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Quantification of Listening Effort Correlates in the Oscillatory EEG Activity: A Feasibility Study

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***Abstract*— So far, a generally accepted objective measure for the listening effort estimation in clinical settings is not existent. Such a measure could support the hearing aid fitting in order to reduce the listening effort in hearing impaired patients by an adequate adaption of their personal hearing aids.**
In the current study, we propose a new measure for the quantification of large-scale listening effort correlates. This measure takes the phase information of the ongoing oscillatory EEG activity into account. The phase was gained from the 32 channel EEG. Then, the entropy of the extracted phase was calculated. We assume that this angular entropy reflects phase synchronization effects of the ongoing activities due to an increased attention on the relevant (speech) signal. Thus, we expect that smaller values of the angular entropy reflect a more "ordered" process of the phase distribution. The new method was tested in 13 young normal hearing subjects using different auditory tasks consisting of differently adapted sentences to create different listening conditions.
The results indicate that the angular entropy can be applied to reveal significantly differences between the solving and the relaxing part of the paradigm, i.e. between a more effortful and a more relaxing listening situation. It is concluded, that the further research includes the development of more effortful listening tasks in order to reveal also differences between the auditory paradigms.

I. INTRODUCTION

Nowadays, there is an increased interest in finding an appropriate objective method for the estimation of listening effort. So far, there are various objective and subjective methods proposed to determine listening effort, e. g. pupil dilatation [1], dual task paradigms [2], [3], galvanic skin response [4], listening effort scales [5] or questionnaires [6]. However, a generally accepted objective measure for the listening effort estimation in clinical settings (e.g., hearing aid fitting procedures) is not existent.
Lately, Pichora-Fuller et al. [7] mentioned that listening effort, which can be defined as the exertion listeners experience by processing natural signals (e.g., speech) in demanding environments, requires always attentional as well as cognitive resources [7], [8]. It is assumed, that the cognitive effort can be influenced by two factors: Firstly, by signal degradation, which can either result from environmental (e.g., background noise) or from biologic variances (e.g., elevated hearing thresholds) [7] and secondly by age-related variations in cognition [7]. In these cases, the listeners use more higher-order cognitive or top-down processes (endogenous modulation), to perceive the interested (speech) signal correctly.
In previous studies [9], [10], [11], we applied a new approach to the problem of listening effort. This approach is based on early stages of selective attention. These attentional stages are endogenously modulated, i.e. they require cognitive effort and are reflected in the instantaneous phase information of auditory (late) evoked potentials (ALRs). In order to extract these correlates of listening effort, different stimulation paradigms were generated. These paradigms were used to evoke the ALRs and they also required a different amount of effort to solve them. This was necessary in order to have two comparable conditions. Then, the stability of the instantaneous phase in the range of the N1 wave was calculated as an objective measure for listening effort. We assume that a higher synchronization of the phase reflects an higher effort to solve the auditory task.
The focus of our current study relies also on the phase information but of the ongoing oscillatory brain activity. Here, compared to auditory evoked potentials, the auditory stimulation is not limited to signals of "short" duration, like tone bursts, syllables or words. For the analysis of these activities we propose the angular entropy. We assume that the angular entropy reflects synchronization effects of the ongoing oscillatory activities. The concept of entropy was considered as it describes the order and disorder of a system or a process and was also previously applied by other authors to analyze the power spectrum of EEG data [12], [13]. We expect that smaller values of the angular entropy reflect a more "ordered" process of the phase distribution, i.e. the phase is more synchronized due to an increased attention on the relevant (speech) signal. In order to extract the possible listening effort correlates, different listening tasks were created. These auditory paradigms were composed of sentences taken from a German sentence test (Oldenburger Sentence Test, [14]) and were adapted in different ways. Thus, we expected that each listening task requires a different level of effort to solve it. Finally, the angular entropy of the EEG data was calculated and analyzed.

II. MATERIALS AND METHODS

A. Experimental Paradigm

The speech material was taken from a German sentence test (Oldenburger Sentence Test (OLSA) [14]) which is principally applied in clinical settings for the detection of the speech intelligibility threshold. Each sentence is spoken by a

