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Identifying Human Memory Encoding Mechanisms from Physiological fMRI data via Machine Learning Techniques

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ABSTRACT

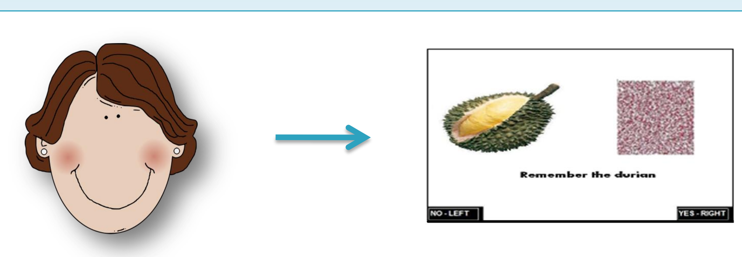
Neuropsychological theories postulate that there are multiple memory systems in the brain but there is controversy as to whether declarative memory is a unitary memory system. In this study, we succeeded in classifying two distinct declarative memory acquisition mechanisms directly from physiological data by the use of machine learning techniques on functional MRI (fMRI) scans of subjects, thereby adding explicit physiological justification to the existence of multiple declarative memory systems.

The data were gathered in previous experiments which were designed so that subjects acquired identical declarative information, but used different processes in doing so. The classification was based on the multi-voxel pattern analysis of neural information obtained from fMRI signals. Support Vector Machines (SVM) based classifiers identified the memory patterns from complex, high dimensional and noisy fMRI activations evoked by participants while they acquired novel information in one of two methods: 1) fast mapping encoding and 2) explicit encoding. For each type of encoding, the classifiers were able to predict whether the subject succeeded in the recollection attempt. In addition, a further classifier succeeded in 3) distinguishing the type of encoding used for novel knowledge acquisition - fast mapping or explicit encoding.

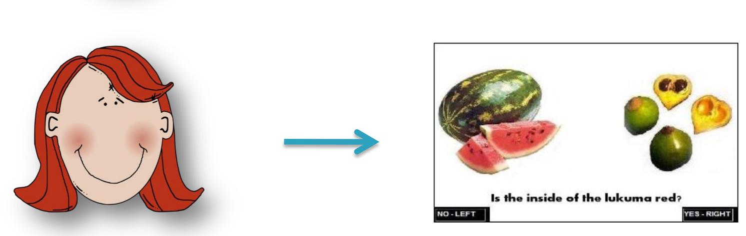
FAST MAPPING VS. EXPLICIT ENCODING

Explicit Encoding (EE) - enables matching explicit episodic encoding of declarative information, for example, learning of historical events , mathematical symbols etc.

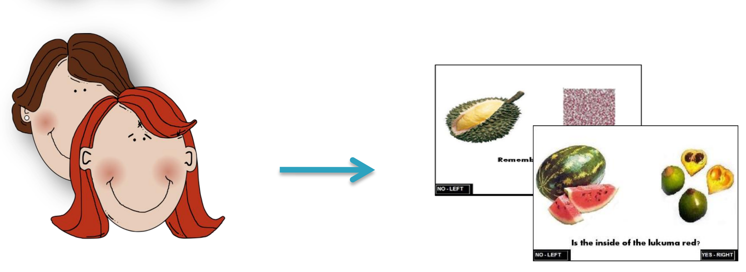
Fast Mapping (FM) - enables rapid acquisition of declarative novel information (arbitrary associations). The FM mechanism allows for a rapid mapping to be created between a word and its referent. Despite the vast literature on the various aspects of FM in children as a word learning mechanism, little is known about the characteristics of this mechanism in adults, or about its neural substrate. It was shown, however, that adults with extensive damage to the Medial Temporal Lobe and the hippocampus **are able to acquire novel declarative associations through FM** despite a profound impairment in declarative learning through EE [1] .



Contrast 1.
Explicit Encoding Task - "recollection success" vs. "recollection failure" conditions.



Contrast 2.
Fast Mapping Task - "recollection success" vs. "recollection failure" conditions.



Contrast 3.
Fast Mapping vs. Explicit Encoding Tasks

STUDY QUESTIONS

The hypothesis is that FM declarative learning depends on cortical structures that are distinct from those essential for learning declarative associations through a matched explicit episodic encoding control paradigm (EE).

In this work, the following questions were asked in regard to the abilities of machine learning techniques used for analysis:

Contrast 1. Is it possible to distinguish between "recollection success" and "recollection failure" conditions in EE-based tasks? What are the brain areas relevant for this contrast?

Contrast 2. Is it possible to distinguish between "recollection success" and "recollection failure" conditions in FM-based tasks? What are the brain areas relevant for this contrast?

