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Estimating Uncomfortable Loudness Levels using Evoked Potentials to Auditory Stimuli for Hearing Aid Fitting *

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Abstract— **Determining the loudest sound level that a person can comfortably tolerate (uncomfortable loudness level: UCL) imposes a strain on people suffering from hearing loss. In the present study, we propose a method of estimating UCL based on auditory evoked potentials (AEPs). Adults with normal hearing (18 men aged 25-56 years) participated in the study. Three tone bursts (S1, S2 and S3; a triplet) of the same frequency (either 1k, 2k or 4k Hz) were presented to the right or left ear with an interstimulus interval of 300 ms. The sound intensity decreased gradually by 5 dB HL from 80 dB (S1) to 70 dB HL (S3). The interval between triplets was 450 ± 50 ms. The frequency of a given triplet differed from the frequency of the preceding triplet. An electroencephalogram was recorded from three scalp electrode sites (Cz, C3, and C4) with the right mastoid reference. The 900-ms period after the onset of the triplet was transformed to a wavelet coefficient and averaged separately by stimulated ear and tone frequency. The UCLs were estimated by linear discriminant analysis on the basis of trained data of the other participants' subjective UCLs and the wavelet coefficients. The mean estimation error was 4.9 ± 5.0 dB. This result suggests that the UCLs could be estimated successfully on the basis of AEPs to triplets of auditory tones.**

I. Introduction

Hearing-impaired people who require hearing aids are increasing as the society is aging. The estimated total number of people suffering from hearing loss of more than 25 dB will exceed 700 million by 2015 around the world. Before using hearing aids, correct fitting is indispensable to set levels of amplification at each frequency band according to the individual user's hearing properties. Hearing threshold level (HTL; i.e. the smallest sound level that they can hear) and uncomfortable loudness level (UCL; i.e. the largest sound level that they can tolerate) are the first hearing properties to be identified.

HTL and UCL are utilized to adjust the dynamic range of the sound pressure generated by hearing aids. HTL, which is used in diagnosing hearing loss as well, can be obtained by a relatively simple test that determines whether the person can hear a tone. UCL, however, requires an evaluation using uncomfortably loud tones, causing the examinee psychological stress and fatigue; therefore it is often estimated from the HTL. But the estimated UCLs do not reflect individual differences, and their low accuracy rates have been an issue. Thus, the development of a method to determine UCLs accurately and with less discomfort is warranted.

Electroencephalogram (EEG) is voltage fluctuations recorded by electrodes placed on the surface of the scalp, detecting the electrical activity of neurons in the brain. Thornton et al. showed a correlation between the latency of V wave of the auditory brainstem response (ABR) to clicking sounds and the UCL of that examinee [1]. Zenker-Castro et al. reported that loudness perceived by an individual could be approximated by the amplitude of auditory steady state response (ASSR) to amplitude-modulated tones [2]. However, the former study does not provide separate UCL estimates at different frequency bands, and the latter requires more than 30 minutes to complete and the accuracy of the estimate is low.

We have demonstrated that when a paired stimulus of pure tones with the same frequency and sound pressure is presented, the auditory evoked potentials (AEPs) of the second tone are different according to the level of UCL measured by subjective report [3]. Moreover, by repeating paired stimuli for approximately 10 minutes, we can obtain the estimations of UCLs with a mean error of less than 5 dB. In this paper, we describe a UCL estimation method using triplets of pure-tone stimuli in order to develop a procedure with minimal burden on examinees.

II. Method

The feasibility of UCL estimation based on AEP was examined by comparing measurements of subjective reports of UCLs and estimated UCLs based on AEPs to tone stimuli.

A. Participants

Normally hearing adults (18 men, 25-56 years old, mean age 39.6 years) participated in the study. None had a history of psychiatric/neurological disorders or drug/alcohol abuse. They gave written informed consent.

