Objective Assessment of Listening Effort in the Oscillatory EEG: Comparison of Different Hearing Aid Configurations

Corinna Bernarding, Daniel J. Strauss, Ronny Hannemann, Harald Seidler, and Farah I. Corona–Strauss

Abstract— **An objective estimate of listening effort could support the hearing aid fitting procedure. Most of the digital hearing aids have already hearing aid settings which are supposed to reduce the listening effort, but the effects of these settings on the individual's listening effort remain unclear.**

In this study, we propose an objective estimate of listening effort using electroencephalographic data. The new method is based on the phase distribution of the ongoing oscillatory EEG activity. We hypothesize that for a non-effortful listening environment the phase is rather uniformly distributed on the unit circle than for a demanding condition. To prove if the phase is uniformly distributed around the unit circle, the Rayleigh Test was applied to the phase of the EEG.

This method was tested in 14 hearing impaired subjects (moderate hearing loss, 65.64 $\pm$7.93 yrs, 7 female). The tested hearing aid settings were a directional microphone combined with a noise reduction algorithm in a medium and a strong setting, the noise reduction setting turned off as well as a setting using omnidirectional microphones. Noise embedded sentences (Oldenburg Sentence Test, OlSa) were used as test materials. The task of the subject was to repeat each sentence.

The results indicate that the objective estimate of listening effort maps the subjectively rated effort and for a listening situation like the presented one, the strong setting of the directional microphone requires the smallest effort.

I. INTRODUCTION

In recent years, the topic 'listening effort' attracted more and more attention in the field of rehabilitative audiology, but a standardized definition of listening effort is still not available. Regarding the literature, listening effort can be described as the exertion listeners experience by processing natural signals (e.g., the process of speech understanding) in demanding environments [1]. This hearing process requires the allocation of attentional as well as cognitive resources [2]. Until now, mainly subjective procedures, like questionnaires [3], rating scales [4] or self-reports are applied to estimate listening effort in hearing aid fitting procedures or studies related to the assessment of listening effort.

There have been different approaches to estimate listening effort objectively. One of the methodologies are dual-task paradigms (see [5] for a review), which are based on a limited capacity theory of cognitive resources. The participants have to perform two competing tasks: a primary listening task and a secondary mostly visual or memory related task. The assumption is, that there is a competition for single limited resources, so that the performance of the secondary task decreases with increasing difficulty level of the primary task. This reduction in secondary task efficiency serves as a measure of listening effort. However, this method is influenced by many factors and requires a large amount of subjects cooperation. As further indices of listening effort, the pupil response [6] and the galvanic skin response [7] were also taken into account. Zekveld et al. [6] showed, that the pupil dilates with increasing cognitive load. In these studies sentences embedded in background noise had to be repeated by the subjects. The increasing pupil diameter is interpreted as an increase of listening effort.

However, a widely accepted method to evaluate listening effort objectively in clinical procedures is still not available. In previous studies [8], 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) . The stability of the instantaneous phase (extracted in the frequency range of the alpha-theta border) in the time interval 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. The new method is based on the phase distribution of the ongoing oscillatory EEG activity. We hypothesize that for a non effortful listening environment the phase is rather uniformly distributed on the unit circle than for a demanding condition. For the latter, it is assumed that the phase is clustered on the unit circle due to an increased auditory attention to the interesting auditory signal. To prove if the phase is uniformly distributed around the unit circle or if it departs from uniformity, the Rayleigh Test was applied to the phase of the EEG. Here, the probability value of the Rayleigh-Test serves as a neural correlate of listening effort.

In order to extract the possible listening effort correlates a realistic listening situation was generated. For this, sentences taken from a German sentence test (Oldenburger Sentence Test) were embedded in background noise. Then, the EEG was recorded from hearing impaired subjects. Additionally,

C. Bernarding, D. J. Strauss, and F. I. Corona–Strauss are with the Systems Neuroscience and Neurotechnology Unit at the Neurocenter, Saarland University Hospital and Saarland University of Applied Sciences, Homburg/Saar, Germany. F. I. Corona–Strauss and D. J. Strauss are also with the Key Numerics GbR, Saarbrücken, Germany. D. J. Strauss is also with the Leibniz–Institut for New Materials, Saarbrücken, Germany.{strauss}@snn-unit.de

R. Hannemann is with Siemens Audiologische Technik GmbH, Erlangen, Germany.

H. Seidler is with MediClin Bosenberg Kliniken, St. Wendel, Germany.

we wanted to investigate the effects of different hearing aid settings on listening effort. The tested hearing aid configurations were a directional microphone combined with a noise reduction algorithm in a medium and a strong setting, the noise reduction setting turned off as well as a setting using omnidirectional microphones.

