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Exploring the Efficacy of Text Embeddings in Early Dementia Diagnosis from Speech

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Abstract—Language impairment is a key biomarker for neurodegenerative diseases such as Alzheimer’s disease (AD). With the rapid growth of Large Language Models, natural language processing (NLP) has become a preferred modality for the early prediction of AD from speech. In this work, we propose a two-stage process for early detection of AD from transcriptions of speech. The first step involves extracting a discriminative text embedding representation using public models from OpenAI. This embedding serves as input for a machine learning classifier in the second stage. In this paper, we investigate three text embedding models and eight machine learning classifiers, both deep learning (DL) based and non-DL based. The evaluation was conducted using the public ADReSSo dataset of 237 patients. The results show that models "ada-002" and "3-small" produce discriminative embeddings that lead to good performance when combined with a Deep Neural Network in classification, achieving accuracy rates of 83.10% and 84.51%, respectively.

Index Terms—Alzheimer’s Disease, Deep Learning, Large Language Model, Natural Language Processing, Speech Classification, Text Embedding.

I. INTRODUCTION

Alzheimer’s Disease (AD) is the leading cause of dementia and one of the most common neurodegenerative disorders. AD prevalence in ageing population is surging, causing increasing charge on society as a whole [1], [2]. AD is characterised by memory impairment and cognitive decline. Many studies have suggested that language impairment is present in most AD patients and may be used to help diagnose and assess the severity of the disease [3].

A patient’s spoken language carries a lot of information on their cognition state and how much their brain has been damaged. Investigating language disorders using Natural Language Processing (NLP) plays an important part in the investigation of cognitive disorders in general.

However, human evaluation in clinical settings can be subjective, leading to inconsistent diagnoses even among experts [4]. This is why, in a Precision Medicine setting, the evolution of Artificial Intelligence including Machine Learning algorithms, is a potential step forward for providing an objective measurability.

The emergence of Large Language Models (LLMs) and Transformer architectures represents a significant advancement in the field of artificial intelligence, particularly in tasks such as text classification and text embedding extraction. These algorithms, exemplified by models like GPT (Generative Pre-trained Transformer), are capable of autonomously learning to understand and generate text from vast datasets. By utilizing transformer architectures, these new models, known as text embedding models, can capture complex semantic information and produce high-quality vector representations for text. Their emergence has revolutionized numerous domains, such as NLP [5], and more specifically, in our context, the early detection of Alzheimer’s Disease from spoken language.

This paper explores the potential of text embedding models to capture informative representations of speech from patients. These representations should be powerful enough to differentiate between the speech of healthy patients and those with Alzheimer’s disease.

Our approach takes as input an audio recording of a patient and delivers a decision, either AD or non-AD. To achieve this, our approach comprises three steps (Figure 1). The initial step involves transcribing the text using the Wav2Vec 2.0 pretrained model algorithm [6]. The second step involves extracting a discriminative representation using text-embedding models. This representation then passes through the third step, which involves a binary classifier to classify the patients.

This paper focuses on the second and third steps. As several text embedding methods (primarily developed by OpenAI) and numerous AI classifiers exist, our goal is to explore the combination yielding the best performance. Our contributions are as follows:

- Regarding the text-embedding models, we have identified three models: ada-002, 3-small, and 3-large. Each model offers an embedding representation of different dimensions. As these models are pre-trained, our contribution involves investigating these models to determine which one is most suitable for the context of Alzheimer’s Disease.

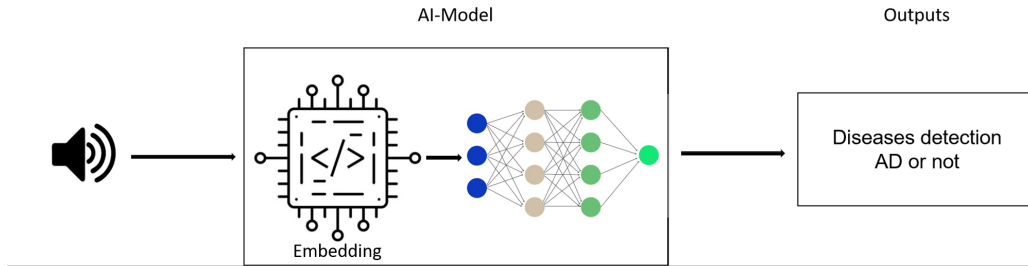


Fig. 1: Overview of the model for AD diagnosis and disease severity prediction from voice.