Contrast 3. Can we predict which of the original mapping paradigms, FM or EE, were used by participant in "recollection success" condition?

It was shown that the answer to these questions is affirmative. The relevant brain areas are depicted below.

MATERIALS AND METHODS

fMRI data collected from twenty five healthy volunteers were used in the study. Thirteen participants performed the FM paradigm, twelve additional participants performed the EE paradigm. In each paradigm, novel and familiar target trials (either FM or EE trials) were intermixed with base line trials.

Support Vector Machine **(SVM)** with a linear kernel used for all the experiments in this work. The classification results were evaluated using cross-validation. In all analyses, the accuracy of prediction was based only on test data that was completely disjoint from the training data. **Feature selection** process was based on univariate scoring methods, ranking features by the individual voxel performance under the predefined metric. Two metrics were explored: **1)** ***Activity*** - selecting voxels that are active in at least one condition relative to a control baseline, and **2)** ***Accuracy*** - scores a voxel by how accurately an SVM classifier can predict the condition of each example in the training set, based on that specific voxel only. The cross-validation success rate is used as a voxel score. To evaluate the statistical significance of observed classification accuracy, the results were compared to those accepted by using a random selection of voxels.

The brain maps for contrasts 1 and 2 were produced with a standard **"searchlight" algorithm** (radius =4mm).

CLASSIFICATION RESULTS

It should be noted that these results were obtained despite the low signal to noise ratio and high multi-dimensionality of fMRI data, for both within-participant and between-participant data sets. The encouraging results show that the model was able to predict the required targets in all 3 contrasts, albeit with different accuracy levels.

Classification results for volumes including the whole brain

EE Paradigm		
Ranking Metric	Within-participant	Between-participants
Accuracy	66%	60.7%
Activity	67%	61.1%

Contrast 1. Explicit Encoding (EE) task - recollection status prediction.

FM Paradigm		
Ranking Metric	Within-participant	Between-participants
Accuracy	73%	66.2%
Activity	71%	65.4%

Contrast 2. Fast Mapping (FM) task - recollection status prediction.

FM vs. EE classification	
Ranking Metric	Between-participants
Accuracy	80.2%
Activity	60.2%

Contrast 3. Memory paradigm prediction

Classification results for volumes with hippocampus voxels excluded from the analysis

EE Paradigm		
Ranking Metric	Within-participant	Between-participants
Accuracy	63.8%	60.3%
Activity	62.3%	75.2%

Contrast 1. Explicit Encoding (EE) task - recollection status prediction.

FM Paradigm		
Ranking Metric	Within-participant	Between-participants
Accuracy	72%	66.5%
Activity	68.3%	65.3%

