33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

The Effects of Age and Hearing Impairment on the Extraction of Listening Effort Correlates

Corinna Bernarding, Daniel. J. Strauss, Ronny Hannemann, Matthias Latzel, Harald Seidler, Ulrich Jobst, Ahmed Bellagnech, Markus Landwehr and Farah I. Corona–Strauss

Abstract— **In clinical practice, an objective method to assess listening effort is still not available. The benefit of such a measure would be to reduce the listening effort in hearing impaired persons by an adequate adaption of their personal hearing aids. In foregoing studies, we have shown that the wavelet phase synchronization stability (WPSS) of auditory late responses (ALRs) could serve as a feasible measure of listening effort. Here, tonal and noise embedded syllabic paradigms were employed to achieve ALR sequences in normal hearing subjects. The aims of this ongoing study were 1) to extract the WPSS of ALR sequences in hearing impaired persons, middle-aged normal hearing persons and younger normal hearing subjects, 2) to investigate possible age-related influences on the WPSS and 3) to examine a feasible influence of the hearing loss on the WPSS. It is concluded, that the WPSS of ALR sequences can be extracted in normal hearing as well as in hearing impaired persons. An age related effect regarding the WPSS was not noticeable and the intergroup comparison of the difference of the WPSS showed a tendency to be larger for the hearing impaired compared to the normal hearing middle-aged subjects. The latest can be interpreted that this subject group showed a larger effort to solve the auditory paradigms.**

I. INTRODUCTION

According to Kiessling et al. [1], the complex process of auditory functioning can be divided into four stages. The first two of these stages are *hearing* and *listening*. In clinical practice, there are various objective and subjective techniques, like audiograms, otoacoustic emissions, brainstem evoked response audiometry to determine the functionality of the first stage, namely the hearing ability. This passive, perceptual function is important for the complete auditive process, because it provides the access to the auditory world [1]. A further substantial component of audiologic functioning is listening. In this phase, cognitive resources are needed to interpret the perceived information [1], [2]. This active part requires attention and mental effort [1] but is usually than rather effortless for young, normal hearing subjects in ideal listening environments [3]. However, those situations are rare, so that this stage is mostly an effortful process. Especially hearing impaired persons have to pay continuously attention during a conversation in order to compensate their hearing loss [4], so that they suffer from the effects of this listening effort - the resulting fatigue [2]. Until now, an objective measure to assess listening effort in hearing aid fitting procedures is not available. Today's hearing aids have already the fitting abilities which assume to reduce the listening effort, e.g. noise reduction algorithms, but an objective adaption of the hearing aids to the individual needs remains an unsolved problem. In previous studies [5], [6], [7], we have shown a possible method to extract neural correlates of listening effort by using tonal and babble noise embedded syllabic paradigms. This method is based on the instantaneous phase information of auditory late responses (ALRs), which is needed to calculate the wavelet phase synchronization stability (WPSS). The WPSS serves as an indicator of the amount of effort, which is required to solve an auditory paradigm.

The aims of this study were 1) to extract the WPSS of ALR sequences in middle-aged hearing impaired persons, middle-aged normal hearing persons and younger normal hearing subjects, 2) to investigate possible age-related influences on the WPSS and 3) to examine a feasible influence of the hearing loss on the WPSS. In order to validate the achieved results from our former study [6], [7], the same syllabic paradigms were used to obtain a difficult and an easy listening condition, but the multitalker babble noise was removed. This was done to ease both listening conditions for the hearing impaired persons.

II. MATERIALS & METHODS

A. Subjects

Three groups of subjects participated in this study: (1) 22 middle-aged subjects (9M/13F) with normal hearing levels (ma_nh; aged 40 to 60 years, mean age: 50.59±5.98 years), (2) 14 middle-aged subjects (7M/7F) with mild to moderate hearing loss (ma_hi; aged 46 to 61 years, mean age: 52.64±5.82 years) and (3) 21 young subjects (11M/10F) with normal hearing levels (y_nh; aged 20 to 35 years, mean age: 25.23±4.16 years). The grade of hearing impairment was defined as the pure tone average (PTA) of the frequencies 0.5kHz, 1kHz, 2kHz, 4kHz [8]. According to this definition of the European Commission, a PTA of 20 dB Hearing Level (HL) or less is classified as normal hearing sensitivity, a mild hearing loss is defined with thresholds in the range of 21 to 39 dB HL and a moderate hearing loss is defined as a PTA from 40 to 69 dB HL. Furthermore, most of the hearing