B. Measurement of Subjective UCL

Intermittent tones of 1k, 2k, and 4k Hz were presented in an ascending order of loudness to one ear at a time using a pure-tone audiometer (AA-72; RION, Japan). Participants were asked to raise their hand when he or she felt the sound was too loud to listen to for a while, and the level was recorded as the subjective UCL for each ear and frequency. Measurements of subjective UCL were obtained twice; before and after EEG recording.

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C. Measurement of EEG

Figure 1 is a schematic diagram of our auditory stimuli. Tone bursts (rise/fall time 3 ms; plateau time 44 ms) were used as auditory stimuli. Three tone bursts (S1, S2 and S3; a triplet) of the same frequency (either 1k, 2k or 4k Hz) were presented to the right or left ear with an interstimulus interval of 300 ms. The sound intensity decreased gradually by 5 dB HL from 80 dB HL (S1) to 70 dB HL (S3). The interval between triplets was 450 ± 50 ms. The frequency of a given triplet differed from the frequency of the previous triplet to avoid the habituation effect on AEP. All triplet conditions consisted of 50 trials each (300 trials in total). Participants were instructed to listen to the auditory stimuli silently without responding to the stimuli. Auditory stimuli were controlled by a personal computer and presented through headphones (HDA200; SENNHEISER, Germany). The sound pressure level of each auditory stimulus was calibrated using a sound level meter (LA-1440; ONO SOKKI, Japan) and acoustic coupler (IEC318; Larson Davis, USA).

An electroencephalogram (EEG) was recorded from three scalp electrode sites (Cz, C3, and C4) according to the 10-20 system using an biosignal amplifier (AP1124; TEAC, Japan). The recording reference was the right mastoid. A vertical electrooculogram (EOG) was also recorded. These signals were processed with a bandpass filter of 0.16 Hz (time constant: 1 s) to 30 Hz and digitized at 1000 Hz. Then a digital bandpass filter of 1–20 Hz was applied offline. The period between 100 ms before and 1000 ms after the onset of S1 was averaged separately by stimulus side (right ear vs. left ear), tone frequency, and electrode site. The baseline was aligned to the mean amplitude of the 100-ms pre-stimulus period. The trials in which EEG or EOG exceeded ± 80 µV were excluded from the analysis.

Moreover, to extract the time-frequency components, the 900-ms period after the onset of the triplet was down-sampled to 100 Hz and transformed to a wavelet coefficient using the Mexican-hat mother wavelet. The scale of the wavelet transformation used integers from 1 to 9 (equivalent to 2.5-25 Hz). The wavelet coefficient was also averaged separately by stimulated ear and tone frequency as an evoked response. Data from one participant whose subjective UCLs could not be obtained due to scaling out and three participants whose minimal average number of trials were less than 15 were excluded from the analysis.

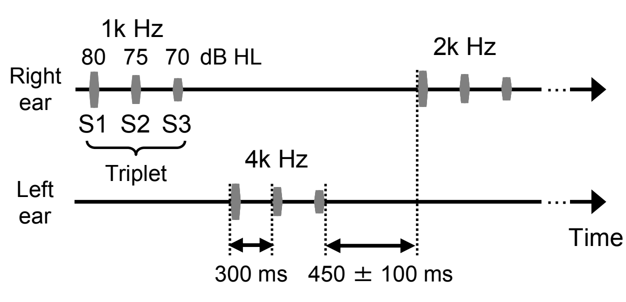

Figure 1. Schematic diagram of auditory stimuli.

D. UCL Estimation based on AEP

The UCLs were estimated by linear discriminant analysis on the basis of trained data of the other participants' subjective UCLs and the evoked responses (wavelet features).

The wavelet features for the estimation were generated in each wavelet scale, by averaging the averaged wavelet coefficients between 0 and 900 ms with a time window of 50 ms (i.e., 9 scales x 18 time windows). By pairing arbitrarily chosen two-wavelet features, the correspondence between the same combinations of other participants' wavelet features and subjective UCLs was learned and used as a trained data. The trained data were created for each tone frequency (pooling ear side).

