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Comparing Linear and Quadratic Models of the Human Auditory System Using EEG

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***Abstract*—Recent studies have highlighted the importance of system identification as an approach for assessing sensory processing in humans using electroencephalography (EEG). These studies typically use linear impulse response estimates of visual and, more recently, auditory function. These methods, which are known as the VESPA and AESPA (Visual/Auditory Evoked Spread Spectrum Analysis) respectively, have been found to be useful for studying sensory processing in both healthy populations and clinical groups and for studying the effects of cognition on sensory processing. While a nonlinear extension of the VESPA has been previously described, no such extension has yet been examined for the AESPA. This paper investigates such an extension and quantifies the relative contribution of linear and quadratic processes to the EEG in response to novel auditory stimuli. While the ability to accurately predict novel EEG is poor, it is highly significant, with a slightly, but again significantly, greater ability to predict using a quadratic model (r=0.0418) over a linear model (r=0.0361).**

I Introduction

A considerable amount of research has been done on the modelling of nonlinear time-invariant systems, most of which has been based on the general mathematical foundation of the Volterra-Wiener approach. The Volterra series was first studied by Vito Volterra around 1880 as a generalization of the Taylor series of a function and was used by Wiener (1958) to model the input-output relationship of a nonlinear system [1].

Several successful examples of the use of nonlinear modelling have been reported across different physiological domains, including those on the retina using inputs of stochastically varying electrical current [2] and light [3]. This approach has also been applied to scalp recorded EEG and in particular the visual evoked potential [4].

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Recently, our group has extended this method to allow for the input of stimuli with more flexible temporal statistics [5]. Specifically, in previous studies researchers took advantage of the fact that the system transfer functions could be obtained by cross-correlating the input and output signals, which was possible as long as the input signals had the property that their autocorrelation function resembled a delta function.

In contrast, our method, which is known as the VESPA/AESPA (Visual/Auditory Evoked Spread Spectrum Analysis)[5,6] utilizes the least squares algorithm to fit a response model of the how the human visual and auditory systems responds to stimulus changes and allows the use of more realistic input signals. These signals are typically presented to the brain by modulating the contrast or intensity of a visual or auditory stimulus while recording EEG [5,6]. Because the VESPA and AESPA in their linear forms have been shown to have useful application across a range of fields, including cognitive neuroscience [7, 8, 9], clinical research [10] and fundamental research on sensory processing [11, 12], it is important to assess the ability of these linear methods to accurately model the system of interest and to assess the potential advantages of incorporating higher order modelling terms. We previously reported such an assessment in terms of the VESPA, which demonstrated that both the linear and quadratic VESPA models could predict novel EEG with only low accuracy, but in a highly significant way [13]. No statistical difference in the ability to predict was found between the linear and quadratic models. This paper aims to conduct a similar examination of the AESPA by quantifying how well the linear AESPA impulse response can predict the EEG in response to a novel stimulus and by how much, if at all, our approach is improved through the inclusion of second order terms in the AESPA analysis.

II Methods

A. Subjects

11 subjects participated in the study (one female; aged 22–35 yr), all of whom had normal hearing. The experiment was undertaken in accordance with the Declaration of Helsinki. The Ethics Committee of St. Vincent's University Hospital in Dublin approved the

experimental procedures and each subject provided written informed consent. These data were presented previously using only a linear analysis [6].

B. Stimuli and Experimental Procedure

A Gaussian broadband noise (BBN) waveform, with energy limited to a bandwidth of 0–22.05 kHz was used as a carried signal. The amplitude of this carrier stimulus was modulated using Gaussian noise signals with uniform power in the range 0–30 Hz, i.e., at a rate of 60 modulations/s. This rate was chosen based on the fact that EEG power below 30 Hz is typically very low. Modulating signals with the desired statistical properties were precomputed and stored. Taking into account the logarithmic nature of auditory stimulus intensity perception, the values of these modulating signals (x) were then mapped to the amplitude of the audio stimulus x', using the following exponential relationship

$$x' = 10^{2x} \quad (1)$$

and normalized to between 0 and 1. It was expected that this would result in a more linear perception of audio intensity modulation. The modulating noise signal was then interpolated to give a smooth transition from one modulation amplitude to the next and stored.

All subjects underwent ten presentations of the amplitude-modulated BBN stimulus using headphones with each presentation lasting 120 s. Subjects were instructed to keep their eyes open and to keep eye movements, blinks and other motor activity to a minimum for the duration of each run.

