Interactive Evolutionary Computation-Based Hearing Aid Fitting

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***Abstract*—An interactive evolutionary computation (EC) fitting method is proposed that applies interactive EC to hearing aid fitting and the method is evaluated using a hearing aid simulator with human subjects. The advantages of the method are that it can optimize a hearing aid based on how a user hears and that it realizes whatever + whenever + wherever (W^3) fitting. Conventional fitting methods are based on the user's partially measured auditory characteristics, the fitting engineer's experience, and the user's linguistic explanation of his or her hearing. These conventional methods, therefore, suffer from the fundamental problem that no one can experience another person's hearing. However, as interactive EC fitting uses EC to optimize a hearing aid based on the user's evaluation of his or her hearing, this problem is addressed. Moreover, whereas conventional fitting methods must use pure tones and bandpass noise for measuring hearing characteristics, our proposed method has no such restrictions. Evaluating the proposed method using speech sources, we demonstrate that it shows significantly better results than either the conventional method or the unprocessed case in terms of both speech intelligibility and speech quality. We also evaluate our method using musical sources, unusable for evaluation by conventional methods, and demonstrate that its sound quality is preferable to the unprocessed case.**

***Index Terms*—Hearing aid, hearing aid fitting, interactive evolutionary computation (EC), optimization, subjective evaluation.**

I. Introduction

DEVELOPED countries are becoming concerned about their aging populations and welfare technologies. It is predicted that in 2025, the number of people 65 years old or older will comprise more than 20% of the entire population in almost all developed countries [1]. This dramatically increasing ratio of seniors, combined with decreasing birthrates, poses a serious social problem. Welfare technologies that compensate for physical impairment are urgently required to help disabled, aged people and their families lead fulfilling lives.

Hearing aid technology is one of the most sought after welfare technologies because it supports communication, which is fundamental to social activities. Digital hearing aids have been introduced to the market over the last two decades, and new digital signal processing technologies, implementing techniques that cannot be implemented in analog hearing aids, are becoming increasingly practical.

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However, the penetration rate of hearing aids is still low in the developed countries. Why have hearing aids not found social acceptance while other aids, such as glasses, have? The answer is in the social response to the use of hearing aids and the imperfect performance of the hearing aids themselves. The social response to hearing aids stems from people's negative impression of hearing aids as a symbol of handicap, and their expensiveness. This stigma could be reduced with promotion and support from hearing aid makers and public administrators. The imperfect performance includes poor speech audibility, poor sound quality, and low flexibility for various situations provided by the current generation of hearing aids, whose base technology was established in the middle of the 1990s [2], [3]. These performance limitations can be broken down in to two fundamental issues: one is in the hearing aids themselves (compensation methods, signal processing techniques, and hardware acoustical characteristics) and the other is in the hearing aid fitting (optimal calibration of signal processing parameters) [4], [5].

In this paper, the authors focus on hearing aid fitting and advocate a new generic fitting methodology that can be applied to various kinds of hearing aids. Although digital hearing aids recently introduced have the potential to compensate for complex hearing impairment, this potential is often stifled by improper fitting. In addition, there has been an increase in the number of kinds of hearings aids and their signal processing parameters. Consequently, hearing aid fitting methods are becoming correspondingly more difficult and more varied. Many conventional fitting methods are specific to a single kind of hearing aid and inflexible to the requirements of individual hearing aid users due to their problem-solving approach. This motivates us to realize a new, generic fitting methodology that takes a fundamentally different philosophical approach.

What new approach can we use to solve the problem of hearing aid fitting? We suggest that interactive evolutionary computation (Interactive EC) be used because of the following favorable features: it optimizes system parameters to fit the user's requirements, it allows us to handle the user's requirements as a black box, it is applicable to various systems by modifying the EC coding. Specifically, we propose a hearing aid fitting method based on interactive EC, *interactive EC fitting*, which optimizes the signal processing parameters of a hearing aid to fit a user's subjective hearing evaluation with no *a priori* knowledge of the user's sensory and perceptual auditory characteristics [6]–[8]. The outcome of this research will contribute to hearing aid fitting and also be the first practical application of the interactive EC to social welfare.

