed over two floors of the largest building on campus. For each participant, 120 objects were randomly assigned to one of two experimental blocks and 40 were selected to act as new items at test. Lists were constructed for two blocks with 60 objects shown at study and test in each block. Within blocks, 20 objects were randomly assigned to three experimental conditions: old items presented in the same context, old items presented in a different context and new items presented in a previously visited context. Twenty of the objects shown at study in each block were discarded and replaced with new objects at test. Objects were presented in colour on a white background using the OpenSesame experiment builder (version 3.1.4 Jazzy James; Mathôt, Schreij & Theeuwes, 2012) installed on a Microsoft Surface Pro 2 tablet running Windows 10.

Object onset on the tablet was paired with a tone, and a bespoke device, which operated by detecting the vibration from the tone via a cable connected to the headphone jack on the tablet, passed a trigger to the EEG amplifier at object onset on each trial. Synchronization of object/tone onset and event markers sent to the EEG device was verified using the BlackBox toolkit (www.blackboxtoolkit.com) to detect timing of the screen change on the tablet, and an oscilloscope to measure the timing of tone onset and the onset of the TTL trigger pulse. Across multiple timing test runs, we found that event markers were consistently delayed by around 8 ms, which we deemed to be satisfactory as the data to be submitted to analyses would be averaged over large-time periods (min:200 ms), and we did not intend to analyse ERP latencies.

The 60 unique locations providing the context for the task were visited twice in each block, and every location was denoted by a marker on the wall, which consisted of a number indicating the trial and a simple coloured shape printed on a white background (see Fig. 1 for examples of stimuli, locations and markers). Markers were used by the experimenter during the task to ensure that the precise locations for stimulus presentation were held constant across participants, and also provided an additional source of contextual information to aid encoding and retrieval. Markers were created from 30 distinct shapes in Microsoft PowerPoint, and were manipulated minimally with respect to colour, orientation and line style to produce 60 different images. The distance between each marker was approximately 12m and assignment of markers to locations was randomized.

### 2.3. Procedure

Prior to starting the experiment, the procedure was described in detail to participants and written consent was obtained, in-line with University of Stirling ethics procedures. During the study phase of each block, the experimenter walked the participant around the route, stopping them at marker locations to view an object on the tablet screen. To minimize movement related EEG artifacts, participants were asked to remain still and fixate on the tablet screen at each marker. When the experimenter was satisfied that the participant was stationary, the instruction was given to start a trial, and the participant touched the tablet with their right index finger to cue the trial. Each trial consisted of a fixation cross displayed in the centre of the screen for 2000 ms, followed by a target object presented for 3000 ms. The extended fixation time pre-stimulus was included to ensure that EEG recordings were not contaminated with residual motion artifacts during the critical phase. Participants were required to remember the object and the location where it was studied and were actively encouraged to take advantage of environmental cues to help them to link objects to specific locations. After 60 trials, participants were escorted back to the lab and given a 3-min break while the experimenter checked on the data quality, prior to commencing the test phase. The basic test procedure was identical to the study phase, participants were led around the route and viewed objects on the tablet at marker locations. After stimulus presentation participants were prompted on screen to decide whether the preceding target was an old object presented in the same location, an old object presented in a different location or a new object. Details of the response options appeared on the tablet screen on each trial and participants were instructed to use their right index finger to make responses. After 60 test trials participants were escorted back to the lab and given a 5-min break before repeating the entire process for the second block.

### 2.4. EEG recording and analysis

EEG was recorded using a mobile ‘EEGo Sports’ system (ANT Neuro,

**Fig. 1.** Materials and locations. Images show examples of the stimuli sampled from the BOSS database, locations from around the building used in the study, and the corresponding marker that appeared at each location. Markers were manipulated with respect to colour, orientation and line style to produce a different marker for each of the 60 locations.

