Investigating the Spacing Effect Using EEG

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Introduction

Spacing effect: distributed practice leads to better long-term memory performance than massed practice.

Present experiment: participants learned unique word–image pairs across two presentations (Pres1 and Pres2) and were tested with recognition and cued recall.

EEG analysis methods

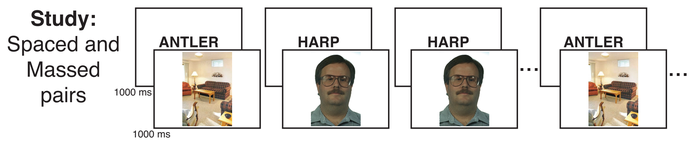
- Measure the similarity of EEG during Pres1 and Pres2 (Manning et al., 2011).

Experiment

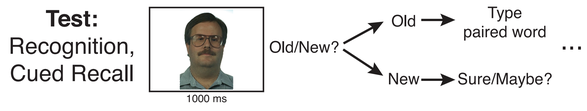
- 31 right-handed adults
- One session, six blocks of four phases: exposure, study, distractor, test.

1. **Exposure**: Familiarization to 50 images from two categories: faces and indoor house scenes. Used to train pattern classifier to predict faces vs houses from EEG.

2. **Study**: Unique noun paired with each image; 28 pairs were presented twice in either a spaced (lag=12) or massed (lag=0) fashion (seven per image category per lag). The remaining 22 pairs were single-presentation distractors or buffers.

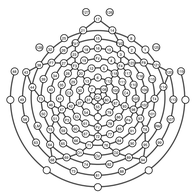


3. Math distractor, 2 minutes.
4. **Test**: Recognition and recall tests were given for old (28) and new (14) images.



Scalp EEG

- 128-channel 250-Hz EGI scalp EEG system; 200 MΩ high-impedance amplifier.
- EEG preprocessing:
  - Filters: 0.1 Hz high-pass, 100 Hz low-pass, 60 Hz band-stop
  - Average reference
  - ICA-based eye blink artifact correction
  - Baseline correction (-200 to 0 ms pre-stimulus)
  - Z-transformed EEG data across all conditions
- Analyses run on 42 electrodes: coverage of parietal, occipital, temporal regions.



Behavioral Results

- Recognition: Spaced (HR $= 0.92$) > Massed (HR $= 0.89$) ($p = .00003$)
- Cued Recall: Spaced (HR $= 0.52$) > Massed (HR $= 0.38$) ($p = 1.9e^{-9}$)

Hypotheses and Predictions

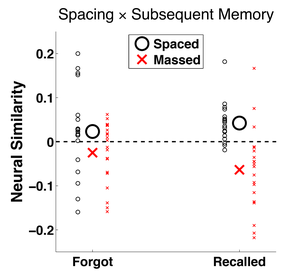
- **Deficient processing**:
  When an item is repeated immediately (massed), attention to the second presentation decreases because the item is already familiar and in short-term memory (Van Strien et al., 2007; Xue et al., 2011). This does not occur for spaced items.
  - Greater Pres1–Pres2 similarity for spaced vs massed, due to less attention for massed.
- **Encoding variability**:
  Because episodic (and neural) context drifts, repeated study events further apart in time are likely to be different vs those closer together (Glenberg, 1979). At retrieval, higher probability that the test context will be similar to one of the spaced contexts as compared to the massed context (e.g., more retrieval cues).
  - Greater Pres1–Pres2 similarity for massed vs spaced, due to more similar contexts for massed.
- **Study-phase retrieval**:
  Repetition of a study item will assimilate the present context (Pres2) with that of all prior occurrences (Pres1) into the memory trace (Cepeda et al., 2009; Thios & D'Agostino, 1976).
  - Greater Pres1–Pres2 similarity for recalled vs forgotten, due to reinstatement of Pres1 during Pres2.

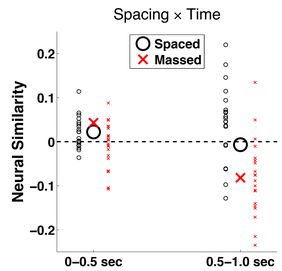
Analysis Methods

- **Data**: EEG voltage measurements from two successive 500 ms windows (0–500 and 500–1000 ms).
- **Classifier**: Elastic net logistic regression; trained on faces and houses from **Exposure phase**.
  - Balanced trial counts
  - α (L1/L2 mixing parameter): 0.2
  - λ (shrinkage parameter): determined by cross validation
- **Neural similarity**: For each individual image, if correct classification of **Study phase** image Pres1 and its repetition at Pres2 in a given time window, compared similarity of presentations.
  - Correct classification allows assumption of stimulus processing.
  - Analyses included 20 subjects (at least 3 correctly classified stimulus repetitions).
  - *Dimensionality reduction*: Principle component analysis (PCA) was run across trials on electrode × time samples. Kept k eigenvectors that capture 85% of variance.
  - *Similarity calculation*: Comparison of **PCA-derived features from EEG samples** for image presentations using dot product (cosine of angle between Pres1 and Pres2 feature vectors).

Results: Similarity Analysis

- Calculated **PCA-derived features from voltage measurements** in two successive 500 ms windows; compared two presentations of an image using dot product.
- 3-way ANOVA on subject similarities: Spacing × Subsequent memory × Time window
  - Main effect of Spacing ($p = .000077$): **Spaced more similar than massed** (M $= 0.033$ vs M $= -0.044$).
  - Main effect of Time ($p = .012$): **Early more similar than late** (M $= 0.0077$ vs M $= -0.0194$).
  - Spacing × Subsequent memory ($p = .077$): **Spaced recalled more similar than massed recalled** (M $= 0.0422$ vs M $= -0.0637$, $p = .00014$).
    - Recalled spaced and recalled massed both different from zero ($p = .00047$ and $p = .0023$).
  - Spacing × Time ($p = .0022$): Similarity increases over time for spaced pairs (*ns*), decreases over time for massed pairs ($p = .00017$).





Summary of Results

Behavioral

- Spaced pairs were remembered better than massed pairs (image recognition and cued word recall).

Representational similarity (Pres1 vs Pres2)

- Spaced images with recalled word pairs more similar than massed
  - Supports: Deficient processing, Study-phase retrieval
  - Challenges: Encoding variability
  - In line with prior fMRI analyses (Xue et al., 2010)
- Massed images with recalled word pairs more dissimilar than spaced.
  - Encoding variability advantage for massed items?

Future Directions

- Similarity comparisons of time–frequency data.
- Examine role of attention (deficient processing) via ERP (P1/N1 components) and oscillatory (e.g., alpha) analyses.
  - Neural repetition suppression during massed Pres2 (e.g., Xue et al., 2011) may lead to attenuated ERP components
  - e.g., increased alpha for massed vs spaced
- *Test phase*: Analyze cued recall activity (e.g., similarity between encoding and retrieval).
- Similarity of Pres1–Pres2 activity may not be temporally coupled.

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