EEG-based detection of the locus of auditory attention with convolutional neural networks

Servaas Vandecappelle[1, 2], Lucas Deckers[2, 1], Neetha Das[2, 1], Amir Hossein Ansari[2], Alexander Bertrand[2], and Tom Francart[1]

[1]KU Leuven, Dept. Neurosciences, ExpORL. Herestraat 49 bus 721, B-3000 Leuven, Belgium

[2]KU Leuven, Dept. Electrical Engineering (ESAT), Stadius Center for Dynamical Systems, Signal Processing and Data Analytics. Kasteelpark Arenberg 10, B-3001 Leuven, Belgium

Abstract

In a multi-speaker scenario, the human auditory system is able to attend to one particular speaker of interest and ignore the others. It has been demonstrated that it is possible to use encephalography (EEG) signals to infer to which speaker someone is attending by relating the neural activity to the speech signals. However, classifying auditory attention within a short time interval remains the main challenge. We present a convolutional neural network-based approach to extract the locus of auditory attention (left/right) without knowledge of the speech envelopes. Our results show that it is possible to decode the locus of attention within 1 to $2\,\mathrm{s}$, with a median accuracy of around $81\,\%$. These results are promising for neuro-steered noise suppression in hearing aids, in particular in scenarios where per-speaker envelopes are unavailable.

Index Terms

Convolutional neural networks (CNN), Auditory attention detection (AAD), Electroencephalography (EEG), Neuro-steered auditory prosthesis, Brain-computer interfaces (BCI)

I. Introduction

In a multi-speaker scenario the human auditory system is able to focus on just one speaker, ignoring all other speakers and noise. This situation is called the "cocktail party problem" (Cherry, 1953). However, elderly people and people suffering from hearing loss have particular difficulty attending to one person in such an environment. In current hearing aids, this problem is mitigated by automatic noise suppression systems. When multiple speakers are present, however, these systems have to rely on heuristics such as the speaker volume or the listener's look direction to determine the relevant speaker, which often fail in practice.

The emerging field of auditory attention decoding (AAD) tackles the challenge of directly decoding auditory attention from neural activity, which may replace such unreliable and indirect heuristics. This research finds applications in the development of neuro-steered hearing prostheses that analyze brain signals to automatically decode the direction or speaker to whom the user is attending, to subsequently amplify that specific speech stream while suppressing other speech streams and surrounding noise. The desired result is increased speech intelligibility for the listener.

In a competing two-speaker scenario, it has been shown that the neural activity (as recorded using electroencephalography (EEG) or magnetoencephalography (MEG)) consistently tracks the dynamic variation of an incoming

speech envelope during auditory processing, and that the attended speech envelope is typically more pronounced than the unattended speech envelope (Ding and Simon, 2012; O'sullivan et al., 2014). This neural tracking of the stimulus can then be used to determine auditory attention. A common approach is stimulus reconstruction, where the post-stimulus brain activity is used to decode and reconstruct the attended stimulus envelope (O'sullivan et al., 2014; Pasley et al., 2012). The reconstructed envelope is then correlated with the original stimulus envelopes, and the one yielding the highest correlation is then considered to belong to the attended speaker. Other methods for attention decoding include the forward modelling approach: predicting EEG from the auditory stimulus (Akram et al., 2016; Alickovic et al., 2016), canonical correlation analysis (CCA)-based methods (de Cheveigné et al., 2018), and Bayesian state-space modeling (Miran et al., 2018).

All studies mentioned above are based on linear decoders. However, since the human auditory system is inherently non-linear (Faure and Korn, 2001), non-linear models (such as neural networks) could be beneficial for reliable and quick AAD. In de Taillez et al. (2017), a feedforward neural network for EEG-based speech stimulus reconstruction was presented, showing that artificial neural networks are a feasible alternative to linear decoding methods.

Recently, convolutional neural networks CNNs have become the preferred approach for many recognition and detection tasks, in particular in the field of image classsification (LeCun et al., 2015). Recent research on CNNs has also shown promising results for EEG classification: in seizure detection (Acharya et al., 2018a; Ansari et al., 2018a), depression detection (Liu et al., 2017), and sleep stage classification (Acharya et al., 2018b; Ansari et al., 2018b). In terms of EEG-based AAD, Ciccarelli et al. (2019) recently showed that a (subject-dependent) CNN using a classification approach can outperform linear methods for decision windows of $10\,\mathrm{s}$.

Both backward and forward models have an inherent trade-off between accuracy and decision window lengths. This trade-off was further investigated by Geirnaert et al. (2020), who showed that robust AAD-based volume control systems favor short window lengths (less than $10\,\mathrm{s}$) with mediocre accuracy over long windows (10 to $30\,\mathrm{s}$) with high accuracy. Current state-of-the-art models are capable of classifying auditory attention in a two-speaker scenario with high accuracy (75 to $85\,\%$) over a data window with a length of $10\,\mathrm{s}$ (e.g., de Cheveigné et al. (2018), Ciccarelli et al. (2019)), but the performance drops drastically when shorter windows are used. However, to achieve sufficiently fast AAD-based steering of a hearing aid, reliable detection in much shorter windows—down to a few seconds—is required.

Apart from decoding which speech envelope corresponds to the attended speaker, it may also be possible to decode the spatial locus of attention. That is, not decoding which *speaker* is attended to, but rather which location in space. The benefit of this approach for neuro-steered auditory prostheses is that no access to the clean speech stimuli is needed. This has been investigated based on differences in the EEG entropy features (Lu et al., 2018), but the performance was insufficient for practical use (below $70\,\%$ for $60\,\mathrm{s}$ windows). However, recent research (Bednar and Lalor, 2018, 2020; O'Sullivan et al., 2019; Patel et al., 2018; Wolbers et al., 2011) has shown that the direction of auditory attention is neurally encoded, indicating that it could be possible to decode the attended sound position or trajectory from EEG. Especially the alpha power activity could be tracked to determine the locus of auditory attention (Frey et al., 2014; Wöstmann et al., 2016), though those studies employed MEG.

The aim of this paper is to further explore the possibilities of CNNs for EEG-based AAD. As opposed to de Taillez

et al. (2017) and Ciccarelli et al. (2019), who aim to decode the attended speaker (for a given set of speech envelopes), we aim to decode the locus of auditory attention (left/right). When the locus of attention is known, a hearing aid can steer a beamformer in that direction to enhance the attended speaker.

