TODO: Please add comments to the document and periodically answer/interact with other people's comments and questions

Abstract

The integration of multisensory information is a core part of human perception, allowing us to form a coherent understanding of the world. This project aims to investigate the shared neural representations underlying proprioceptive and visual perception by leveraging curriculum learning and cross-modal transfer learning with EEG data. **Our primary objective is to demonstrate that transfer learning between these modalities is facilitated by an integrated perceptual world model encoded in neural activity.**

Due to current limitations in data collection, we utilize synthetic datasets and publicly available EEG data to develop and test our models. Participants in our experiment manipulate objects varying systematically in visual features—such as edges, shapes, colors, sizes, and textures—while their EEG signals and proprioceptive data (arm positions and movements) are recorded. Simultaneously, we collect EEG data during visual fixation tasks on the same objects with and without manipulation.

We design a neural network architecture comprising a shared encoder and modality-specific decoders. The encoder is first trained to predict proprioceptive data from EEG signals collected during the object manipulation task. Through transfer learning, we adapt this encoder to predict visual features from EEG data obtained during visual fixation. Curriculum learning is employed to progressively increase task complexity, starting from simple movement data (gyroscopic time series data) and basic visual features (bins, overt features, less precision, or less difficult features to predict) to more complex movement data (joint positions in 3d space over time) and intricate visual attributes (more precision, more features, more difficult features).

To validate our approach, we implement interpretability techniques such as latent space visualization using t-SNE and feature importance analysis via saliency maps. These methods allow us to examine the learned representations and identify which visual features are most effectively predicted from the EEG data.

The outcomes of this project have the potential to advance our understanding of how the brain integrates sensory information. Moreover, they may contribute to the development of more effective brain-computer interfaces and machine learning models that emulate human perceptual processes. By preparing thorough experimental protocols and developing robust models now, we position ourselves to effectively transition to empirical data collection in the near future, likely next semester.

Deliverables

(similar to workshop document but now with partners in groups divided among the team and coordinated between the team so all members)

- **1.1. Literature Review Document (entire team)**
  - **Purpose:** Summarize current research on curriculum learning, transfer learning, and integrated perceptual models using EEG data.
  - **Contents:**
    - Key findings from recent papers.
    - Gaps in existing research that the project to your understanding aims to fill.
    - Potential methodologies and tools.
- **1.2. Dataset Identification and Acquisition (entire team)**
  - **Action:** Find publicly available datasets that resemble the data we plan to collect.

    Proprioceptive ground truth data: accelerometer data from specific joints of the arm, and key points (pose estimation data of the human body (ideally the arm))

Visual ground truth data: we will be predicting visual feature data by varying the objects someone is manipulating

Varying Object Visual Features

- **Use a set of objects that vary systematically in visual features.**
  - **Edges:** Objects with sharp edges vs. rounded edges, number edges
  - **Color:** Different colors or levels of color complexity, patterns.
  - **Shape:** Various geometric shapes (e.g., cube, sphere, pyramid).
  - **Size:** Small vs. large versions of the object.
  - **Texture:** Smooth vs. textured surfaces.
- **Ensure that the objects are similar enough in terms of manipulability to keep the proprioceptive aspect consistent.**

  - **Possible Datasets:**
    - **EEG Motor Movement/Imagery Dataset (PhysioNet):** For proprioceptive data.

        - **EEG Visual Object Recognition Dataset:** For visual fixation data.

    - **Deliverable:** A compiled list of datasets with descriptions, access details, and relevance to your project.

2. Synthetic Data Generation (2-3 people)

Deliverable 2.1: Synthetic EEG Data

- **Description:**
    - Generate synthetic EEG data simulating neural activity during:
        - Object manipulation with visual fixation (simultaneous proprioceptive and visual processing).
        - Visual fixation only (without manipulation).
    - Include realistic noise and artifacts to mimic real EEG data.
- **Outcome:**
    - A dataset of synthetic EEG signals corresponding to different tasks and complexity levels.
    - Code and documentation detailing the data generation process.