The accuracy of UCL estimations was determined using the mean error, calculated as the mean of the absolute values of the difference between subjective and estimated UCLs for each participant, side (right or left ear), and tone frequency. The mean error was calculated for all combinations of wavelet features (amount of combinations were 13,041).

III. RESULTS

A. Subjective UCLs

The mean ± standard deviation of the first and second subjective UCLs were 96.3 ± 9.8 and 99.3 ± 8.3 dB HL, respectively, when collapsed across ears (right and left) and frequencies (1k, 2k, and 4k),. The mean individual difference between the first and second measurements was 26.3 dB (35 dB maximum). The subjective UCLs were larger in the second measurement than in the first measurement (p = .001). The intra-individual variance between the first and second measurements was 4.0 ± 4.3 dB. Moreover, the mean ± standard deviation of subjective UCLs for each frequency (1k, 2k, and 4k Hz) were 98.8 ± 7.4, 98.1 ± 8.0, 96.7 ± 8.9 dB HL, respectively, when collapsed across ears (right and left) and measurement order (first and second). These results suggest that subjective UCLs contain both large individual differences and inter-individual variations.

B. EEG

Figure 2 (a) shows grand mean waveforms (GMWs) elicited by the triplets (S1, S2, and S3) at the central site (Cz). Examinees were categorized into high and low UCL groups on the basis of the mean subjective UCL calculated by collapsing ears (right and left) and tone frequencies. The bold line represents the GMW of the participants with subjective UCLs greater than 100 dB (high UCL group), and the fine line represents the GMW of participants with subjective UCLs smaller than 100 dB (low UCL group). The onsets of S1, S2, and S3 are indicated by solid lines. Regardless of the level of subjective UCL, a negative component (N1 component) and a positive component (P2 component) occurred approximately 100 ms and 200 ms after each stimulus presentation, respectively. While there was no difference in AEPs to S1, AEPs to S2 and S3 differed according to the level of subjective UCLs, in that the amplitude was smaller in the low UCL group than in the high UCL group.

Figure 2 (b) shows the mean amplitude values of the N1 and P2 components for each stimulus at central site (Cz). The amplitude of N1 component decreased monotonically from S1 to S3 regardless of the level of UCL. In contrast, the amplitudes of P2 component elicited by S2 and S3 differed between high and low UCL groups; the amplitudes were smaller for examinees whose subjective UCLs were lower.

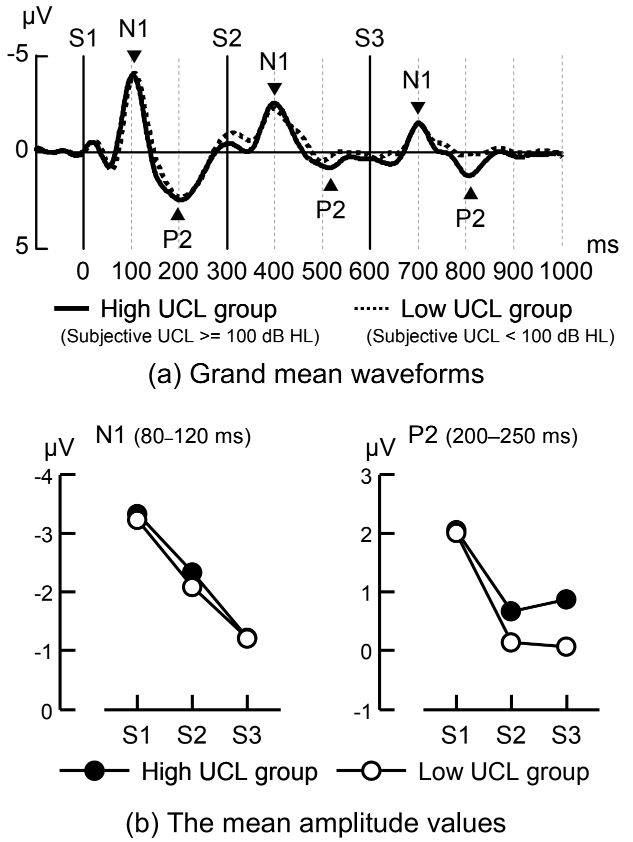

Figure 2. (a) Grand mean waveforms for each UCL group, (b) The mean amplitude values of N1 (80–120 ms) and P2 (200–250 ms).