II. Materials and Methods

A. Experiment setup

The dataset used for this work was gathered previously (Das et al., 2016). EEG data was collected from 16 normal-hearing subjects while they listened to two competing speakers and were instructed to attend to one particular speaker. Every subject signed an informed consent form approved by the KU Leuven ethical committee.

The EEG data was recorded using a 64-channel BioSemi ActiveTwo system, at a sampling rate of $8196\,\mathrm{Hz}$, in an electromagnetically shielded and soundproof room. The auditory stimuli were low-pass filtered with a cut-off frequency of $4\,\mathrm{kHz}$ and presented at $60\,\mathrm{dBA}$ through Etymotic ER3 insert earphones. APEX 3 was used as stimulation software (Francart et al., 2008).

The auditory stimuli were comprised of four Dutch stories, narrated by three male Flemish speakers (DeBuren, 2007). Each story was $12\,\mathrm{min}$ long and split into two parts of $6\,\mathrm{min}$ each. Silent segments longer than $500\,\mathrm{ms}$ were shortened to $500\,\mathrm{ms}$. The stimuli were set to equal root-mean-square intensities and were perceived as equally loud.

The experiment was split into eight trials, each $6\,\mathrm{min}$ long. In every trial, subjects were presented with two parts of two different stories. One part was presented in the left ear, while the other was presented in the right ear. Subjects were told to attend to one of the two. In subsequent trials, subjects attended either to the second part of the same story (so they could follow the story line) or to the first part of the next story. After each trial, subjects completed a multiple-choice quiz about the attended story. In total, there was $8 \times 6\,\mathrm{min} = 48\,\mathrm{min}$ of data per subject. For an example of how stimuli were presented, see Table I. (The original experiment (Das et al., 2016) contained 12 additional trials of $2\,\mathrm{min}$ each, collected at the end of every measurement session. These trials were repetitions of earlier stimuli and were not used in this work.)

The attended ear was alternated over consecutive trials to get an equal amount of data per ear (and per subject), which is important to avoid the lateralization bias described by Das et al. (2016). Stimuli were presented in the same order to each subject, and either dichotically or after head-related transfer function (HRTF) filtering (simulating sound coming from $\pm 90°$). As with the attended ear, the HRTF/dichotic condition was randomized and balanced within and over subjects. In this work we do not distinguish between dichotic and HRTF to ensure there is as much data as possible for training the neural network.

B. Data preprocessing

The EEG data was filtered with an equiripple FIR bandpass filter and its group delay was compensated for. For use with linear models, the EEG was filtered between 1 and $9\,\mathrm{Hz}$, which has been found to be an optimal frequency range for linear attention decoding (Ding and Simon, 2012; Pasley et al., 2012). For the CNN models, a broader bandwidth between 1 and $32\,\mathrm{Hz}$ was used, as de Taillez et al. (2017) show that this is more optimal. In both cases, the maximal bandpass attenuation was $0.5\,\mathrm{dB}$ while the stopband attenuation was $20\,\mathrm{dB}$ (at 0 to $1\,\mathrm{Hz}$) and $15\,\mathrm{dB}$

TABLE I: First eight trials for a random subject. Trials are numbered according to the order in which they were presented to the subject. Which ear was attended to first was determined randomly. After that, the attended ear was alternated. Presentation (Dichotic/HRTF) was balanced over subjects with respect to the attended ear. Adapted from Das et al. (2016).

Trial	Left Stimulus	Right Stimulus	Attn. Ear	Presentation
1	Story1, part1	Story2, part1	Left	Dichotic
2	Story2, part2	Story1, part2	Right	HRTF
3	Story3, part1	Story4, part1	Left	Dichotic
4	Story4, part2	Story3, part2	Right	HRTF
5	Story2, part1	Story1, part1	Left	Dichotic
6	Story1, part2	Story2, part2	Right	HRTF
7	Story4, part1	Story3, part1	Left	Dichotic
8	Story3, part2	Story4, part2	Right	HRTF

(at 32 to $64\,\mathrm{Hz}$). After the bandpass filtering the EEG data was downsampled to $20\,\mathrm{Hz}$ (linear model) and $128\,\mathrm{Hz}$ (CNN).

Data of each subject was divided into a training, validation and test set (for more information about each set, see Section II-D). Per set, data segments were generated with a sliding window equal in size to the chosen window length and with an overlap of $50\,\%$. Data was normalized on a subject-by-subject basis, based on statistics of the training set only, and in such a way that proportions between EEG channels were maintained. Concretely, for each subject we calculated the power per channel based on the $10\,\%$ trimmed mean of the squared samples. All channels were then divided by the square root of the median of those 64 values (one for each EEG channel). Data of each subject was thus normalized based on a single (subject-specific) value.

C. Convolutional neural networks

A convolutional neural network (CNN) consists of a series of convolutional layers and non-linear activation functions, typically followed by pooling layers. In convolutional layers, one or more convolutional filters slide over the data to extract local data features. Pooling layers then aggregate the output by computing, for example, the mean. Similarly to other types of neural networks, a CNN is optimized by minimizing a loss function, and the optimal parameters are estimated with an optimization algorithm such as stochastic gradient descent.

Our proposed CNN for decoding the locus of auditory attention is shown in Fig. 1. The input is a $[64, T]$ matrix, where 64 is the number of EEG channels in our dataset and T is the number of samples in the decision window. (We tested multiple decision window lengths, as discussed later in Section III.) The first step in the model is a convolutional layer, indicated in blue. Five independent [64×17] spatio-temporal filters are shifted over the input matrix, which, since the first dimension is equal to the number of channels, each result in a time series of dimensions $[1 \times T]$. Note that "17" is $130\,\mathrm{ms}$ at $128\,\mathrm{Hz}$, and $130\,\mathrm{ms}$ was found to be an optimal filter width —that is, longer or shorter decision window lengths gave a higher loss on a validation set. A rectifying linear unit (ReLu) activation function is used after the convolution step.

