IEC-based Hearing Aid Fitting

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***Abstract*— In this paper, we propose a new hearing aid fitting method based on an interactive evolutionary computation (IEC). First, we identify the problems with current hearing aid fitting methods and propose an IEC fitting method to improve the fitting process with completely different approach from that of conventional fitting methods. Then, we design an experimental hearing aid system and evaluate the IEC fitting method. Using speech and music sources, we show that our proposed IEC fitting method outperforms conventional ones.**

1 Introduction

Some countries are concerned about their aging population. For example, the Japanese population segment over 65 years of age is predicted to make up 17% and 25% of the total Japanese population in the years 2000 and 2015, respectively. In an aging society, it is desirable to develop welfare devices, such as hearing aids, that support the activity of its people.

Hearings aids are not only for people who are born hearing-impaired or who lost their hearing due to illness or accident, but also for those who are hearing-impaired due to aging.

Due to the diverse nature of hearing impairment, several signal processing techniques are necessary to fully personalize hearing aid characteristics such as the tempo, the frequency, or the volume of input sounds. Since digital hearing aids with a higher potential to perform such complex processing have been developed and put on the market, the hardware can better compensate for hearing loss now.

However, it is still difficult to fully take advantage of their capacity to compensate hearing-impairment and gain wide satisfaction among users. There are two main reasons related to software: (1) it is almost impossible for us to understand the total hearing characteristics, from peripheral to central, of each person, and (2) it is difficult to optimize the parameters of signal processing in a hearing aid to adjust the compensation characteristics for each person. Despite (or perhaps because of) these difficulties, conventional hearing aid fitting has been conducted based on two, rather limited, hypotheses: (a) impaired hearing might be estimated by combining perceptual hearing characteristics measured individually under restricted conditions, and (b) hearing-impairment might be compensated by bringing the characteristics of the hearing-impairment close to that of people with normal hearing.

In this paper, we propose a new hearing aid fitting method based on an interactive evolutionary computation (IEC) which solves the difficulties described above. The approach of this fitting method is completely different from that of the conventional fitting methods; it does not require previous measurement of a user's hearing characteristics, and therefore, allows users to fit their hearing aids at any time under any acoustic environment, not only with clarity of sound but with quality and preference, as well. First, we point out the problems of conventional fitting methods in section 2 and propose the IEC fitting method in section 3. Then, we design an experimental hearing-impairment compensation system and evaluate the proposed IEC fitting method from several tests that could not be used for the conventional hearing aids in sections 4 and 5.

2 Conventional Hearing Aid Fitting

2.1 Approach on which the compensation of hearing-impairment is based

Many conventional studies on the compensation for hearing-impairment have been conducted based on the two hypotheses mentioned in section 1. These hypotheses take a *bottom-up* approach that estimates total hearing from measured sensory and perceptual characteristics, fragmentary auditory knowledge, and past experience of hearing aid fitting (see the Figure 1 left.)

Conventional approaches to compensate for hearing-impairment require previous measurement of the auditory characteristics of hearing aid users using pure tones or band noise and attempt to adjust the differences between the estimated hearing characteristics of the hearing-impaired person and that of a person with normal hearing.

However, these approaches have several problems: (1) it is time-consuming to measure auditory characteristics under the restricted environment using an artificially-produced sound, (2) it is fundamentally impossible to compensate for hearing based on sound preferences because measured auditory characteristics are at the level of sensation and perception, (3) auditory characteristics are usually independently mea-

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sured, and their mutual effects cannot be reflected in the compensation for hearing-impairment, and (4) it is doubtful that adjusting the hearing characteristics of a hearing-impaired person to those of a person with normal hearing leads to the best compensation.

Essentially, no one can really know how other people hear. As long as compensation for hearing-impairment is based on approaches that estimate how a hearing-impaired person hears measured data, i.e. the *bottom-up* approach, we cannot overcome these problems. A different approach is required.

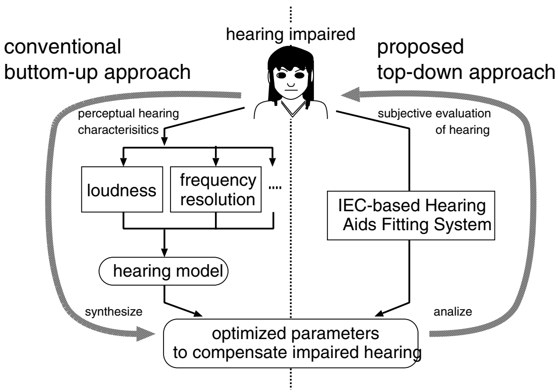

Figure 1: A conventional bottom-up approach to the study of hearing characteristics (left) and the proposed top-down approach (right).

