

Prestimulus theta activity predicts correct source memory retrieval

Richard J. Addante^{a,1,2}, Andrew J. Watrous^{a,1}, Andrew P. Yonelinas^{a,b,c}, Arne D. Ekstrom^{a,b}, and Charan Ranganath^{a,b}

^aCenter for Neuroscience, ^bDepartment of Psychology, and ^cCenter for Mind and Brain, University of California, Davis, CA 95616

Edited by Edward E. Smith, Columbia University, New York, NY, and approved May 18, 2011 (received for review September 29, 2010)

Recent evidence indicates that the processing of a stimulus can be influenced by preceding patterns of brain activity. Here we examine whether prestimulus oscillatory brain activity can influence the ability to retrieve episodic memories. Neural activity in the theta-frequency band (4–8 Hz) was enhanced before presentation of test items which elicited accurate recollection of contextual details of the prior study episode (“source retrieval”), relative to trials for which item recognition was successful but source retrieval failed. Poststimulus theta activity was also related to source retrieval, and the magnitude of poststimulus theta was predicted by the magnitude of the prestimulus theta effects. The results suggest that ongoing neural processes occurring before stimulus onset might play a critical role in readying the brain for successful memory retrieval.

EEG | oscillation

Research on the neural basis of human memory has generally proceeded from the assumption that memory retrieval is driven by incoming stimuli that cue recovery of past experiences. However, recent research suggests that fluctuations in neural activity *prior* to stimulus presentation can also play a critical role in determining how a stimulus will be processed (1–4). For example, synchronous electrophysiological activity observed just before stimulus presentation has been found to modulate behavior on psychophysical, conditioning, motor, and attentional tasks (2, 5–8). It is unclear, however, whether other cognitive functions such as episodic memory retrieval are influenced by prestimulus neural activity.

Previous research has shown that cueing subjects to retrieve from memory leads to sustained changes in neural activity (9–14). These results indicate that brain networks are sensitive to the intention to retrieve from memory, but it is not known whether this neural activity has any impact on memory retrieval. Evidence from event-related potential (ERP) studies indicates that the intention to retrieve might not be related to successful memory retrieval (13, 15). However, an examination of oscillatory brain activity, rather than sustained activity, may prove more useful in revealing such retrieval effects. Computational models suggest an important role for theta oscillations (4–8 Hz) in memory functions (16), particularly in the rodent hippocampus (17–19), a region which has been shown to also be particularly important for humans in source recognition (20). In addition, results from studies using scalp and intracranial electroencephalography (EEG) suggest that cortical theta activity during stimulus presentation may be correlated with successful episodic memory (21–23), and that theta oscillations before initial stimulus presentation are associated with more effective encoding (24).

Here we examine whether neural activity that occurs before the presentation of a retrieval cue would predict whether the item would elicit successful episodic *retrieval* (Fig. 1). Seventeen healthy college-aged subjects encoded a series of words by making pleasantness or animacy judgments. After a short delay, they were presented with a mixture of studied and novel words and indicated whether the item was old or new (“item memory”) as well as the context in which the item had been encountered (“source memory”). Prior work has indicated that item- and

source-recognition discriminations recruit distinct brain regions (25, 26) and may be supported by different cognitive processes (27), but it is not known whether ongoing oscillatory activity before the onset of a retrieval cue can influence the likelihood of successful item or source retrieval. To address this issue, we recorded scalp EEG during a test of item and source memory, and analyzed prestimulus activity as a function of whether the test item elicited successful recollection responses.

Results

Item-recognition accuracy was high [i.e., the average hit rate (0.80) was significantly greater than the false alarm rate (0.18), $P < 0.00001$], and source memory accuracy for the items that were correctly recognized was above chance (i.e., the average proportion of correct source judgments for recognized items was 0.73, $P < 0.0000001$; Fig. S1 shows response distributions). We were interested in whether theta activity before the onset of a retrieval cue was related to a subject’s ability to recollect source details learned during the encoding session, and so as in previous ERP and functional imaging studies (28–32), we compared trials with both an accurate item and source response (i.e., item-correct and source-correct, “item+source”) with trials receiving only an accurate item judgment (i.e., item-correct and source-incorrect, “item-only”). Spectral power was estimated every 10 ms from –450 ms to 900 ms (1,350 ms total), and the total epoch was then divided into nine 150-ms bins. The prestimulus effects are first described, followed by poststimulus effects.

Memory differences in theta power were apparent before stimulus onset first at left temporal and then across frontal and left lateralized regions of the scalp. Analyses of the difference between item+source and item-only trials for the –300 ms to –150 ms time window (Fig. 2A) revealed significant differences at left temporal (T7) and left parietal (Cp5) sites (bootstrap-corrected $P < 0.05$ for both sites; the procedure is detailed in *SI Methods*). During the –150 to 0 ms time window, this effect became progressively more widespread (Fig. 2D), as theta power at left temporal, left parietal, and midfrontal electrode sites was significantly higher for item+source than for item-only trials (Fig. 2D). Fig. 2B and E show the time course of theta activity under each condition at representative left temporal (T7) and frontal electrodes (electrode Fz), respectively, along with the time-frequency spectrograms for the difference in oscillatory power between item+source and item-only trials at these sites. Further analyses were conducted to determine whether theta phase alignment across trials differed between item+source and item-only, but no significant effects were observed.

Author contributions: R.J.A., A.P.Y., and C.R. designed research; R.J.A. performed research; A.J.W., A.D.E., and C.R. contributed new reagents/analytic tools; R.J.A. and A.J.W. analyzed data; and R.J.A., A.J.W., A.P.Y., A.D.E., and C.R. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

¹R.J.A. and A.J.W. contributed equally to this work.