In the average pooling step, data is averaged over the time dimension, thus reducing each time series to a single number. After the pooling step, there are two fully connected (FC) layers. The first layer contains five neurons (one

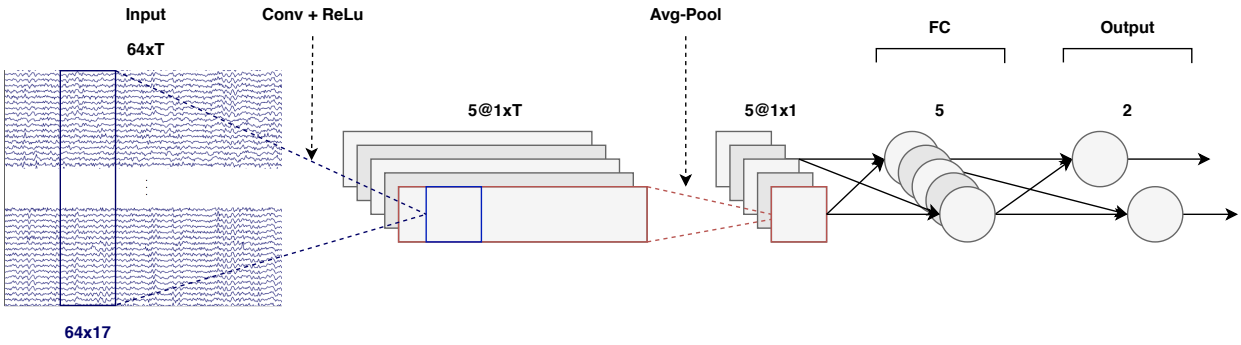

Fig. 1: CNN architecture (windows of T samples). Input: T time samples of a 64-channel EEG signal, at a sampling rate of $128\,\mathrm{Hz}$. Output: two scalars that determine the attended direction (left/right). The convolution, shown in blue, considers $130\,\mathrm{ms}$ of data over all channels.

for each time series) and is followed by a sigmoid activation function, and the second layer contains two (output) neurons. These two neurons are connected to a cross-entropy loss function. Note that with only two directions (left/right), a single output neuron (coupled with a binary cross-entropy loss) would have sufficed as well. With this setup it is easier to extend to more locations, however. The full CNN consists of approximately 5500 parameters.

The implementation was done in MATLAB 2016b and MatConvNet (version 1.0-beta25), a CNN toolbox for MATLAB (Vedaldi and Lenc, 2015). The source code is available at https://github.com/exporl/locus-of-auditory-attention-cnn.

D. CNN training and evaluation

The model was trained on data of all subjects, including the subject it was tested on (but without using the same data for both training and testing). This means we are training a subject-specific decoder, where the data of the other subjects can be viewed as a regularization or data augmentation technique to avoid overfitting on the (limited) amount of training data of the subject under test.

To prevent the model from overfitting to one particular story, we cross-validated over the four stories (resulting in four folds). That is, we held out one story and trained on the remaining three stories (illustrated in Table II). Such overfitting is not an issue for simple linear models, but for the CNN we propose here, our experiments have shown that it is an issue (see Section III-C). Indeed, even showing only the EEG responses to a part of a story could result in the model learning certain story-specific characteristics. That could then lead to overly optimistic results when the model is presented with the EEG responses to another (albeit different) part of the same story. Similarly, since each speaker has their own "story-telling" characteristics (for example, speaking rate or intonation), and a different voice timbre, EEG responses to different speakers may differ. Therefore, it is possible that the model gains an advantage by having "seen" the EEG response to a specific speaker, so we retained only the folds wherein the same speaker was never simultaneously part of both the training and the test set. In the end, only two folds remained (see Table II). We refer to the combined cross-validation approach as *leave-one-story+speaker-out*.

TABLE II: Cross-validating over stories and speakers. With the current dataset, there are only two folds that do not mix stories and speakers across training and test sets. Left: story 1 as test data; story 2, 3 and 4 as training data and validation data (85/15 % division, per story). Right: similarly, but now with a different story and speaker as test data. In both cases the story and speaker are completely unseen by the model. The model is trained on the same training set for all subjects and tested on a unique, subject-specific, test set.

Story	Speaker	Subject 1	Subject 2	...	Subject 16
1	1	test	test	...	test
2	2	train/val			
3	3	train/val			
4	3	train/val			

Story	Speaker	Subject 1	Subject 2	...	Subject 16
1	1	train/val			
2	2	test	test	...	test
3	3	train/val			
4	3	train/val			

In an additional experiment we investigated the subject-dependency of the model (see Section III-D), where, in addition to cross-validating over story and speaker, we also cross-validated over subjects. That is, we no longer trained and tested on N subjects, but instead trained on $N-1$ subjects and tested on the held-out subject. In this case we obtain a generic decoder, which is ideal in the sense that no re-training is needed for new subjects, making it more suitable for real-life applications. This also eliminates any potential overfitting on electrode position, etc.

We trained the network by minimizing the cross-entropy between the network outputs and the corresponding labels (the attended ear). We used mini-batch stochastic gradient descent with an initial learning rate of 0.3 and a momentum of 0.9. We applied a step decay learning schedule that decreased the learning rate after epoch 10 and 35 to 0.15 and 0.075, respectively, to assure convergence. The batch size was set to 20, partly because of memory constraints, and partly because we did not see much improvement with larger batch sizes. Weights and biases were initialized by drawing randomly from a normal distribution with a mean of 0 and a standard deviation of 0.5. Training ran for 100 epochs, as early experiments showed that the optimal decoder was usually found between epoch 70 and 95. Regularization consisted of weight decay with a value of 5×10^{-4}, and, after training, of selecting the decoder in the iteration where the validation loss was minimal. Note that the addition of data of the other subjects can also be viewed as a regularization technique that further reduces the risk of overfitting.

All hyperparameters given above were determined by running a grid search over a set of reasonable values. Performance during this grid search was measured on the validation set.

Note that in this work the decoding accuracy is defined as the percentage of correctly classified decision windows on the test set, averaged over the two folds mentioned earlier (one for each story narrated by a different speaker). Moreover, to capture the general performance of the CNN, the reported accuracy for each subject is the mean accuracy of 10 different training runs of the model, each with a different (random) initialization.

E. Linear baseline model (Stimulus reconstruction)

A linear stimulus reconstruction model (Biesmans et al., 2017) was used as baseline. In this model, a spatio-temporal filter was trained and applied on the EEG data and its time-shifted versions up to $250\,\mathrm{ms}$ delay, based on

least-squares regression, in order to reconstruct the envelope of the attended stimulus. The reconstructed envelope was then correlated (Pearson correlation coefficient) with each of the two speaker envelopes over a data window with a pre-defined length, denoted as the decision window (different lengths were tested). The classification was made by selecting the position corresponding to the speaker that yielded the highest correlation in this decision window. The envelopes were calculated with the "powerlaw subbands" method proposed by Biesmans et al. (2017); that is, a gammatone filter bank was used to split the speech into subbands, and per subband the envelope was calculated with a power law compression with exponent 0.6. The different subbands were then added again (each with a coefficient of 1) to form the broadband envelope. Envelopes were filtered and downsampled in the same vein as the EEG recordings.