2.2 Conventional Method of Hearing Aid Fitting

Conventional hearing aid fitting is based on the approach of compensation for hearing-impairment as described in section 2.1. It has been presumed that reducing the difference between normal and impaired hearing characteristics results in better fitting of hearing aids.

The first step in most conventional hearing aid fitting methods is to measure an audiogram of a hearing aid user. An audiogram is the frequency characteristics of sound that a person feels in minimum, moderate, and maximum level and measured by pure tones in every octave frequency width. The second step is to estimate amplified-attenuated characteristics according to input sound pressure level (SPL) obtained from the audiogram. Since the audible range of hearing-impaired people is narrower than that of people with normal hearing, amplification of low SPL sound and attenuation of high SPL sound is necessary (see Figure 4.)

The difficulty in hearing aid fitting is that the compression characteristic depends on the frequency, the person, and may be nonlinear. The estimation of the audible range from an audiogram is just a simple approximation, and hearing aid fitting is based on the rough mapping from the approximation to the estimated compression characteristic.

Furthermore, both measurement and fitting are conducted based on heuristics and trial-and-error methods (see left side in Figure 2) by fitting engineers and otologists who are not necessarily hearing aid users themselves. As previously mentioned, the hearing aid user is the only one who can evaluate the fitting. Measurements with low level auditory characteristics do not reflect the level of user preference at a psychological level.

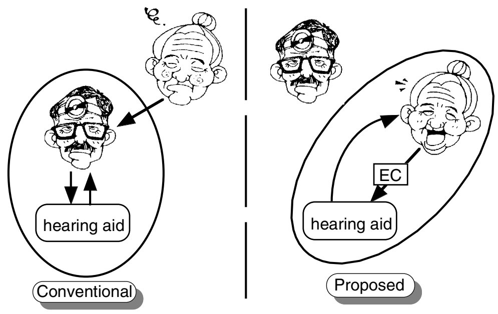

Figure 2: Conventional hearing aid fitting (left) and proposed one (right).

3 Interactive EC-Based Fitting

3.1 Proposal of an IEC fitting method

We propose an IEC fitting method that is different from conventional fitting methods and solves several problems associated with the conventional fitting method [7, 6, 14]. The IEC fitting method optimizes the fitting parameters of a hearing aid based on the end user's evaluation of sounds heard (see Figure 2 right). This method does not estimate how a hearing aid user hears previously measured auditory characteristics but starts from how a hearing aid user hears. This is said to be a *top-down* approach (see Figure 1 right).

The key technology of the proposed fitting method is an interactive evolutionary computation (EC). The interactive EC is an EC technology that optimizes systems based on human evaluation. Simply stated, it is an EC whose fitness function is replaced by human evaluation. As the EC is a fitness-based search, it is applicable to a search of psychological space, such as a preference space, where we cannot obtain gradient information and, therefore, cannot use gradient methods. The interactive EC has been applied to several fields such as CG graphics, industrial design, music creation, speech processing, VR, data-mining, database retrieval, education, games, and so on [12, 13]. We have studied not only its applications but also its interface. Some of them are adopted in our experimental IEC fitting system in section 4.

In the IEC fitting method, EC generates several parameter sets that determine the characteristics of signal processing filters in hearing aids as EC individuals; i.e. EC generates multiple hearing aids. Sound processed by each hearing aid is displayed to a hearing aid user when he or she chooses one from a screen display. The hearing aid user evaluates the displayed sounds and returns his or her subjective evaluation as a fitness value to the EC. EC generates next individuals, hearing aid characteristics, based on the feedback from subjective fitness values. This cooperative operation is iterated until the user finds a satisfactory sound.

3.2 Characteristics of IEC fitting

The primary advantage of the IEC fitting is that it allow hearing aid users to personally fit their hearing aids at any time, at any place, and with any sound source.

The IEC fitting does not require previous measurement of auditory characteristics unlike conventional fitting methods, and the EC automatically optimizes the fitting characteristics. This feature frees users from the fitting with an artificially-produced sound, such as pure tone or band noise, at hearing aid shops or hospitals with the support of hearing aid engineers and otologists. This is important because the users can fit their hearing aids in the acoustic environment where they use their hearing aids: music in a living room, talking and noise in an office or crowded market, etc. The IEC fitting in a familiar environment has the potential for both an enjoyable fitting and an enjoyable usage of a well-fitted hearing aid.

Another advantage is that the proposed IEC fitting method does not depend on the signal processing used in hearing aids. The proposed IEC fitting is not a compensation method for hearing impairment but an optimizing method for the compensation method. This allows hearing aid manufacturers to adopt the method without significantly changing their products.