This paper is organized as follows. In Section II, we introduce the current state of hearing aid fitting and interactive EC, and

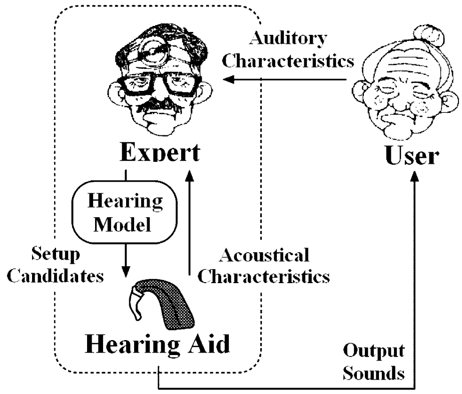

Fig. 1. Typical framework of a conventional hearing aid fitting.

then discuss the conditions that must be met by a new generic fitting methodology. In Section III, we propose an interactive EC fitting method and explain its theory, design, and system implementation. In Section IV, we experimentally evaluate the performance of the interactive EC fitting in terms of speech audibility and sound quality. In Section V, we discuss the effectiveness of interactive EC fitting based on our experimental results and comment on its future development and extensions. In Section VI, we conclude the paper and outline our plans for future work.

II. State of Related Works

A. Hearing Aid Fitting

Before providing a background on the current state of hearing aid fitting, we must specify who we want to target with our fitting. In this study, we focus on the hearing-impaired with mild or moderate impairment who comprise the majority of hearing aid users. Congenitally hearing-impaired people with severe impairment need specialized training for hearing rather than hearing aids; although hearing aids exists for such people, their mechanisms are quite different from those in popular hearing aids. In this paper, we target hearing-impaired people who have the ability to judge sound quality and their preference for hearing.

Fig. 1 shows the typical framework of a conventional fitting for mildly or moderately hearing-impaired people [9]. The framework consists of a hearing aid, a hearing aid user, and a fitting expert (an audiologist or medical doctor). The expert plays the main role and the fitting outcome is strongly influenced by his/her knowledge and skill.

A conventional fitting procedure consists of four stages.

Stage 1: measurement of the user's auditory characteristics.

Stage 2: modeling of the user's auditory characteristics.

Stage 3: adjustment of a hearing aid based on the model.

Stage 4: fine-tuning of the hearing aid based on the user's reports.

Existing automatic fitting systems developed for computers are based on the conventional fitting methodology. These "knowledge-based expert systems" emulate the behavior of a human expert.

In Stage 1, an expert measures a user's auditory characteristics in terms of sensory and perceptual levels. Comprehensive hearing characteristics in terms of cognitive and preference levels are essentially ignored. In Stage 2, the expert classifies the user by type of auditory characteristic and selects a suitable hearing compensation method for the user. In Stage 3, the expert manually adjusts a hearing aid with the selected hearing compensation method. It is uncommon for experts to directly adjust hearing aid signal processing parameters. Rather, experts normally adjust the hearing compensation characteristics of the hearing aid and the hearing aid automatically determines its signal processing parameters based on the hearing compensation characteristics. In Stage 4, the expert manually readjusts the hearing aid to reflect the user's evaluation of speech audibility and sound quality using the current fitting. Usually, Stage 4 is repeated several times until the user attains satisfaction from the fitting result, and the entire process is repeated according to impairment progress.

Many of the problems with conventional fitting are the result of the following four features of its methodology.

- **Conventional Feature 1**: fitting is performed by someone other then the user;
- **Conventional Feature 2**: fitting is only based on sensory and perceptual auditory characteristics;
- **Conventional Feature 3**: fitting requires special knowledge and skill;
- **Conventional Feature 4**: fitting procedures have low versatility.

Conventional Feature 1 forces experts to estimate the user's hearing despite the fact that no one can experience another person's hearing. The comprehensive hearing of a hearing-impaired person depends deeply on the type of the impairment, the degree of the impairment, the age of the onset of the impairment, the person's sound preferences, and his or her environment [10]. Suppose there are two persons with moderate hearing impairment—their comprehensive hearing may be different even if they have the same auditory characteristics in sensory and perceptual levels. Experts must therefore estimate the comprehensive hearing of each user based only on cues from the user's auditory characteristics in terms of sensory and perceptual levels and his or her subjective hearing reports. The reports themselves also have serious problems. The adjectives to describe hearing in terms of loudness, sound quality, and speech intelligibility include *loud*, *metallic*, and *boxy* [11]. The interpretation of such adjectives is different among normal-hearing people and even more disparate between experts with normal hearing and users with impaired hearing. Conventional Feature 1 also causes secondary problems: users may get tired of visiting their fitting experts frequently, and in the worst case, might think it too much trouble to visit for fine-tuning.