C. EEG acquisition

EEG data were recorded from 130 electrode positions, filtered over the range 0–134 Hz, and digitized at the rate of 512 Hz using a BioSemi Active Two system. Synchronization between the audio stimuli and the recorded EEG data was ensured by including the signal on the parallel port of the presentation computer, indicating the onset and offset of the stimuli, among the recorded signals. EEG data were digitally filtered with a high-pass filter, where the passband was > 2 Hz and with a -60 dB response at 1 Hz and a low-pass filter with passband < 35 Hz and a -50 dB response at 45 Hz. The data at each channel were rereferenced to the average of the two mastoids.

D. Signal Processing

The estimation of the AESPA is based on the assumption that the output EEG, $y(t)$, consists of a convolution of the audio amplitude modulation signal, $x(t)$, with an unknown impulse response $w(\tau)$, plus noise, i.e.,

$$y(t) = \omega(\tau) * x(t) + noise. \quad (2)$$

Given the known audio amplitude modulation signal and the measured EEG, we obtain $w(\tau)$, i.e., the AESPA, by performing linear least squares estimation (see [5] for details).

The values of $x(t)$, were assumed to be constant across each 16.67 ms modulation period and the initial modulation values, i.e., the linear values obtained prior to the exponential mapping, were used. This seemed reasonable under the assumption that the exponential mapping would actually result in a more linear intensity perception.

The AESPA was estimated using a sliding window from 200 ms pre-stimulus to 400 ms post- stimulus that was advanced sample by sample. This window was chosen in order to present the AESPA using an interval similar to that typically used for plotting the average Auditory Evoked Potential (AEP). However, the meaning of the interval is slightly different (see [6] for details). It should also be noted that we restricted our analysis to just the fronto-central electrode site Fz, given the topographic distributions observed in previous AESPA studies [6].

E. Quantification of Model Performance

In order to quantify the AESPA method's ability to accurately model the auditory system, we carried out the following analysis. Firstly, for each subject, we determined the linear AESPA and quadratic AESPA models by averaging the corresponding AESPAs over 9 of the 10 runs undertaken by that subject. We then used the stimulus waveform from the one remaining run as input to these models in order to predict the output EEG for that run. We then computed Pearson correlation coefficients between the predicted output EEG and the actual recorded EEG for that run. This process was repeated 10 times for each subject by rotating the run to be tested each time and the correlation coefficients were averaged within each subject, excluding those runs where the resulting correlation was not found to be significant at the $p < 0.01$ level.

III RESULTS

Fig. 1 plots both the linear and quadratic AESPA responses averaged across all subjects at fronto-central electrode location Fz, referenced to the average of the two mastoids. The nonlinear AESPA is plotted on a color scale with two time axes. The value of the AESPA at any point on this 2-D plot represents the strength of the relationship between the EEG at any given time point and the interaction (product) of the two inputs at the preceding times denoted by the x and

y axes. Qualitatively the diagonal of the quadratic responses seems to be quite similar to the trajectory of the linear model, which is not surprising. However, it is interesting to note that there are some non-zero clusters off the diagonal. These include negativities indicating a relationship between stimuli at 80 and 120 ms preceding the EEG and some positive ridges between about 80 and 120 ms just off the diagonal.

Table 1 lists the percentage of test trials that were predicted significantly for both linear and nonlinear models for each subject, where we

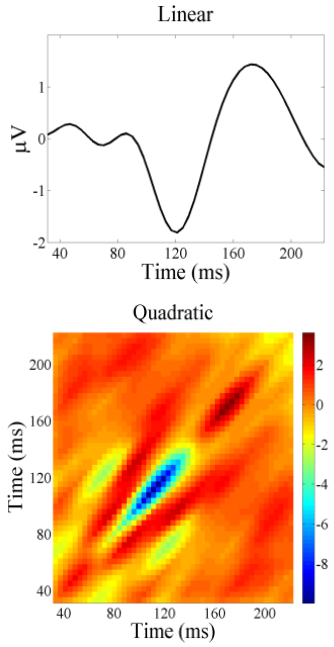

Fig. 1. Linear (upper) and quadratic (lower) AESPA responses at electrode location Fz, averaged across all subjects.

determined significance using a threshold of $p < 0.01$. A considerable number of trials were found to be significant with an average of ~80% for the linear model and an average of ~90% for the quadratic model. While the number of significantly predicted trials was high, the strength of the correlations was low. Table 1 also shows the average Pearson correlation coefficients between the recorded EEG from one of the ten trials for each subject and the predicted EEG based on the other nine trials. This average was carried out averaging only those test runs where a significant result was found. The average across all subjects was r=0.0361 for the linear case and r=0.0418 for the nonlinear case. It should be noted that even for those subjects for whom the same numbers of trials were found to be significant using the linear and nonlinear models, the correlation coefficients were increased when using the nonlinear model. A paired t-test revealed that correlation coefficients using the nonlinear model were higher than those using the nonlinear model (p = 0.0019).