The disadvantage of the IEC fitting may be that users become tired through iterative fitting operations as well as any other interactive EC applications. Since the interactive EC users have to cooperate with tireless computers, we cannot avoid this problem of fatigue.

To reduce the problem of fatigue from interactive EC applications, several trials to modify the interactive EC have been proposed, such as improving the input interface [10, 3], improving the display interface [3, 4], accelerating EC convergence [2], etc.

The IEC fitting has a high possibility to provide us with new facts or knowledge on compensation for hearing-impairment and audio psychology through the top-down approach as shown in the right half of Figure 1. The IEC fitting can handle fitting at a higher psychological level, such as cognition and preference, while conventional ones are based on lower psychological levels, such as sensation and perception. Therefore, we expect to obtain new knowledge on hearing by analyzing the optimized parameters, which was difficult to obtain from conventional fitting methods. Such expected new facts or knowledge on the compensation for hearing-impairment includes the dependency on a kind of target sounds, the individuality of hearing preference, the mutual relationship among parameters, etc.

4 Experimental Hearing Aid System with IEC Fitting

The experimental IEC fitting-based system consists of three parts: a hearing aid, an EC part, and an interface part for an interactive EC. The hearing aid consists of two parts; one part to determines the compensation characteristics for hearing-impairment, and the other performs signal processing. Figure 3 shows our experimental system. In this section, we explain the three main parts of this system.

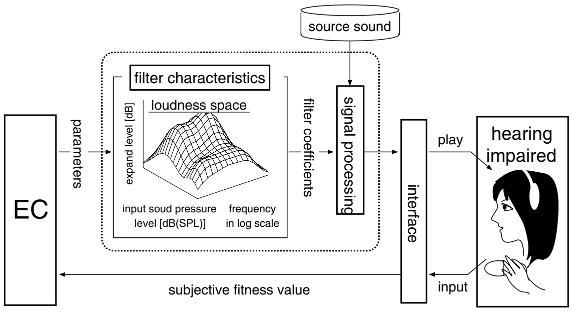

Figure 3: Our experimental IEC-based hearing aid fitting system.

4.1 3-D loudness space for hearing-impairment compensation

The proposed IEC fitting is not a compensation method of hearing-impairment but an optimizing method for the compensation method. This allows it to be applied to any hearing aid by any manufacturer.

For our experimental hearing aid, we propose the construction of a 3-D loudness space whose axes consist of input SPL, frequency, and amplification level which compensate for hearing impairment [7, 8]. It is believed that loudness compensation is the most effective method to improve impaired hearing and it is widely applied to commercial hearing aids. The coefficients of signal processing filter in hearing aids are based on the loudness characteristics.

Loudness compensation is based on loudness functions which describes relationships between the physical input SPL and the user's subjective loudness level in several frequency bands. The audible sound level range of sensorineural hearing-impaired people is generally narrower than that of people with normal hearing as shown in Figure 4. Since a simple amplification of an input sound based on hearing loss for each frequency sometimes causes discomfort, adaptive loudness compensation keeps the output SPL within the narrow range of impaired hearing. This has been realized in digital hearing aids [1].

In conventional loudness compensation methods, fitting loudness functions are measured by using pure tones or bandpass noises with several center frequencies and SPLs. If complete loudness characteristics are needed, many parameters need to be optimized. However, it is difficult to quantify words expressing loudness, and we need to consider the combination or the effects of loudness, user preference, and the environment.

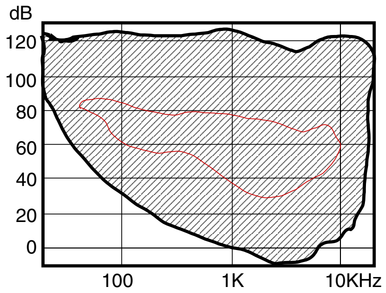

Figure 4: Examples of audible ranges. The audible range of impaired hearing, inner area, is generally narrower than that of normal hearing, hatched area.

We can interpret the loudness-based fitting methods in a 3-D space consisting of input SPL, frequency, and amplification level calculated from the difference between the loudness functions of hearing-impaired users and people with normal hearing. Conventional loudness compensation is a method used to calculate several points on the 3-D space with previous measurements (see Figure 5 left.) If we can directly construct this 3-D space with a few parameters of its space shape, we can avoid the previous measurements that were bottlenecking conventional fitting methods.