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 and with the Key Numerics GbR, Saarbrücken, Germany. D. J. Strauss is also with the Leibniz–Institut for New Materials, Saarbrücken, Germany. {bernarding, corona, strauss}@snn-unit.de

R. Hannemann and M. Latzel are with Siemens Audiologische Technik GmbH, Erlangen, Germany {ronny.hannemann, matthias.latzel}@siemens.com

H. Seidler, U. Jobst, A. Bellagnech, M. Landwehr are with MediClin Bosenberg Kliniken, St. Wendel, Germany {harald.seidler, ulrich.jobst}@mediclin.de

impaired subjects had a high–frequency or sloping hearing loss, respectively. In Fig. 1 are shown the mean pure tone audiograms (top) and the corresponding standard deviations (bottom) for the three subject groups.

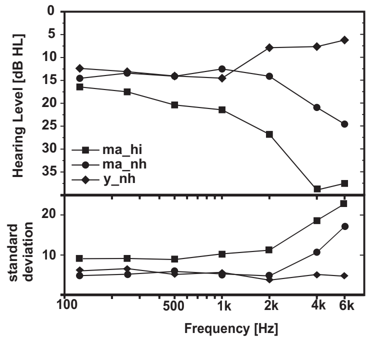

Fig. 1. Mean pure tone audiograms (top) and corresponding standard deviations (bottom) for the three subject groups (ma_hi=middle-aged hearing impaired subjects, ma_nh=middle-aged normal hearing subjects, y_nh=young normal hearing subjects).

B. Data Acquisition and Auditory Stimuli

ALRs were recorded with a commercially available amplifier (g.tec USBamp, Guger Technologies Austria, bandpassfilter: 1-30Hz, sampling frequency: 512Hz). Ag/AgCl-electrodes were attached as follows: mastoid (positive, ipsilateral to the stimulus), vertex (reference) and upper forehead (ground). Electrodes impedances were always below 10kΩ. Artifacts were rejected by an amplitude threshold of 50μV. Auditory stimuli were consonant-vowel syllables, which were recorded by a female speaker (sampling frequency: 16kHz). After collection of the syllables, their amplitudes were normalized, followed by the application of a window. The window consisted of three major parts: the rise and fall time, which were, respectively, the first and second halves of a Gaussian window with a total duration of 50ms; and a plateau time of 150ms of duration with a flat amplitude of 1. The syllables had a duration of 200ms and were calibrated after windowing as described in [9].

C. Experimental Syllabic Paradigm and Inclusion Criteria

Two paradigms with different degree of difficulty were constructed. The difficulty level was accomplished by the combination of the syllables.
"Difficult Syllable Paradigm (DSP)": We expected this paradigm to be more difficult to solve because the syllables had the same vowel and different plosives.
"Easy Syllable Paradigm (ESP)": This paradigm should be easier to solve, because the syllables had different vowels and consonants.
In the paradigms the syllables had randomized order and randomized interstimulus interval, which ranged from 1–2s. The randomized order was used to maximize the entropy of the experiment such that their solution requires an effortful task. The auditory paradigms were presented monaurally at 65dB Sound Pressure Level (SPL). The subjects were instructed to pay attention to the stimulus and to press a button after the detection of the target syllable, which was in all the cases the same syllable. Each syllabic paradigm lasted 10 min and short pauses were made between them after subjects request. The subjects inclusion criteria for the study was: (1) the ALRs had an identifiable waveform of the N1-P2 complex; and (2) they detected correctly at least 80% of the target syllables.

D. Behavioral Measures

For both experimental paradigms, the median reaction time (RT) and the performance accuracy were determined for each subject in order to complement our electrophysiological data. The performance accuracy *d'*, which was proposed by the theory of signal detection [10] and also applied to support event–related potential studies (e. g. [11]), was calculated as $d' = z(false\ alarm\ rate) - z(hit\ rate)$ [10], where z is the z-transform. The hit rate is the probability to detect correctly the target syllable and the false alarm rate corresponds to the probability to respond to a distractor syllable.