²To whom correspondence should be addressed. E-mail: rjaddante@ucdavis.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1014528108/-DCSupplemental.

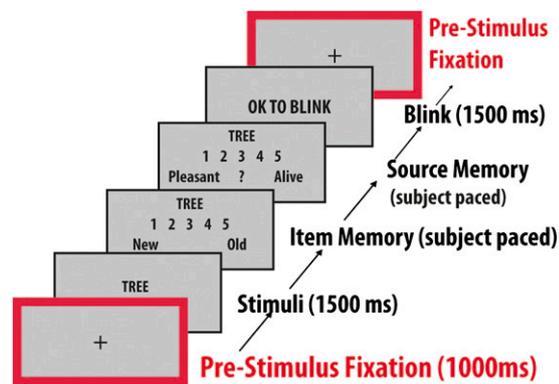


Fig. 1. Schematic depiction of the memory retrieval paradigm.

To determine whether the prestimulus theta modulation reflected a more generalized item-recognition memory effect, we contrasted item hits against trials in which a studied item was incorrectly judged to be new (“item-incorrect”). This contrast did not reveal significant differences at any electrode site before stimulus onset (-150 to 0 ms, all t values < 1.5 , all $P > 0.15$). Thus,

prestimulus theta appears to be predictive of accurate retrieval of study details rather than old/new recognition discriminations.

Could the prestimulus theta effects have been driven solely by poststimulus theta activity, due to temporal imprecision of the wavelet analysis method? Several factors weigh against this possibility. First, there were no significant memory effects observed between 0 and 300 ms poststimulus, so it is unlikely that a prestimulus effect (-300 to 0 ms before stimulus onset) could be produced by a temporal blurring of a later poststimulus effect. Second, we varied the filter parameters of the wavelet analysis to increase temporal resolution (by decreasing the wavelet cycles from 5.7 - to 3 - or 1 -cycle wavelets; see *SI Methods* for details), and the pattern of prestimulus memory effects was unchanged (significant at bootstrap-corrected levels of $P < 0.05$) (Fig. S2). Third, in addition to the wavelet analyses, we conducted an analysis using a Fourier transform on the window from -450 to 0 ms. This analysis, which specifically assessed activity restricted to the prestimulus period, also revealed a significant prestimulus memory effect [$t(16) = 1.92$, one-tailed $P = 0.036$]. Finally, we conducted a series of simulations to quantify the extent of filter smearing produced by the wavelet analysis (Fig. S3; see *SI Methods* for details). These simulations revealed that a poststimulus theta oscillation would result in a large poststimulus difference and a relatively small prestimulus difference using the