II. MATERIALS AND METHODS

A. Hearing aid fitting

In the experiments a comercial available behind-the-ear hearing aid was tested. The devices were fitted according to the individual's audiogram. The hearing aid setting *directional speech enhancement* is a combination of a directional microphone technique together with a Wiener filter noise reduction. In order to see objective differences regarding the listening effort, four conditions were investigated. For this, the devices were fitted, besides the basic settings, with the noise reduction and the directional microphone setting on plus the DSE feature in (a) a medium (DSEmed) and (b) a strong setting (DSEstr), (c) the DSE feature turned off (DSEoff), and as a control condition with (d) omnidirectional microphones (ODM). The last condition was selected, because it was assumed that this feature requires the largest amount of listening effort. Thus, this condition was regarded as a control condition.

B. Stimulus materials and calibration of the auditory stimuli

The speech material was taken from a German sentence test (Oldenburg Sentence Test (OlSa) [9]) which is principally applied in clinical settings for the detection of the speech intelligibility threshold. The sentences were embedded in multitalker babble noise (International Speech Test Signal (ISTS) [10]) composed of international speech tokens naturally produced by female voices. Additionally, a cafeteria noise (downloaded from a data base of auditory signals [11]) was added to the audio signals consisting of clattering dishes and cutlery. The auditory stimuli were calibrated using a hand-held sound level meter and a pre-polarized free field 1/2" microphone. For measuring a single sound source, the loudspeaker for the calibration was placed 1 m in front of the sound level meter at the level of the subject's head. For measuring overlapping sound sources, the sound level meter was placed in a distance of 1 m in the center of the loudspeakers. The calibrated intensities were set to the following values: The intensities of the speech materials (OlSa) were fixed at 65 dB L_{Aeq} (normal conversation level). The ISTS noise had a level of 60 dB L_{Aeq} and the cafeteria noise was set to 67 dB L_{AFmax}.

C. Experimental design

Before the experimental session started, the subjects performed an adaptive speech intelligibility test in order to guarantee that the subjects were able to discriminate at least 80% of the presented speech material. For this, the subject's hearing aids were fitted with the DSEmed setting and an adaptive OlSa was performed to achieve the speech intelligibility threshold (loudspeaker configuration S0N0, intelligibility level at 50% was determined). Finally, the 80 % intelligibility level was calculated using the stated discrimination function in the manual of the OlSa. Four loud speakers were positioned in a distance of 1 m from the subject's head at 0°, 135°, 180°, and 225°. A total of 50 OlSa sentences together with the ISTS noise were presented at the frontal loudspeaker at 0°. Additionally, three distracting noises (two time-delayed ISTS and cafeteria noise sequences) were played at the rear side of the subject at 135°, 180°, and 225°. The task of the subject during the experiment was to repeat the heard words of the sentence. Thus, a sinus tone (1kHz, duration: 40ms) was added after each sentence to indicate the point of time (silent gap with a duration of 5s) where the subject's response was expected. The responses were written down by the experimenter. All four hearing aid configurations ((a) DSEmed, (b) DSEstr, (c) DSEoff, (d) ODM) were tested in randomized order. Furthermore, the subjects were asked to rate their perceived effort after each tested hearing aid setting using a seven point scale (no effort - very little effort - little effort - moderate effort - considerable effort - much effort - extreme effort) and their experienced speech intelligibility (excellent - very good - good - satisfactory - sufficient - unsatisfactory - insufficient) [12]. Additionally, the subjects should determine their preferred hearing aid setting for a listening situation like the presented one.

D. Participants and inclusion criteria

A total of 14 subjects (mean age: 65.64, sd: ± 7.93 years, 7 female) participated in this study. The subjects were included if they had at least 80 % artifact free EEG data. Furthermore, only experienced hearing aid users with a moderate hearing loss entered the study. Finally, we had 13 included subjects (mean age: 65.54 ± 8.24 years, 6 female/ 7 male). One subject was excluded due to artifacts. Fig. 1 depicts the mean pure tone audiograms (top) and the corresponding standard deviations (bottom) of the included subjects.