Enschede, Netherlands) with 32 Ag/AgCl electrodes, positioned in accordance with the 10/20 system, and including left and right mastoid channels. During recording CPz acted as the reference and AFz as ground. The sampling rate was set to 500Hz (bandwidth DC 0–130Hz) and impedances were maintained below 20 kΩ. Data were recorded using EEGo Sports software (version 1.7.2) and analysed offline in EEGLAB (version 13.5.6b; Delorme and Makeig, 2004), which is an open source toolbox for MATLAB (version 8.6 - R2015b, MathWorks, Natick, MA, USA). Raw EEG data were filtered with a 0.1Hz high-pass filter cut-off, to facilitate comparison with prior ERP memory studies (see Tanner et al., 2015 for discussion and recommendations). Channel locations were imported, and the data were re-referenced to linked mastoids. Bad sections of data were rejected based on visual inspection, and bad channels were detected (using EEGLAB pop_rejchan function with a setting of ±3 standard deviations) and interpolated as required (mean channels interpolated = 0.7; min = 0, max = 2). Continuous EEG data were separated into 1000 ms epochs, starting 100 ms prior to object onset at test. Epochs were rejected when deflections exceeded 100 μV or when drift from baseline exceeded ±75 μV in any of the channels using built-in artifact detection (excluding data from frontal channels).

An additional copy of the data was high-pass filtered at 1Hz for use in Independent Components Analysis (ICA), as prior research has demonstrated that filtering between 1 and 2Hz produces good results (Winkler et al., 2015). This copy of the data was processed using the same basic procedures outlined above (i.e., channel labelling, re-referencing, epoching, artifact rejection). The 1Hz high-pass filtered data was submitted to ICA using the Extended InfoMax algorithm implemented in EEGLAB to identify blink, eye-movement and muscle related artifacts. Upon completion of the first pass of ICA, epochs were rejected on the basis of visual inspection of IC activations, before running ICA for a second time to improve the quality of decomposition (Delorme et al., 2007). ICA weights from the 1Hz high-pass filtered data (which is only used for ICA) were then copied to the 0.1Hz filtered data (which is used for the final analysis). Independent components (ICs) related to eye blinks, horizontal eye-movements and muscle noise were rejected from the 0.1Hz high-pass filtered data, based on visual inspection of component scalp maps, power spectrum and raw component activation, which resulted in between 2 and 4 well-characterized ICA components being rejected for each participant. Following rejection of artifactual components, the data was low-pass filtered with a cut-off of 40Hz and baseline corrected with respect to the pre-stimulus period (−100 to 0 ms). The resulting artifact free EEG epochs were then used to form ERPs.

To examine memory effects in depth, ERPs were formed for two contrasts. In the first contrast analysis of basic memory effects focused on hits and correct rejections, collapsing across factors involving context retrieval. The mean number of trials contributing to waveforms for hits was 64 (s.d. = 12) and 31 (s.d. = 6) for correct rejections. The second contrast included the factor of context and focused on accurate retrieval of object and contextual information to examine neural correlates of associative recognition. The mean number of trials contributing to waveforms for same location context hits was 26 (s.d. = 6) and 24 (s.d. = 5) for different location context hits. ERPs were quantified by measuring the mean amplitude over time windows of interest (300–500 ms, 500–800 ms) with respect to the mean pre-stimulus baseline, to be consistent with previous identifications of FN400 and left-parietal old/new effects (see Rugg and Curran, 2007, for a review). Statistical comparisons were performed on six electrode sites (frontal: F3, Fz, F4; parietal: P3, Pz, P4), using repeated measures ANOVA and paired samples t-tests as required (significance level $p = 0.05$). The Greenhouse-Geisser correction for non-sphericity was employed (Greenhouse and Geisser, 1959), and corrected degrees of freedom are reported where necessary.

## 3. Results

### 3.1. Behavioural results

Memory performance and response times are shown in Table 1. Performance for new objects was highest and was accompanied by the shortest response times overall. As predicted on the basis of previous behavioural studies, memory performance was slightly higher for the same location trials, and was accompanied by shorter response times than were evident for the different location trials.

Analysis of the mean accuracy data confirmed that performance was higher for new items than for same location ($t(16) = 5.73$, $p < 0.001$) or different location ($t(16) = 7.39$, $p < 0.001$) old items. Comparison of old items as a function of location revealed no significant difference in performance across conditions ($t(16) = 0.84$, $p = 0.41$), despite the presence of a small numerical increase in accuracy for same location old items. Analysis of the response time data confirmed that reaction times were faster for new items compared to same location ($t(16) = 5.62$, $p < 0.001$) and different location ($t(16) = 9.59$, $p < 0.001$) old items. Crucially, comparison of both classes of old items demonstrated significantly faster response times for same location items ($t(16) = 3.14$, $p = 0.006$). In short, memory performance was affected by reinstating context at test, with objects presented in the same location retrieved faster than those presented in a different location.