- Concerning the classification step, our contribution involves conducting a comparative study of AI models, DL-based models, and traditional models. This will enable us to select the most suitable classifier for our context, and to determine the most appropriate classifier for each type of embedding. Ultimately, we aim to identify the combination of text embedding and classifier that is best suited to our context.

The remainder of the paper is structured as follows. Section II provides a summary of the suggested methods for early Alzheimer’s disease detection. We describe our evaluation pipeline in Section III. In Section IV, we report our findings on the chosen dataset. Section V summarizes our findings and future prospects.

II. STATE OF THE ART

The early detection of Alzheimer’s disease (AD) through a preclinical stage with a unified framework of speech parameter extraction and language models (LLMs) has attracted considerable interest in recent years [7]. Machine learning algorithms and computational approaches have been investigated by researchers and medical professionals to identify changes in speech. In this regard, researchers have explored various techniques for using speech as a biomarker for classifying AD [8], [9], [10].

A system for early detection of AD comprises two main stages: feature extraction and classification. In this state-of-the-art review, we focus on the extraction of features from speech in the form of audio. The techniques typically involve analyzing speech and extracting features directly from the audio or from their transcriptions.

In addition to analyzing speech data alone, researchers are exploring the fusion of multiple modalities for a more robust representation in early AD detection. By combining information from various sources such as acoustic and language features, fusion approaches aim to enhance the accuracy and reliability of detection systems [11]. Techniques like feature-level fusion and decision-level fusion are being investigated to effectively integrate data from different modalities.

In the past, acoustic and language features could only be extracted through handcrafted methods. However, recently, with the evolution of ML algorithms and especially

DL, the latter are utilized as feature extraction tools, known as DL-based embedding feature extraction.

In the following, we present an overview of the various approaches of each category proposed in the literature.

A. Input features and embeddings

In this section, we explore feature extraction through acoustic and linguistic dimensions. Acoustic features encompass pitch and spectral content, while linguistic features include lexical and syntactic elements.

Dementia causes changes in people’s speech, observed through shifts in vocabulary and sentence construction. The linguistic aspects analyzed in this study focus on individual words and were extracted from manually transcribed databases. Individuals with AD tend to use shorter sentences and have a limited vocabulary w.r.t those without the condition. These linguistic features are expressed as proportions relative to the total number of words spoken in each instance, e.g., the percentage of adjectives used w.r.t the overall number of words uttered [12]. Words’ usage is important in understanding human language. Words can be represented as Bag-of-Words (BoW)[13] and Linguistic Inquiry and Word Count (LIWC)[13], encoding information about the words and their meanings. Other methods, like GloVe, Word2Vec [14], and TF-IDF [15], give us numerical representations of words based on how they are used and how often they appear.

On the speech signal side, there are various acoustic features that can be derived from audio signals [16]. These features encompass different aspects of the sound, such as its temporal properties, frequency composition, and amplitude variations. Among these features, we mention Mel-Frequency Cepstral Coefficients (MFCCs)[17], Linear Predictive Cepstral Coefficients (LPCC) [18], and Linear Predictive Cosine Transform coefficients (LPCT) [19].

B. Deep learning embeddings

In the previous section, we mentioned that features are hand-crafted, whether from acoustic signals in audio or linguistically from text. Recently, models based on Deep Learning architectures have been used to extract a discriminative representation of the input.

