

# EEG-to-Text Translation Using the Thought2Text Framework

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## 1. Introduction

Decoding human cognitive activity into natural language has emerged as one of the most ambitious challenges in artificial intelligence, cognitive neuroscience, and brain-computer interface (BCI) research. Traditional BCIs have primarily focused on classification-based tasks, such as detecting motor intentions or identifying simple event-related patterns from neural signals. However, recent advances in multimodal deep learning and large language models (LLMs) have opened the possibility of translating more abstract human thoughts—such as semantic concepts evoked by visual stimuli—into coherent natural language. Achieving such a capability would unlock new applications in assistive communication, accessibility technology, augmented and virtual reality, and neuroadaptive interfaces.

Among noninvasive neural measurement techniques, electroencephalography (EEG) offers several practical advantages: it is inexpensive, portable, and widely deployable in real-world environments. Yet EEG poses substantial challenges for semantic decoding due to its low spatial resolution, high noise, and strong inter-subject variability. Furthermore, prior approaches to EEG-to-text generation have frequently relied on limited vocabularies or classification frameworks, restricting the expressive capability of the system. Methods such as EEG2TEXT attempt to generate open-vocabulary text but do not fully leverage the reasoning ability and contextual understanding of modern LLMs. As a result, high-quality natural-language generation directly from EEG signals has remained largely unexplored.

A fundamental obstacle in EEG-based language decoding is the language interference problem: when subjects read or listen to text, the neural signals contain entangled linguistic processing components, making it difficult to isolate cognitive content. To bypass this issue, the Thought2Text framework introduces an alternative paradigm in which EEG is collected during visual stimulus presentation rather than linguistic tasks. By grounding the EEG representations in CLIP-generated image embeddings and leveraging large-scale instruction-tuned LLMs, Thought2Text demonstrates that it is possible to train a model to generate natural language descriptions of perceived images directly from EEG signals. The CVPR2017 EEG dataset, containing time-synchronized image-EEG pairs, provides the basis for learning such associations.

Thought2Text proposes a three-stage multimodal training pipeline: (1) learning an EEG

encoder aligned with CLIP’s visual semantic space, (2) priming the LLM using image embeddings, and (3) fine-tuning a multimodal projection layer to accept EEG embeddings during inference. This staged approach is necessary because end-to-end EEG-to-text training is unstable due to data scarcity and noise; visual grounding acts as an intermediate scaffold that stabilizes the alignment process. The success of the original framework illustrates the feasibility of transforming noninvasive neural activity into coherent natural language with the help of modern multimodal models.

In our implementation, we extend this framework in two important directions. First, we replace the original Mistral-7B-Instruct backbone with DeepSeek-7B, a more advanced and instruction-capable language model offering improved reasoning depth and richer text generation. Second, we introduce a suite of prompt-enhancement strategies designed to encourage more descriptive, detailed, and contextually rich outputs from the LLM. Prompt engineering is a well-established method for shaping the behavior of instruction-tuned models, and in our experiments it significantly improves the semantic adequacy of the generated captions under the same EEG embeddings.

By integrating these improvements within the Thought2Text pipeline, our system aims to produce higher-quality EEG-to-text generations while adhering to the core multimodal alignment principles established in the literature. This enhanced approach highlights the potential of combining neural decoding with modern LLM reasoning, and contributes to the broader effort toward building practical, low-cost “thought-to-text” systems capable of supporting real-world BCI applications.

## 2. Methods of Training

### 2.1 Description of the Chosen Neural Network

Our method builds on the multimodal EEG-to-text generation pipeline proposed in the Thought2Text framework, but extends it by using DeepSeek-7B as the language model and incorporating enhanced prompting strategies. The system consists of three major components: an EEG encoder, a multimodal projection layer, and a large language model. The EEG encoder is implemented using a ChannelNet-style multichannel convolutional neural network that processes 128-channel EEG signals cropped between 20–460 ms. It produces a 512-dimensional EEG embedding along with object classification logits. Training the encoder involves two supervision signals: an MSE loss that enforces alignment between EEG embeddings and CLIP image embeddings, and a cross-entropy loss that predicts the ImageNet-derived object label corresponding to the visual stimulus. This dual-loss design grounds the EEG embedding space in visual semantics and follows the alignment principles validated in the Thought2Text paper.