**Table 1**
Behavioural results. Memory performance and response times at test (S.E.). Participants were faster and more accurate at detecting new items overall and differences for old objects as a function of location were evident in response times, with same location trials exhibiting shorter response times than different location trials. Memory performance appears slightly higher for objects presented in the same location at test.

| | Same location | Different location | New |
|---|---|---|---|
| Accuracy (%) | 76.52 (3.54) | 72.88 (3.23) | 95.88 (1.04) |
| Response times (ms) | 1482.72 (102.35) | 1831.40 (121.95) | 821.24 (62.27) |

### 3.2. ERP results

This section will report the results of ERP contrasts, analyses in the first section focus on quantifying basic memory effects, while analyses in the second section focus on assessing the influence of context.

#### 3.2.1. Basic memory effects

Given the use of novel mobile EEG recordings the first ERP contrast was employed to characterize basic memory effects, excluding the factor of context, to demonstrate that reliable retrieval related signals could be observed. Fig. 2 shows grand average ERPs for hits and correct rejections from a selection of representative sites, evidencing the presence of positivity for hits during the 300–500 ms latency interval over frontal sites, followed by a negativity over posterior sites between 500 and 800 ms. Initial analysis was designed to identify variations in the pattern of old/new effects across time windows. ANOVA with the factors of test status (old, new), scalp location (frontal, parietal), electrode (left, midline, right) and time window (300–500 ms, 500–800 ms), revealed a significant 2-way interaction between test status and time window [$F(1,16) = 20.56$, $p < 0.001$, $\eta p^2 = 0.56$], and a marginally significant 4-way interaction between test status, scalp location, electrode and time window [$F(2,32) = 3.14$, $p = 0.057$, $\eta p^2 = 0.16$], suggesting changes in the pattern of memory effects across time windows.

Follow-up analyses were then performed separately for each time window to characterize the pattern of effects, using ANOVA with the factors of test status (old, new), scalp location (frontal, parietal) and electrode (left, midline, right). Results for the early time window revealed a significant 2-way interaction between test status and scalp location [$F(1,16) = 7.29$, $p = 0.016$, $\eta p^2 = 0.31$]. Subsidiary analysis of separate locations confirmed the presence of a significant old/new difference at frontal locations only [$F(1,16) = 10.17$, $p = 0.006$, $\eta p^2 = 0.39$], with waveforms for hits more positive going than correct rejection waveforms. Results for the 500–800 ms time window also revealed a significant 2-way interaction between test status and scalp location [$F(1,16) = 11.17$, $p = 0.004$, $\eta p^2 = 0.41$]. Subsidiary analysis of separate scalp locations confirmed the presence of a significant old/new difference at parietal locations across electrodes [$F(1,16) = 11.11$, $p = 0.004$, $\eta p^2 = 0.41$], with waveforms for hits more negative going than correct rejection waveforms. In sum, the preceding analysis evidenced the presence of bilateral mid-frontal old/new effect that appears consistent with the timing and distribution of the FN400, and posterior effects consistent with the presence of the LPN during the 500–800 ms interval.

#### 3.2.2. Context effects

The second contrast focused on source hits for both location conditions to assess old/new differences as a function of retrieved associations between objects and locations. Fig. 3 shows grand average ERPs for correct rejections and item and context hits split by location from a selection of representative sites. Inspection of the data evidences the presence of a positivity for hits in both conditions during the 300–500 ms time window, with apparent differences in the distribution of old/new effects as a function of context at test. Old/new differences are apparent over frontal locations in both conditions, but effects for same location hits are more broadly distributed, extending towards posterior locations in the left hemisphere. Between 500 and 800 ms a negativity over posterior sites is present in both conditions but appears larger in magnitude for same location trials. For different location trials frontal old/new differences appear to be sustained into the 500–800 ms time window.