Deep learning embedding-based approaches consist of extracting discriminative representations of data obtained

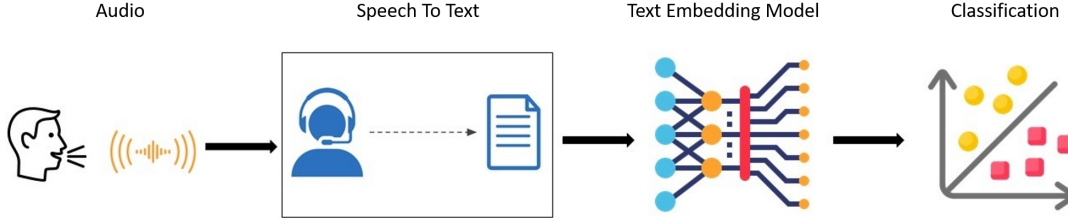


Fig. 2: Schematic showing the feature representation that are derived from speech.

through deep learning models. These embeddings effectively capture significant features or representations of the input data [20]. They are particularly useful for tasks like classification [4], clustering, and similarity computation. In various domains, different types of deep learning embeddings have been commonly employed, such as audio embedding and text embedding [21].

C. Fusion based approaches

The fusion of acoustic and linguistic signals entails integrating acoustic and linguistic knowledge from the source data into a unified input description. In essence, this approach aims to leverage the complementary nature of audio and textual evidence of sounds to develop models capable of performing more effectively in tasks such as speech recognition, sentiment analysis, or text processing. The techniques employed for fusion may vary depending on the task and the quality of the source data [21][22]. A recently published survey [23] identified the most popular embeddings used in the AD context: BERT [24], Generative Pre-trained Transformer (GPT) [25], Transformer [26], DistilBERT [27], and RoBERTa [28]. Our approach lies in the category utilizing linguistic features while employing DL models for text embedding representation.

III. METHODS

To investigate how speech can be used as an input to identify dementia, our approach includes two main steps: 1) Feature extraction and 2) Classification. The flowchart of our method is illustrated in Figure 2.

The input is a speech transcribed into text, followed by a feature extraction step based on a text-embedding model. Then, a ML classifier (both DL-based and non-DL-based) is applied. In this paper, our investigation focuses on finding suitable text-embedding-based features and classifiers for AD classification.

Text embeddings are numerical representations of text that capture the semantics, or meaning, of words, phrases, or entire documents. They are foundational in many NLP tasks, such as sentiment analysis and text classification. In our approach, we evaluate three text embedding models from OpenAI¹: text-embedding-ada-002 (ada-002), text-

embedding-3-large (3-large), and text-embedding-3-small (3-small). Table I presents a comparison of the three text embedding models. The first model "ada-002", is a text embedding solution optimized for adaptive learning. The second model, "3-large", is an automatic large-scale embedding model capable of processing multiple languages. The third model, "3-small", is a small-scale model with good performance in resource efficiency.

A. Classification

For the classification task, we evaluated classical machine learning models and deep neural networks using the text embedding features as input.

Regarding classical machine learning models, we considered the following classifiers: Logistic Regression (LR), Support Vector Classifier (SVM), Random Forest (RF), Bagging Classifier (Bagging), Extra Trees Classifier (ExtraTrees), XGBoost and Multilayer Perceptron (MLP).

Regarding DL-based models, we considered the Deep Neural Network (DNN) composed of sequential dense layers.

IV. EXPERIMENTAL RESULTS

A. Dataset

The ADReSSo Challenge offered benchmark datasets for three tasks: AD classification, MMSE score regression, and disease prognosis [29], [30]. The dataset for AD classification consisted of audio recordings from the "Cookie Theft" picture description task, taken from the Boston Diagnostic Aphasia Examination [31]. This task is commonly used to detect language disorders. Cognitively healthy individuals and AD patients recorded their descriptions of the "Cookie Theft" picture following the guidelines of the Boston Diagnostic Aphasia Examination. There were a total of 237 audio files in the dataset. In order to address potential bias, the files were split into training and test sets, with a 70/30 ratio and careful consideration of sex and age distributions. The training set had 166 instances, with 87 diagnosed as probable AD patients and 79 as healthy elderly controls. The test set consisted of 71 instances, with 35 AD patients and 36 cognitively normal individuals.