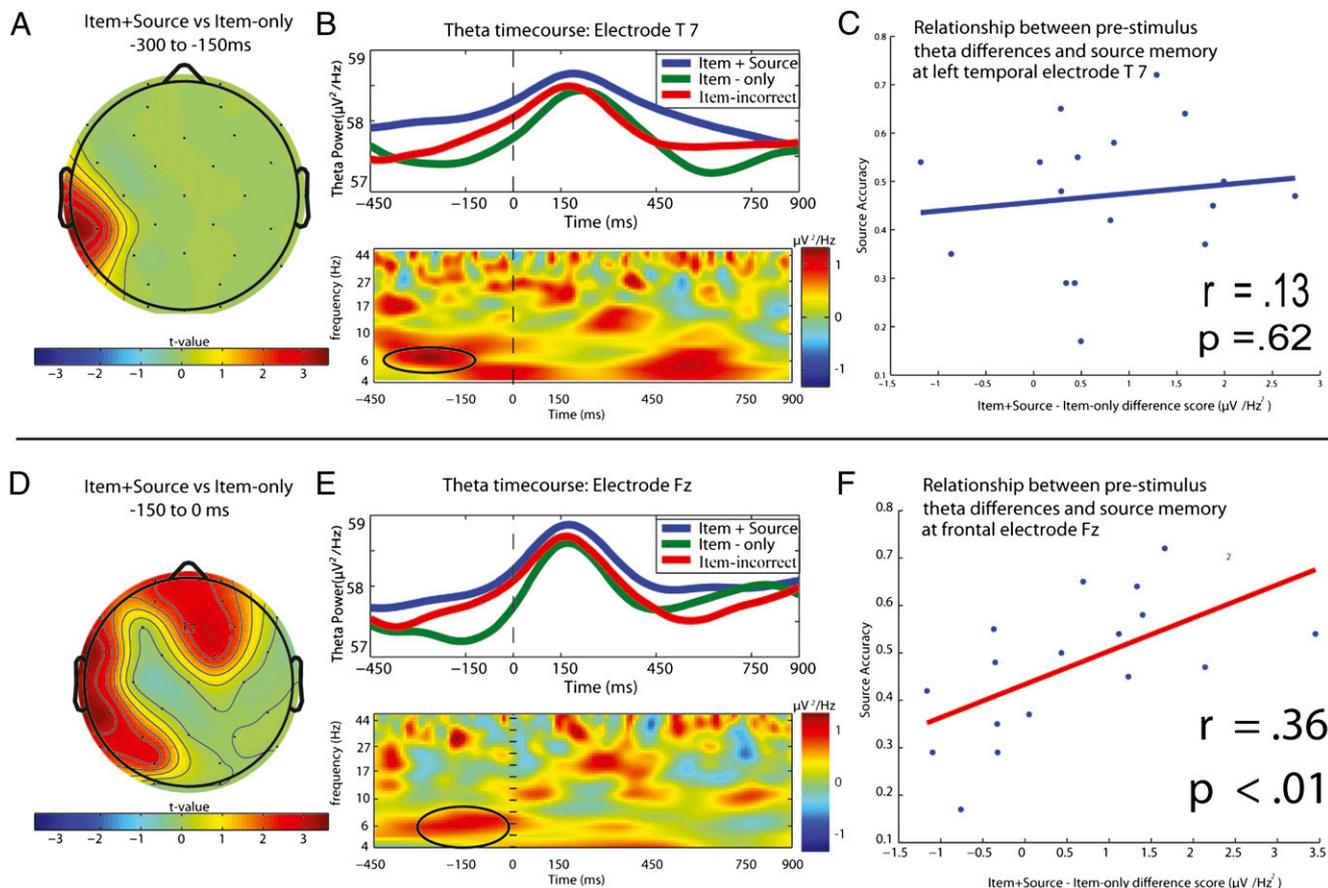


Fig. 2. Prestimulus theta is enhanced before successful episodic retrieval. (A) Bootstrap-corrected topographic significance map of prestimulus theta-band activity differences between item-correct with source-correct (item+source) and item-correct with source-incorrect (item-only) trials during the -300 to -150 ms time window. (B) (Upper) Average theta-power time course for item+source, item-only, and item-incorrect trials at left posterior temporal electrode site T7. (Lower) Item+source versus item-only difference spectrogram at electrode T7. (C) Relationship between theta differences at T7 during the prestimulus window (-300 to -150 ms) and source memory accuracy. (D) Topographic significance map of prestimulus theta-band activity differences between item+source and item-only trials during the -150 to 0 ms time window. (E) (Upper) Average theta-power time course for item+source, item-only, and item-incorrect trials at midfrontal electrode site Fz (labeled in A). (Lower) Item+source versus item-only difference spectrogram at electrode Fz. (F) Relationship between theta differences at electrode Fz during the prestimulus window (-300 to -150 ms) and source memory accuracy. Participants who showed larger prestimulus theta differences between item+source and item-only trials at site Fz also showed higher source memory accuracy.

same 5.7-cycle wavelet analysis applied to the real data (Fig. S3 *B* and *C*), and that this would be eliminated using a 1-cycle wavelet analysis (Fig. S2). In contrast, the source memory effect that we observed was large during the prestimulus period and diminished during the poststimulus period (Fig. 2 *D* and *E*), which is consistent with our simulation of what would be expected if the effect were driven solely by prestimulus activity (Fig. S3 *A* and *C*).

Because correct source decisions are typically associated with confident item-recognition judgments (27), it is possible that the prestimulus theta increases described above influenced the likelihood of making a confident response, rather than being specifically related to accurate source memory retrieval. To assess this possibility, we examined prestimulus theta activity preceding correct rejections as a function of response confidence using the same wavelet analysis procedure that was used in the source memory analysis described earlier. We did not find any significant prestimulus theta differences between high- and low-confidence correct rejections, which suggests that prestimulus theta activity was related to memory retrieval rather than confidence per se.

We next examined whether individual differences in source memory accuracy were correlated with the magnitude of the prestimulus theta source memory effects we observed from -300 to -150 ms (Fig. 2*A*) and -150 to 0 ms (Fig. 2*D*) (see details in *SI Methods*). As shown in Fig. 2*C*, the initial prestimulus theta differences between conditions at left temporal sites (-300 to -150 ms; Fig. 2*A*) were not significantly correlated with behavioral measures of source memory accuracy ($r^2 = 0.13$; $P = 0.62$). However, during the next prestimulus period of -150 to 0 ms (Fig. 2 *D* and *E*), theta-power differences between source memory conditions at frontal electrode Fz were positively correlated with individual differences in source memory accuracy ($r^2 = 0.36$; $P < 0.01$; similar effects were observed at other frontal electrodes, although not for left parietal or temporal electrodes during the prestimulus periods). The results suggest that, across subjects, prestimulus frontal theta activity directly relates to a subject's ability to remember episodic details in response to a retrieval cue. To determine whether these differences might also be observed within subjects, we sorted all old trials (regardless of memory performance) for each subject into five equally sized bins based on the magnitude of theta. We found that, for the highest-ranking theta bin, there was a larger proportion of trials that were item+source compared with item-only trials [i.e., Mean (M) = 0.19 vs. 0.15 , respectively; $t(32) = 2.11$;

$P < 0.05$], whereas for the lower-ranking theta bins, there was no significant difference in the proportions of item+source and item-only trials [all $t(32) < 1.02$, all $P > 0.31$]. The latter results suggest that, even within subjects, higher prestimulus theta is predictive of accurate source memory.

Our next analyses focused on activity that occurred after the retrieval cue was presented. Consistent with previous studies that reported increases in theta power during successful episodic retrieval (33–36), we also found that poststimulus theta activity was related to successful retrieval. As shown in Fig. 3*A*, theta power at left parietal electrode locations between 450 and 600 ms poststimulus was significantly higher on item+source trials than on item-only trials. Theta-power time courses for item+source, item-only, and item-incorrect trials for a left parietal electrode (electrode P7), along with the time-frequency spectrogram for the power difference between item+source and item-only trials, are presented in Fig. 3*B*. Notably, this site showed both significant pre- and poststimulus activity related to retrieval of source information. Correlational analyses revealed that participants who showed larger poststimulus (300–450 ms) theta effects at left parietal sites also showed higher source accuracy (Fig. 3*C*; $r^2 = 0.58$, $P = 0.014$).