Initial analysis was designed to identify variations in the pattern of effects across time windows using ANOVA with the factors of condition (same, different, new), scalp location (frontal, parietal), electrode (left, midline, right) and time window (300–500 ms, 500–800 ms). ANOVA revealed a significant 4-way interaction between condition, scalp location, electrode and time window [$F(4,64) = 4.88$, $p = 0.02$, $\eta p^2 = 0.23$], confirming changes in the pattern of effects across time windows. Subsidiary analysis were performed separately for each time window. Analysis of the 300–500 ms window revealed a significant main effect of condition [$F(2,32) = 3.78$, $p = 0.034$, $\eta p^2 = 0.19$], and a marginally significant 3-way interaction between condition, scalp location and electrode [$F(3,47.3) = 2.79$, $p = 0.051$, $\eta p^2 = 0.15$]. Analysis for the later 500–800 ms time window revealed a significant interaction between condition, scalp location and electrode [$F(2.8,44.9) = 2.92$, $p = 0.048$, $\eta p^2 = 0.15$]. As can be seen in Fig. 3, these findings indicate the presence of reliable memory effects in each time window and suggest changes in the pattern of effects across time windows as a function of condition.

The next level of analysis was designed to establish the pattern of old/new differences for each condition using ANOVA with the factors of test status (old, new), scalp location (frontal, parietal) and electrode (left, midline, right). Analysis for same location trials between 300 and 500 ms revealed a significant main effect of test status [$F(1,16) = 5.43$, $p = 0.033$, $\eta p^2 = 0.25$], confirming the presence of significant old/new differences across locations and sites. Analysis for different location trials revealed a significant main effect of test status [$F(1,16) = 8.48$, $p = 0.01$, $\eta p^2 = 0.35$], and a significant 3-way interaction between test status, scalp location and electrode [$F(2,32) = 4.02$, $p = 0.028$, $\eta p^2 = 0.20$]. Subsidiary analysis revealed a significant main effect of test status [$F(1,16) = 12.89$, $p = 0.002$, $\eta p^2 = 0.45$] at frontal locations only, with waveforms for different location hits more positive going than waveforms for correct rejections across sites.

Analysis for same location trials between 500 and 800 ms revealed a significant interaction between test status, scalp location and electrode [$F(1.3,20.3) = 18.55$, $p < 0.001$, $\eta p^2 = 0.54$]. Subsidiary analysis at frontal locations revealed no main effects or interactions including the factor of test status. Analysis at posterior locations revealed a significant