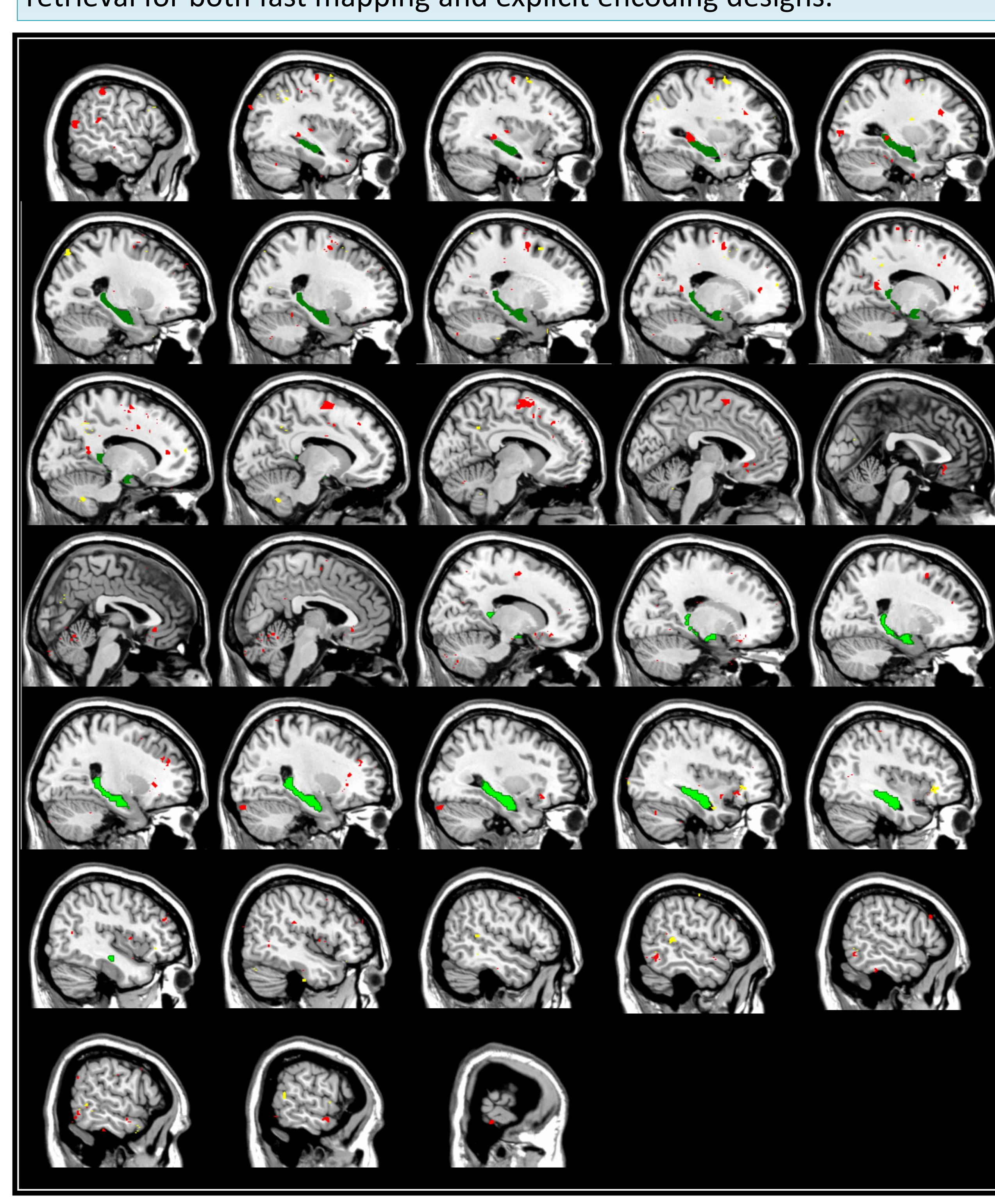
Contrast 2. Fast Mapping (FM) task - recollection status prediction.

FM vs. EE classification	
Ranking Metric	Between-participants
Accuracy	80.3%
Activity	59.8%

Contrast 3. Memory paradigm prediction

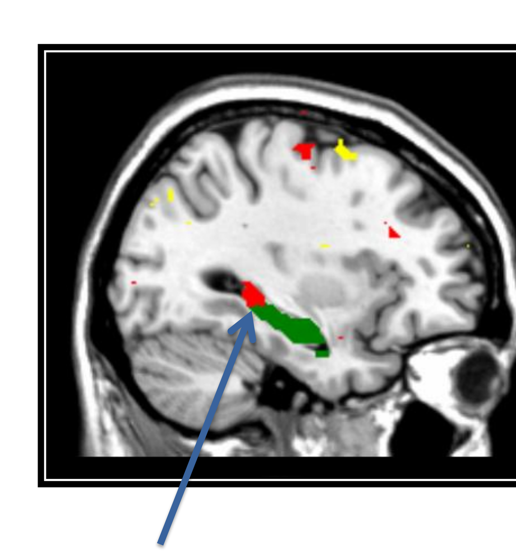
BRAIN MAPS

The basic question being addressed in the current study is whether the registered fMRI signal carries information about the particular patterns of knowledge acquisition and retrieval. It appears that although both FM and EE lead to the acquisition of declarative memory as reflected in the post-scan recognition performance, they do so by recruiting very distinct neural networks that can be efficiently distinguished using SVM. At the second stage, we leveraged these results addressing the question as to where the discriminative patterns reside in the brain. It is important to clarify which memory structures are involved in information retrieval for both fast mapping and explicit encoding designs.



The 'recollection success/failure' contrast.
FM activations are shown in yellow; EE activations are shown in red. Slices are presented in saggital view from the left (top; -) to the right (bottom; +) hemisphere. All results are rendered onto the Montreal Neurological Institute (MNI) reference brain.

◆ EE ◆ FM ◆ Hippocampus



A clear evidence of hippocampus involvement in EE task, not found for FM task.

Another point concerns investigating the role of the hippocampus and the surrounding medial-temporal cortices for relational memory functioning. Two observations follow immediately from the brain maps and the results depicted in the tables above: 1) The hippocampus is involved in EE paradigm but not in FM paradigm; 2) Removal of the hippocampus values does not heavily affect the classification performance and the immediate contribution of the hippocampus is less prominent comparing to other brain areas.

[1] Sharon.T., Moscovitch, M., Gilboa, A.(2011). Rapid neocortical acquisition of long-term arbitrary associations independent of the hippocampus. *PNAS 2011*