For a fair comparison with the CNN, the linear model was also trained in a *leave-one-story+speaker-out* way. In contrast to the CNN, however, the linear model was not trained on any other data than that of the subject under testing, since including data of other subjects harms the performance of the linear model.

F. Minimal expected switch duration

For some of the statistical tests below, we use the minimal expected switch duration (MESD) proposed by Geirnaert et al. (2020) as a relevant metric to assess AAD performance. The goal of the MESD metric is to have a single value as measure of performance, resolving the trade-off between accuracy and the decision window length. The MESD was defined as the expected time required for an AAD-based gain control system to reach a stable volume switch between both speakers, following an attention switch of the user. The MESD is calculated by optimizing a Markov chain as a model for the volume control system, which uses the AAD decision time and decoding accuracy as parameters. As a by-product, it provides the optimal volume increment per AAD decision.

All MESD values reported in this work are based on the decoding accuracy as defined at the end of Section II-D.

III. Results

A. Decoding performance

Four different decision window lengths were tested: 10, 5, 2 and $1\,\mathrm{s}$. This defines the amount of data that is used to make a single left/right decision. In the AAD literature, decision windows range from approximately 60 to $5\,\mathrm{s}$. In this work, the focus lies on shorter decision windows. This is done for practical reasons: in neuro-steered hearing aid applications the detection time should ideally be short enough to quickly detect attention switches of the user.

Figure 2 shows the decoding accuracy at 1 and $10\,\mathrm{s}$ for the CNN and the linear model. For both decision windows the CNN had a higher median decoding accuracy, but a larger inter-subject variability. Two subjects had a decoding accuracy below $50\,\%$ and were therefore not considered in the subsequent analysis, nor are they shown in the figures below.

For $1\,\mathrm{s}$ decision windows, a Wilcoxon signed-rank test yielded significant differences in detection accuracy between the the linear decoder model and the CNN ($W = 3$, $p < 0.001$), with an increase in median accuracy from $58.1\,\%$ to $80.8\,\%$. Similarly, for $10\,\mathrm{s}$ decision windows, a Wilcoxon signed-rank test showed a significant difference

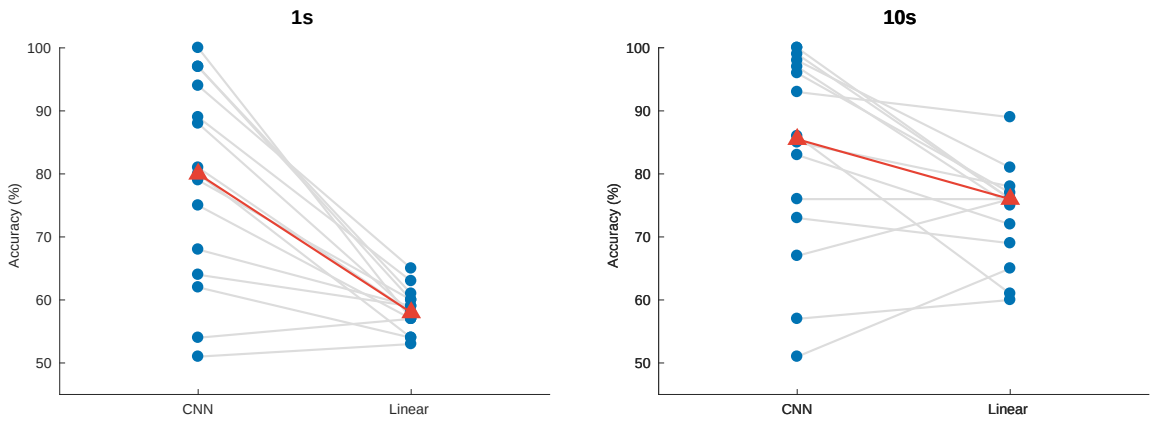

Fig. 2: Auditory attention detection performance of the CNN for two different window lengths. Linear decoding model shown as baseline. Blue dots: per-subject results, averaged over two test stories. Gray lines: same subjects. Red triangles: median accuraries.

between the two models ($W = 16$, $p = 0.0203$), with the CNN achieving a median accuracy of $85.1\,\%$ compared to $75.7\,\%$ for the linear model.

The minimal expected switch duration (MESD) (Geirnaert et al., 2020) outputs a single number for each subject, given a set of window lengths and corresponding decoding accuracies. This allows for a direct comparison between the linear and the CNN model, independent of window length. As shown in Fig. 3, the linear model achieves a median MESD of $22.5\,\mathrm{s}$, while the CNN achieves a median MESD of only $4.03\,\mathrm{s}$. A Wilcoxon-signed rank shows this difference to be significant ($W = 14$, $p = 0.0134$).

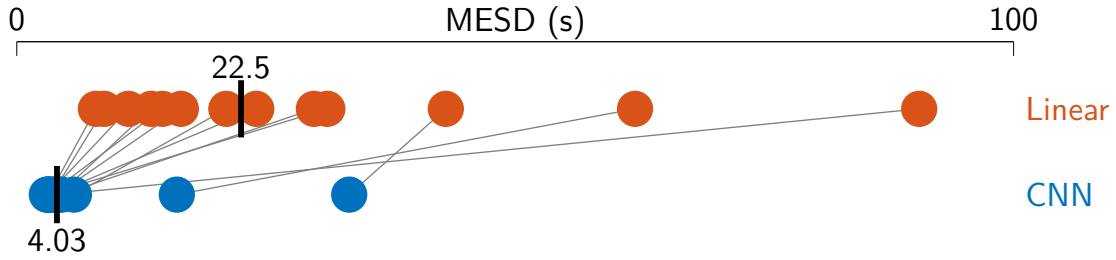

Fig. 3: Minimal expected switch durations (MESDs) for the CNN and the linear baseline. Dots: per-subject results, averaged over two test stories. Gray lines: same subjects. Vertical black bars: median MESD. One subject with an MESD of more than $350\,\mathrm{s}$ (CNN) is not shown in the figure, but was included in the calculation of the median.

It is not entirely clear why the CNN fails for two of the 16 subjects. Our analysis shows that the results depend heavily on the story that is being tested on: for the two subjects with below $50\,\%$ accuracy the CNN performed poorly on story 1 and 2, but performed well on story 3 and 4 ($80\,\%$ and higher). Our results are based on story 1 and 2, however, since story 3 and 4 are narrated by the same speaker and we wanted to avoid having the same speaker

in both the training and test set. It is possible that the subjects did not comply with the task in these conditions.