¹<https://platform.openai.com/docs/guides/embeddings/>

TABLE I: Classification results for the AD detection task for the three models embedding

Text embedding model	Classifier	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
text-embedding-ada-002	SVM	85.92	84.21	88.89	86.49
	LR	77.46	76.32	80.56	78.38
	RF	74.65	70.46	86.11	77.50
	Bagging	78.88	73.33	91.67	81.48
	ExtraTrees	76.06	72.09	86.11	78.48
	xgboost	77.46	76.32	80.56	78.38
	MLP	76.06	74.35	80.55	77.33
	DNN	83.10	81.58	86.11	83.78
text-embedding-3-large	SVM	80.28	83.00	77.78	80.00
	LR	73.24	72.98	75.00	73.97
	RF	71.83	70.00	77.78	73.68
	Bagging	69.01	65.91	80.56	72.50
	ExtraTrees	71.83	69.05	80.56	74.36
	xgboost	73.24	72.97	75.00	73.97
	MLP	84.51	83.78	86.11	84.93
	DNN	76.06	74.35	80.55	77.33
text-embedding-3-small	SVM	77.46	75.00	83.33	78.95
	LR	83.10	85.29	80.56	82.86
	RF	74.65	72.50	80.56	76.31
	Bagging	78.87	76.92	83.33	80.00
	ExtraTrees	76.06	75.68	77.78	76.71
	xgboost	78.87	78.37	80.55	79.45
	MLP	78.87	78.38	80.56	79.45
	DNN	84.51	90.32	77.78	83.80

B. Evaluation Protocol

The evaluation protocol concerns both the training and testing stages. During training, we used the grid search technique to find the best combination of hyperparameters. For each hyperparameter, a set of values is suggested, and then all combinations are evaluated.

To optimize the hyperparameters, cross-validation, consisting of dividing the training set into n folds (5 in our experiments) n was used. Each fold takes turns playing the role of the validation set, while the remaining $(n - 1)$ folds are used for training. This process is repeated n times, performing n evaluations. The combination performance is the average of all evaluations. For each classifier, the combination of hyperparameter values yielding the best performance was retained. In the test stage, after fixing the best hyperparameters, we used, for evaluation, standard metrics: accuracy, precision, recall, and F1-Score.

C. Results

In this section, we discuss the results of our approach on the test dataset, which involves two main steps: feature extraction using text embedding models and classification using machine learning algorithms. Three text embedding models are evaluated to extract a discriminative representation

of the text. This representation then serves as the input for the ML classifiers.

The binary classification results, summarized in Table I, presents the classifications using three different embedding models: "ada-002", "3-large", and "3-small". The evaluated classifiers include Support Vector Machine, Logistic Regression, Random Forest, Bagging, ExtraTrees, XGBoost, Multi-Layer Perceptron, and Deep Neural Network.

Our DNN model consists of four dense layers with 512, 256, 128, and 2 units respectively. Each layer uses ReLU activation and is followed by a dropout layer with a dropout rate of 0.1. The model concludes with a final softmax layer.

To compare classifier performances, we consider usual metrics, namely accuracy, precision, recall, and F1 score. To visually demonstrate which embedding method performs best, the results are grouped by classifier, showcasing the three embedding methods in Figure 3.

D. Discussion

Based on the results we have obtained, we can draw two observations. The first pertains to the ML classifier, and the second concerns the text embedding method.

Regarding the text embedding models, out of the 8 classifiers tested, in 6 cases, the "3-large" model yields the lowest performance, and only in the case of MLP does it provide the highest performance. This may be justified by

