Needle in the neural haystack: EEG signatures of concept learning while viewing naturalistic educational materials

The goal of this study is to take major steps toward bridging the gap between research and practice by more directly exploring the relationship between instruction and learning. This involves applying tools from neuroscience to provide fine-grained analysis of learners' neural responses to instructional materials as they are presented in real-time. Specifically, we have piloted an experiment where college-age participants view pre-recorded human anatomy lectures during wireless electroencephalograph recording (EEG) and concurrent eye tracking. Learning was assessed using a pre-post multiple-choice test of basic concepts presented during instruction. This allowed us to look for reliable electrophysiological differences at the time of instruction between participants who learn and do not learn the same material. By identifying the neural markers that accompany successful knowledge encoding using realistic educational materials, we may ultimately use these markers to explore additional instructional context effects on, and infer neural and cognitive processes involved in student learning.

Theoretical framework

Instructors and educational researchers are continually exploring ways to improve student engagement and learning. In particular, significant research has been conducted to evaluate the efficacy of various pedagogical approaches in the context of introductory college-level classes (NRC, 2012). The majority of this research proposes a theoretical account of how students learn, designs instruction to reflect these theories, and then vets the model of learning by comparing the success of the instructional methods using pre- and post-tests or student engagement measures. Some work has gone further to delve into how students are physically and mentally engaged by these teaching approaches, but these studies - including our own past work - does not directly describe what is occurring inside students' brains (see Ansari & Coch, 2006). While basic research in cognitive science and neuroscience is advancing our knowledge of how people learn, research in these domains has traditionally been restricted to laboratory settings with contrived non-naturalistic learning paradigms. Such laboratory settings have the advantage of allowing precise control over stimulus parameters, but the major disadvantage of being only distantly applicable to real-world education.

Cognitive neuroscience's traditional reliance on laboratory settings for studies of learning has been buoyed by two significant challenges. First, research equipment for measuring neural activity has been expensive, bulky, and cumbersome, resulting in an experimental environment more reminiscent of a medical procedure than a learning opportunity. And second, due to the very low signal-to-noise ratio common in neuroscience methods, it has been necessary to tightly control the timing of stimulus presentation, limiting the moment of learning to a very small time window. However, recent developments are allowing researchers to overcome these challenges.

Methods

The first challenge has been overcome with a new class of affordable, portable wireless EEG headsets. One such device, the Emotiv EPOC, was recently validated as yielding recordings that are, for current purposes, effectively indistinguishable from other research-grade EEG systems (Debener et al., 2012; Badcock et al., 2013). While our current research is conducted with volunteer participants at a laboratory workstation, it nevertheless represents a first step toward using this new mobile platform for education experiments that would ultimately be untethered from the laboratory and conducted in real learning contexts.

In the current study, we address the second challenge by using new analytical tools for studying resting-state EEG data in the time-frequency domain. Rather than time-locking neurophysiological data to the short presentation of discrete stimuli (e.g., event related potentials), we investigate the oscillatory dynamics of EEG data during relatively extended time windows when a concept is described using naturalistic instructional material. Recent laboratory studies have demonstrated that low-frequency brain rhythms (e.g., theta-band) have a modulatory effect on high-frequency cortical activity (e.g., gamma-band), and that this cross-frequency coupling is correlated with performance on learning tasks (Canolty et al., 2006; Canolty & Knight, 2010). In the present study we aim to observe these established effects in a more authentic educational context.

The research discussed here comes from a laboratory study we conducted to determine the feasibility of using mobile EEGs in the classroom setting. For this laboratory study one of the authors who teaches college-level anatomy prepared a series of five instructional videos of different anatomical systems (the heart, stomach, kidney, lungs, and skin). Each of these videos was approximately three minutes in length and prepared to mimic a typical lecture (voice-annotated PowerPoint slideshows), while avoiding the repetition of vocabulary terms in order to minimize repeated exposure. Each 3-minute video included three illustrated and annotated slides. The first slide provided a general functional overview of the anatomical system and described high-level structures and regions, and the subsequent two slides each described a set of low-level structures and functions.