B. Effect of decision window length

Shorter decision windows contain less information and should therefore result in poorer performance compared to longer decision windows. Figure 4 visualizes the relation between window length and detection accuracy.

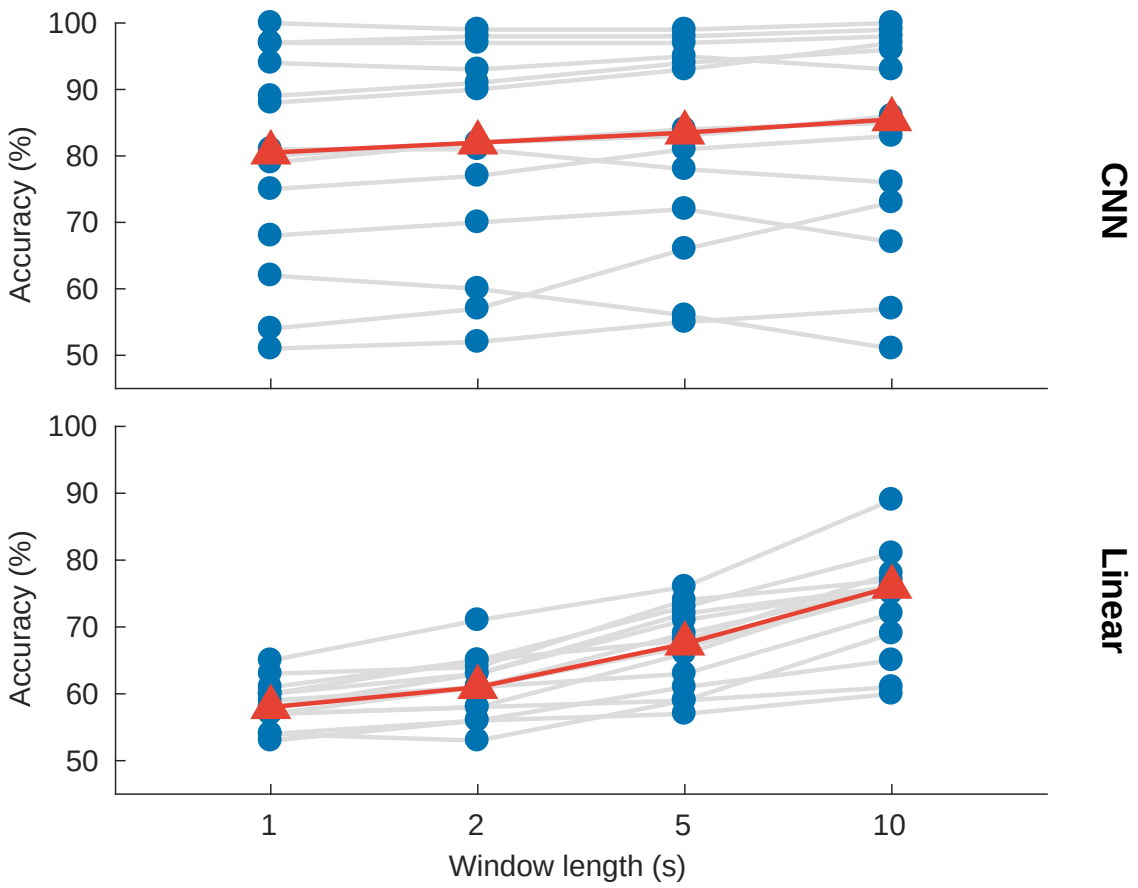

Fig. 4: Auditory attention detection performance (decision windows of 1, 2, 5 and 10 s). Blue dots: per-subject results, averaged over two test stories. Gray lines: same subjects. Red triangles: median accuracies.

A linear mixed-effects model fit for decoding accuracy, with window length as fixed effect and subject as random effect, did not show a significant effect of window length ($df = 62$, $p = 0.399$) for the CNN model (Fig. 4, top). In contrast, for the linear model, the same method did find a significant effect of window length ($df = 62$, $p < 0.001$) (Fig. 4, bottom).

C. Effect of validation procedure

In all previous results we used a *leave-one-story+speaker-out* scheme to prevent the CNN from gaining an advantage by already having seen EEG responses elicited by the same speaker or different parts of the same story

(see Section II-D). However, it is noted that in the majority of the AAD literature, training and test sets often do contain samples from the same speaker or story (albeit from different parts of the story).

To investigate the impact of cross-validating over speaker and story, we trained the CNN again, but this time using data of each trial. Here, the training set consisted of the first $75\,\%$ of each trial, the validation set of the next $15\,\%$, and the test set of the last $15\,\%$.

Figure 5 shows the results of both strategies for decision windows of $1\,\mathrm{s}$. Other window lengths show similar results. Clearly, even though the test and training set were always disjoint, performance was significantly better when the network had already seen other examples from the same story or speaker during training. For decision windows of $1\,\mathrm{s}$, using data from all trials resulted in a median decoding accuracy of $92.8\,\%$ (Fig. 5, left), compared to only $80.8\,\%$ when leaving out both story and speaker (Fig. 5, right). A Wilcoxon signed-rank test shows this difference to be significant ($W = 91$, $p = 0.0134$).

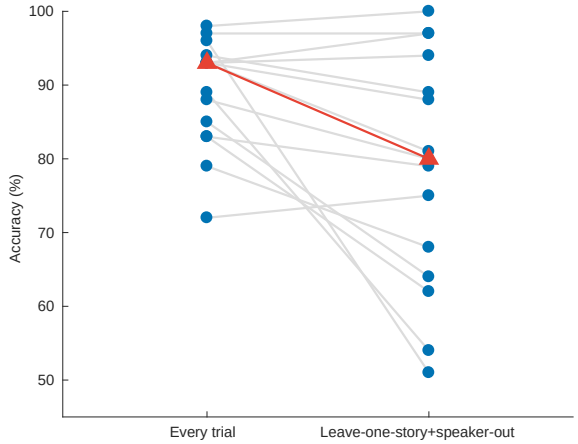

Fig. 5: Impact of the model validation strategy on the performance of the CNN (decision windows of $1\,\mathrm{s}$). In *Every trial*, the training, validation and test sets are extracted from every trial (although always disjoint). In *Leave-one-story+speaker-out*, the training set does not contain examples of the speakers or stories that appear in the test set.