Deliverable 2.2: Synthetic Proprioceptive Data

- **Description:**
    - Simulate proprioceptive data representing arm positions and movements during object manipulation.
    - Vary movement data complexity to support curriculum learning (e.g., from simple axis tilt sequences ((pitch, roll, yaw) over time) to complex data (joint keypoints moving in 3d space over time)).
- **Outcome:**
    - A dataset of synthetic proprioceptive measurements aligned with EEG data.
    - Code and documentation explaining the generation process.

Deliverable 2.3: Synthetic Visual Data

- **Description:**
    - Create synthetic visual data representing objects with varying features:
        - Edges (simple to complex).
        - Shapes (basic to intricate).

        - Colors (monochrome to multicolored).
        - Sizes (small to large).
        - Textures (smooth to rough).
    - Extract visual features numerically for model training (e.g., feature vectors).
- **Outcome:**
    - A dataset of synthetic visual features corresponding to each object.
    - Code for generating images and extracting feature vectors.

3. Data Processing Pipelines (2-3)

Deliverable 3.1: Data Preprocessing Scripts

- **Description:**
    - Develop scripts for preprocessing synthetic EEG data:
        - Filtering (e.g., band-pass filtering).
        - Artifact removal (e.g., simulated eye blinks, muscle artifacts).
        - Normalization and scaling.
    - Preprocess proprioceptive and visual data as needed.
- **Outcome:**
    - Reusable code modules for data preprocessing.
    - Documentation explaining each preprocessing step.

Deliverable 3.2: Data Synchronization and Alignment

- **Description:**
    - Implement methods to synchronize EEG, proprioceptive, and visual data using the shared time vector.
    - Ensure accurate temporal alignment across modalities.
- **Outcome:**
    - Synchronized datasets ready for model training.
    - Code and documentation on synchronization procedures.

4. Model Architecture Development (2-4 people)

Deliverable 4.0: Find Latest Neural Network Architectures

- **Description:**
    - Find the latest or best state-of-the-art EEG Deep Learning architectures that would work well for our project

Deliverable 4.1: Neural Network Architecture Design

- **Description:**
    - Design the neural network architecture, including:
        - **Shared Encoder:**
            - Processes EEG data to extract latent representations.
            - May include convolutional layers for spatial features and LSTM or Transformer layers for temporal dependencies.
        - **Proprioceptive Decoder:**
            - Predicts proprioceptive data from the latent representations.
        - **Visual Decoder:**
            - Predicts visual features from the latent representations.
- **Outcome:**
    - Detailed architecture diagrams and descriptions.
    - Code implementation using frameworks like PyTorch.

5. Algorithm Implementation (3-5)

Deliverable 5.1: Curriculum Learning Implementation

- **Description:**
    - Develop training strategies that progressively introduce data of increasing complexity within each modality.
        - For proprioception: Start with predicting simpler overarching movement data (axis tilt, gyroscopic data), advancing to complex representations of movement data (key points).
        - For vision: Start with predicting basic visual features (edges, shape, relative size), progressing to complex features (color, texture).
    - Implement mechanisms to adjust learning rates or task difficulty.
- **Outcome:**

    - Code implementing curriculum learning schedules.
    - Documentation on curriculum strategies and rationale.

Deliverable 5.2: Cross-Modal Transfer Learning Implementation

- **Description:**
    - Implement transfer learning techniques between modalities:
        - Pre-train the shared encoder on proprioceptive prediction tasks.
        - Transfer the encoder to visual feature prediction tasks.
        - Experiment with different transfer learning approaches (e.g., freezing layers, fine-tuning).
- **Outcome:**
    - Code for transfer learning models.
    - Initial results demonstrating transfer learning effectiveness on synthetic data.

6. Model Training and Evaluation (all team)

Deliverable 6.1: Training Models on Synthetic Data

- **Description:**
    - Train the models using synthetic datasets:
        - Evaluate the performance of the encoder and decoders on their respective tasks.
        - Optimize hyperparameters for best performance.
- **Outcome:**
    - Trained models saved for future use.
    - Training logs and performance metrics.

Deliverable 6.2: Performance Analysis

- **Description:**
    - Assess model performance using appropriate metrics:
        - Regression metrics (e.g., MSE, RMSE) for continuous outputs.
        - Classification metrics (e.g., accuracy, F1-score) if applicable.
    - Compare models trained with and without curriculum and transfer learning.

- **Outcome:**
  - A report summarizing model performance.
  - Plots and graphs illustrating training progress and results.