Participants were recruited for paid participation via fliers posted throughout the Psychology Building and the School of Education, or for course credit through the

Psychology department's subject pool at a large mid-western university. Participants were brought into the lab and spent a few minutes putting on the Emotiv headset, making minor adjustments to improve electrical contact between the felt electrode pads (soaked in saline) and the scalp. The Emotiv system records 14 usable EEG channels referenced to the left mastoid, with a sampling rate of 128Hz and online bandpass filtering of 0.16 – 43Hz. Participants were then given a 15-question multiple-choice pre-test on relevant anatomical material (3 questions on material in each of the 5 videos; each question included the option "I don't know" to minimize lucky guesses). After the pre-test the participants watched the five anatomy videos in a randomized sequence. The videos were displayed on a Tobii monitor and student eye movements were recorded using infrared cameras. During this time they had no access to pen and paper for notes nor could they review the videos. Once the sequence of videos was finished, participants completed a post-test identical to the pre-test.

Participant data were later excluded from further analysis if the wireless Emotiv headset lost contact with the recording computer during the experiment, or if high electrode impedances or muscle artifacts prevented clean EEG recordings, leaving 23 participants total in the present study. Eyeblinks and eye movement artifacts were identified using independent component analysis (ICA), and were subtracted from these participants' EEG data.

In each 3-minute anatomy video, we identified the moment when the instructor mentioned a vocabulary word (e.g., the word "rugae") that would have indicated the correct answer to a specific question on pre/post-test (e.g., about the interior lining of the stomach, respectively). This time point became the beginning of a 5-second-wide epoch in which participants would have been exposed to the relevant learning material. Participants who answered the relevant question incorrectly at pre-test, but correctly at post-test, were considered to have learned the term during that epoch. Conversely, participants who were incorrect at both pre-test and post-test were considered to have not learned during that epoch. We have not yet analyzed epochs where participants were correct at pre-test).

We replicated Canolty et al.'s (2006) analysis of theta-gamma cross-frequency coupling in resting-state EEG by identifying individual theta (4-8Hz) troughs across the entire EEG recording, and then averaging the amplitude envelope of the Hilbert-transformed EEG signal in 1-second sub-epochs (500ms on each side of trough minimum) for 4Hz wide frequency bands, centered every 2Hz from 10-40Hz (Figure 1). A modulation index (Tort, Komorowski, Eichenbaum, & Kopell, 2010) was calculated to quantify the extent to which gamma (30-40Hz) amplitude was correlated with the relative phase of the theta rhythm. This modulation index was calculated separately for "learned" epochs and "not-learned" epochs.

Findings

Learning and test performance. Averaging the material across all lecture videos, participants already knew (on pre-test) the answers to an average of 3.1 questions out of 15 (21%), subsequently "learned" (measured on post-test) the answers to 6.1 questions (41%), and failed to learn the answers to another 5.8 questions on post-test (39%). There was no significant difference between the proportion of learned items and not-learned items, yielding a roughly equivalent number of learned and not-learned EEG epochs.

Cross-frequency coupling. Analysis of EEG data showed robust evidence of theta-phase / gamma-amplitude cross-frequency coupling. The power of high frequency oscillatory activity was modulated by the phase of lower-frequency theta rhythms, as illustrated in the chart below from a representative single-subject (Figure 1). As expected, the modulation index was significantly higher at frontal electrode sites ($F(2,26) = 4.283$, $p = .025$), so our subsequent analyses were isolated to the four frontal electrode channels of the Emotiv headset.

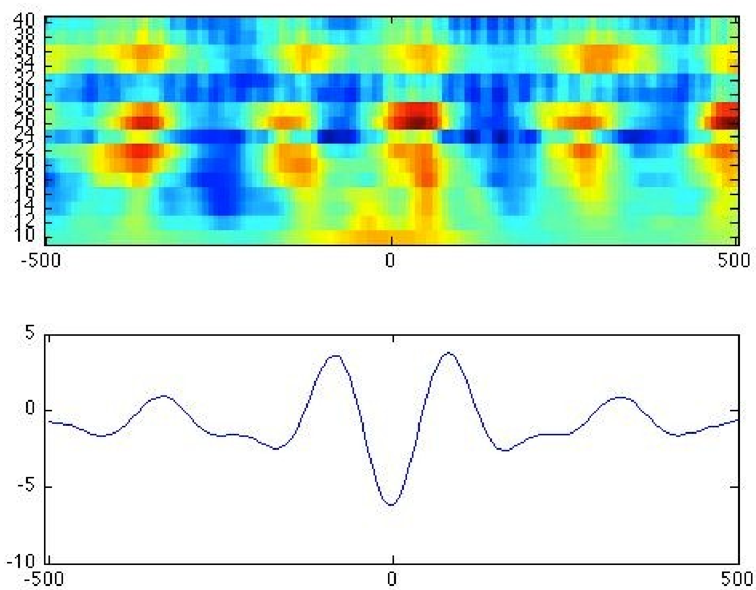

Figure 1. Phase-amplitude cross-frequency coupling for a representative single subject, at a frontal electrode site. The top chart illustrates wavelet-transformed oscillatory power in discrete frequency bands (vertical axis), time-locked and averaged to the trough of the theta rhythm (red colors indicate higher power). The bottom chart shows the event related

potential (vertical axis is microvolts) of the same data, ± 500ms surrounding the theta trough.