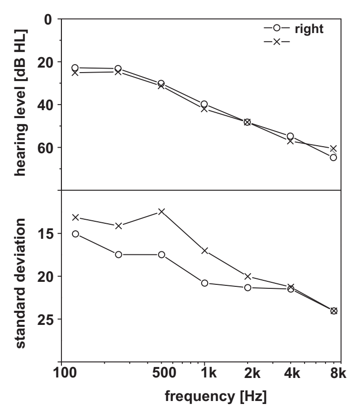

Fig. 1. Mean pure tone audiograms (top) and corresponding standard deviations (bottom) of the included subjects.

E. Data acquisition and preprocessing

The EEG was recorded using a commercially available biosignal amplifier (g.tec USBamp, Guger Technologies

Austria) with a sampling frequency of 512Hz. 16 active electrodes were placed according to the international 10-20 system, with Cz as reference and a ground electrode placed at the upper forehead. The data was bandpass-filtered from 0.5 to 40Hz. A trigger signal indicated the onset and offset of each sentence. Thus, the EEG data could be analyzed during the presentation of the sentences (duration approx. 2s). After extraction of the EEG data for each sentence, artifacts were rejected if the maximum amplitude threshold of each EEG segment exceeded $\pm 70\mu V$.

F. Data analysis

For the quantification of phase synchronization processes of the oscillatory EEG, the distribution of the instantaneous phase on the unit circle was investigated. The instantaneous phase $\phi_{a,b}$ of each EEG channel 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 $x \in L^2(\mathbb{R})$ is given by the complex argument from the complex wavelet transform with the signal: $\phi_{a,b} = arg(\mathcal{W}_\psi x)(a,b))$.

To prove if the instantaneous phase is uniformly distributed (random process) around the unit circle or if the phase departs from uniformity and has a mean direction, the Rayleigh Test was applied to the phase data [13]. For this, the mean resultant vector $\bar{R}$ of the phase values has to be calculated. Assuming we have a set of unit vectors $x_1, ..., x_n$ with the corresponding phase angles $\phi_i, i = 1, ..., n$, then the mean resultant vector can be determined by $\bar{R} = \sqrt{\bar{C}^2 + \bar{S}^2}$ with the Cartesian coordinates of the mean phase angle $\bar{C} = \frac{1}{n}\sum_{i=1}^{n}\cos\phi_i$ and $\bar{S} = \frac{1}{n}\sum_{i=1}^{n}\sin\phi_i$ [14]. The mean resultant vector $\bar{R}$ can be interpreted as a measure of concentration of a data set. The two illustrations of Fig. 2 depict the phase values of a uniform (Fig. 2a) and a non uniform distribution (Fig. 2b)) projected on the unit circle together with their corresponding mean resultant vector $\bar{R}$. If $\bar{R}$ is close to 0 (see Fig. 2a)), $\bar{R} = 5.5 \cdot 10^{-17}$), then the phase values are more dispersed on the unit circle, i.e., the data is distributed uniformly. Otherwise, if $\bar{R}$ is close to 1 (see Fig. 2b), $\bar{R} = 0.9936$), then the phase is more clustered on the unit circle and has a common mean direction. The null hypothesis H_0 of the Rayleigh Test states that the data samples are uniformly distributed around the unit circle, i.e., it rejects uniformity when $\bar{R}$ is sufficiently large [14]. An approximation of the probability value Pr under H_0 can be calculated [14] by $Pr = e^{\sqrt{1+4n+4(n^2-(n\bar{R})^2)}-(1+2n)}$. A small probability value Pr indicates to reject the null hypothesis, this means the data departs from uniformity [13].

In order to facilitate the comparison between the subjectively perceived listening effort and the objective result of the Rayleigh Test on the phase values of the oscillatory EEG, we defined that the *objective Listening Effort (OLEosc)*$\propto$ $(1 - Pr)$ for a specific scale a and a suitable auditory paradigm.

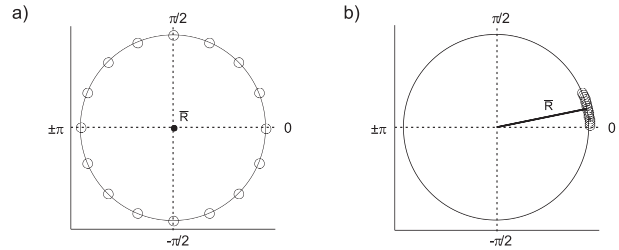

Fig. 2. Illustration of two data sets ($n = 16$ samples) of phase values (black circles) together with their corresponding mean resultant vector $\bar{R}$ on the unit circle showing a) a uniform distribution ($\bar{R} = 5.5 \cdot 10^{-17}$) and b) a non uniform distribution ($\bar{R} = 0.9936$).