Deliverable 6.3: Comparative Analysis, Feature Importance, and Visualization

- **Description:**
  - Use interpretability techniques to understand what features are being learned and transferred:
    - Visualize latent spaces with t-SNE or PCA.
    - Generate saliency maps to identify important EEG features.
    - Analyze which visual features are best predicted.
- **Outcome:**
  - Visualizations and insights into model behavior.
  - Understanding of how the integrated perceptual model is represented in the network.

Comparative Analysis:

Base Models:

- **Model A (Integrated):** Encoder trained on simultaneous proprioceptive-visual task EEG data
- **Model B (Sequential):** Encoder trained on proprioception-only EEG data
- **Model C (Visual-Only):** Encoder trained from scratch on visual-only EEG data
- **Model D (Random):** Randomly initialized encoder as control baseline

Transfer Learning Tests:

- Transfer each model to visual-only task prediction
- Measure:
  - Transfer speed (learning curves)
  - Final performance metrics
  - Sample efficiency
  - Generalization to novel stimuli

Expected Results that Would Support Our Hypothesis:

- Model A should show:
  - Faster transfer learning
  - Better final performance
  - Better generalization
  - More structured latent representations

- Performance ranking should be: A > B >=< C > D

Additional Validation Tests:

- Cross-validation across different:
  - Visual features
  - Movement types
  - Task complexities
- Ablation studies removing different aspects of integration
- Analysis of learned representations using:
  - t-SNE visualization
  - Feature importance maps
  - Representation similarity analysis between modalities

This design allows us to:

1. Demonstrate that simultaneous training creates better transferable representations
2. Rule out simple transfer effects from single-modality training
3. Quantify the advantage of integrated learning
4. Show that the advantage comes from shared representational structure

7. Experimental Protocols for Future Data Collection

Deliverable 7.1: Detailed Experimental Protocol Document

- **Description:**
  - Prepare a comprehensive protocol for data collection, including:
    - Participant recruitment and consent procedures.
    - Detailed task instructions (simultaneous manipulation and visual fixation).
    - Equipment setup and calibration.
    - Data recording and storage guidelines.
- **Outcome:**
  - A ready-to-implement experimental protocol.
  - Compliance with ethical standards and best practices.

Deliverable 7.2: Ethics Application Preparation

- **Description:**
  - Compile all necessary documents for Institutional Review Board (IRB) approval:
    - Study objectives and significance.

        - Methodology and procedures.
        - Risk assessment and mitigation strategies.
        - Participant information sheets and consent forms.
- **Outcome:**
    - A complete ethics application ready for submission.
    - Increased likelihood of swift approval due to thorough preparation.

8. Data Collection Preparation

Deliverable 8.1: Equipment and Resource Planning

- **Description:**
    - Identify and plan for all resources needed for data collection:
        - EEG equipment and specifications.
        - Motion capture or IMU devices for proprioceptive data.
        - Visual stimuli preparation (objects with varying features).
        - Eye-tracking equipment if used.
- **Outcome:**
    - An inventory of required equipment.
    - A procurement or reservation plan to ensure availability.

Deliverable 8.2: Pilot Study Design

- **Description:**
    - Plan a pilot study to test and refine the experimental setup:
        - Objectives of the pilot (e.g., testing equipment synchronization, task feasibility).
        - Criteria for success and potential adjustments.
- **Outcome:**
    - A pilot study protocol ready to execute once equipment is available.
    - Preparedness to troubleshoot and refine before full-scale data collection.

9. Documentation and Code Management

Deliverable 9.1: Codebase Documentation

- **Description:**
    - Document all code thoroughly:
        - Use docstrings and comments.

        - Provide clear instructions for running scripts and reproducing results.
        - Include requirements and environment setup guides.
- **Outcome:**
    - A well-documented codebase that is maintainable and accessible to all team members.

Deliverable 9.2: Reporting and Publication Preparation

- **Description:**
    - Prepare reports and potential publications:
        - Summarize methodologies, experiments, and findings.
        - Draft sections for conference papers or journal articles.
        - Include figures, tables, and diagrams illustrating key points.
- **Outcome:**
    - A comprehensive report that can be used for internal review or as a basis for future publications.
    - Readiness to disseminate findings to the broader scientific community.