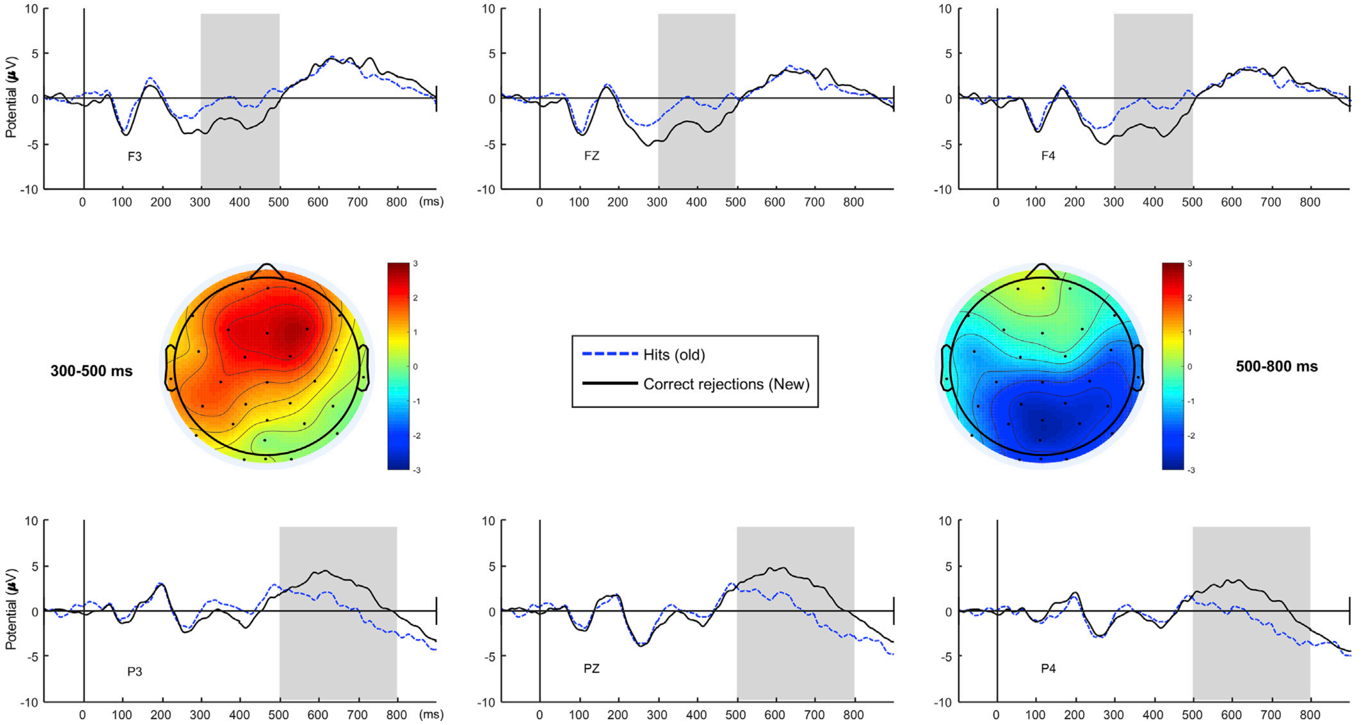

**Fig. 2.** Grand average ERPs for hits and correct rejections from a representative selection of electrode sites. Boxes highlight latency intervals of interest for FN400 (300–500 ms) and LPC memory effects (500–800 ms). Topographic maps depict time-averaged differences between hits and correct rejections for both time intervals.