Our proposed 3-D loudness space method forms the shape of a 3-D loudness space by combining 3-D Gaussian functions by optimizing the shape parameters of the Gaussian functions using genetic algorithms (GA) (see Figure 5 right) [7, 5]. It is important that this optimization is based on how hearing aid users subjectively hear any sounds in their daily life.

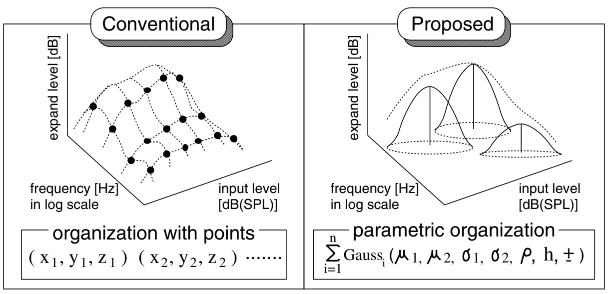

Figure 5: Conventional loudness compensation based on a loudness function (left) and the proposed loudness compensation based on a loudness space (right).

4.2 GA experimental condition

The GA parameters used in our experiment described in section 5 are shown in Table 1. Hearing aid users hear sounds processed by the 3-D loudness space method as phenotype of a GA individual and rate these sounds at five levels ranging from *bad* to *good* based on how easy these sounds are to hear, how these sounds match their preference, etc. We decided to use five discrete levels rather than a continuous range based on our previous studies [2, 3, 10, 11]. The number of parameters to form the 3-D loudness space is the number of genes, 35 (= 7 parameters of a 3-D Gaussian function × 5 functions). The number of individuals is limited to 20 because it is difficult for humans to compare and evaluate too many individuals, which is common to any interactive EC applications. These conditions are based on our preliminary experiments that some human subjects really operated the prototype IEC fitting system.

Table 1: GA conditions of the IEC fitting

Parameters	35
Coding	binary coding
Selection	roulette wheel and 4 elite strategy
Cross-over	one point cross-over, 80% rate
Mutation	2% rate
# of Individuals	20
Initial condition	random
Fitness values	subjective evaluation on hearing in 5 levels

The condition of signal processing part is 16 kHz sampling frequency, 8 msec. windowing, and 64 points on a loudness space, which is based on previous loudness compensation research [1].

4.3 Interface of interactive GA

The experimental IEC fitting system displays 20 small windows on a screen (see Figure 6). Each window has a button to play a sound and five buttons for the user to input subjective fitness value at five rating levels. Below these 20 windows, A generation number is displayed along with three buttons to sort individuals by rating, go on to the next generation after the GA operation, and exit.

All operations are mouse driven. A hearing aid user plays sounds processed with fitting parameters generated by GA and inputs his or her subjective fitness values. It becomes easier to compare individuals in fitness value order when the sorting function is used. After confirming that the rating is correct, GA is applied and goes to next generation. This process continues until a satisfactory sound is obtained.

The design of the interface for this experimental system was based on our previous studies [10, 11, 2, 3, 5].

5 Evaluation of the IEC fitting Method

The effectiveness of the IEC fitting with a loudness space method is evaluated through human operations and several experiments on sound quality and syllable articulation.

Conventionally, improving the articulation of words has been the criteria of compensation for hearing impairment. It sometimes caused certain sounds to be uncomfortable despite the improved articulation. There-

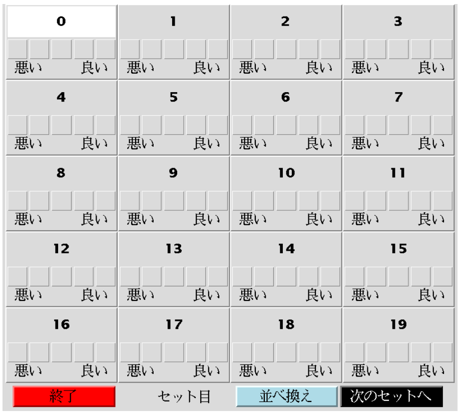

Figure 6: The IEC fitting interface displayed on a computer screen. The Japanese words in each window means *bad* and *good*.

fore, we evaluate the IEC fitting based not only articulation but also sound quality.

Hearing aid fitting methods often use speech not various sounds to tune the device. However, the IEC fitting method can optimize hearing aids for any sound and has the possibility for hearing-impaired people to enjoy hearing again. Therefore, we apply the IEC fitting method to musical hearing and evaluate its capability to compensate musical hearing.

5.1 *Evaluation for Speech Hearing*

5.1.1 *Experimental Conditions*

First, subjects operate the IEC fitting for approximately 2-second speech sound. Then, they participate in psychological tests for sound quality and syllable articulation tests using (1) processed sounds from the proposed IEC fitting, (2) processed sounds from the conventional loudness compensation and (3) unprocessed, original sounds [1].