The primary focus of our current analysis was to investigate differences between epochs when participants learned or did not learn the presented lecture material. We indeed found that average modulation indexes for theta/gamma cross-frequency coupling at frontal electrode sites were significantly different between these two epoch types ($t(22) = 2.169$, $p = .041$). Specifically, the theta rhythm's modulation of gamma power was significantly reduced when participants successfully encoded lecture material for subsequent recall on the post-test (see Figure 2).

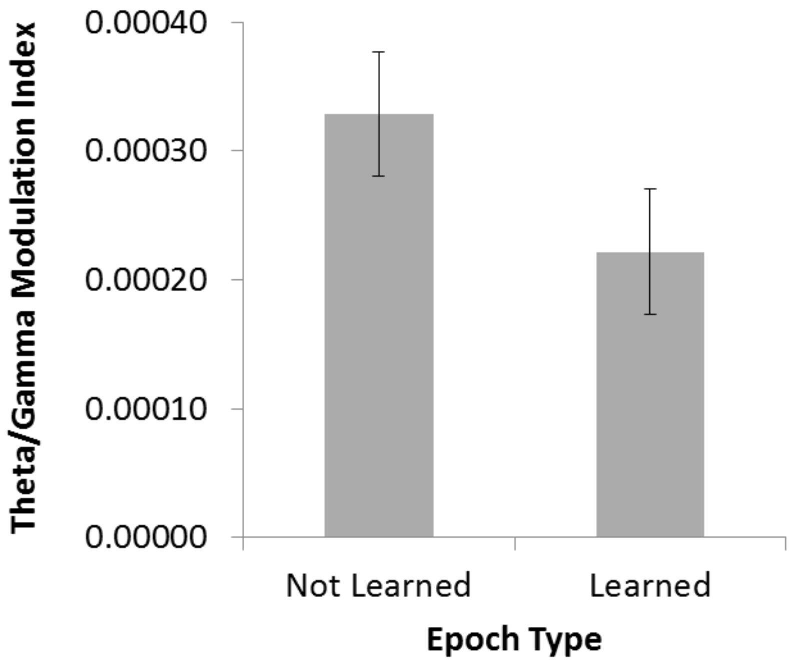

Figure 2. Modulation index of theta (4-8Hz) phase on gamma (30-40Hz) power, separated between epochs when participants learned the material and did not learn the material. Error bars indicate 95% within-subject confidence interval.

Conclusions

The current results provide an important proof of concept that neurophysiological correlates of learning can be measured while students view naturalistic educational materials. Our observation of theta/gamma cross-frequency coupling differences in extended time windows of EEG recording is both consistent with previous laboratory studies (e.g. Sederberg et al., 2003), and relevant for future explorations of instructional context on neural activity during student learning.

While we observed *decreased* theta/gamma coupling, this should not be interpreted as a decrease or reduction in any specific cognitive process. The functional underpinnings of theta/gamma coupling are not yet well-established, and both increases and decreases in oscillatory synchrony between frequency bands have been observed in simple learning tasks (e.g., Burke et al., 2013). What is significant about the present findings, nevertheless, is that such differences could be observed using analytical tools for quantifying resting-state EEG during relatively long recording epochs while participants watched naturalistic lecture videos.

Moreover, these neurophysiological differences were measured using a low-cost mobile EEG recording device, providing a compelling demonstration that neurophysiological studies of student learning need not be tethered to laboratory environments. Future work will explore these effects in various educational settings.

Significance

This work has scholarly significance in two major ways. First, we believe this advances neuroscience work through the application in more authentic educational contexts and over temporal intervals a few orders of magnitude beyond most memory encoding laboratory experiments. Second, we believe this work advances education research through the application of neuroscientific measures to more deeply quantify student engagement and learning in a complex environment. In combination, this research line can help to significantly advance our understanding of what effect instruction has on students. We believe that bridging the current gap between neuroscience and education will transform the paradigm for research on learning in higher education.

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