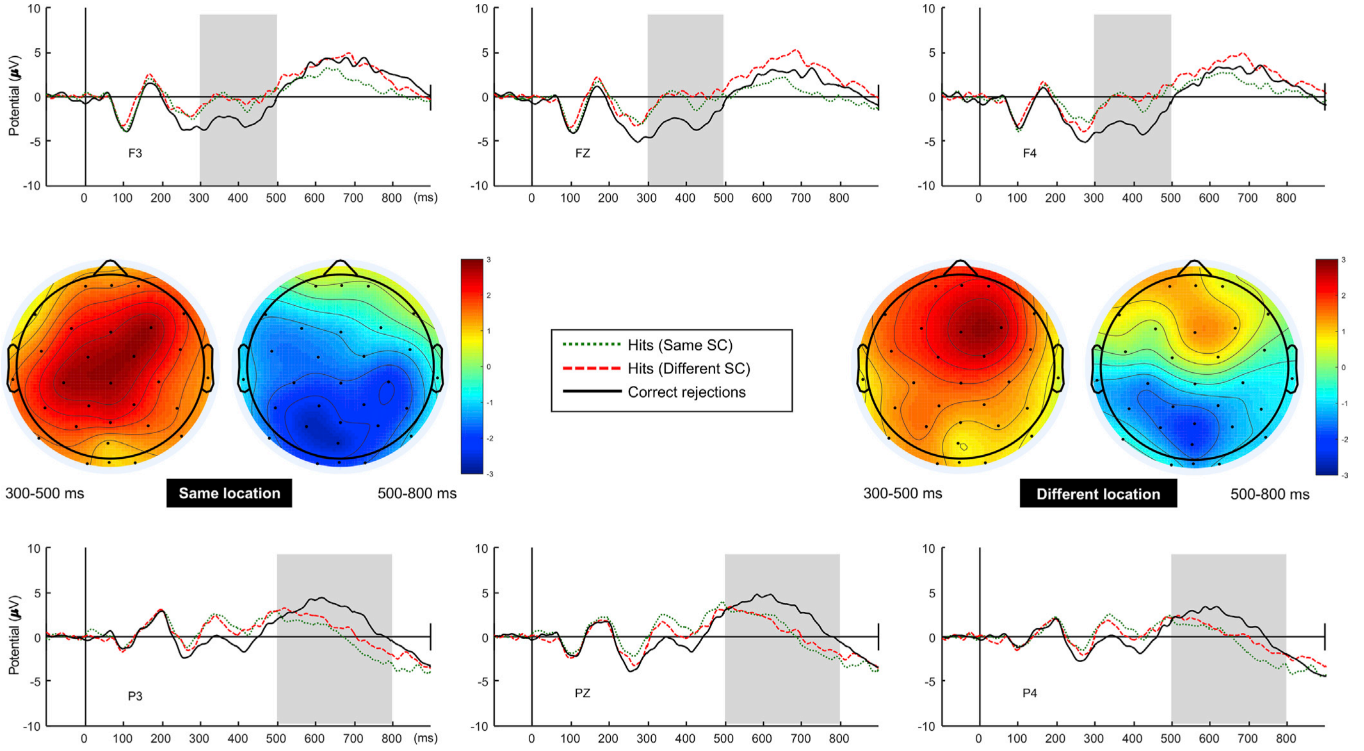

**Fig. 3.** Grand average ERPs for source hits split by location and correct rejections from representative electrode sites. SC in figure legend stands for Source Correct. Boxes highlight latency intervals of interest for FN400 (300–500 ms) and LPC memory effects (500–800 ms). Topographic maps depict time-averaged differences between both classes of hits and correct rejections for both time intervals.

main effect of test status [$F(1,16) = 8.94$, $p = 0.009$, $\eta p^2 = 0.36$], confirming the presence of a broadly distributed old/new difference across sites for same location trials. Initial analysis for different location trials also revealed a significant 3-way interaction between test status, scalp location and electrode [$F(1.5,24.2) = 16.97$, $p < 0.001$, $\eta p^2 = 0.52$]. Subsidiary analysis of separate locations failed to reveal significant main effects or interactions including the factor of test status. Nonetheless, focused analysis at Fz where old/new differences were apparent confirmed the presence of a significant old/new difference ($t(16) = 2.34$, $p = 0.032$), with waveforms for different location trials continuing to be more positive going than waveforms for correct rejections at mid-frontal sites between 500 and 800 ms.

A further set of analysis was designed to compare the magnitude of old/new effects found in the same and different location conditions during the 300–500 ms time interval. As can be seen in Fig. 3, and consistent with the analysis reported above, ERPs to same and different locations are very similar over frontal scalp sites, but slight differences are evident at posterior electrodes. To capture potential differences in magnitude across the scalp, analysis was performed on subtraction data including all electrodes in an ANOVA with the factors of condition (same, different) and electrode (FP1, FPz, FP2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, POz, O1, Oz, O2). Results failed to reveal main effects or interactions including the factor of condition, suggesting that the old/new effects for same and different locations between 300 and 500 ms were of equivalent magnitude, consistent with the clearly overlapping same and different location ERP waveforms shown in Fig. 3. In sum, memory for same and different location old items did not differ between 300 and 500 ms, with both conditions exhibiting mid-frontal old/new effects. Differences were present in the later 500–800 ms time window however, with a posterior negativity only evident for same location trials, with waveforms for different location trials continuing to be slightly more positive going than waveforms for correct rejections at frontal sites between 500 and 800 ms.

## 4. Discussion

The current study had two specific goals 1) to demonstrate that ERP signatures associated with episodic memory in prior lab-based work can be detected in real word settings using mobile EEG, and 2) to assess the impact of real world context on the ERP correlates of retrieval. Here, to address these goals, we employed mobile EEG during a recognition memory task, pairing images of objects with unique physical locations to provide context. As expected, behavioural results demonstrated that memory was affected by manipulating context at test, with objects presented in the same context retrieved faster than those presented in a different context. In terms of ERP effects, the basic memory contrast clearly demonstrated that it is possible to record ERP data during real world remembering, revealing two well established ERP correlates of episodic retrieval reported in prior lab-based studies. To be clear, we detected FN400 old/new effects traditionally associated with familiarity between 300 and 500 ms, and a late posterior negativity (LPN) often linked to reconstructive processing or evaluation of retrieval outcomes between 500 and 800 ms. We also assessed whether the observed old/new effects differed as a function of whether participants could accurately remember the context (i.e., location) in which the objects were studied. These data revealed that the FN400 and LPN effect were both affected by context: the FN400 effect was sustained into the 500–800 ms time window only for objects recognised in different contexts, whereas the LPN was evident between 500 and 800 ms only for objects encountered in the same context.