Conventional Feature 2 stems from the hypothesis that speech audibility for a hearing-impaired person is improved by compensating for the difference between his or her auditory characteristics and the auditory characteristics of a person with normal hearing. The first problem is with the auditory characteristics used in conventional fittings. These characteristics are partially measured in terms of sensory and perceptual levels using pure tones and/or bandpass noises under restricted experimental conditions. As a result, they do not represent the flexible comprehensive hearing system that exists between the peripheral and the central nervous system for natural sounds in day-to-day environments. For instance, the sound pressure level for which we feel discomfort with a bandpass noise may be comfortable if the sound is a pleasant voice. However, conventional fitting has no methodology to reflect this comprehensive hearing in terms of cognitive and preference levels [12]–[14].

The second problem is in the assumption that fittings become better as the auditory characteristics of a hearing-impaired person are adjusted so that they are close to those of normal-hearing people. When a hearing-impaired person is presented with a processed sound that is similar to what a normal-hearing person would hear, he or she might feel uncomfortable because he or she is not accustomed to that sound [12].

Even if both problems are solved, there remains a further serious problem: conventional fittings cannot precisely reflect the combined effects of frequency bands and sound pressure levels, since it is impossible to measure the auditory characteristics for all of their combinations [15], [16].

Conventional Feature 3 results in a variance in fitting outcomes between experts, difficulty for experts lacking extensive experience, and a burden on users to find skilled experts. Although the initial stages of fitting, Stages 1–3 are often explained in detail in manuals or performed by automatic systems [11], [17]–[23], [9], the fine-tuning stage that is the most important for user satisfaction, Stage 4, is still strongly influenced by the special knowledge and skill of the fitting expert.

Conventional Feature 4 results in many specialized fitting methods and systems depending on the types of hearing aids. This consequently increases the burden on experts to continually familiarize themselves with new fitting methods and systems. The digitalization of hearing aids aggravates this situation further because it increases the number of types of hearing aids and signal processing parameters that must be adjusted.

B. Interactive Evolutionary Computation (EC)

Interactive EC, a technology inspired by the biologically modeled optimization method, EC, is applied to human-computer interaction to optimize a target system based on human subjective evaluation [24].

There are many design tasks that should be based on human evaluation, such as artistic or aesthetic design, control for virtual reality or comfortableness, and signal processing to increase visibility or audibility. However, approaches that model human evaluation characteristics, including individual preference, are difficult to realize. Interactive EC is a technology that embeds a user into an optimization system, with the evaluation system considered as a black box rather than as a computational evaluation model. Unlike most other nonlinear optimization methods, the EC does not use the gradient information of the searching space, and is therefore suitable for optimizing tasks which are evaluated in a psychological space. EC makes use of genetic algorithms (GAs), evolutionary strategies (ES), genetic programming (GP), and evolutionary programming (EP). The proposed interactive EC makes additional use of IGA, IES, IGP, and IEP, as well.

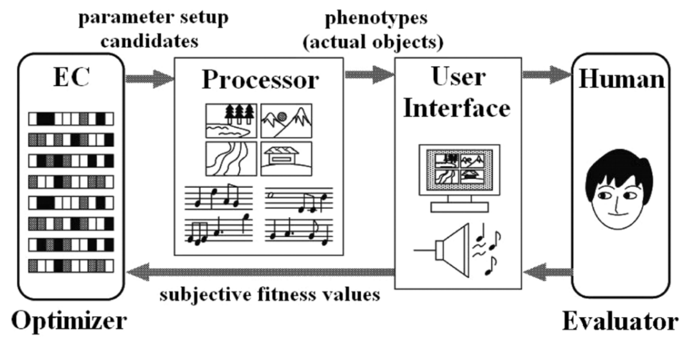

Fig. 2. A general outline of interactive EC systems.