One account of the preceding results is that theta activity before stimulus onset is related to a preparatory process that facilitates or enables the retrieval of episodic details when a retrieval cue is eventually presented. If so, we might expect there to be a relationship between pre- and poststimulus theta effects. To test this prediction, we measured the correlation between prestimulus theta effects (i.e., theta-power difference between item+source and item-only trials during the prestimulus period of -300 to 0 ms) at each electrode and poststimulus theta effects at each electrode during three successive poststimulus epochs (0 – 300 ms, 300 – 600 ms, and 600 – 900 ms), while correcting for multiple comparisons (see *SI Methods* for details). We found that the prestimulus theta differences related to source retrieval at frontal sites predicted poststimulus theta differences during the 300 – 600 ms time window (Fig. 4*B*) at the left parietal site, where we observed significant poststimulus-related memory-related theta increases (Fig. 3*A*). These correlations were not significant in earlier (Fig. 4*A*) or later (Fig. 4*C*) time windows. This pattern of findings cannot be accounted for by volume conduction or temporal autocorrelation, because we did not observe frontal–left parietal theta difference correlations during the 0 – 300 ms time window (Fig. 4*A*). Instead, these results suggest that frontal

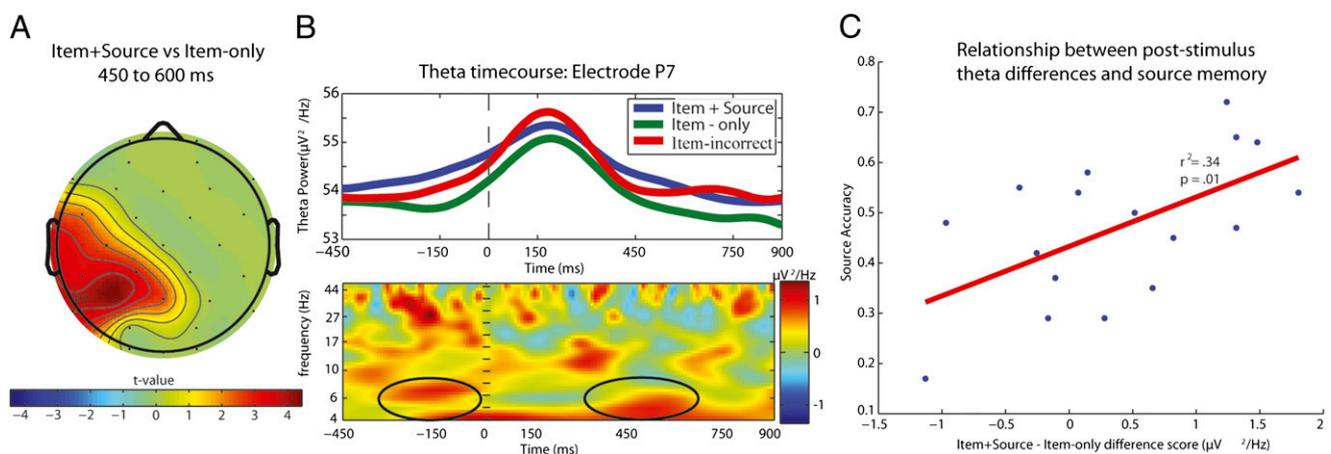


Fig. 3. Poststimulus parietal theta is enhanced during successful episodic retrieval. (*A*) Bootstrap-corrected topographic significance map of theta-band activity differences between item+source and item-only trials during the poststimulus (450–600 ms) time window. (*B*) (*Upper*) Average theta-power time course for item+source, item-only, and item-incorrect trials for left parietal electrode P7. (*Lower*) Item+source versus item-only difference spectrogram at electrode P7. (*C*) Relationship between theta differences at electrode P7 during the poststimulus window (300–450 ms) and source memory performance. Participants with larger poststimulus theta differences between item+source and item-only trials also showed higher source memory accuracy.

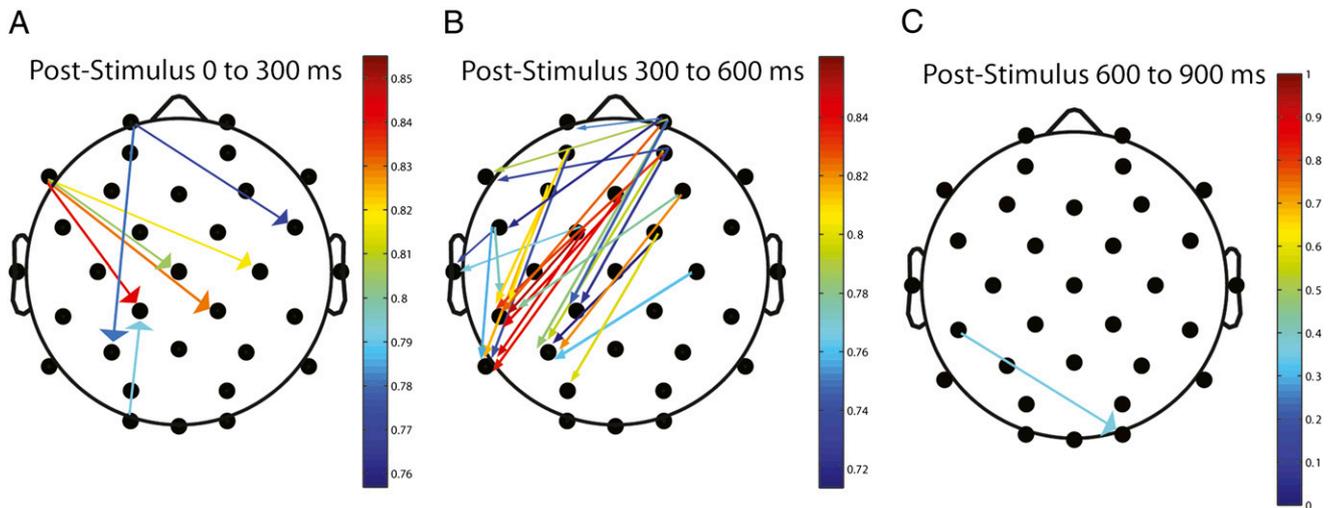


Fig. 4. Frontal prestimulus theta effects are correlated with parietal poststimulus theta effects. Topographic plot of correlations between prestimulus theta effects (–300 to 0 ms) and poststimulus theta differences between electrodes during different poststimulus time windows: 0–300 ms (A), 300–600 ms (B), and 600–900 ms (C). Significant correlations between electrodes at each latency are bootstrap-corrected for multiple comparisons (detailed in *SI Methods*). Arrows indicate a significant correlation, and the direction of the arrow goes from pre- to poststimulus correlation: Arrow start indicates the prestimulus electrode; arrow end (i.e., arrowhead) indicates the poststimulus electrode. The color scale indicates the magnitude of the Pearson's correlation coefficient. Note the increased correlation (B) between frontal prestimulus theta differences and left parietal poststimulus theta differences during 300–600 ms poststimulus (compare with the lower portion of Fig. 3B).