D. Subject-independent decoding

In a final experiment we investigated how well the CNN performs on subjects that were not part of the training set. Here, the CNN is trained on $N - 1$ subjects and tested on the held-out subject—but still in a *leave-one-story+speaker-out* manner, as before. The results are shown in Fig. 6. For windows of $1\,\mathrm{s}$, a Wilcoxon signed-rank test shows that leaving out the test subject results in a significant decrease in decoding accuracy from $80.8\,\%$ to $69.3\,\%$ ($W = 14$, $p = 0.0134$). Surprisingly, for one subject the network performs better when its data was not included during training. Other window lengths show similar results.

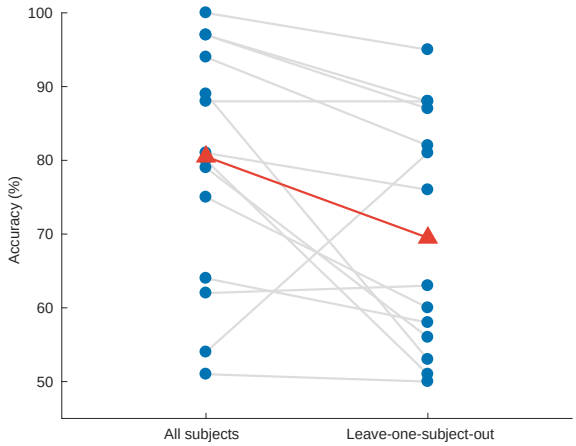

Fig. 6: Impact of leaving out the test subject on the accuracy of the CNN model (decision windows of 1 s). Blue dots: per-subject results, averaged over two test stories. Gray lines: same subjects. Red triangles: median accuracies.

IV. Discussion

We proposed a novel CNN-based model for decoding the direction of attention (left/right) without access to the stimulus envelopes, and found it to significantly outperform a linear decoder that was trained to reconstruct the envelope of the attended speaker.

A. Decoding accuracy

The CNN model resulted in a significant increase in decoding accuracy compared to the linear model: for decision windows as low as 1 s, the CNN's median performance is around 81 %. This is also better than entropy-based direction classification presented in literature (Lu et al., 2018), in which the average decoding performance proved to be insufficient for real-life use (less than 80 % for decision windows of 60 s). Moreover, our network achieves an unprecedented median MESD of only 4.03 s, compared to 22.5 s for the linear method, allowing for robust neuro-steered volume control with a practically acceptable latency.

Despite the impressive median accuracy of our CNN, there is clearly more variability between subjects in comparison to the linear model. Figure 4, for example, shows that some subjects have an accuracy of more than 90 %, while others are at chance-level—and two subjects even perform below chance level. While this increase in variance could be due to our dataset being too small for the large number of parameters in the CNN, we observed in Section II-D that the poorly performing subjects do better on story 3 and 4, which were originally excluded as a test set in the cross-validation. Why our system performs poorly on some stories, and why this effect differs from subject to subject, is not clear, but nevertheless it does impact the per-subject results. This story-effect is not present in the linear model, probably because that model has far fewer parameters and is unable to pick up certain intricacies of stories or speakers.

Interestingly, there was no significant effect of window length on accuracy. For the CNN, the median accuracy for windows of 1 s was 80.8 %, compared to 85.1 % for windows of 10 s. One would expect a larger increase, as it is

the case in the linear model: $58.1\,\%$ for windows $1\,\mathrm{s}$ compared to $75.7\,\%$ for windows of $10\,\mathrm{s}$. We hypothesize that this is due to the fact that the CNN does not know the stimulus and is only required to decode the locus of attention. As opposed to traditional AAD techniques, it does not have to relate the neural activity to the underlying speech envelopes. The latter requires computing correlation coefficients between the stimulus and the neural responses, which are only sufficiently reliable and discriminative when computed over long windows.

Lastly, we evaluated our system using a *leave-one-story+speaker-out* approach, which is not commonly done in the literature. While for linear models this is probably fine, our results demonstrate that for artificial neural networks a stricter cross-validation is required, as they appear to be able to overfit to the characteristics of a specific story or speaker (despite the use of a non-overlapping training and test set, and despite the fact that the network only sees the neural responses), thereby yielding results that are possibly overly optimistic.

B. Future improvements

We hypothesize that much of the variation within and across subjects and stories currently observed is due to the small size of the dataset. The network probably needs more examples to learn to generalize better. However, a sufficiently large dataset, one which also allows for the strict cross-validation used in this work, is currently not available.

Partly as a result of the limited amount of data available, the CNN proposed in this work is relatively simple. With more data, more complex CNN architectures would become feasible. Such complex CNN architectures may benefit more from generalization features such as dropout and batch normalization, not discussed in this work.

Also, for a practical neuro-steered hearing aid, it may be beneficial to make soft decisions. Instead of the translation of the continuous softmax outputs into binary decisions, the system could output a probability of left or right being attended, and the corresponding noise suppression system could adapt accordingly. In this way the integrated system could benefit from temporal relations or the knowledge of the current state to predict future states. The CNN could for example be extended by a long short term memory (LSTM) network.

C. Applications

The main bottleneck in the implementation of neuro-steered noise suppression in hearing aids thus far has been the detection speed (state-of-the-art algorithms only achieve reasonable accuracies when using long decision windows). This can be quantified through the MESD metric, which captures both the effect of detection speed and decoding accuracy. While our linear baseline model achieves a median MESD of $22.5\,\mathrm{s}$, our CNN achieves a median MESD of only $4.03\,\mathrm{s}$, which is a major step forward.

Moreover, our CNN-based system has an MESD of $5\,\mathrm{s}$ or less for 10 out of 16 subjects (7 subjects even have an MESD below $4\,\mathrm{s}$), which is what we assume the minimum for an auditory attention detection system to be feasible in practice.[1] (For reference, an MESD of 5 corresponds to a decoding accuracy of $70\,\%$ at $1\,\mathrm{s}$.) On the

[1]Note that while a latency of $5\,\mathrm{s}$ may at first sight still seem long for practical use, it should not be confused with the time it takes to actually *start* steering towards the attended speaker: the user will already hear the effect of switching attention sooner. Instead, the MESD corresponds to the total time it takes to switch an AAD-steered volume control system from one speaker to the other in a *reliable* fashion by introducing an optimized amount of "inertia" in the volume control system to avoid spurious switches due to false positives (Geirnaert et al., 2020).

other hand, one subject does have an MESD of $380\,\mathrm{s}$, and two subjects have an infinitely high MESD due to below $50\,\%$ performance. The inter-subject variability thus remains a challenge, since the goal is to create an algorithm that is both robust and able to quickly decode attention within the assumed limits for all subjects.