Fig. 2 shows the general outline of an interactive EC system. EC is a multipoint searching method and generates multiple parameter vectors. The target system to be optimized generates sounds, images, or other outputs based on the parameters generated by the EC and presents them to the interactive EC user. The user gives his or her subjective evaluations as numerical values in response to the presented sounds or images, and the evaluation values are fed back into the EC. The EC generates new parameters for candidate solutions based on the fed-back subjective evaluation values and evolutionary operators. The parameters of the target system are optimized toward each user's preference by iterating this procedure. In this paper, we propose an interactive EC system where the target is hearing aid fitting, a process we call interactive EC fitting.

Interactive EC research started with Dawkins' biomorph of 1986 and has been an active field since the early 1990s [25]. There are currently two research directions in interactive EC: application-oriented research and human interface research.

Applications of the interactive EC research can be categorized into three fields: the artistic field, the engineering field, edutainment and other fields. Artistic applications include graphic arts and animation, three-dimensional (3-D) CG lighting, music generation, editorial design, industrial design, and facial image generation. Engineering applications include speech processing and synthesis, virtual reality, media database retrieval, data mining, image processing, control and robotics, food industry, and geophysics. Hearing aid fitting is one of interactive EC applications in this field. Applications in other fields include education, entertainment, social systems, and so on.

Interactive EC research on human interfaces mainly focuses on reducing the unavoidable human fatigue that results from any human-machine interaction-based system. This fatigue problem is especially serious for interactive EC fitting users because elder nonprofessionals have to cooperate with a tireless computer to optimize their hearing aids iteratively. Research aimed at reducing fatigue, therefore, includes attempts at improving fitness input interfaces and displays based on fitness prediction, accelerating EC convergence especially in early EC generations, examining combinations of interactive and normal EC, and investigating active user intervention.

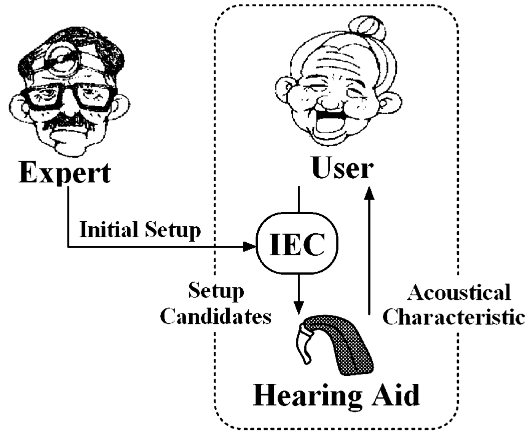

Fig. 3. Framework of interactive EC fitting.

Details of this research area can be found in our survey paper [24] that includes 251 interactive EC papers. Interactive EC research is still active and special issues on interactive EC were issued by some journals [26]–[29].

Interactive EC research seems to have a natural potential in technologies that compensate for the impairment of human physical functions. Recall the problems with conventional hearing aid fitting, as outlined in Section II-A. Interactive EC has a potential to solve these problems by changing the method of hearing aid fitting itself. This research is also worthy of mention as the first interactive EC application to welfare equipment.

III. Proposed Interactive EC Fitting

A. Problem Solving Approach

Here, we propose a new method for hearing aid fitting based on an interactive EC that we call *interactive EC fitting*. This method should allow us, in principle, to solve existing problems through a different philosophical approach to that taken with conventional fittings.

Conventional hearing aid fittings have fundamental problems due to Conventional Features 1–4. We propose solving these problems by introducing opposing and complementary features:

- **New Feature 1**: fitting is performed by the users themselves;
- **New Feature 2**: fitting is based on actual comprehensive hearing;
- **New Feature 3**: fitting is performed using operations that are easy for nonexperts;
- **New Feature 4**: fitting is easily applicable to various hearing aids.

Fig. 3 shows the framework of interactive EC fitting. The system includes three elements: a hearing aid, a user, and the interactive EC fitting core. The role of the hearing aid is to perform signal processing on input sounds with each candidate of signal processing parameters being arrived at through the fitting procedure. The role of the user is to listen to the output sounds from the hearing aid and to evaluate them based on his or her subjective hearing criteria.