Before considering the ERP findings in further detail, it is necessary to clarify the implications of the behavioural data. Importantly, memory retrieval was affected by manipulation of context - a significant difference in response times was observed for same versus different location objects, supporting the view that changes in context matter. Nonetheless, the absence of significant differences in the accuracy of retrieval is somewhat surprising, given that a number of prior studies have demonstrated better memory performance when study context was repeated at test (e.g., Smith and Vela, 1992; Hayes et al., 2007). The current results are, however, consistent with other work investigating context effects on recognition (e.g., Godden and Baddeley, 1980; Jacoby, 1983) which also demonstrate no change in accuracy. From a theoretical perspective the fact that accuracy is not poorer when the context changes between study and test provides support for ‘reinstatement’ accounts of retrieval (cf. Bjork and Richardson-Klavehn, 1989). By this account presenting items in the same context facilitates successful retrieval, but when items are encountered in a different context at retrieval participants reinstate the learning context themselves, eliminating any potential reduction in performance. The longer response times for different context trials found in the current study therefore provides support for the view that additional processing is required when the relationship between object and context is breached. An important implication of the reinstatement view is that additional processing must have been required for different location objects, leading to a clear expectation of differences in the neural correlates of retrieval as a function of changes in context.

The current experiment clearly demonstrates that mobile EEG allows the neural correlates of episodic memory retrieval to be detected in real world settings. Based on previous laboratory based studies we expected *a priori* that our recognition memory task would be associated with the FN400 and left-parietal old/new effects; instead we observed clear FN400 and LPN effects. The fact that left parietal old/new effects were not evident in any of the memory contrasts in the current study emphasizes that examining memory in the real world may lead to a different view of retrieval than is suggested by laboratory based studies. Whilst the current results cannot explain why the left parietal effect is absent, the data do provide further support for the claim that episodic recollection is not always associated with a left parietal old/new effect (for discussion see MacLeod and Donaldson, 2017). It remains the case, of course, that changes in the nature of the memory task between the laboratory and the real world may be responsible for the absence of left parietal effects. For example, strong links between recollection related left-parietal old/new effects and retrieval of contextual detail are largely obtained in laboratory based studies employing words or verbal stimuli, whereas the present study combined images of objects with real physical locations. Similarly, in lab studies memory stimuli are typically shown in rapid succession, whereas the current real-world study required a slower pace. Regardless, the current findings demonstrate that retrieval related ERPs can be observed during real world remembering, and that the neural correlates of retrieval vary depending on the way in which context is examined.

In contrast to the left parietal old/new effect, the present data provide clear evidence that FN400 effects were present for successful retrieval of both same and different location items. The fact that the FN400 effect was sustained for different context trials is compatible with the reinstatement account outlined above, evidencing that additional processing was indeed required when there was a mismatch between item and context. More broadly, these findings fit well with previous evidence that using more complex stimuli to test recognition memory produces a distinct pattern of results, with context influencing FN400 effects associated with familiarity (rather than left parietal effects associated with recollection). As noted in the introduction, the majority of studies reporting contextual influences on FN400 effects employ visual images (e.g., Ecker et al., 2007; Graham and Cabeza, 2001), consistent with the current design, where to be remembered objects were embedded in rich environmental contexts. Critically, the current findings do not just demonstrate that context influences the FN400, as was the case in prior work (e.g., Tsivilis et al., 2001; Ecker et al., 2007), but argues strongly that the FN400 may be directly involved in the retrieval of contextual information - at least during real world remembering.