theta activity may influence poststimulus theta activity at left parietal and temporal regions that is related to the recollection of episodic details.

Discussion

The present results demonstrate that oscillatory activity in the theta band before the onset of a retrieval cue is correlated with successful episodic retrieval. Specifically, prestimulus theta power was enhanced for items that were recognized and associated with correct source memory judgments, and larger prestimulus theta effects were also related to better source memory accuracy, both across subjects and across trials within a subject. This effect could not be attributed to a propensity to make more confident judgments, nor was it a generalized correlate of item recognition, because theta activity was specifically related to successful source retrieval. In addition, we found that poststimulus increases in theta were related to source recollection, consistent with prior studies (33–36). Our study extends these findings to show that frontal prestimulus theta effects were significantly correlated with left parietal poststimulus effects, suggesting that preparatory processes may directly impact the later retrieval processes. These findings provide neural evidence for the idea that episodic retrieval is not solely driven by retrieval cues, but rather that it reflects an interaction between cues and one's preceding neurocognitive state.

These findings add to accumulating evidence indicating that prestimulus neural activity can influence performance on a number of different cognitive tasks (2, 5–8). For example, several recent studies have shown that prestimulus neural activity is related to successful memory encoding (24, 37–40). Furthermore, conditioning rabbits during peaks of high theta activity leads to almost twice the levels of learning as during low theta periods (7, 41). To our knowledge, however, no studies have investigated whether prestimulus oscillatory activity can influence successful episodic retrieval. We believe this may be because prestimulus activity is traditionally treated as noise in studies of episodic retrieval. For instance, in ERP studies, the prestimulus baseline is usually subtracted out when averaging poststimulus ERPs.

The precise functional relationship between prestimulus theta and memory retrieval is not yet clear, but our results suggest

several possibilities that can be tested in future studies. One possibility is that prestimulus theta is related to fluctuations in attention or arousal that may benefit subsequent cue processing. Indeed, subjects were cued before presentation of each test item, and this could have led to an intentional increase in anticipatory attention. There are aspects of the data, however, that seem problematic for this account. For example, theta enhancements were not present for item-only trials or for confident correct rejections. It is not clear why item recognition or the ability to reject unstudied items would not also benefit from enhanced attention. Other evidence against an attention account comes from studies reporting that theta *suppression* increased monitoring efficiency, whereas increases in theta resulted in *poorer* performance on attention tasks (42). Furthermore, when prestimulus effects have been found for attention, they have been related to decreases in occipital alpha (2, 43), rather than increases in theta power, as observed here. We did not observe significant prestimulus differences in alpha power (8–12 Hz), nor was it correlated with behavioral measures of memory in ways that the theta results were.

A second possibility is that prestimulus theta reflects a neurocognitive state that facilitates the processing of retrieval cues in a manner that can influence recollection (44). For instance, fronto-parietal theta activity may have reflected the adoption of a “retrieval orientation,” which is a state that specifies the kind of information that is sought after when evaluating a retrieval cue (13, 44). This idea is broadly consistent with functional magnetic resonance imaging results reported by Quamme et al. (45) indicating that activity in several brain regions may reflect whether participants are oriented to use recollection or familiarity as the basis for a memory decision. A related possibility is that prestimulus theta effects reflected the maintenance of an “episodic retrieval mode” (14). This might be conceived as a preparatory process by which the brain regions that are involved in episodic retrieval (e.g., frontal and parietal cortex; see ref. 46) are activated in anticipation of a retrieval cue. This proposal is consistent with the fact that theta was observed over left parietal sites both before stimulus onset as well as after stimulus onset, and that the two effects were tightly coupled with source memory accuracy. If the retrieval mode account is correct, then theta

power for correctly rejected new items should be intermediate between that seen for the item+source and the item-only trials. This is because correct rejections could occur in trials when the episodic retrieval mode is more engaged (i.e., high theta trials) and in trials when the retrieval mode is less engaged (i.e., low theta trials). In fact, a post hoc analysis indicated that, at both the frontal and left parietal sites, this was the pattern of results we observed.

A third possibility is that prestimulus theta reflects the reinstatement of a contextual state that is similar to the contextual state at study (47). Reinstatement of contextual details such as spatial location (48), emotional state (49), or even state of intoxication (50) can facilitate recall of items that were experienced in that context. Furthermore, the reinstatement of physical context cues has been shown to increase recollection-based recognition more so than familiarity-based items (51), which parallels the current finding that prestimulus theta was specifically enhanced for item+source trials and not for item-only trials.