C. UCL Estimation

Figure 3 shows the difference wavelet features that were calculated by subtracting the wavelet features of the low UCL group from the wavelet features of the high UCL group. The result indicates that the wavelet features after S2 and S3 differed substantially. In the low UCL group, the wavelet features less than 5 Hz were small, especially after S3, .

Figure 4 (a) shows the distribution of estimated UCLs (by linear discrimination) and subjective UCLs (pooled across ears and tone frequencies) for the smallest mean error calculated for each combination. The size of the circles indicates the number of cases. A circle whose center is on the broken line signifies that the UCL estimated by the analysis of AEP corresponded with the subjective UCL that was actually measured. Although to variable degrees, UCLs are successfully estimated. The mean error was 4.9 ± 5.0 dB. In 72.6% of the cases, the estimate errors were less than 5 dB, and the correlation between the actual measurements and estimates was $r = .566$ ($p < .001$).

Figure 4 (b) shows the distribution of estimated and subjective UCLs for each tone frequency. The mean errors of each tone frequency (1k, 2k, 4k Hz) were 3.2 ± 3.6, 5.7 ± 5.8 and 5.9 ± 5.4 dB, respectively. Although the mean estimation errors varied among tone frequencies, UCLs were estimated successfully in all tone frequencies.

Figure 5 (a) shows the frequencies of wavelet features that were used in the best 1% of the estimations, and Figure 5 (b) shows the frequencies by the time window. Figure 5 demonstrates that the wavelet features after S3 are effective in UCL estimation. Particularly, the wavelet features of the 150-200 ms period after S3 were used in more than 15% of the top 1% estimations. This window coincides with the period that is shown with a great difference in the grand mean waveforms in Figure 2 and wavelet features in Figure 3.

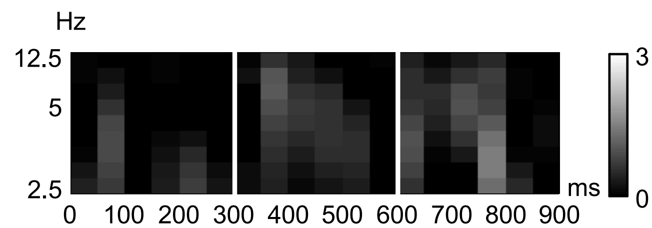

Figure 3. Difference wavelet features (high UCL group – low UCL group).