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male voice and consists of the following structure: subject - verb - numeral - adjective - object (e.g. Peter buys three red cups). This sentence test also includes a speech simulating background noise which is built by the test material. Three different paradigms were generated. We expected that each paradigm requires a different amount of effort from the subjects. The paradigms consisted of the same 100 sentences, which were processed in the following ways: *Paradigm 1 (PD1)*: This paradigm consisted of the original sentences, presented without any background noise. *Paradigm 2 (PD2)*: The second paradigm was built by the original sentences, which were embedded in the speech simulating background noise at a signal-to-noise ratio (SNR) of 0dB, which corresponds to a cocktail-party environment [15]. *Paradigm 3 (PD3)*: Here, 25% of the information of each sentence was removed. For this, the sentences were divided into 20 equally spaced segments. Then, every fifth segment was removed. In order to smooth the transitions to the removed segments, a gaussian window was used (window size: $\sim$ 50ms). Additionally, the sentences were also embedded in the same speech simulating background noise at a SNR of +10dB. The paradigms were presented two times. For the first time of the presentation (condition A), the subject's task was to repeat the last word of each sentence. Thus, a sinus tone (1kHz, duration: 40ms) was added after each sentence to indicate the point of time (silent gap; duration: 2s) to give the response. Here, we expected that the last two paradigms (PD2 and PD3) require more effort from the subjects to solve them compared to PD1. In the second part of the experiment (condition B), we wanted to extract correlates, where the subjects do not listen attentively to the speech material to create a more effortless condition. In order to minimize a spontaneous mental drift, we added also the sinus tone and the silent gap to the sentences, but this time the tone occurred randomly after the sentences. The subjects task was to relax and to tell the experimenter if the tones were presented after the sentences. In all conditions the subjects were instructed to keep their eyes closed and to minimize movements in order to avoid muscular artifacts. The subjects responses were written down by the experimenter. This was done to examine if the same speech intelligibility level is guaranteed in all paradigms. Additionally, we used a subjective seven-step "Listening Effort Scale" (no effort - very little effort - little effort - moderate effort - considerable effort - much effort - extreme effort) [16], where the subjects were asked to rate their required effort during the tasks. The sentences were calibrated according to the norms [17] and presented via headphones (Sennheiser, HD250) at 65dB SPL to the right ear of the subjects. The whole experiment lasted around 40min and short breaks were made on subjects demand.

B. Subjects and Data Acquisition

A total of 13 subjects participated in this study (mean age 24.28±3.12 years, 7 F/ 6 M). The subjects were student volunteers from the Saarland University and Saarland University of Applied Sciences, with no history of hearing problems and normal hearing thresholds (below 15dB (HL)). All subjects were native German speakers. After a detailed explanation of the procedure, all participants signed a consent form. The continuous EEG was recorded with a commercially available amplifier (g.tec USBamp, Guger Technologies Austria) using a sampling frequency of 512Hz. The 32 gold-electrodes were placed according to the international 10-20 system, with Cz as reference and a ground electrode placed at the upper forehead. In all measurements electrode impedances were kept below $5k\Omega$. The data was bandpass-filtered from 0.5 to 40Hz. A trigger signal indicated the onset and offset of each sentence. So it was possible to extract only the EEG data during the presentation of the sentence. Artifacts were rejected if either the maximum amplitude threshold exceeded $\pm 70\mu$V or the standard deviation exceeded $\pm 40\mu$V within a moving time window (window size: 50ms).

C. Data Analysis

For the quantification of large-scale phase synchronization processes of brain oscillations we propose the angular entropy H. This new approach is based on the distribution of the instantaneous phase information. The phase $\phi_{a,b}$ was extracted by the application of the continuous wavelet transform. Let $\psi_{a,b}(\cdot) = |a|^{-1/2}\psi((\cdot - b)/a))$ where $\psi \in L^2(\mathbb{R})$ is the wavelet with $0 < \int_{\mathbb{R}} |\Psi(\omega)|^2 |\omega|^{-1} \mathrm{d}\omega < \infty$ ($\Psi(\omega)$ is the Fourier transform of the wavelet), and $a, b \in \mathbb{R}$, $a \neq 0$. The wavelet transform $\mathcal{W}_\psi : L^2(\mathbb{R}) \longrightarrow L^2(\mathbb{R}^2, \frac{\mathrm{d}a\mathrm{d}b}{a^2})$ of a signal $x \in L^2(\mathbb{R})$ with respect to the wavelet ψ is given by the inner L^2–product $(\mathcal{W}_\psi x)(a, b) = \langle x, \psi_{a,b} \rangle_{L^2}$. The instantaneous phase of a signal $x \in L^2(\mathbb{R})$ can be achieved by taking the complex argument from the complex wavelet transform with the signal: $\phi_{a,b} = arg(\mathcal{W}_\psi x)(a, b))$. We divided the phase values into N bins and each bin has the probability $p_i, I = \{-\pi, -\pi + \frac{\pi}{10}, ..., +\pi\}$, with $\sum_i^N p_i = 1$. Then, the normalized angular entropy can be defined by

$$H = -\sum_{i \in I} \frac{p_i \cdot \ln p_i}{\ln N}. \qquad (1)$$

We expect that for effortful listening conditions the angular entropy reveals smaller values compared to easier listening conditions. This could be seen as a more "ordered" and synchronized process of the phase distribution of the ongoing oscillatory activities. In order to compare the new proposed measure with traditional analysis methods, we analyzed also the power spectrum of the EEG data. For the calculation of the power spectrum of each band, the Fourier transform was applied. The following frequency bands were analyzed: theta (4-8Hz), alpha (8-12Hz), beta (12-30Hz) [18].