The language model backbone is DeepSeek-7B, chosen for its strong reasoning

capabilities and ability to generate detailed, coherent descriptions. DeepSeek-7B replaces the Mistral-7B model used in the original framework. A multimodal projection layer maps EEG embeddings into the token embedding space of the LLM so they can be used as conditioning signals during generation. During training, the projection layer is the only component updated, while both the EEG encoder and the LLM remain frozen.

## 2.2 Architecture and Design Decisions

Our system follows the three-stage architecture defined in Thought2Text as shown in Figure 1. In Stage 1, the EEG encoder is trained using EEG–image pairs to learn an embedding space aligned with CLIP features while also supporting object classification. In Stage 2, the LLM is trained using CLIP image embeddings instead of EEG, enabling it to incorporate multimodal embeddings while preserving the stability of the frozen backbone. In Stage 3, EEG embeddings replace image embeddings, and only the multimodal projection layer is trained so the LLM can interpret EEG-driven inputs.

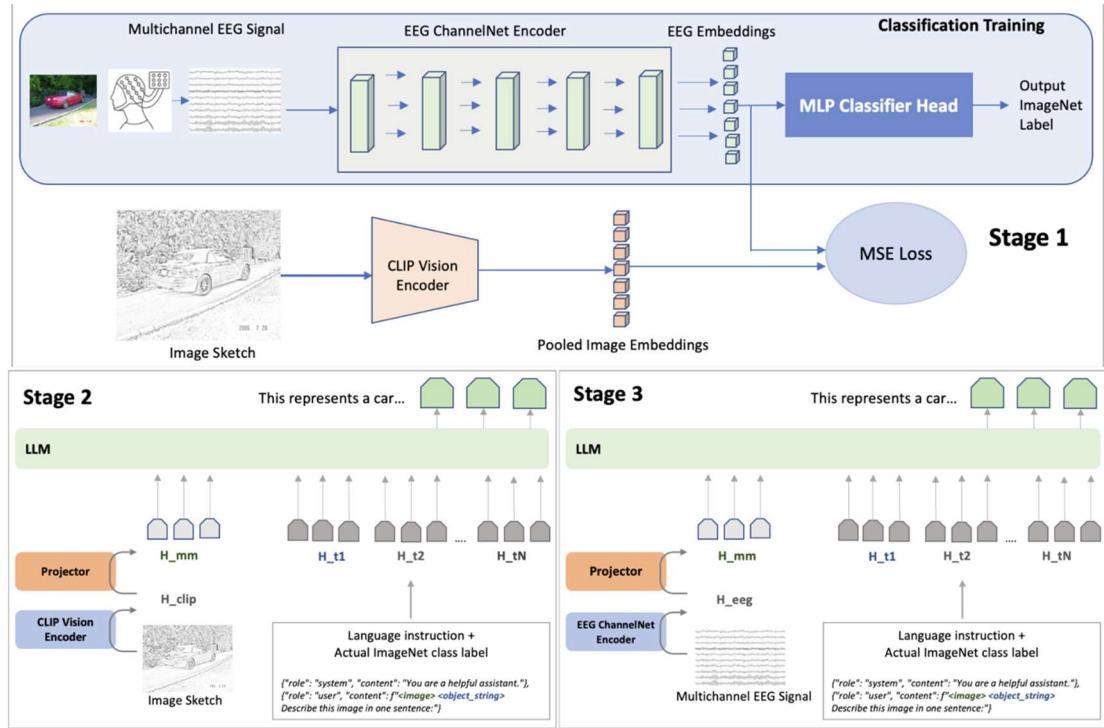


Figure 1: Multi stage training process for Thought2Text solution.

This staged design is necessary because EEG data is noisy and extremely limited compared to typical language model training datasets. Aligning EEG signals with CLIP embeddings provides a semantically meaningful intermediate representation, making downstream LLM training feasible. Freezing all components except the projection layer also prevents overfitting and instability. Additionally, we introduce enhanced instruction prompts during inference—such as detailed or creative prompts—to encourage the model to generate richer and more descriptive output.