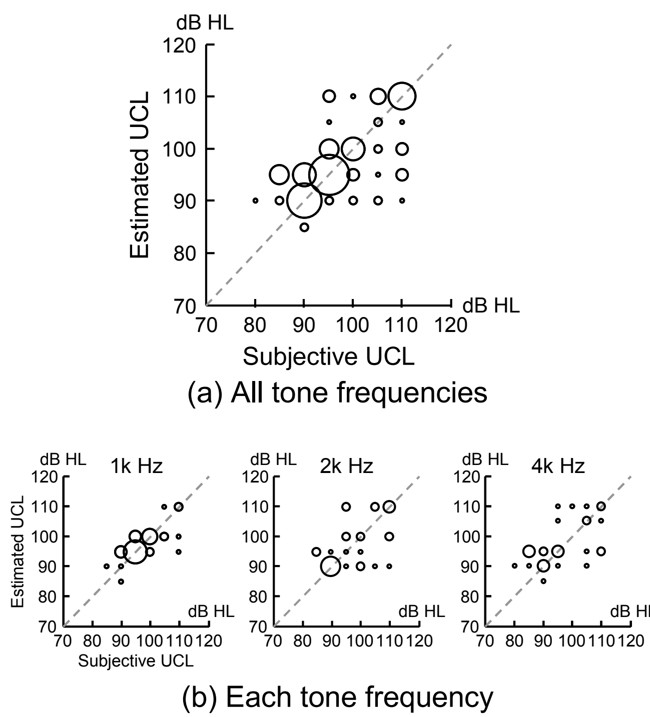

Figure 4. Distribution of the subjective and estimated UCLs

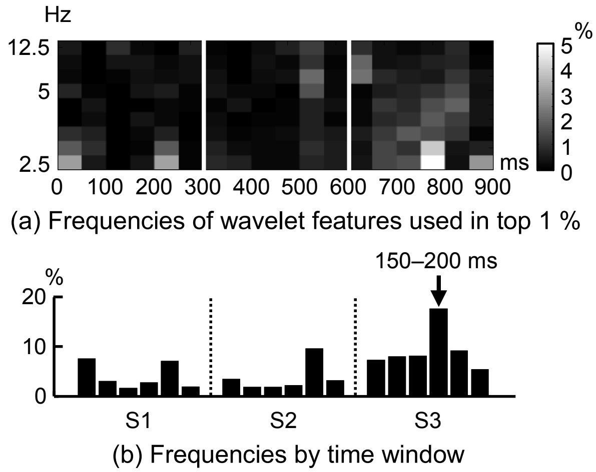

Figure 5. Selected features in the top 1 % estimations.

IV. Discussion

When a triplet of auditory tones was presented with a sound pressure that people normally expecience, AEPs to the second and third tones were reduced in amplitude for people with lower subjective UCLs. A linear discriminant analysis of the wavelet features showed that it was possible to estimate UCLs with a mean error of less than 5 dB. Mean errors were smaller when the wavelet features following S3 (especially 150-200 ms after the presentation of S3) were used in the estimation. These results indicate that the AEPs after S3 contain information about UCL, and that UCL can be estimated by its analysis.

The mean estimation error between subjective UCLs and estimated UCLs was 4.9 ± 5.0 dB. Considering that the minimum scale of a typical audiometer is 5 dB, and that the variance between the two actually-measured subjective UCLs was 4.0 ± 4.3 dB, this can be considered an acceptable error range for the measurement of hearing properties.

Amplitudes of AEPs (both N1 and P2 component) to S2 and S3 decreased more than to S1. This was due to the effect of successive presentation of tone stimuli in short intervals [4]. This study demonstrated that the decreasing characteristics of P2 component differed depending on the levels of subjective UCL, and it decreased to a greater degree in the low UCL group than in the high UCL group. One interpretation of this result concerns the possible relationship between tolerance for loud tones and duration of the refractory period. It is plausible that in the low UCL group, processing of S1 was not completed, so that S2 and S3 were not analyzed (inhibited).

In contrast, AEPs to S1 did not show differences due to levels of UCL. Additionally, the frequency used in the top 1% of estimations was lower compared to S3. Within the ordinarily experienced sound pressure range, the amplitude of the N1 component to tone stimuli increases almost linearly [5]. Therefore, it is highly likely that AEPs to S1 reflect the physical properties of tone stimuli and contain little information about UCLs. It can be concluded that the successive presentation of tone stimuli is necessary to realize a UCL estimation method using sound pressure levels requiring little burden on users.

The mean estimation error for each tone frequency varied among tone frequencies. These differences in the error may reflect the difference of standard deviations of subjective UCLs among tone frequencies. Additional experiments and explorations are needed to evaluate for the presence of the effect of tone frequency on the mean estimation error.

V. Conclusion

From the analysis of AEPs to pure tones presented in triplets descending from 80 dB by 5 dB decrements, which are commonly experienced sound pressures, we conclude that UCLs of normally hearing individuals can be estimated with a mean error of less than 5 dB. If the present method could be applied to individuals with hearing loss, the necessary determination of the UCL could be accurately estimated without causing examinees psychological stress or fatigue.

We plan to utilize a similar methodology for individuals with hearing loss to confirm the applicability of this approach. In addition, we will use the UCLs that were estimated in the present study for actual hearing aid adjustments, to verify its effectiveness.

References

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