The number of normal hearing subjects with 6 kinds of simulated hearing impairments is 8, and the number of hearing-impaired subjects is 3.

Male and female voices are used for both normal and hearing-impaired subjects and multiple talking noises are used for just hearing-impaired subjects.

The number of IEC generations is unlimited for normal hearing subjects, while number of the generations is limited to 10 for hearing-impaired subjects.

In psychological tests to evaluate sound quality, pairs of two sounds, which are randomly selected from Conditions (1), (2), and (3), are presented to the subjects. They iteratively select one sound from a pair of two sounds based on ease of hearing and preference. Experimental sounds are same as that of previous operation tasks. The number of presentations of each pair for each speech sound is 15.

In syllable articulation tests to evaluate sound clarity, processed male vowel-consonant-vowel (VCV) syllables, like /*aba*/, for each condition are used. The subjects answer VCV syllables as they hear them for Conditions (1), (2), and (3). The number of VCV syllables is 70. Three hearing-impaired subjects participated in the articulation tests. The number of presentations of each syllable is 10.

5.1.2 *Results and Discussion*

The results from the psychological tests and from the VCV syllable articulation tests are shown in Table 2 and Table 3, respectively. The quality of the processed sounds by the IEC fitting is significantly better than that of sounds that were either unprocessed or processed by conventional loudness compensation. The syllable articulations of the processed sounds by the IEC fitting are considerably higher as well. It is shown that the IEC fitting is obviously effective in compensating for hearing impairment with speech.

Table 2: Subjective test results. Speech quality is compared using (1) the proposed IEC fitting method, (2) the conventional fitting method, and (3) no compensation for hearing impairment. The numbers of "significantly better" evaluations by the sign test with ($p < 0.05$) among the 75 pairs are listed.

(1) is significantly better than (3)	53/75
(3) is significantly better than (1)	4/75
(1) is significantly better than (2)	58/75
(2) is significantly better than (1)	0/75
(2) is significantly better than (3)	13/75
(3) is significantly better than (2)	42/75

Table 3: The results of 210 EC syllable articulations among (1) the proposed IEC fitting method, (2) the conventional fitting method, and (3) no hearing impaired compensation.

(a) From (3) to (1).

changes in confusion	increased	decreased
20%–40%	13/210	16/210
40%–60%	0/210	13/210
60%–100%	0/210	16/210
total	13/210	45/210

(b) From (3) to (2).

changes in confusion	increased	decreased
20%–40%	14/210	13/210
40%–60%	14/210	11/210
60%–100%	13/210	14/210
total	41/210	38/210

5.2 *Evaluation for Musical Hearing*

5.2.1 *Experimental Conditions*

First, subjects operate the IEC fitting using about 3-second musical sound. Then, they participate in psychological tests for sound quality tests using Condition (3), unprocessed original music, and Condition (1), music processed by the proposed IEC fitting. Conventional loudness compensation is not used here, since it is only designed for speech hearing.

Three hearing-impaired subjects participate in the experiments. One orchestral piece is used in previous operation. The number of IEC generations is unlimited; they can operate the IEC fitting until they are satisfied with the processed sound.

Subjects iteratively select one sound from a pair from Conditions (3) and (1) based on ease of hearing and preference. Four kinds of music were used in the psychological tests to evaluate sound quality; one is same as that of previous operation tasks, and the others are a solo saxophone performance, female vocals of Latin music, and male vocals of rock 'n' roll. The number of presentations of each pair for each musical sound is 15.

5.2.2 *Results and Discussion*

The results from psychological tests are shown in Table 4. The quality of the processed sounds by the IEC fitting is significantly better than that of unprocessed sounds. It is shown that the IEC fitting is effective in compensating hearing impairment not only for speech hearing but also for musical hearing.

Table 4: Subjective test result for sound sources. Musical selection compensated by (1) the IEC fitting method and (3) no compensation are compared by six subjects. The numbers of the significantly superior method with ($p < 0.01$) are shown.

(1) is better than (3)	18/24
(3) is better than (1)	1/24
no significant difference	5/24

6 Conclusion

We proposed the IEC-based hearing aid fitting method that optimizes the signal processing parameters of hearing aids based only on the user's evaluation. This feature can solve conventional problems, such as the need for support by specialists, the difficulty to reflect user's individuality, the restrictive and time-consuming fitting conditions, etc.

We evaluated the IEC fitting method with a speech and a musical source through human operation and psychological experiments. The results have shown that the IEC fitting improves sound quality and sound clarity significantly better than a conventional fitting method.

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