E. Synchronization Stability and Listening Effort

For the analysis of the ALRs, we used the WPSS that was introduced in [12] for the quantification of auditory attention in ALR single sweeps. The larger the WPSS, the larger the effort, resulting from an increased attention to detect the target syllable. We have shown in [6], [7], that the WPSS is a robust measure and independent from the amplitude fluctuations of the N1 wave. As a general definition, for the determination of the WPSS we need an adaptation of the derived phase locking measure between two signals to our problem. 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 $(\mathcal{W}_\psi x)(a,b) = \langle x, \psi_{a,b} \rangle_{L^2}$. We define the synchronization stability $\Gamma_{a,b}$ of a sequence $\mathcal{X} = \{x_m \in L^2(\mathbb{R}) : m = 1, \ldots, M\}$ of M ALR sweeps by

$$\Gamma_{a,b}(\mathcal{X}) := \frac{1}{M} \left| \sum_{m=1}^{M} e^{\imath \arg((\mathcal{W}_\psi x_m)(a,b))} \right|. \qquad (1)$$

Note that (1) yields a value in $[0, 1]$. The wavelet used in this study was the 4th–derivative of the complex Gaussian function, as in [5], [6], [7], [12].

III. RESULTS & DISCUSSION

A. Behavioral Data

The Fig. 2 represents the means and the standard deviations of the median RTs and of the d'prime values for the different subject groups and conditions. On the left y-axis, the RT values (black markers) are displayed, whereas the d'prime values (gray markers) are shown on the right y-axis. In all subject groups, the RT is slightly larger for the DSP. It can also be seen, that there is a clear tendency of a decrease of the d'prime values for the DSP compared to the ESP.

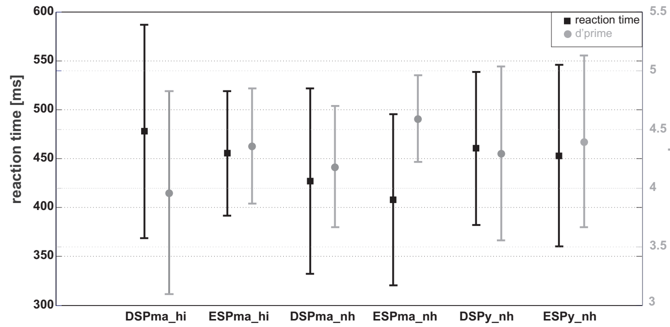

Fig. 2. Grand average and standard deviations of the median reaction times (left y-axis, black markers) and the d'prime values (right y-axis, gray markers) for the different subject groups (ma_hi=middle-aged hearing impaired subjects, ma_nh=middle-aged normal hearing subjects, y_nh=young normal hearing subjects and paradigms (DSP and ESP)

Furthermore, it is noticeable, that the difference between the d'prime values of the DSP and the ESP for the young subject group is smaller compared to the two middle-aged groups. This can be interpreted, that both paradigms were relatively easy to solve for the young subjects. These observations indicate, that the DSP was more difficult to solve as the ESP, especially for the middle-aged subjects. Nevertheless, neither the inter nor the intra group comparison of the RT and the d'prime values was significantly different (p>0.05).

B. Synchronization Stability and Listening Effort

The WPSS was calculated for each subject and condition for the scale $a = 40$ using 70 ALR sweeps, which were evoked by correctly detected target syllables. This scale was also selected in previous studies [6], because a good temporal localization of the maximum of the WPSS in the expected range of the N1-P2 complex (approx. 50 to 250 ms) can be achieved. In Fig. 3 is plotted the grand average of the ALRs (left side) and the normalized WPSS with the corresponding results of the time resolved ANOVA (right side) for the different conditions. From top to bottom are the results for the three subject groups shown (a) ma_hi subjects, b) ma_nh subjects, c) y_nh subjects). A clear shape of the N1-P2 complex is visible in the ALRs for both paradigms (DSP and ESP) and for each subject group. A detailed analysis of the waveforms revealed no statistical significance (p>0.05) for the N1 and P2 amplitudes and latencies, neither between the subject groups nor between the conditions. The results of the WPSS for the middle-aged subject groups show, that the WPSS is larger for the DSP (black line) compared to the ESP (gray line) in the expected time interval of the N1 wave (approx. 50-150ms). It can be interpreted, that solving the DSP compared to the ESP requires more effort from the ma_nh subjects as well as from the ma_hi subjects. This difference of the WPSS in the time interval of the N1 wave reached also statistical significance for both middle-aged subject groups. The latter can be seen by a negative peak (dotted gray line) in the results of the time resolved (one way) ANOVA. For the young subjects, no difference of the WPSS is noticeable.