In addition to characterizing the functional significance of the prestimulus theta effects observed here, it will be important to identify the brain regions that contributed to these effects. Our results are broadly consistent with computational models suggesting an important role for hippocampal theta oscillations (4–8 Hz) in memory functions (17–19) and more generally with findings suggesting that the hippocampus is critical for source recollection (20). However, these models emphasize the importance of theta *phase* for memory encoding and retrieval, and we did not observe significant changes in prestimulus theta phase alignment as a function of successful memory retrieval. In general, the role of the hippocampus in the generation of scalp-recorded theta remains to be characterized. It is unlikely that the effects that we observed at the scalp directly reflected volume-conducted hippocampal field potentials, due to its neuroanatomical arrangement as a closed electrical field. Nonetheless, it is possible that the theta effects at left superior temporal sites 300 ms before stimulus onset reflected cortico-hippocampal interactions (52–54) that set the stage for memory retrieval. For instance, one possibility is that effective episodic retrieval is facilitated by prestimulus interactions between the hippocampus and left temporal cortex (–300 to –150 ms), followed by left temporal, parietal, and frontal cortex. This pattern of prestimulus activity, in turn, may lead to enhanced poststimulus theta synchronization between the hippocampus and left parietal and/or temporal cortex. Further work using invasive intracranial recordings, as well as experiments assessing the effects of hippocampal damage on patterns of scalp EEG, will be needed to assess this possibility.

Conclusions

There are many factors that influence whether episodic memory retrieval will succeed or fail, including the way information is encoded and the kinds of cues available during retrieval (55). The present results suggest that, in addition to such factors, fluctuations in brain activity before a retrieval cue might also influence how a cue will be processed. The results are consistent with the idea that theta oscillations play an important role in the dynamics of memory retrieval (56) and also open up new questions about the role of state-related variables in memory (44). Furthermore, it is conceivable that one might be able to increase the likelihood of episodic retrieval by inducing frontal theta oscillations before retrieval or by presenting retrieval cues during or immediately after periods of theta synchronization.

Methods

Subjects, Stimuli, and Procedure. Seventeen right-handed undergraduate students (nine males) were recruited from the University of California–Davis Psychology Department subject pool, and received credit for participation. Subjects were free from neurological, visual, motor, or other medical dis-

orders, and the experiment was conducted as approved by the University of California–Davis Institutional Review Board protocol for research on human subjects. Word stimuli were presented in uppercase letters in a white font centered on a black background screen (Fig. 1). Each stimulus was only presented once during both study and test. Subjects were seated 44 inches away from the screen.

During the study, subjects encoded 200 words (presented in 4 lists of 50 words each) during an incidental encoding task. Two separate encoding tasks (i.e., pleasantness and animacy judgments) were used which served as the basis for source memory decisions during retrieval (i.e., indicate whether each item is pleasant or not, yes or no; is this item “alive” in real life, yes or no). These encoding tasks were selected to lead to roughly comparable levels of memory. The two encoding tasks were presented in a blocked ABBA design, counterbalanced between subjects for the order of the two tasks. Before each study block, the instructions for the next task were read to the subject, and there was a practice session of 10 stimuli that the experimenter and subject performed together to be sure that the subject completely understood the task and was performing it correctly. None of the practice stimuli appeared in the test phase. There was a 15-min filler task before the retrieval phase of the experiment commenced.

During retrieval, the 200 stimuli presented during the encoding phase were randomly intermixed with 100 new words (lures), for a total of 300 test stimuli (Fig. 1). The test stimuli were presented in 6 test sessions of 50 stimuli each. Before each stimulus presentation, a fixation cross appeared in the middle of the screen for 1,000 ms, during which subjects were instructed not to blink, so as to minimize ocular artifacts in the EEG. The retrieval probe then appeared on the screen for 1,500 ms, during which time the subject viewed the stimuli but was not yet cued to respond (Fig. 1). Subjects were also instructed not to blink while each stimulus was on the screen. After the 1,500-ms probe, subjects were asked first to make an item-recognition judgment followed by a source-recognition judgment; each of these responses was subject-paced and therefore provided a variable temporal jittering of each subsequent stimulus's presentation.

For item-recognition judgments, subjects responded on a 5-point confidence scale, with 5 indicating that they were sure it was old, 4 that it was probably old, 3 that they were guessing, 2 that it was probably new, and 1 that they were sure it was new. Studied items that received a 5 or 4 response were treated as “correct-item” recognition trials. For source-recognition judgments, subjects also responded on a 5-point scale, with 5 indicating that they were sure it was from the animacy encoding task, 4 that it was probably from the animacy task, 3 that they were guessing, 2 that it was probably from the pleasantness task, and 1 indicating that they were sure it was from the pleasantness task. “Correct source” memory trials included the items studied under the animacy encoding conditions that received 5 or 4 responses and the items studied under the pleasantness encoding conditions that received 1 or 2 responses. Guess responses were not included in the EEG analysis.

EEG Acquisition and Analysis. EEG was recorded using a BioSemi ActiveTwo Recording System with a 32-channel electrode cap conforming to the standard International 10-20 System of electrode location, sampled at a rate of 1,024 Hz. Subjects were instructed to minimize jaw and muscle tension, eye movements, and blinking. Electrooculogram (EOG) was monitored in the horizontal direction and vertical direction, and these data were used to eliminate trials contaminated by blink, eye movement, or other artifacts.

All EEG analyses were performed using custom MATLAB code and functions from the EEGLAB Toolbox for MATLAB (57). Raw EEG data were referenced to average mastoids, down-sampled to 512 Hz, and high-pass-filtered at 0.5 Hz to optimize independent component analysis (ICA) decomposition. These data were epoched from 1.25 s before the onset of the retrieval item to 2.4 s following the retrieval item, and was baseline-subtracted in the time domain from –200 to 0 ms. This step was necessary for artifact rejection and correction, because trial-to-trial variability in direct current (DC) offsets can make it difficult to detect artifacts. Baseline correction in the time domain effectively amounts to subtracting a scalar and therefore should have no impact on frequency components. Epochs containing single-channel data exceeding three SD of the channel's mean across epochs were removed to optimize ICA decomposition, as were epochs containing data five SD from the pooled channel mean. This procedure was designed to remove primarily nonbiological noise while allowing “common” artifacts (such as eye blinks) to remain. Data were then decomposed into temporally independent components using Infomax ICA (58). Artifactual components (eye blinks, muscle tension, etc.) were removed by hand, as were any remaining noisy epochs.

