A Similarity Retrieval System for Multimodal Functional Brain Images

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Functional Brain Imaging

- Study how the brain works
- Imaging while subject performs a task
- Image represents some aspect of the brain e.g.
  - **fMRI**: brain blood oxygen level
  - **ERP**: scalp electric activity
Motivation

- Given a database of functional brain images from various subjects, cognitive tasks, and image modality.
- Database users need to retrieve similar images
- A system that can automatically perform this retrieval will reduce amount of time and effort users spend during this task
Contributions

1. Created a similarity retrieval system for multimodal brain images
   I. fMRI, ERP, and combined fMRI-ERP
   II. User interface
2. Developed feature extraction methods for fMRI and ERP data
3. Developed pair-wise similarity metrics
4. Simulated human expert similarity scores
Outline

- Background
  - fMRI
  - ERP
  - Existing Similarity Retrieval Systems for these modalities
- Feature Extraction Process
- Similarity Metric
- User Interface
- Retrieval Performance
- Simulate Human Expert
Functional Magnetic Resonance Imaging (fMRI)

- A non-invasive brain imaging technique
- Records blood oxygen level in brain
- While imaging, subject performs a task
fMRI Statistical Images

Statistical Analysis

Voxel Thresholding
Event-Related Potentials (ERP)

- A non-invasive brain imaging technique
- Records electric activity along scalp
- While imaging, subject performs a task
ERP Source Localization

- Researchers want to identify the **electric activity** and its source for each electrode
- But, **multiple sources** for each electrode

- **LORETA** approximates anatomic locations of sources
## Comparison of fMRI and ERP Data

<table>
<thead>
<tr>
<th></th>
<th>fMRI</th>
<th>ERP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spatial resolution</strong></td>
<td>Good (in mm)</td>
<td>undefined/poor</td>
</tr>
<tr>
<td><strong>Temporal resolution</strong></td>
<td>Poor (in sec)</td>
<td>Excellent (in msec)</td>
</tr>
</tbody>
</table>
## Similarity Retrieval Systems for fMRI Images

<table>
<thead>
<tr>
<th>Feature</th>
<th>Our System</th>
<th>Codebook</th>
<th>Wavelet</th>
<th>Bipartite</th>
<th>RV-Coefficient</th>
<th>Correspondence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retain &quot;Most Important&quot; Voxels</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Whole Brain Similarity</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Region of Interest Similarity</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Feature Selection</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
Similarity Retrieval Systems for ERP Images

No relevant literature found
Similarity Retrieval Systems for Combined fMRI-ERP Images

No relevant literature found
Outline

- Background
- Feature Extraction Process
  - fMRI features
  - ERP features
- Similarity Metric
- User Interface
- Retrieval Performance
- Simulate Human Expert
fMRI Feature Extraction

1. Centroid
2. Avg Activation Value
3. Var Activation Value
4. Volume
5. Avg Distance to Centroid
6. Var of those Distances

Original database → Threshold → Approximate cluster centroids → Perform clustering

Perform connected component analysis

Compute region vectors
ERP Feature Extraction

Select time-segment

Task A

Task B

$T_1$

$T_{100}$

$T_1$

$T_{100}$

(X,Y,Z) positions of retained voxels

Compute feature

Task A

Task B

$T_{50}$

$T_{100}$

$T_{50}$

$T_{100}$

Compute voxel-wise statistically significant difference between means

Threshold
Outline

- Background
- Feature Extraction Process
- Similarity Metric
  - Summed Minimum Distance
  - Similarity Score for Combined fMRI-ERP Images
- User Interface
- Retrieval Performance
- Simulate Human Expert
Summed Minimum Distance (SMD) for fMRI and ERP Images

Subject Q

Subject T

\[ Q2T = \frac{\sum_{r \in Q} \min_{s \in T} d_E(r, s)}{N_Q} \]