Fig. 2 shows 1000 ms worth of recorded EEG and the corresponding linear and quadratic model predictions for the best performing subject (subject 5). The EEG plotted is from run 1 for that subject, while the model predictions are based on the AESPAs obtained using runs 2-10 for that subject.

TABLE I
PERCENTAGE OF TRIALS WHERE PREDICTED EEG (USING A MODEL FIT FROM 9 TRIALS) AND RECORDED EEG (FROM THE 10TH TRIAL) WERE SIGNIFICANTLY CORRELATED. PEARSON CORRELATION COEFFICIENTS FOR ONLY THOSE RUNS WHERE A SIGNIFICANT RESULTS WAS FOUND ARE ALSO SHOWN

Subject	% of significant linear runs	% of significant nonlinear runs	r_{linear}	$r_{nonlinear}$
1	100%	100%	.0495	.0536
2	70%	80%	.0341	.0380
3	80%	90%	.0322	.0365
4	90%	90%	.0470	.0508
5	100%	100%	.0519	.0602
6	40%	60%	.0182	.0259
7	60%	90%	.0236	.0288
8	90%	100%	.0272	.0350
9	100%	100%	.0304	.0315
10	70%	80%	.0273	.0305
11	90%	90%	.0444	.0619
MEAN	**80.1%**	**89.1%**	**.0361**	**.0418**

IV DISCUSSION

We have obtained linear and quadratic models of the auditory system based on spread spectrum stimulation of that system while recording EEG. The acquired models have been shown to have significant predictive power by comparing their output in response to novel stimuli with actual recorded EEG to those novel stimuli.

Despite the fact that such a large percentage of correlation tests carried out were found to be statistically significant, the correlation values obtained were not remarkably high. This was not terribly surprising given the notoriously noise nature of the EEG signal. Because of the lack of spatial resolution on the scalp as a result of volume conduction and the extremely deleterious effects of any muscle movements

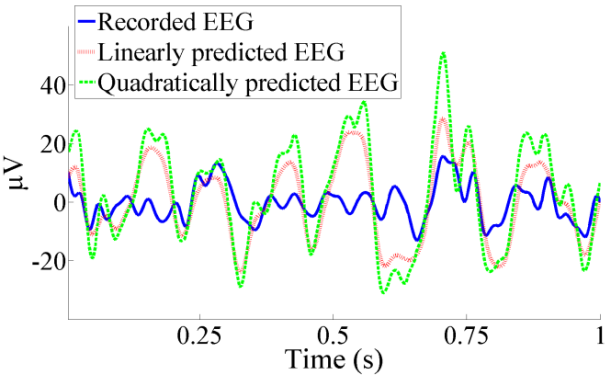

Fig. 2. One second of recorded EEG from the first 120s run of subject 5 at electrode location Fz and the corresponding model predictions for that run from the linear and quadratic models. The models were fit using data from runs 2-10 of subject 5.

(including blinks), one would not expect a signal originating from, presumably, just auditory cortex to be completely predictable. However, Fig. 2 gives a sense of how, in some instances, the AESPA method can significantly predict previously unseen EEG.

Furthermore, unlike in the case of the VESPA [13], we have found a small, but significant improvement with the addition of a second order to our modelling approach. This suggests that there are meaningful interactions between stimuli at different time points that affect the subsequent EEG activity. The fact that evidence for nonlinear processing exists is not at all surprising given the necessarily nonlinear nature of real world objects such as the brain. In fact, the fact that the auditory system responds in a highly nonlinear way to auditory intensity has been well documented [14]. We attempted to correct for some of this nonlinearity using our mapping (1), however many other types of nonlinearity exist in the brain, such as saturation and burst firing.

Having made this point, it is interesting to contrast our results with those obtained using the VESPA stimulus where although the average r value was higher for the quadratic model than the linear model, no statistically significant difference was found. That study used fewer subjects (seven), and as such, the lack of an effect may have been due to the lack of statistical power. Another possible reason for this is that over the range of contrast levels studies in [13], the early visual system may behave in a relatively linear manner [15].

In general the ability to predict novel EEG in response to auditory stimuli was poorer than previously found in vision [13]. This likely stems from the low signal-to-noise ratio of the AESPA response compared with that of the VESPA. Previous work has suggested that this may be due to the fact that many cells in auditory cortex appear to be specialized for processing discrete events [6], a fact that likely has an evolutionary basis.

V CONCLUSION

Use of the linear AESPA method and its quadratic extension has enabled us to model how the auditory system responds to novel amplitude-modulated stimuli. When modelling single trial EEG, a small, but significant improvement was observed when using the quadratic model compared with the linear model. Some explanations for this have been offered and some suggested improvements to the model have been suggested. This work suggests the AESPA as a useful framework with which to investigate characteristics of the auditory system, both in the healthy brain and in the case of neurological or psychiatric disorder.

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