The interactive EC fitting core consists of three modules: the **Optimization Module**, the **Conversion Module**, and the **User Interface Module**.

The optimization module generates candidate compensation characteristic parameters. These candidate parameters are individuals produced by EC based on the evaluation results given by the hearing aid user as fitness values. The conversion module converts the candidate compensation characteristic parameters into hearing aid signal processing parameters. The user interface module provides the user with an environment for playing sounds produced by the hearing aid adjusted with the setup candidate's signal processing parameters while evaluating the results on a numerical scale, six candidates at a time.

In addition to proposing interactive EC fitting, we also introduce a novel modeling of hearing compensation space for accelerating the fitting time of the hearing aid in our experiment, which is mentioned in a later section with Fig. 5.

We purposefully design the optimization module and the conversion module not to directly generate signal processing parameter candidates by EC. Instead, we define a compensation characteristic search space, which is drastically narrower than the signal processing parameter search space. By searching this narrower space using EC, we can efficiently reduce the user fatigue that arises from requiring the evaluation of many individuals.

The interactive EC fitting system works interactively according to the following iterative procedure. First, the optimization module generates a set of individuals, hereby known as the candidate compensation characteristics. These characteristics are randomly initialized upon the first iteration. The conversion module converts the compensation characteristics into candidate signal processing parameter vectors. The user actively selects each of the candidate vectors in turn, listens to sounds output by the hearing aid using the candidate, and evaluates it on a numerical scale until all the candidate vectors have been evaluated. The results are then passed back through the user interface module. The user interface module returns the numerical evaluation results to the optimization module. Finally, the optimization module uses the evolutionary operations of selection, crossover and mutation, based on the evaluation scores, to generate the next set of candidate compensation characteristics. This procedure is repeated until the user obtains a satisfactory hearing aid parameterization.

There are two kinds of questions that are immediately raised by the interactive EC fitting method. One is regarding the advantages of the system; "what benefits are expected?" and "are such benefits realizable?". The other is regarding its potential disadvantages; "doesn't it cause undesirable side effects?" and "are such side effects preventable?" First, we will address these questions from a theoretical viewpoint based on the interactive EC fitting's New Features 1–4. In Section IV, we will address them again from a practical viewpoint based on our experimental results from our evaluation of the interactive EC fitting's performance.

New Feature 1—fitting is performed by the users themselves—eliminates many fitting restrictions. With this new feature, users can fit their hearing aids whenever and wherever they want, which should also reduce the number of visits they have to make to fitting experts. A potential obstacle to realizing this benefit is that if evaluations are not sufficiently stable the EC will not converge. However, some fluctuation in evaluation scores should be acceptable, and the benefits are promising for those users possessing the ability to consistently evaluate their own hearing.

A possible side effect of New Feature 1 would be that the fitting results might become harmful to users' auditory systems. Some users make invalid evaluations and mislead the hearing aid calibration, resulting in, e.g., overamplification or distortion. To avoid such problems, the interactive EC fitting could ideally be embedded with prior knowledge of the user's auditory characteristics measured under supervision. Although this supervision requires an expert, interactive EC fitting would nevertheless reduce the difficulty for experts to precisely estimate users' hearing.

New Feature 2—fitting is based on actual comprehensive hearing—also eliminates many fitting restrictions by allowing users to fit their hearing aids for any sound, using any evaluation criteria. Taking New Features 1 and 2 together, highly flexible fitting, "fitting whenever and wherever for what kind of sounds with what kind of evaluation criteria," namely, whatever + whenever + wherever (W^3) fitting, would be achieved. For instance, it would be possible to perform fittings using regular office conversations, noisy speech in a market, sounds from a television, music in a living room, and others—instead of being limited to the use of pure tones in a fitting examination chamber. Consequently, the labor required to frequently measure auditory characteristics would be saved. These benefits are especially promising for users who continually evaluate and reevaluate their hearing.

New Feature 2 might also introduce side effects, but these are the same side effects addressed by New Feature 1, and the same solutions can be applied.