Single subject–preprocessed EEG data were next subjected to spectral decomposition using wavelets. Wavelet analysis provides an estimate of the power of a signal with good spectral and temporal resolution (59). Spectral power was computed from 4 to 50 Hz by convolving a Morlet wavelet (cycles = 5.7) with the observed signal at each electrode site. After accounting for edge artifacts associated with time-frequency analysis, we obtained power values from –450 to 900 ms for each stimulus. Spectral domain baseline subtraction was not performed because the prestimulus window, used most commonly for this procedure, is the time of interest in this study. To reduce the number of statistical comparisons, we averaged the resulting spectro-

grams across time (150-ms time bins) and frequency band (theta: 4–8 Hz; alpha: 9–12 Hz; beta: 13–30 Hz; gamma: 31–50 Hz) before pooling the data across subjects. Further details of the statistical analysis and control analysis performed are available in *SI Methods*.

ACKNOWLEDGMENTS. The authors thank Ali Mazaheri for helpful comments on earlier drafts and Liang-Tien (Frank) Hsieh and Abhiram Varadarajan for helpful assistance with data simulations. Work was supported by National Institute of Health Grants: R01 MH59352-01 (to A.P.Y.), R01 MH068721 (to C.R.), R01 MH083734 (to C.R. and A.P.Y.), and T32 MH18882-22 (to R.J.A.).