Another difficulty in neuro-steered hearing aids is that the clean speech envelopes are not available. This has so far been addressed using sophisticated noise suppression systems (Aroudi et al., 2018; O'Sullivan et al., 2017; Van Eyndhoven et al., 2017). If the speakers are spatially separated, our CNN might elegantly solve this problem by steering a beamformer towards the direction of attention, without requiring access to the envelopes of the speakers at all. Note that in a practical system the system would need to be extended to more than two possible directions of attention, depending on the desired spatial resolution.

For application in hearing aids, a number of other issues need to be investigated, such as the effect of hearing loss (Holmes et al., 2017), acoustic circumstances (for example, background noise, speaker locations and reverberation (Aroudi et al., 2019; Das et al., 2018, 2016; Fuglsang et al., 2017)), mechanisms for switching attention (Akram et al., 2016), etc. The computational complexity would also need to be reduced. Especially if deeper, more complex networks are designed, CNN pruning will be necessary (Anwar et al., 2017). Then a hardware DNN implementation, or even computation on an external device such as a smartphone could be considered. Another practical obstacle are the numerous electrodes used for the EEG measurements. Similar to the work of (Fiedler et al., 2016; Mirkovic et al., 2015; Montoya-Martínez et al., 2019; Narayanan Mundanad and Bertrand, 2018), it should be investigated how many and which electrodes are minimally needed for adequate performance.

In addition to potential use in future hearing devices, fast and accurate detection of the locus of attention can also be an important tool in future fundamental research. Thus far it was not possible to measure compliance of the subjects with the instruction to direct their attention to one ear. Not only may the proposed CNN approach enable this, but it will also allow to track the locus of attention in almost real-time, which can be useful to study attention in dynamic situations, and its interplay with other elements such as eye gaze, speech intelligibility and cognition. Note that for this application, the leave-one-story out strategy is not required, and much higher performance can be achieved by training on the same material used for testing.

In conclusion, we proposed a novel EEG-based CNN for decoding the locus of auditory attention (based only on the EEG), and showed that it significantly outperforms a commonly-used linear model for decoding the attended speaker. Moreover, we showed that the way the model is trained impacts the results significantly, and that a thoughtful cross-validation where both the speaker and story are unseen by the model is important—at least when dealing with models that are more complex than typical linear models. Although there are still some practical problems, the proposed model approaches the desired real-time detection performance. Furthermore, as it does not require the clean speech envelopes, this model has potential applications in realistic noise suppression systems for hearing aids.

V. Acknowledgements

The work was funded by KU Leuven Special Research Fund C14/16/057 and C24/18/099, Research Foundation Flanders (FWO) project nrs. 1.5.123.16N and G0A4918N, the European Research Council (ERC) under the European

Union's Horizon 2020 research and innovation programme (grants no. 637424 (T. Francart) and no. 802895 (A. Bertrand)). A. Ansari is a postdoctoral fellow at FWO. We thank Simon Geirnaert for his constructive criticism and for help with some of the technical issues we encountered.

REFERENCES

Acharya, U. R., Oh, S. L., Hagiwara, Y., Tan, J. H., and Adeli, H. (2018a). Deep convolutional neural network for the automated detection and diagnosis of seizure using EEG signals. *Computers in biology and medicine*, 100:270–278.

Acharya, U. R., Oh, S. L., Hagiwara, Y., Tan, J. H., Adeli, H., and Subha, D. P. (2018b). Automated EEG-based screening of depression using deep convolutional neural network. *Computer methods and programs in biomedicine*, 161:103–113.

Akram, S., Presacco, A., Simon, J. Z., Shamma, S. A., and Babadi, B. (2016). Robust decoding of selective auditory attention from MEG in a competing-speaker environment via state-space modeling. *NeuroImage*, 124:906–917.

Alickovic, E., Lunner, T., and Gustafsson, F. (2016). A system identification approach to determining listening attention from EEG signals. In *24th European Signal Processing Conference (EUSIPCO), Aug 28-Sep 2, 2016. Budapest, Hungary*, pages 31–35. IEEE.

Ansari, A. H., Cherian, P. J., Caicedo, A., Naulaers, G., De Vos, M., and Van Huffel, S. (2018a). Neonatal seizure detection using deep convolutional neural networks. *International journal of Neural Systems*, page 1850011.

Ansari, A. H., De Wel, O., Lavanga, M., Caicedo, A., Dereymaeker, A., Jansen, K., Vervisch, J., De Vos, M., Naulaers, G., and Van Huffel, S. (2018b). Quiet sleep detection in preterm infants using deep convolutional neural networks. *Journal of Neural Engineering*, 15(6):066006.

Anwar, S., Hwang, K., and Sung, W. (2017). Structured pruning of deep convolutional neural networks. *ACM Journal on Emerging Technologies in Computing Systems (JETC)*, 13(3):32.

Aroudi, A., Marquardt, D., and Daclo, S. (2018). EEG-based auditory attention decoding using steerable binaural superdirective beamformer. In *2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Calgary, Alberta, Canada*, pages 851–855. IEEE.

Aroudi, A., Mirkovic, B., De Vos, M., and Doclo, S. (2019). Impact of different acoustic components on eeg-based auditory attention decoding in noisy and reverberant conditions. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 27(4):652–663.

Bednar, A. and Lalor, E. C. (2018). Neural tracking of auditory motion is reflected by delta phase and alpha power of EEG. *NeuroImage*, 181:683–691.

Bednar, A. and Lalor, E. C. (2020). Where is the cocktail party? Decoding locations of attended and unattended moving sound sources using EEG. *NeuroImage*, 205:116283.

Biesmans, W., Das, N., Francart, T., and Bertrand, A. (2017). Auditory-inspired speech envelope extraction methods for improved EEG-based auditory attention detection in a cocktail party scenario. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 25(5):402–412.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *The Journal of the acoustical society of America*, 25(5):975–979.

Ciccarelli, G., Nolan, M., Perricone, J., Calamia, P. T., Haro, S., O'Sullivan, J., Mesgarani, N., Quatieri, T. F., and Smalt, C. J. (2019). Comparison of Two-Talker Attention Decoding from EEG with Nonlinear Neural Networks and Linear Methods. *Scientific Reports*, 9(1):11538.

Das, N., Bertrand, A., and Francart, T. (2018). EEG-based auditory attention detection: boundary conditions for background noise and speaker positions. *Journal of Neural Engineering*, 15(6):066017.