New Feature 3—fitting is performed using operations that are easy for nonexperts—reduces user fatigue and enhances the ability to iterative fine-tune for optimal hearing aid setups. However, the realization of these benefits depends on the operability. Superficial operations are very easy; they involve nothing more than repeatedly selecting candidate vectors, listening to sounds processed using them, and giving numerical evaluation values to each candidate. However, the evaluation itself may be difficult for people who are hearing impaired, since they are not accustomed to evaluating sounds in terms of speech intelligibility, sound quality, preference, comfort, etc. This difficulty may lengthen the fitting time and, in the worst case, prevent convergence. Although this problem is unpredictable, we believe it would be gradually resolved as users, through the iterative fitting process, became more acclimatized to the evaluation stage. The realization of this feature does not introduce any undesirable side effects.

New Feature 4—fitting is easily applicable to various hearing aids—reduces the time and cost for hearing aid manufacturers to develop fitting methods for newly released hearing aids and the time required for experts to learn them. These benefits are possible because the interactive EC fitting does not care which type of hearing aid it is being used with; the only information it requires to fit a hearing aid is the user's evaluation scores, the number of fitting parameters and the range of each parameter. Although it may not be trivial to design EC genes and parameters, it is much easier than creating a new fitting method for each type of hearing aid. Finally, there are no undesirable side effects associated with this feature, either.

B. *System Implementation*

To confirm the effectiveness of the interactive EC fitting, we develop and evaluate a prototype system consisting of an optimization module, a conversion module, a user interface module, and a hearing-aid simulator. Extensive knowledge and advanced techniques related to hearing characteristics, impairment, compensation, and human hearing test methods are necessary to develop and evaluate this system. Although this detailed information is essential for hearing aid researchers and audiologists, it is unnecessarily specific for EC researchers, who are mainly interested in how the EC works to achieve an interactive EC fitting. In this paper, we therefore take a global view of the system implementation and evaluation methodology, while focusing instead on the software architecture and experimental results. Details on the hardware architecture used, such as the sound card, amplifier, head phones, sound treated room, etc., will therefore be provided in a separate paper for readers in audiology. Fig. 4, which is a specific realization of Fig. 2, shows the organization of the prototype fitting.

The prototype is realized using a hearing aid simulator instead of a real commercial hearing aid because we want to obtain more generalized results. The hearing aid simulator emulates one of the latest popular hearing compensation techniques, loudness compensation [11], [15], [30], [22], [31], [16], wherein nonlinear signal processing is performed to adaptively compress input sounds into the user's audible range according to their spectra. Loudness compensation has many signal processing parameters, filter coefficients, to be optimized, and so auditory characteristics must be measured at many points for the conventional fitting of loudness compensation hearing aids. For instance, the number of points that must be measured is $20 \times 10 \times 2 = 400$ if the audible range is divided into 20 frequency bands and 10 sound pressure levels and each point is assigned with 2 measurement trials. This can be visualized using the 3-D illustration in the conversion module of Fig. 4.

1) Design of the Conversion Module: We implement a method we call *loudness surface method* for efficiently reducing the number of points that must be measured. The method approximates many points on a surface in a 3-D space spanned by frequency on the X axis, sound pressure level on the Y axis, and amplification rate on the Z axis, using a summation of Gaussian functions, as defined in (1), where Gaussian function parameters and the surface are shown in Fig. 5. We call the surface formed by the summation of Gaussian functions the *loudness surface*. The loudness surface method substitutes the task of directly measuring many points with the task of parametrically determining the shape of the loudness surface. The conversion module thus forms a loudness surface using the candidate parameters generated by the optimization module, extracts the appropriate points from the loudness surface,