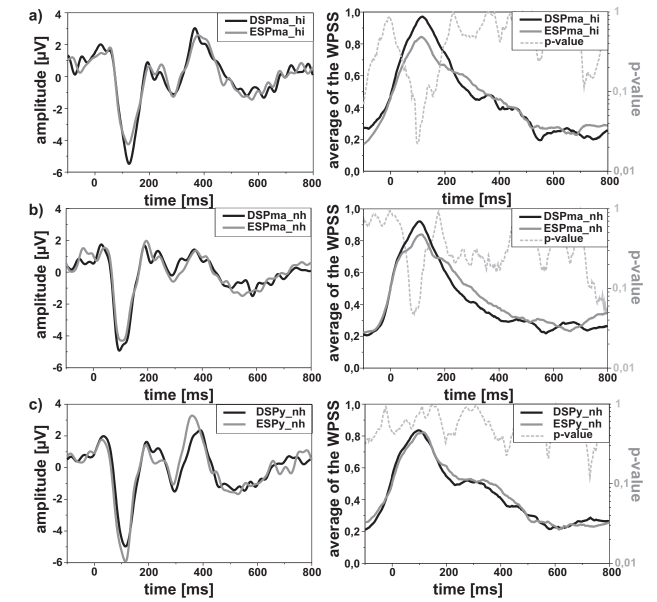

Fig. 3. Left: Grand average of the ALRs for both conditions (DSP (black line) and ESP (gray line)) and subject groups (a) ma_hi subjects, b) ma_nh subjects, c) y_nh subjects). Right: Corresponding normalized average of the WPSS (left y-axis) with the results of the time-resolved ANOVA (DSP vs. ESP; right y-axis in logarithmic scale)

This is in line with the behavioral results (cf. III-A) and the subjective judgements of the younger participants. Most of them reported, that the detection of the target syllable in both conditions required the same level of effort. The difference of the grand normalized WPSS between the two paradigms for each subject group was analyzed. This difference was calculated for a better comparison of the WPSS between the subject groups. Thus, we assumed to reduce the influence of the exogenous components, like intensity variations resulting from different hearing thresholds, on the N1 wave and the WPSS, respectively. This difference is illustrated in Fig. 4. On the left side, the difference of the WPSS (DSP minus ESP) is plotted for the three subject groups (dotted black line: ma_hi subjects, dotted dark gray line: ma_nh subjects, dotted light gray line: y_nh subjects). It is noticeable, that in the time interval of the N1 wave, which is marked by a gray rectangle, the difference is larger for the ma_hi subjects compared to the normal hearing participants. Beside this, the WPSS difference is also larger for the middle-aged subjects compared to their younger counterparts. On the right side, the mean difference of the WPSS for each subject group in the range of the N1 wave (102.93ms to 115ms) is illustrated. These interval values of the N1 component are the minimum and maximum values of the mean N1 latencies, separately averaged for each subject group and condition. It can be seen that the mean difference of the WPSS is the largest for the hearing impaired subject, followed by the result of the middle-aged subject group, whereas the difference is the smallest for the youngest group. This can be interpreted, that the hearing impaired subjects had to pay more attention to detect the target syllable compared to the normal hearing subjects. These aforementioned observations

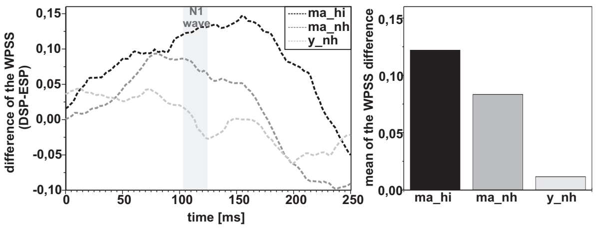

Fig. 4. Left: Difference of the grand normalized WPSS (DSP minus ESP) over the time for the three subject groups (dotted black line: ma_hi subjects, dotted dark gray line: ma_nh subjects, dotted light gray line: y_nh subjects). The gray rectangle indicates the interesting time window of the N1 wave. Right: Mean of the WPSS difference (DSP minus ESP) in the analyzed time window of the N1 wave (cf. left panel, gray rectangle).

are also noticeable in the individual results. In Fig. 5 are the representative results of three participants from each subject group illustrated (top: ma_hi subject, middle: ma_nh subject, bottom: y_nh subject). On the left panel, are the ALRs for

