Final Report for "Integrating fMRI and EEG to examine learning and memory consolidation" - *Marc Coutanche and Natasha Tokowicz*

Starting with our first few encounters with a specific word form, object or concept, our brain transforms it from a fleeting perceptual experience to a stable memory trace that can be reactivated at will. A central component of this learning process is memory consolidation – a process that stabilizes a new memory trace, and integrates it with existing lexical, perceptual, and semantic knowledge. Our understanding of how initial learning connects to later consolidation has been limited by these two important processes being typically studied separately across different neuroscientific methodologies – functional magnetic resonance imaging (fMRI) and electroencephalography (EEG). Through our LRDC Internal Award, we combined fMRI and EEG in an investigation that brought together PI Coutanche's expertise in using fMRI to understand learning and memory with PI Tokowicz's expertise in using EEG to understand second-language word learning.

This award, with additional support from PI Coutanche's start-up fund, allowed us to conduct a multi-session experiment with both methods, as the same participants learned and retrieved word–visual concept pairings. Twenty-two participants completed three sessions. They first learned new associations between Dutch words and rare animals during an initial fMRI scan. The next day, participants retrieved the pairings, and learned an additional set of associations during an EEG session. Finally, approximately one month later, participants retrieved the associations during a second fMRI scan.

The grant has led to a number of outcomes. The first paper from this work, analyzing data from the two fMRI sessions, is currently being revised for *NeuroImage* with the PIs' graduate

students as first and second authors. PI Coutanche's graduate student, Heather Bruett, presented results from the work at the 2019 Annual Meeting of the Psychonomic Society. The EEG data has been processed (to give event-related potentials [ERPs]) and is available to serve as data for a future graduate student's project to integrate the data from both modalities. Additionally, the study provided preliminary data for a pending grant at the National Science Foundation.

More generally, the award has allowed the PIs to extend their research programs in new and intersecting directions. PI Coutanche has extended his research of learning new words for visual concepts to include words of a second-language, as well as incorporating EEG into study design and analysis. PI Tokowicz has extended her work of second-language learning to include visual concepts, as well as incorporating fMRI into study design and analysis. The use of the two methods give results that are greater than the sum of their parts. For example, although fMRI has been used to examine the *results* of gradual memory consolidation (i.e., long-term memories) for decades, we understand very little of *how* particular neural patterns are formed in human learners. With recent developments in multivariate analytical approaches, we can now track the neural trace for specific items in memory, such as a particular object (Coutanche & Thompson-Schill, 2015) or episode (Chadwick, Hassabis, Weiskopf, & Maguire, 2010). Although these findings have helped us probe neural markers for successful storage, the process (i.e., the *how*) of memory consolidation has not received as much attention from fMRI investigators. Yet, several ERP components have been linked to successful memory formation. One such ERP component, the late positive component (LPC; observed 450-750ms after stimulus-onset) is frequently observed in comparisons of successful versus unsuccessful memory recognition (Paller, Kutas, & McIsaac, 1998). Relevant to consolidation, the size of this LPC increases the day after learning (without any intervening training) only for novel words (Palmer, Havelka, & van Hooff, 2013).

A second relevant ERP component, the N400, is linked to semantic processing (e.g., Tolentino & Tokowicz, 2009), and has also been linked to consolidation: the N400 is attenuated only once a person sleeps after learning (believed to be important for full consolidation; Lin & Yang, 2014).

Our initial (under review) paper reports new findings from the fMRI sessions of the funded study, which shows that reinstatement of neural activity between encoding and retrieval represents multiple conceptual levels, which relate to behavioral outcomes. The results give a neural explanation for our ability to represent and remember concepts at various semantic granularities. The paper reports evidence of both overlap and dissociation between how item and category information is processed in encoding and retrieval. Similar computations in specific brain regions were involved in mnemonically-meaningful pattern robustness during encoding, regardless of whether word–visual concept pairings were neurally measured at the item or category level. These results demonstrate that different cognitive representations of concepts (here, item and category) can share neural space in some regions, while diverging in others. More generally, this is evidence that concepts exist at multiple dimensions in the brain.

In addition to the findings described above, the internal award allowed the PIs to mentor two graduate students through GSRs (one for each lab). The award thus brought together a team of two principal investigators and two graduate students, who met regularly to discuss the project, worked together for the design and analysis plans, and in the process shared knowledge from our different research domains and methodological expertise. This shared knowledge, in addition to the conference presentation and submitted paper, has helped enhance the training and experiences of both students.