\[ \text{SMD} = \frac{(Q2T + T2Q)}{2} \]
## Sample SMD Scores

<table>
<thead>
<tr>
<th>Choose a Match to View</th>
<th>SMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 HealthyAOD_11</td>
<td>0.00</td>
</tr>
<tr>
<td>2 HealthyAOD_8</td>
<td>11.82</td>
</tr>
<tr>
<td>3 HealthyAOD_1</td>
<td>15.33</td>
</tr>
<tr>
<td>4 HealthyAOD_13</td>
<td>15.47</td>
</tr>
<tr>
<td>5 HealthyAOD_6</td>
<td>16.38</td>
</tr>
<tr>
<td>6 HealthyAOD_9</td>
<td>16.47</td>
</tr>
<tr>
<td>7 HealthyAOD_12</td>
<td>19.01</td>
</tr>
<tr>
<td>8 HealthyAOD_4</td>
<td>21.31</td>
</tr>
<tr>
<td>9 HealthyAOD_3</td>
<td>21.32</td>
</tr>
<tr>
<td>10 HealthyAOD_5</td>
<td>21.53</td>
</tr>
<tr>
<td>11 HealthyAODMean_con</td>
<td>22.98</td>
</tr>
<tr>
<td>12 HealthyAOD_15</td>
<td>24.43</td>
</tr>
<tr>
<td>13 FaceUpVsFixation_14</td>
<td>25.91</td>
</tr>
<tr>
<td>14 HealthyAOD_7</td>
<td>26.83</td>
</tr>
<tr>
<td>15 HealthyAOD_10</td>
<td>27.44</td>
</tr>
<tr>
<td>16 FaceUpVsFixation_4</td>
<td>27.98</td>
</tr>
<tr>
<td>17 FaceUpVsFixation_9</td>
<td>28.18</td>
</tr>
<tr>
<td>18 FaceUpVsFixation_20</td>
<td>28.21</td>
</tr>
<tr>
<td>19 FaceUpVsFixation_3</td>
<td>28.50</td>
</tr>
<tr>
<td>20 FaceUpVsFixation_19</td>
<td>28.59</td>
</tr>
</tbody>
</table>
Similarity Score for Combined fMRI-ERP Images

$SIM(i,j) = \alpha SMD_{fMRI}(i,j) + (1-\alpha)SMD_{ERP}(i,j)$
Outline

- Background
- Feature Extraction Process
- Similarity Metric

User Interface

- Retrieval Performance
- Simulate Human Expert
GUI: Front Page

Similarity Retrieval Tool for Multimodal Brain Images

Choose Modality
- fMRI
- ERP
- Both

fMRI Threshold: 0.01
ERP Threshold: 10
Scope: Global
ERP Timeframe: TF1: 101, TF2: 121
Alpha: 0

Upload Database

Query Brain

Query Brain Viewer
- Slices: -26.8.25
  - Axial
  - Coronal
  - Sagittal
- All Slices

fMRI Feature Weights
- Cluster Centroid
- Cluster Area
- Voxel Mean Distance to Centroid
- Voxel Mean Activation Value
- Variance of Voxel Activation Values
- Variance of Voxel Distances to Centroid

Return Top: 15 Matches

Get Matches
# GUI: Retrievals with SMD Scores

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<tr>
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<td>28.21</td>
</tr>
<tr>
<td>19 FaceUpVsFixation_3</td>
<td>28.50</td>
</tr>
<tr>
<td>20 FaceUpVsFixation_19</td>
<td>28.59</td>
</tr>
</tbody>
</table>
GUI: Query-Target Activations (fMRI)
GUI: Query-Target Activations (ERP)
Outline

- Background
- Feature Extraction Process
- Similarity Metric
- User Interface

Retrieval Performance
- Data Sets
- fMRI Retrieval Performance
- ERP Retrieval Performance
- Combined fMRI-ERP Retrieval Performance

Simulate Human Expert
Data Sets for fMRI Retrievals

- **Checkerboard** -- 12 subjects (Face Recognition)
- **SB** -- 15 subjects (Memorization)
- **Central-Cross** -- 24 subjects (Face Recognition)
- **AOD** -- 15 subjects (Sound Recognition)
Data Set for ERP Retrievals

View Human Faces (Face Up) -- 15 subjects

View Houses (House Up) -- 15 subjects
Data Set for Combined fMRI-ERP Retrievals

- ERP: same data set as used in ERP retrieval

- fMRI:
  - Task: Face recognition using a house up background
  - Same subjects and images as data set for ERP retrieval
fMRI Retrieval Performance

1. RFX Retrievals

2. Individual Brain Retrieval

3. Testing Group Homogeneity

4. Feature Selection
fMRI Retrieval Score

\[
\text{Retrieval Score} = \frac{1}{N \times N_{rel}} \left( \sum_{i=1}^{N_{rel}} R_i - \frac{N_{rel}(N_{rel} + 1)}{2} \right)
\]

Perfect score: \( \text{Retrieval Score} = 0 \)

Random score: \( \text{Retrieval Score} \sim 0.5 \)

Worst score: \( \text{Retrieval Score} = 1 \)
fMRI Individual Brain Retrievals

- Use individual brain as query

<table>
<thead>
<tr>
<th></th>
<th>Mean Retrieval Scores (Top 6% activated voxels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Checkerboard</td>
<td>0.09</td>
</tr>
<tr>
<td>SB</td>
<td>0.16</td>
</tr>
<tr>
<td>Central-Cross</td>
<td>0.21</td>
</tr>
<tr>
<td>AOD</td>
<td>0.26</td>
</tr>
</tbody>
</table>
Testing Group Homogeneity for fMRI