## 2.3 Manual and/or Automatic Hyperparameter Optimization

Hyperparameter optimization in our system is performed manually and focuses on stabilizing multimodal alignment while improving the richness and adequacy of generated text. For model training (Stages 1–3), we tune conventional parameters such as learning rate, batch size, weight decay, warmup ratio, and gradient accumulation steps, following the stability requirements reported in the Thought2Text paper. These manually selected parameters were sufficient for achieving stable convergence given the limited EEG dataset.

In addition to the training-time hyperparameters, we also optimized several inference-time hyperparameters, including the prompt template used to condition the language model. Our inference code implements three prompt types—basic, detailed, and creative—each corresponding to a predefined textual template that modifies how the model interprets the EEG-derived embedding. The basic prompt (“<image><label\_string> Describe this image in one sentence:”) produces short factual captions, whereas the detailed prompt encourages descriptions containing colors, background elements, and actions. The creative prompt, in contrast, elicits more expressive and imaginative descriptions. By systematically evaluating these prompt options during inference, we treated prompt selection as a tunable hyperparameter that directly affects caption richness and semantic adequacy. Incorporating prompt engineering into the hyperparameter optimization process allowed us to improve the descriptive quality of the generated text without modifying the underlying model weights.

This inclusion of prompt engineering as part of the hyperparameter search allowed us to meet the goal of improving output quality while keeping the model architecture unchanged. The prompt variations represent a lightweight yet highly impactful form of parameter optimization, aligning with modern LLM practices where prompt selection can function as a controllable inference hyperparameter influencing generation performance.

## 2.4 Scientific References Supporting the Methods

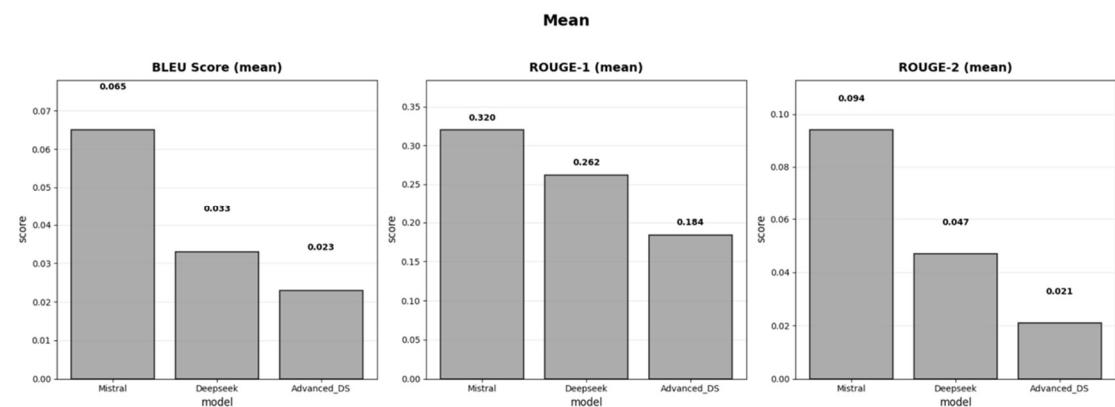
The methods in this work are directly supported by the design principles presented in the Thought2Text paper. The paper demonstrates that EEG signals are too noisy for end-to-end decoding and therefore require a three-stage training pipeline, including EEG – CLIP visual alignment, image-conditioned LLM fine-tuning, and EEG-conditioned projection learning. It further shows that grounding EEG in CLIP’s semantic embedding space stabilizes training and significantly improves text generation quality. The decision to freeze the LLM and train only a lightweight