III. RESULTS AND DISCUSSION

One subject had to be excluded from the analysis due to too many artifacts in the EEG data. So, we had a total of 12 included subjects. For the interpretation of the Listening Effort scale, a number was added to each level of the scale (ranging from 1 (very little effort) to 7 (extreme effort)). Then, the mean and the standard deviation were calculated. For each paradigm, the following ratings were obtained: PD1: 1.16±0.38 (no effort), PD2: 2.75±0.96 (very little effort - little effort), PD3: 3.33±1.15 (little effort - moderate effort). All subjects could repeat correctly 100% of the last words of the first paradigm (PD1; original sentences). For the other paradigms, the performance was only slightly reduced. They achieved for PD2 a mean of 97.91±1.62% and for PD3 a mean of 98.41±3.17%. If we compare the results of the Listening Effort scale and this "Speech Intelligibility Test", we can notice that we have almost the same speech intelligibility level in all three cases and only a slight enhancement of the required effort to solve PD2 and PD3 compared to the original sentences. Thus, due to the similar levels of correctly reported words we can assume that we do not measure objectively the speech intelligibility level.

For the analysis of the angular entropy, the artifact free data was shortened (93,000 samples $\sim$ 180s) to obtain an equal length of the EEG data for each paradigm and subject. The angular entropy was calculated for different scales a, ranging form 10 to 60 in steps of 2. The wavelet ψ used in this study was the 6th-derivative of the Gaussian wavelet as in [10]. Note that each scale a can be associated with a 'pseudo' frequency f_a in Hz by $f_a = Tf_\psi/a$, where T is the sampling period and f_ψ is the center frequency of the wavelet ψ [19]. Thus, the analyzed scales covered a frequency range from 5.12Hz to 30.72Hz, which corresponds to the EEG frequency bands. Fig. 1 shows (representative for the results of the other two paradigms (PD2 and PD3)) the power spectrum estimates for the first paradigm (PD1) and each electrode location. The power for each frequency band and condition (A and B) is illustrated as a bar graph (from left to right (light grey to black): theta-, alpha- and betaband). None of the power spectra showed a statistical significance ((one-way) ANOVA, p>0.05) between the two conditions. Thus, the power spectrum was not further analyzed.

In Tab. I, the results of the ANOVA for the analysis of the angular entropy (condition A vs. condition B) for each paradigm are shown. For reasons of clarity, only electrode positions are depicted, where the difference of the angular entropy between the conditions was significantly different (p<0.05). The angular entropy was always significantly enhanced for condition B (relaxing part) compared to condition A (solving the paradigm) for the shown electrode positions. It can be seen that most of the involved electrodes are located in the frontal areas (e.g. F3, F4, FC4) within the theta range. Also [20] noted in a study related to audiospatial attention, that the theta band activity is increased with attention in frontal as well as parietal locations. For these reasons, the focus of our further analysis was more in the frequency range of the theta band.

In Fig. 2 the grand averages of the angular entropy (over all the 12 included subjects) for two different scales, all tested paradigms and conditions and different electrode locations are depicted. The left side shows the results of the angular entropy (y-axis) calculated for a scale a=40 (corresponds to the α/θ-border) for different electrode positions. On the lower x-axis the three different paradigms are depicted. The filled circles represent the results of condition A (solving the paradigm) and the unfilled ones represent condition B (relaxing part). The same is illustrated on the right side, but for a scale a=48 (corresponds to the center of theta band). It can be seen, that in all paradigms and all illustrated electrodes, the angular entropy is enhanced for condition B (relaxing part) compared to condition A (solving the paradigm). This means, that the angular phase for the effortful condition is not uniformly distributed, i.e. the phase is more "ordered" and synchronized in these conditions. We can interpret, that due to the smaller values of the angular phase entropy the speech understanding process (solving the paradigm) for the three different listening conditions requires more effort from

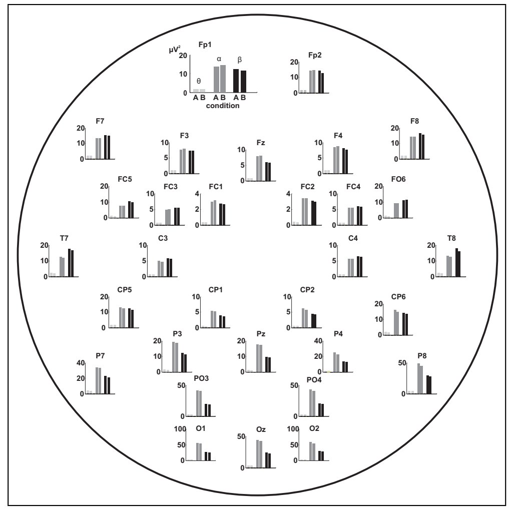

Fig. 1. Results of the EEG power spectrum analysis for PD1 (representative for all paradigms; topographically illustrated; p>0.05). The three main blocks of the power spectrum correspond to one frequency band (left to right (light grey to black): theta-, alpha- and beta band). Each bar of one block corresponds to one condition (left: condition A, right: condition B).