- SB
- CB
- AOD
- Central-Cross
ERP Retrieval Performance
Subject #8 Retrievals

<table>
<thead>
<tr>
<th></th>
<th>Subject 8</th>
<th>Subject 12</th>
<th>Subject 14</th>
<th>Subject 13</th>
<th>Subject 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>0.00</td>
<td>0.11</td>
<td>0.23</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom</td>
<td>0.70</td>
<td>0.75</td>
<td>0.78</td>
<td>0.91</td>
<td>0.95</td>
</tr>
</tbody>
</table>
Combined fMRI-ERP Retrieval

\[
\text{SIM}(i,j) = \alpha \text{SMD}_{\text{fMRI}}(i,j) + (1-\alpha) \text{SMD}_{\text{ERP}}(i,j)
\]

- \(\alpha = 0.0\), ERP only
- \(\alpha = 0.3\)
- \(\alpha = 0.6\)
- \(\alpha = 1.0\), fMRI only
Outline

- Background
- Feature Extraction Process
- Similarity Metric
- User Interface
- Retrieval Performance

- Simulate Human Expert
  - Simulation Method
  - Data Set
  - Testing Function Performance
Simulate Human Expert

- Current retrieval system requires some expert knowledge

<table>
<thead>
<tr>
<th></th>
<th>Centroid Only</th>
<th>Centroid and Average Activation Value Only</th>
<th>Average Activation Value Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation Coefficients</td>
<td>0.60</td>
<td>0.64</td>
<td>0.52</td>
</tr>
</tbody>
</table>

- Estimate a function to generate similarity scores with high correlation to expert scores
Simulation Method

1. Uniform feature representation: create codebook and encode each subject

2. Concatenate the codebook features for each pair of subjects

3. Create eigenfeatures

4. Estimate a function

5. Test function performance
1. Uniform Feature Representation
2. Concatenate Codebook Features

- $XYZ \rightarrow$ Centroid
- $A \rightarrow$ Avg Activation Value
- $VA \rightarrow$ Var Activation Value
- $S \rightarrow$ Size (Volume)
- $D \rightarrow$ Avg Distance to Centroid
- $VD \rightarrow$ Var of those Distances
3. Create Eigenfeatures

Use PCA to project each feature onto $N$ principal components. Here $N=1$.

$$(\text{proj}^X_{S_1}, \text{proj}^X_{S_1})$$

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>A</th>
<th>VA</th>
<th>S</th>
<th>D</th>
<th>VD</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1,S1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>S1,S2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td>S1,S3</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td>S3,S3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
</tbody>
</table>

$$(\text{proj}^V_{S_1}, \text{proj}^V_{S_1})$$
4. Estimate a Function

- Linear function using linear regression
- Non-linear function using generalized regression neural networks (GRNN)
5. Test Function Performance

- The Pearson Correlation Coefficient (CC)
  
  \[
  \frac{\sum_{i=1}^{n} (\hat{y}_i - \mu_{\hat{y}}) (y_i - \mu_y)}{(n - 1) \sigma_{\hat{y}} \sigma_y}
  \]

- The Average Absolute Error (A-ABSE)
  
  \[
  \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{n}
  \]

- The Root Mean Square Error (RMSE)
  
  \[
  \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n}}
  \]
Data Set

fMRI data (Central-Cross) -- 23 subjects -- Face Recognition task

+ Human Expert Generated Pair-wise Similarity Matrix
## Overall Function Performance

<table>
<thead>
<tr>
<th></th>
<th>Original Codebook Features</th>
<th></th>
<th>Eigenfeatures</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Linear Function</td>
<td>Non-Linear Function</td>
<td>Linear Function</td>
<td>Non-Linear Function</td>
</tr>
<tr>
<td><strong>Training</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-ABSE</td>
<td>1.82</td>
<td>0</td>
<td>2.11</td>
<td>0.58</td>
</tr>
<tr>
<td>RMSE</td>
<td>2.25</td>
<td>0</td>
<td>2.57</td>
<td>0.82</td>
</tr>
<tr>
<td>CC</td>
<td>0.52</td>
<td>1</td>
<td>0.35</td>
<td>0.96</td>
</tr>
<tr>
<td><strong>Testing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-ABSE</td>
<td>2.26</td>
<td>1.74</td>
<td>2.18</td>
<td>1.36</td>
</tr>
<tr>
<td>RMSE</td>
<td>2.83</td>
<td>2.32</td>
<td>2.67</td>
<td>1.77</td>
</tr>
<tr>
<td>CC</td>
<td>0.23</td>
<td>0.59</td>
<td>0.25</td>
<td>0.76</td>
</tr>
</tbody>
</table>
Feature Selection

XYZ $\rightarrow$ Centroid
A $\rightarrow$ Avg Activation Value
VA $\rightarrow$ Var Activation Value
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D $\rightarrow$ Avg Distance to Centroid
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Contributions

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Future Direction

- Add more modalities to the system
- Obtain more expert scores for function estimation
- Obtain more data
- Develop similarity metrics other than SMD
Acknowledgements

Prof. Linda Shapiro
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