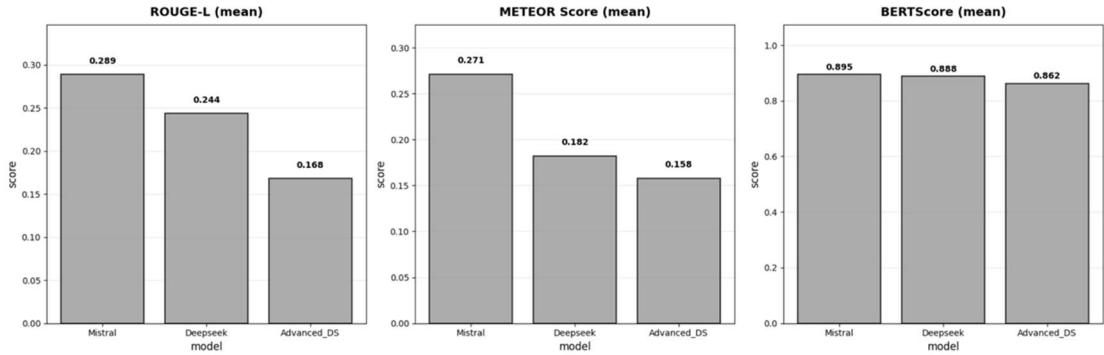
projection layer is also justified in the paper, which reports that this strategy avoids overfitting and enables the LLM to interpret multimodal inputs effectively. Lastly, the use of GPT-4-generated captions and instruction-style text for supervision supports our use of enhanced prompting, as the paper highlights the importance of rich linguistic targets for producing coherent EEG-based text generation.

### 3.Evaluation

Evaluation of the EEG-to-Text generation system employed multiple complementary metrics to assess different aspects of performance. String-based metrics including BLEU, ROUGE (with variants ROUGE-1, ROUGE-2, and ROUGE-L), and METEOR measured surface-level similarity between generated and reference texts. Semantic metrics, particularly BERTScore, evaluated deeper meaning preservation by comparing contextual embeddings. We follow the standard evaluation methods for our results.

We got three csv results in total. In the csv files content 5 contents, which are Ground Truth Image, Expected objects, Predicted object, Expected Caption, and Generated Caption. The evaluation is mainly about the Expected Caption and Generated Caption. Using Jupyter notebook to finish the evaluation and get the data visualization. The results are as below:





The DeepSeek-7B-Base model demonstrated lower scores compared to Mistral-7B-Instruct on metrics evaluating exact word overlap such as BLEU, METEOR and ROUGE. And the Advanced inference DeepSeek model even got lower scores compared to other two models. However, it achieved nearly equivalent performance on BERTScore, which means all the model performance good in deeper meaning preservation.

Basic prompts with both models showed compact but metric-favorable performance profiles, while detailed prompts expanded the richness dimensions at some cost to traditional accuracy metrics. Comparative bar charts highlighted how different prompt types affected specific aspects like word count, vocabulary diversity, and descriptive term frequency. The qualitative results bad do not mean that the model performance bad. Qualitative examination of generated text provided insights beyond quantitative metrics. Example comparisons showed that while Mistral often produced more factually accurate descriptions matching expected objects, DeepSeek with detailed prompts generated more elaborate and contextually rich text, even when containing some inaccuracies. For example, where a mistal prompt gave "*A young girl is wearing a pink dress and sitting on a swing.*" basic DeepSeek prompts produced "*A girl is sitting on a chair.*", and detailed DeepSeek prompts generated "*A young woman with long, dark hair is sitting on a couch. She has her legs crossed and she is looking at the camera.*" The downside is that in trying to be more descriptive, it sometimes made things up or got details wrong. There's a basic trade-off here between being detailed and being accurate.

The models' errors typically fell into three categories: misidentifying objects, leaving out details, or inventing elements that weren't there. The error also shows up during other LLM use cases. These patterns show specific opportunities for improving both

the models and how users prompt them.

## 4. Conclusions

This project identified several key findings for EEG-to-Text generation. First, the choice of language model is crucial, as models differ in their ability to follow instructions and generate accurate text. Second, how the model is prompted has a major effect: more detailed instructions lead to richer and more descriptive outputs. However, this increased descriptiveness is often accompanied by a slight decrease in strict factual accuracy, highlighting a trade-off between detail and precision.

These findings are subject to certain limitations, including potential constraints on generalizability from the dataset, the inherent challenge of measuring creative quality, and the focus on single sentences rather than extended text.

In summary, this project shows that DeepSeek-7B is promising for EEG-to-Text tasks, especially when used with detailed prompts to create richer descriptions. However, Mistral-7B performs better when the priority is metric-based accuracy. The strong influence of prompt engineering highlights that how we instruct the model is as important as the model itself for brain-computer interfaces.