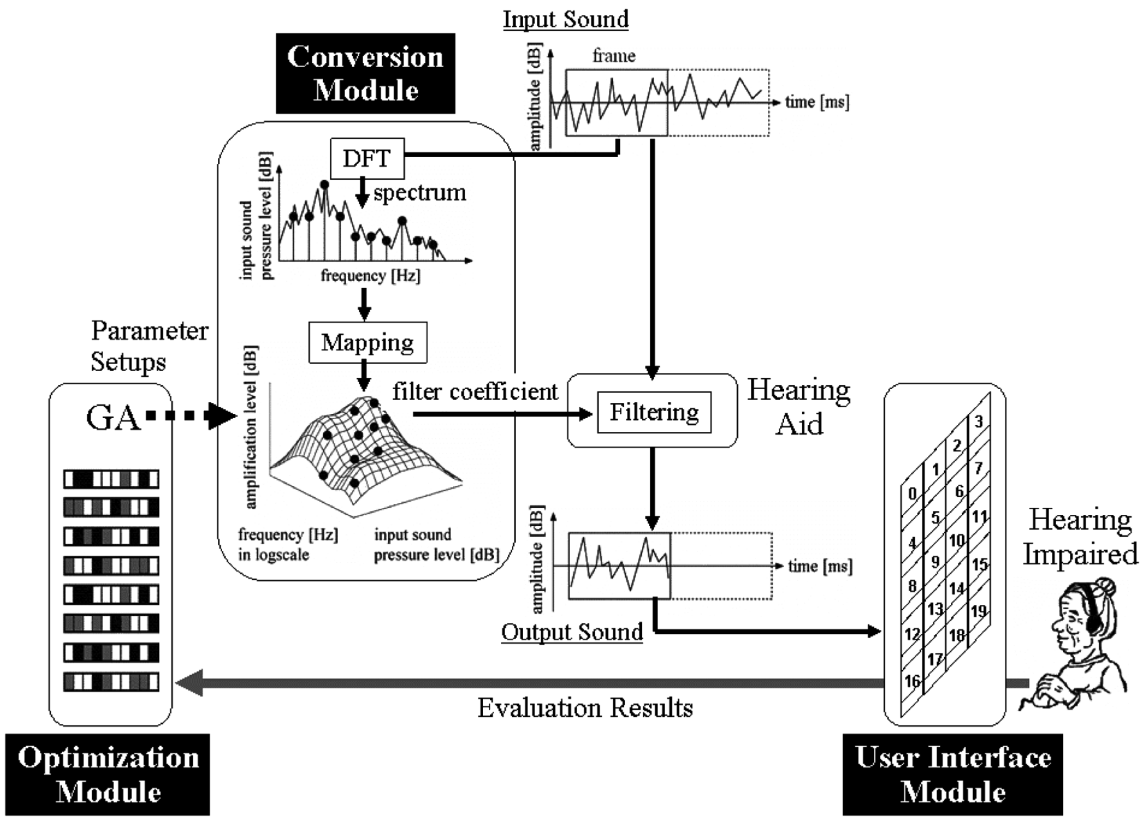

Fig. 4. Organization of the prototype interactive EC fitting.

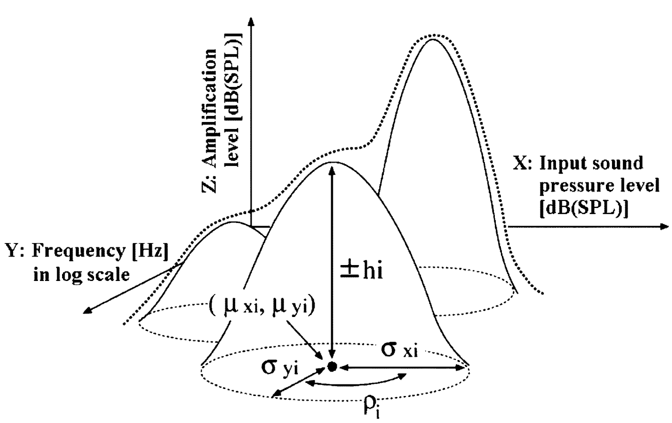

Fig. 5. The loudness surface used in the conversion module.

and converts them into candidate signal processing parameter vectors

$$\mathrm{LS}(x,y)=\sum_{i=1}^{n}\mathrm{Gauss}_i(\mu_{xi},\sigma_{xi},\mu_{yi},\sigma_{yi},\rho_i,h_i,\pm). \quad (1)$$

2) Design of the Optimization Module: We design the optimization module to search for the best loudness surface shape, corresponding to the best signal processing parameter configuration, for a hearing aid. In other words, the optimization module iteratively generates loudness surface parameters until the best shape is obtained. We adopt a simple GA for this search and designed the bit length of each parameter according to the human sensitivity to frequency and input sound pressure level (SPL). Tables I and II show the conditions adopted for the parameters and GA operations used in the optimization module. Note that the GA operations are customized for interactive EC under a strong restriction of population size and maximum generation