The Rayleigh Test was performed on the instantaneous phase extracted from the right mastoid electrode for a scale $a = 40$. 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 [15]. Thus, the scale $a = 40$ corresponds to a pseudo frequency of 7.68Hz (alpha-theta border). This scale and electrode channel were determined in a previous study related to the extraction of listening effort correlates but gained from the evoked EEG activity [8].

III. RESULTS AND DISCUSSION

Fig. 3 shows the mean and standard deviation values of the objective listening effort measures (black squares; left y-axis) together with the results of the subjective listening effort rating (gray circles; right y-axis). The x-axis represents the four tested hearing aid configurations. It can be noted, that the objective listening effort measure mirrors the subjectively rated effort in all hearing aid settings. As proposed, the application of the omnidirectional microphone setting (control condition) requires the largest listening effort objectively determined, as well as subjectively rated. Furthermore, the results indicate that, for a listening situation like the presented one, the strong setting of the directional speech enhancement feature seems to decrease the listening effort compared to the other settings (one-way ANOVA, ODM vs. DSEstr, p=0.002). This can be explained as this setting should remove distracting (background) noises maximally, thus, the listening process is eased resulting in a small listening effort. The Fig. 4 and 5 represent the mean and standard deviation values of the percentage of correctly repeated words and the speech intelligibility scales (subjectively rated) for the four hearing aid configurations. The mean percentage of correctly repeated words of the three directional microphone settings is around 80%. This result is also reflected in the subjective speech intelligibility rating. Here, listening with the ODM setting is rated between sufficient and unsatisfactory. Thus, we can interpret that using the ODM setting, the subjects were exposed to a difficult listening situation. As a result, the listening effort was increased as presented in Fig. 3. In order to exclude that the presented results are independent of

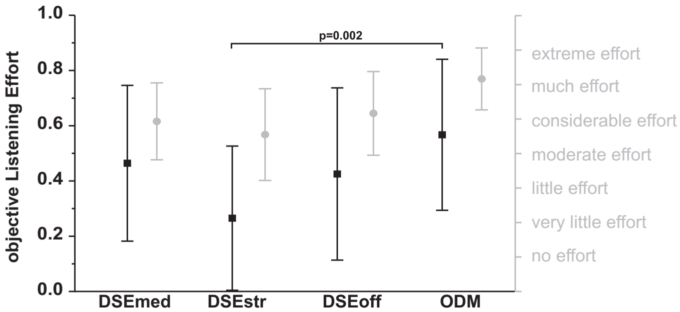

Fig. 3. Mean and standard deviation values of the objective listening effort measure (black squares; left y-axis) and the subjective listening effort rating (gray circles; right y-axis).

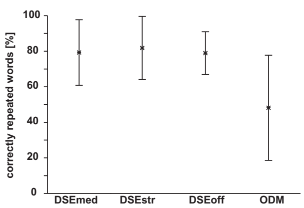

Fig. 4. Mean and standard deviation values of the percentage of correctly repeated words for each hearing aid setting.

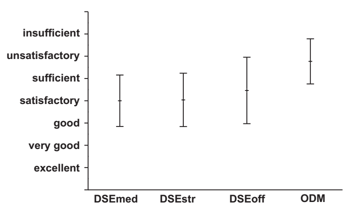

Fig. 5. Mean and standard deviation values of the subjective speech intelligibility scale.

the presentation order of the hearing aid settings (e.g. fatigue effects according to the measurement time; resulting in an increased attention and effort to solve the auditory task), the objective listening effort values were sorted according to the presentation order. This was done additionally to the randomized testing of the four hearing aid configurations during the measurements. Fig. 6 depicts the objective listening effort (y-axis) for each of the 13 subjects sorted by the order of applied hearing aid configuration (x-axis, 1st to 4th setting, black to white bars) together with the mean results (last four columns). It can be noted, that there is no effect of the presentation order on the objective listening effort measure. Note, the growing tendency of the objective listening effort of subject 1 is related to the order of the presented hearing aid settings (DSEmed, DSEstr, DSEoff, ODM). Thus, we

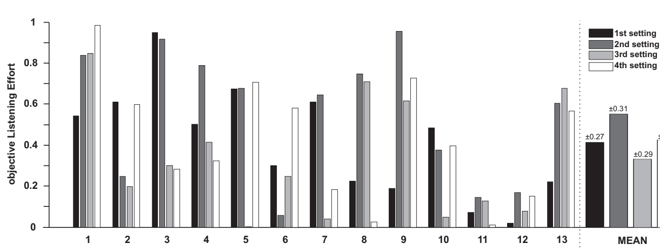

Fig. 6. Individual and mean results of the objective listening effort measure sorted by the presentation order of the hearing aid settings.

can interpret that the objectively measured listening effort indeed reflects the individuals' perceived listening effort for the tested hearing aid setting and is not a correlate of an increased fatigue due to the measurement time.