Das, N., Biesmans, W., Bertrand, A., and Francart, T. (2016). The effect of head-related filtering and ear-specific decoding bias on auditory attention detection. *Journal of Neural Engineering*, 13(5):056014.

de Cheveigné, A., Wong, D. D., Di Liberto, G. M., Hjortkjær, J., Slaney, M., and Lalor, E. (2018). Decoding the auditory brain with canonical component analysis. *NeuroImage*, 172:206–216.

de Taillez, T., Kollmeier, B., and Meyer, B. T. (2017). Machine learning for decoding listeners' attention from electroencephalography evoked by continuous speech. *European Journal of Neuroscience*.

DeBuren (2007). Radioboeken voor kinderen. http://www.radioboeken.eu/kinderradioboeken.php?lang=NL.

Ding, N. and Simon, J. Z. (2012). Emergence of neural encoding of auditory objects while listening to competing speakers. *Proceedings of the National Academy of Sciences*, 109(29):11854–11859.

Faure, P. and Korn, H. (2001). Is there chaos in the brain? i. concepts of nonlinear dynamics and methods of investigation. *Comptes Rendus de l'Académie des Sciences-Series III-Sciences de la Vie*, 324(9):773–793.

Fiedler, L., Obleser, J., Lunner, T., and Graversen, C. (2016). Ear-EEG allows extraction of neural responses in challenging listening scenarios—a future technology for hearing aids? In *38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Orlando, FL, USA*, pages 5697–5700. IEEE.

Francart, T., Van Wieringen, A., and Wouters, J. (2008). APEX 3: a multi-purpose test platform for auditory psychophysical experiments. *Journal of Neuroscience Methods*, 172(2):283–293.

Frey, J. N., Mainy, N., Lachaux, J.-P., Müller, N., Bertrand, O., and Weisz, N. (2014). Selective modulation of auditory cortical alpha activity in an audiovisual spatial attention task. *Journal of Neuroscience*, 34(19):6634–6639, doi:https://doi.org/10.1523/JNEUROSCI.4813–13.2014.

Fuglsang, S. A., Dau, T., and Hjortkjær, J. (2017). Noise-robust cortical tracking of attended speech in real-world acoustic scenes. *NeuroImage*, 156:435–444.

Geirnaert, S., Francart, T., and Bertrand, A. (2020). An interpretable performance metric for auditory attention decoding algorithms in a context of neuro-steered gain control. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 28(1):307–317.

Holmes, E., Kitterick, P. T., and Summerfield, A. Q. (2017). Peripheral hearing loss reduces the ability of children to direct selective attention during multi-talker listening. *Hearing research*, 350:160–172.

LeCun, Y., Bengio, Y., and Hinton, G. (2015). Deep learning. *Nature*, 521(7553):436.

Liu, N., Lu, Z., Xu, B., and Liao, Q. (2017). Learning a convolutional neural network for sleep stage classification. In *Image and Signal Processing, BioMedical Engineering and Informatics (CISP-BMEI), 2017 10th International Congress, Shanghai, China*, pages 1–6. IEEE.

Lu, Y., Wang, M., Zhang, Q., and Han, Y. (2018). Identification of auditory object-specific attention from single-trial electroencephalogram signals via entropy measures and machine learning. *Entropy*, 20(5):386.

Miran, S., Akram, S., Sheikhattar, A., Simon, J. Z., Zhang, T., and Babadi, B. (2018). Real-time tracking of selective auditory attention from M/EEG: A bayesian filtering approach. *Frontiers in Neuroscience*, 12.

Mirkovic, B., Debener, S., Jaeger, M., and De Vos, M. (2015). Decoding the attended speech stream with multi-channel EEG: implications for online, daily-life applications. *Journal of Neural Engineering*, 12(4):046007.

Montoya-Martínez, J., Bertrand, A., and Francart, T. (2019). Optimal number and placement of eeg electrodes for measurement of neural tracking of speech. *bioRxiv*.

Narayanan Mundanad, A. and Bertrand, A. (2018). The effect of miniaturization and galvanic separation of EEG sensor devices in an auditory attention detection task. In *40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Honolulu, Hawai*, pages 77–80. IEEE.

O'Sullivan, A. E., Lim, C. Y., and Lalor, E. C. (2019). Look at me when I'm talking to you: Selective attention at a multisensory cocktail party can be decoded using stimulus reconstruction and alpha power modulations. *European Journal of Neuroscience*, (March):1–14.

O'sullivan, J. A., Power, A. J., Mesgarani, N., Rajaram, S., Foxe, J. J., Shinn-Cunningham, B. G., Slaney, M., Shamma, S. A., and Lalor, E. C. (2014). Attentional selection in a cocktail party environment can be decoded from single-trial EEG. *Cerebral Cortex*, 25(7):1697–1706.

O'Sullivan, J., Chen, Z., Herrero, J., McKhann, G. M., Sheth, S. A., Mehta, A. D., and Mesgarani, N. (2017). Neural decoding of attentional selection in multi-speaker environments without access to clean sources. *Journal of Neural Engineering*, 14(5):056001.

Pasley, B. N., David, S. V., Mesgarani, N., Flinker, A., Shamma, S. A., Crone, N. E., Knight, R. T., and Chang, E. F. (2012). Reconstructing speech from human auditory cortex. *PLoS biology*, 10(1):e1001251.

Patel, P., Long, L. K., Herrero, J. L., Mehta, A. D., and Mesgarani, N. (2018). Joint representation of spatial and phonetic features in the human core auditory cortex. *Cell reports*, 24(8):2051–2062 doi:https://doi.org/10.1016/j.celrep.2018.07.076.

Van Eyndhoven, S., Francart, T., and Bertrand, A. (2017). EEG-informed attended speaker extraction from recorded speech mixtures with application in neuro-steered hearing prostheses. *IEEE Transactions Biomedical Engineering*, 64(5):1045–1056.

Vedaldi, A. and Lenc, K. (2015). Matconvnet: Convolutional neural networks for matlab. In *Proceedings of the 23rd ACM international conference on Multimedia*, pages 689–692. ACM.

Wolbers, T., Zahorik, P., and Giudice, N. A. (2011). Decoding the direction of auditory motion in blind humans. *Neuroimage*, 56(2):681–687.

Wöstmann, M., Herrmann, B., Maess, B., and Obleser, J. (2016). Spatiotemporal dynamics of auditory attention synchronize with speech. *Proceedings of the National Academy of Sciences*, pages 3873–3878 doi:https://doi.org/10.1073/pnas.1523357113.