TABLE I

ELECTRODE POSITIONS, IN WHICH THE (ONE-WAY) ANOVA TEST FOR THE ANALYSIS OF THE ANGULAR ENTROPY REVEALED SIGNIFICANT DIFFERENCES (CONDITION A VS. CONDITION B).

frequency band	scale	PD1	PD2	PD3
β	10	FC4	F3,FP2	-
	14	O3, F4	FC4	-
	16	F4, FC4	-	-
	18	F4	-	-
	22	FP2	-	FC5
α	24	-	PO4	-
	26	-	-	FC3
	30	-	T7	F8, FO6
	32	-	F3	-
	34	T7	FP1	-
	36	-	P4, F3	CP2
	38	-	P8	-
θ	40	-	-	T7,P8
	44	F3	F3,FP1,F2	-
	46	-	FP2	-
	48	F7, FC4	F4	T7
	50	F7	FC2	FC4, P8
	52	F8	CP2	-
	54	P7	OZ	P4
	56	-	-	CP6
	58	-	CP2	-
	60	PO3, T7	PO4	-

the subjects as the only repetition if the signal tone indicating the gap for the response exists or not. The subjectively rated

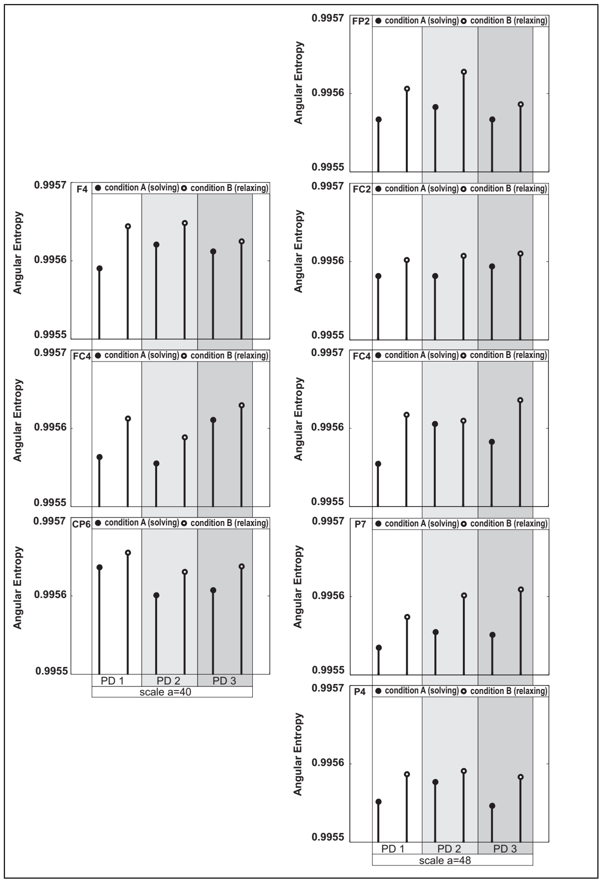

Fig. 2. Grand average (over all the 12 subjects) of the normalized angular entropy (y-axis) for two different scales (left: a=40 (7.6Hz); right: a=48 (6.4Hz)) and electrodes. On the lower x-axis the three different paradigms (left to right: PD1 to PD2) are represented. The filled circles represent the results of condition A (solving the paradigm) and the unfilled ones represent condition B (relaxing part). It can be noticed that the angular entropy is for all the cases (PD1 to PD3) enhanced for the relaxing (condition B) compared to the solving part (condition A) of each paradigm.

effort indicated, that the three paradigms require almost the same amount of effort from the young subjects to solve them. Therefore, a part of our future work will be to develop new auditory tasks in order to increase this level of effort. Thus, we expect that we can also differentiate objectively between different amounts of effort needed to solve the auditory tasks by calculating the angular entropy of the ongoing EEG.

IV. CONCLUSIONS AND FUTURE WORK

In this study, we propose a new measure for the analysis of listening effort correlates in oscillatory brain activity, namely the angular entropy. The angular entropy, which is based on the instantaneous phase information of the ongoing EEG activity, was extracted in different auditory paradigms and conditions. It can be concluded that the angular entropy showed significantly differences between the solving and the relaxing part of the paradigm. Further work includes the modulation of the auditory paradigms in order to increase the level of effort.

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