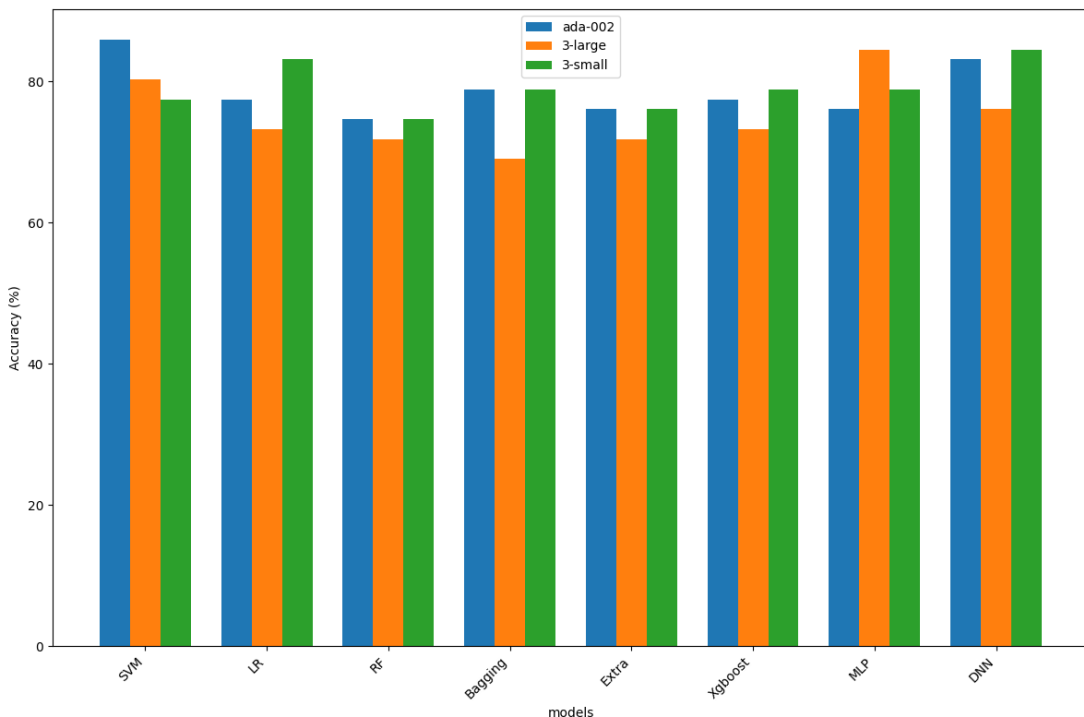


Fig. 3: Evaluation of Classifier Accuracy by Embedding Model

the fact that this model generates an embedding representation of a very high dimension (3072), and given that the dataset is small, the ML algorithms do not find enough data to learn their hyperparameters. For the other two models, "ada-002" and "3-small," the results are close in the case of Bagging, RF, XGBoost, and DNN. With the remaining models, the performance alternates.

When averaging the accuracy across all classifiers by embedding method, we find 79.04% for "3-small", and 78.6% for "ada-002". Whereas for "3-large," it is 73.84%.

A representation in a very high dimension remains a rich one, but it is essential, especially in our case with a small dataset, to apply certain techniques such as data augmentation and transfer learning.

The second observation concerns the ML classifiers, for the two best embedding models, "ada-002" and "3-small". The DNN is among the top two best models. It is the best model for "3-small", with an accuracy of 84.51%, and the second-best model for "ada-002" with 83.10%, following SVM which 85.92%. This is somewhat expected given the capabilities of DNNs demonstrated in the literature compared to traditional ML. However, it is unexpected that there is not a larger gap with traditional ML models. This can be justified by the fact that DNNs require a large quantity of data to effectively learn their parameters.

It is important to note that the last two points are based on the accuracy metric, but this analysis is almost identical for the other metrics, precision, recall, and F1-score.

V. CONCLUSIONS

In this paper, we have investigated the capacity of text embedding models based on Large Language Models to aid in the early diagnosis of dementia. Our main approach was to use text embedding models to generate a discriminant text embedding, a vector representation of transcribed speech text, that captures the semantic meaning of the input. Subsequently, an ML classifier is applied to classify patients as either having AD or not. Three embedding models from OpenAI were investigated, along with a set of eight classifiers. The results have shown that the models "ada-002" and "3-small" are the most effective, and the DNN classifier outperforms the traditional ML classifiers.

Future work includes improving DNN performance by using techniques such as transfer learning and data augmentation. Moreover, the used text embedding models are pretrained and do not account for the specificity of our data. We plan to create a second embedding specific to our context by using DL-based models, similar to the existing models. We will also explore a multimodal approach by considering other modalities such as handwriting analysis-based AD assessment [32], [33], [34], [35], [36], in addition to speech's [10], [37].

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