- Fox MD, Snyder AZ, Vincent JL, Raichle ME (2007) Intrinsic fluctuations within cortical systems account for intertrial variability in human behavior. *Neuron* 56:171–184.
- Mazaheri A, Nieuwenhuis IL, van Dijk H, Jensen O (2009) Prestimulus alpha and mu activity predicts failure to inhibit motor responses. *Hum Brain Mapp* 30:1791–1800.
- van Dijk H, Schoffelen JM, Oostenveld R, Jensen O (2008) Prestimulus oscillatory activity in the alpha band predicts visual discrimination ability. *J Neurosci* 28:1816–1823.
- Raichle ME (2009) A paradigm shift in functional brain imaging. *J Neurosci* 29:12729–12734.
- Linkenkaer-Hansen K, Nikulin VV, Palva S, Ilmoniemi RJ, Palva JM (2004) Prestimulus oscillations enhance psychophysical performance in humans. *J Neurosci* 24:10186–10190.
- Wyart V, Tallon-Baudry C (2009) How ongoing fluctuations in human visual cortex predict perceptual awareness: Baseline shift versus decision bias. *J Neurosci* 29:8715–8725.
- Seager MA, Johnson LD, Chabot ES, Asaka Y, Berry SD (2002) Oscillatory brain states and learning: Impact of hippocampal theta-contingent training. *Proc Natl Acad Sci USA* 99:1616–1620.
- Makeig S, et al. (2002) Dynamic brain sources of visual evoked responses. *Science* 295:690–694.
- Nyberg L, et al. (1995) Functional brain maps of retrieval mode and recovery of episodic information. *Neuroreport* 7:249–252.
- Grady CL, McIntosh AR, Beig S, Craik FI (2001) An examination of the effects of stimulus type, encoding task, and functional connectivity on the role of right prefrontal cortex in recognition memory. *Neuroimage* 14:556–571.
- Düzel E, et al. (1999) Task-related and item-related brain processes of memory retrieval. *Proc Natl Acad Sci USA* 96:1794–1799.
- Düzel E, et al. (2001) Comparative electrophysiological and hemodynamic measures of neural activation during memory-retrieval. *Hum Brain Mapp* 13:104–123.
- Herron JE, Wilding EL (2004) An electrophysiological dissociation of retrieval mode and retrieval orientation. *Neuroimage* 22:1554–1562.
- Lepage M, Ghaffar O, Nyberg L, Tulving E (2000) Prefrontal cortex and episodic memory retrieval mode. *Proc Natl Acad Sci USA* 97:506–511.
- Morcom AM, Rugg MD (2002) Getting ready to remember: The neural correlates of task set during recognition memory. *Neuroreport* 13:149–152.
- Lisman JE, Idiart MA (1995) Storage of 7 +/- 2 short-term memories in oscillatory subcycles. *Science* 267:1512–1515.
- Hasselmo ME, Bodelón C, Wyble BP (2002) A proposed function for hippocampal theta rhythm: Separate phases of encoding and retrieval enhance reversal of prior learning. *Neural Comput* 14:793–817.
- Buzsáki G (2002) Theta oscillations in the hippocampus. *Neuron* 33:325–340.
- Hasselmo ME, Eichenbaum H (2005) Hippocampal mechanisms for the context-dependent retrieval of episodes. *Neural Netw* 18:1172–1190.
- Eichenbaum H, Yonelinas AP, Ranganath C (2007) The medial temporal lobe and recognition memory. *Annu Rev Neurosci* 30:123–152.
- Nyhus E, Curran T (2010) Functional role of gamma and theta oscillations in episodic memory. *Neurosci Biobehav Rev* 34:1023–1035.
- Klimesch W, Doppelmayr M, Schwaiger J, Winkler T, Gruber W (2000) Theta oscillations and the ERP old/new effect: Independent phenomena? *Clin Neurophysiol* 111:781–793.
- Sederberg PB, Kahana MJ, Howard MW, Donner EJ, Madsen JR (2003) Theta and gamma oscillations during encoding predict subsequent recall. *J Neurosci* 23:10809–10814.
- Guderian S, Schott BH, Richardson-Klavehn A, Düzel E (2009) Medial temporal theta state before an event predicts episodic encoding success in humans. *Proc Natl Acad Sci USA* 106:5365–5370.
- Weis S, et al. (2004) Process dissociation between contextual retrieval and item recognition. *Neuroreport* 15:2729–2733.
- Ranganath C, Heller AS, Wilding EL (2007) Dissociable correlates of two classes of retrieval processing in prefrontal cortex. *Neuroimage* 35:1663–1673.
- Yonelinas AP (2001) Components of episodic memory: The contribution of recollection and familiarity. *Philos Trans R Soc Lond B Biol Sci* 356:1363–1374.
- Davachi L, Mitchell JP, Wagner AD (2003) Multiple routes to memory: Distinct medial temporal lobe processes build item and source memories. *Proc Natl Acad Sci USA* 100:2157–2162.
- Wilding EL, Rugg MD (1996) An event-related potential study of recognition memory with and without retrieval of source. *Brain* 119:889–905.
- Ranganath C, et al. (2004) Dissociable correlates of recollection and familiarity within the medial temporal lobes. *Neuropsychologia* 42:2–13.
- Wilding EL, Doyle MC, Rugg MD (1995) Recognition memory with and without retrieval of context: An event-related potential study. *Neuropsychologia* 33:743–767.
- Guo C, Duan L, Li W, Paller KA (2006) Distinguishing source memory and item memory: Brain potentials at encoding and retrieval. *Brain Res* 1118:142–154.
- Gruber T, Tsivilis D, Giabbiconi CM, Müller MM (2008) Induced electroencephalogram oscillations during source memory: Familiarity is reflected in the gamma band, recollection in the theta band. *J Cogn Neurosci* 20:1043–1053.
- Guderian S, Düzel E (2005) Induced theta oscillations mediate large-scale synchrony with mediotemporal areas during recollection in humans. *Hippocampus* 15:901–912.
- Burgess AP, Gruzeliel JH (1997) Short duration synchronization of human theta rhythm during recognition memory. *Neuroreport* 8:1039–1042.
- Osipova D, et al. (2006) Theta and gamma oscillations predict encoding and retrieval of declarative memory. *J Neurosci* 26:7523–7531.
- Otten LJ, Quayle AH, Akram S, Ditewig TA, Rugg MD (2006) Brain activity before an event predicts later recollection. *Nat Neurosci* 9:489–491.
- Otten LJ, Quayle AH, Puvaneswaran B (2010) Prestimulus subsequent memory effects for auditory and visual events. *J Cogn Neurosci* 22:1212–1223.
- Gruber MJ, Otten LJ (2010) Voluntary control over prestimulus activity related to encoding. *J Neurosci* 30:9793–9800.
- Adcock RA, Thangavel A, Whitfield-Gabrieli S, Knutson B, Gabrieli JD (2006) Reward-motivated learning: Mesolimbic activation precedes memory formation. *Neuron* 50:507–517.
- Berry SD, Thompson RF (1978) Prediction of learning rate from the hippocampal electroencephalogram. *Science* 200:1298–1300.
- Beatty J, Greenberg A, Deibler WP, O'Hanlon JF (1974) Operant control of occipital theta rhythm affects performance in a radar monitoring task. *Science* 183:871–873.
- O'Connell RG, et al. (2009) Uncovering the neural signature of lapsing attention: Electrophysiological signals predict errors up to 20 s before they occur. *J Neurosci* 29:8604–8611.
- Rugg MD, Wilding EL (2000) Retrieval processing and episodic memory. *Trends Cogn Sci* 4:108–115.
- Quamme JR, Weiss DJ, Norman KA (2010) Listening for recollection: A multi-voxel pattern analysis of recognition memory retrieval strategies. *Front Hum Neurosci* 4:61.
- Buckner RL, Wheeler ME (2001) The cognitive neuroscience of remembering. *Nat Rev Neurosci* 2:624–634.
- Polyn SM, Norman KA, Kahana MJ (2009) Task context and organization in free recall. *Neuropsychologia* 47:2158–2163.
- Smith SM (1979) Remembering in and out of context. *J Exp Psychol Hum Learn* 5:460–471.
- Bower GH (1981) Mood and memory. *Psychol Today* 15:60–69.
- Goodwin DW, Powell B, Bremer D, Hoine H, Stern J (1969) Alcohol and recall: State-dependent effects in man. *Science* 163:1358–1360.
- Gruppuso V, Lindsay DS, Masson ME (2007) I'd know that face anywhere! *Psychon Bull Rev* 14:1085–1089.
- Benchenane K, et al. (2010) Coherent theta oscillations and reorganization of spike timing in the hippocampal–prefrontal network upon learning. *Neuron* 66:921–936.
- Jutras MJ, Buffalo EA (2010) Synchronous neural activity and memory formation. *Curr Opin Neurobiol* 20:150–155.
- Fell J, Axmacher N (2011) The role of phase synchronization in memory processes. *Nat Rev Neurosci* 12:105–118.
- Tulving E, Thomson DM (1973) Encoding specificity and retrieval processes in episodic memory. *Psychol Rev* 80:352–373.
- Hasselmo ME, Hay J, Ilyn M, Gorchetchnikov A (2002) Neuromodulation, theta rhythm and rat spatial navigation. *Neural Netw* 15:689–707.
- Delorme A, Makeig S (2004) EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J Neurosci Methods* 134:9–21.
- Bell AJ, Sejnowski TJ (1995) An information-maximization approach to blind separation and blind deconvolution. *Neural Comput* 7:1129–1159.
- van Vugt MK, Sederberg PB, Kahana MJ (2007) Comparison of spectral analysis methods for characterizing brain oscillations. *J Neurosci Methods* 162:49–63.