A second neural correlate of retrieval was present in the current data: an LPN effect was observed between 500 and 800 ms, but only for objects presented in the same location at study and test. As noted earlier, this late onsetting negativity is often linked to reconstructive processing or evaluation of retrieval outcomes, although the precise functional role of this old/new difference remains a matter of debate (for review see Mecklinger et al., 2016). In source tasks, the LPN is thought to be implicated in reconstruction of the study episode, retrieving and evaluating associations between items and context, and is not thought to be specifically linked to the correctness of source decisions (Johansson and Mecklinger, 2003; Mecklinger et al., 2016). The current findings appear to stand in direct contrast to work demonstrating that the LPN is smaller when context is retrieved more easily (Mecklinger et al., 2007), and studies linking LPN amplitude to task difficulty (e.g., Friedman et al., 2005; Sommer et al., 2018), given that in the current study we would expect same context trials to be associated with less reconstructive processing and reduced task demands. By contrast, the pattern of results outlined here are more consistent with work investigating reality monitoring, which shows an increase in LPN amplitude for perceived than for imagined items (e.g., Leynes and Kakadia, 2013). Mapping these findings onto our own data, for items presented in the same location the context was directly perceived, whereas, accurate contextual information for different location items had to be mentally reconstructed or imagined, resulting in LPN effects only for items tested in the original context.

## 5. Conclusion & future directions

Here we aimed to investigate episodic memory outside of the laboratory by employing mobile EEG to monitor neural correlates of recognition memory, pairing object images with physical locations. Crucially, this study is the first to capture known ERP signatures of memory in real world settings, and the results reveal two well established correlates of episodic retrieval reported in prior laboratory based studies, the FN400 old/new effects and the late posterior negativity (LPN). The pattern of results demonstrates a strong link between the retrieval of contextual information in real world settings and the FN400 effect. A substantial amount of future work using a real world approach will be required to validate these findings and to fully establish the functional significance of the differences observed. Here we have reported effects in grand-average data that are consistently present across subjects (see Fig. S1 & Fig. S2 for examples of single-subject waveforms and mean effects for each contrast). On the basis of lab-based investigations, however, we know that there is a great deal of between-subject variance in the ERP signatures of episodic memory (for discussion see MacLeod and Donaldson, 2017). Future work should therefore examine the neural signatures of memory at the level of single-subjects or single trials. Various measures have recently been developed that facilitate estimation of between-subject and trial-to-trial variation in EEG data (e.g., Delorme et al., 2015; Oruç et al., 2011; Ouyang et al., 2016). However, studies designed to examine between subject variability in well-established ERP components (e.g., N400) typically have more than 100 trials per subject/condition to reduce noise (e.g., Cruse et al., 2014). Due to trial numbers in critical contrasts we were unable to examine our data using this kind of analytic approach, nonetheless the Supplemental Figures reveal a high degree of consistency across participants.

We believe that our work takes an important first step along the road of establishing a more ecologically valid view of memory, which is vital for progress in understanding how retrieval operates in daily life. Importantly, the current study also contributes to a growing literature highlighting potential applications for mobile imaging techniques. Over the last two decades, mobile EEG has been applied in a wide range of topic areas, and the scope of its potential has yet to be fully realised. Mobile EEG was primarily developed for BCI applications, where the aim is to detect reliable signals on a single trial basis to support interactions with devices and assistive technologies. The potential of mobile EEG has also long been appreciated in clinical settings, where the focus is on detecting neural signatures associated with various disorders (e.g., epilepsy; Askamp and van Putten, 2014) in single subjects, for ambulatory monitoring and neurofeedback (e.g., motor rehabilitation; Kranczioch et al., 2014). From a pure research perspective, the majority of work to date has been technically oriented, seeking to establish that reliable neural signals can be obtained during motion using laboratory paradigms known to elicit robust effects. Building on this proof-of-concept work, the potential of mobile EEG has recently been highlighted in a number of areas including sports performance and spatial navigation (Park et al., 2015, 2018; Ladouce et al., 2017), where capturing neural signatures of cognition during motion is key, and ergonomics (Mehta and Parasuraman, 2013), where facilitating investigation in naturalistic settings is crucial. The value added by a mobile approach in the current study was that it provided an unprecedented opportunity to address new questions that cannot be answered in a laboratory setting - such as, how the presence of real context influences neural correlates of episodic memories.

At this stage using mobile EEG to investigate memory is in itself novel and moving research out of the lab and into the world requires a deliberate and incremental approach - many more steps are needed to establish how neural correlates of memory behave during entirely naturalistic behaviour. However, on the basis of the current findings it is clear that mobile EEG will become an important tool to assist with the identification and monitoring of memory impairments such as dementia, where assessing the operation of memory on an individual level in familiar but noisy and dynamic environments is critical.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2019.03.013.

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