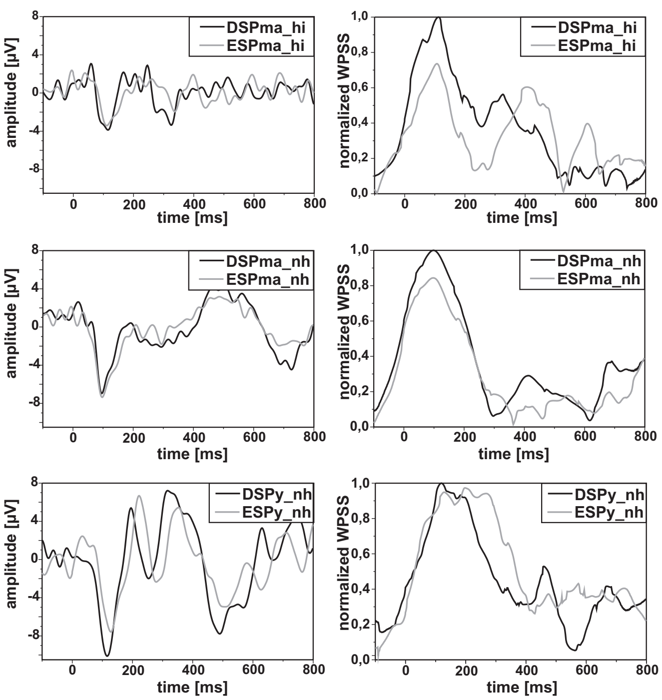

Fig. 5. Individual results for a representative subject of each group (top: ma_hi subject, middle: ma_nh subject, bottom: y_nh subject). Left: ALRs for the two conditions (DSP (black line) and ESP (gray line)). Right: Corresponding normalized WPSS for both paradigms (DSP (black line) and ESP (gray line)

both paradigms shown. A clear N1 component is visible for all the subjects and conditions. On the right panel are plotted the corresponding WPSS. For a better comparison of the WPSS between the groups, the WPSS was normalized for this figure. Here, the WPSS is also larger for solving the DSP compared to the ESP for the middle-aged subjects in the interval of the N1 component, whereas the WPSS for the both conditions is almost the same for the younger participant. Furthermore, the difference between the WPSS of both conditions is the largest for the hearing impaired subject.

IV. CONCLUSIONS AND FUTURE WORK

In this study, we presented a feasible way to extract listening effort correlates in hearing impaired subject. Thus, we used syllabic paradigms for the recording of ALR sequences. The results of the WPSS were compared between the measured hearing impaired, middle-aged normal hearing and young normal hearing subjects. The findings of this study have shown that 1) the WPSS of ALR sequences can be extracted in normal hearing as well as in hearing impaired persons, 2) an age related effect on the WPSS was not noticeable and 3) the intergroup comparison of the difference of the WPSS showed a tendency to be larger for the ma_hi subjects compared to the ma_nh participants. This can be interpreted, that the hearing impaired persons required more effort to solve the paradigms as their normal hearing counterparts. In order to evaluate these findings and to investigate the effects of the hearing loss on the WPSS and the listening effort, respectively, a part of our future work will be to increase the population of the hearing impaired subjects as well as the degree of hearing loss.

REFERENCES

[1] 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.

[2] 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.

[3] 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.

[4] E. Edwards, “The future of hearing aid technology,” *Trends in Amplification*, vol. 11, pp. 31–45, 2007.

[5] D. J. Strauss, F. I. Corona-Strauss, C. Bernarding, M. Latzel, and M. Froehlich, “On the cognitive neurodynamics of listening effort: A phase clustering analysis of large–scale neural correlates,” in *Conf Proc IEEE Eng Med Biol Soc*, 2009, pp. 2078–2081.

[6] 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.

[7] C. Bernarding, F. I. Corona-Strauss, M. Latzel, and D. J. Strauss, “Auditory streaming and listening effort: An event–related potential study,” in *Conf Proc IEEE Eng Med Biol Soc*, vol. 2010:1, 2010, pp. 6817–6820.

[8] B. Shield, “Evaluation of the social and economic costs of hearing impairment - a report for hear-it,” HEAR-IT, Tech. Rep., oct 2009.

[9] European Committee for Standardization, “Electroacustics- audiometric equipment. part 3: Test signals of short duration.” The European Standard. EN 60645-3:2007.” Technical Report, 2007.

[10] J. L. Yanz, “The application of the theory of signal detection to the assessment of speech perception,” *Ear and Hearing*, vol. 5:2, pp. 64–71, 1984.

[11] P. A. Oates, D. Kurtzberg, and D. R. Stapells, “Effects of sensorineural hearing loss on cortical event–related potential and behavioural measures of speech–sound processing,” *Ear and Hearing*, vol. 23, pp. 399–415, 2002.

[12] D. J. Strauss, W. Delb, R. D’Amelio, Y. F. Low, and P. Falkai, “Objective quantification of the tinnitus decompensation by measures of auditory evoked single sweeps,” *IEEE Trans Neural Syst Rehabil Eng.*, pp. 74–81, 2008.