IV. CONCLUSIONS

In this study, we propose an objective estimate of listening effort using ongoing electroencephalographic data. The new method is based on the phase distribution of the ongoing oscillatory EEG activity, which can be mapped using the Rayleigh Test. The p-value of this test serves then as an objective indicator of the listening effort.

The results indicate that the objective estimate of listening effort maps the subjectively rated effort. For a listening situation like the presented one, the strong setting of the directional microphone requires the smallest effort. Nevertheless, larger studies with an increased population of the subjects are still necessary to validate this measure.

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REFERENCES

[1] M. K. Pichora-Fuller and G. Singh, "Effects of age on auditory and cognitive processing: implications for hearing aid fitting and audiologic rehabilitation," *Trends Amplif*, vol. 10, pp. 29–59, 2006.

[2] J. Kiessling, M. K. Pichora-Fuller, S. Gatehouse, D. Stephens, S. Arlinger, T. Chisolm, A. C. Davis, N. P. Erber, L. Hickson, A. Holmes, U. Rosenhall, and H. von Wedel, "Candidature for and delivery of audiological services: special needs of older people." *International Journal of Audiology*, vol. 42 Suppl 2, pp. 2S92–101, 2003.

[3] S. Gatehouse and W. Noble, "The speech, spatial and qualities of hearing scale(ssq)," *International Journal of Audiology*, vol. 43, pp. 85–99, 2004.

[4] L. E. Humes, "Dimensions of hearing aid outcome," *J Am Acad Audiol*, vol. 10, pp. 26–39, Jan 1999.

[5] P. A. Gosselin and J.-P. Gagné, "Use of a dual–task paradigm to measure listening effort," *Canadian Journal of Speech–Language Pathology and Audiology*, vol. 34:1, pp. 43–51, 2010.

[6] A. A. Zekveld, S. E. Kramer, and J. M. Festen, "Pupil response as an indication of effortful listening: the influence of sentence intelligibility," *Ear Hear*, vol. 31, pp. 480–490, Aug 2010.

[7] C. L. Mackersie and H. Cones, "Subjective and psychophysiological indexes of listening effort in a competing-talker task," *J Am Acad Audiol*, vol. 22, pp. 113–122, Feb 2011.

[8] D. J. Strauss, F. I. Corona-Strauss, C. Trenado, C. Bernarding, W. Reith, M. Latzel, and M. Froehlich, "Electrophysiological correlates of listening effort: Neurodynamical modeling and measurement," *Cogn Neurodyn*, vol. 4, pp. 119–131, 2010.

[9] K. Wagener, V. Kühnel, and B. Kollmeier, "Entwicklung und Evaluation eines Satztests in deutscher Sprache I: Design des Oldenburger Satztests," *Z Audiol*, vol. 38, no. 1, pp. 4–15, 1999.

[10] I. Holube, S. Fredelake, M. Vlaming, and B. Kollmeier, "Development and analysis of an International Speech Test Signal (ISTS)," *Int J Audiol*, vol. 49, no. 12, pp. 891–903, Dec 2010.

[11] I. Data Base: AudioMicro, "Stock audio library," 2013, uRL: http://soundbible.com/. Online - 30th of January 2014.

[12] L. Volberg, M. Kulka, C. A. Sust, and H. Lazarus, "Ergonomische bewertung der sprachverständlichkeit," in *Fortschritte der Akustik - DAGA 2001*, Hamburg, 2001.

[13] P. Berens, "Circstat: A matlab toolbox for circular statistics," *Journal of Statistical Software*, vol. 31, no. 10, pp. 1–21, 9 2009.

[14] K. V. Mardia and P. E. Jupp, *Directional Statistics*, ser. Wiley Series in Probability and Statistics. John Wiley and Sons, LTD., 2000.

[15] D. J. Strauss, W. Delb, and P. K. Plinkert, "Analysis and detection of binaural interaction in auditory brainstem responses by time–scale representations," *Computers in Biology and Medicine*, vol. 24, pp. 461–477, 2004.