TABLE I
PARAMETER CONDITIONS USED IN THE OPTIMIZATION MODULE

parameter	lower	upper	step	unit	bit
(1) number of Gaussian functions n	1	5	1	no unit	3
parameters of the i-th Gaussian function ($1 \le i \le 5$)					
(i-1) X coordinate μ_{xi}	0.00	90.00	2.81	dB(SPL)	5
(i-2) X-way radius σ_{xi}	1.00	90.00	2.81	dB(SPL)	5
(i-3) Y coordinate μ_{yi}	0.00	3.90	0.12	$\log_2$ Hz	5
(i-4) Y-way radius σ_{yi}	0.00	3.90	0.12	$\log_2$ Hz	5
(i-5) distortion degree ρ_i	0.000	1.000	0.125	no unit	3
(i-6) height h_i	0.00	30.00	1.88	dB(SPL)	4
(i-7) convex direction $\pm$	–	+	1	no unit	1

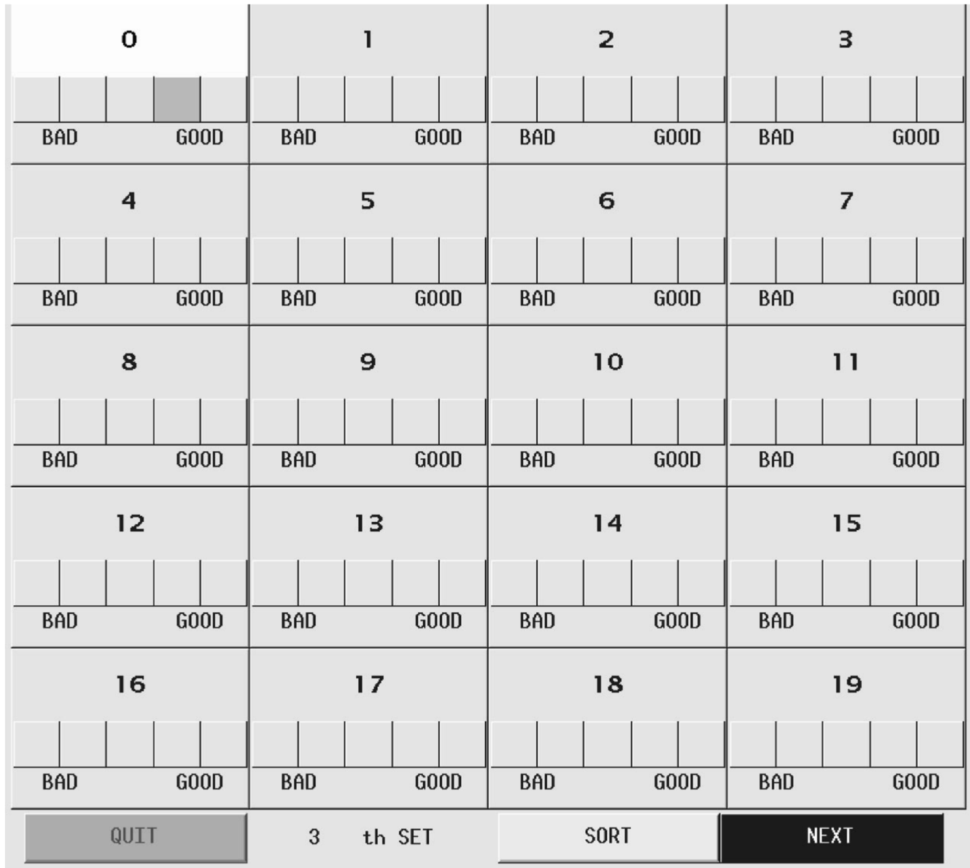

Fig. 6. Interface screen in the user interface module.

TABLE II
GA CONDITIONS USED IN OPTIMIZATION MODULE

optimizer	simple GA
coding	binary
selection	roulette wheel with 4 elites
crossover rate	One point (80%)
mutation rate	2%
initialization	random
number of parameters	$1 + 5 \times 7 = 36$
population size	20
number of generation	maximum 20
fitness function	user's evaluations in 5 levels

number; these conditions are a feature of interactive EC and are quite different from those used for noninteractive GA.

3) Design of the User Interface Module: Fig. 6 shows the interface screen of the user interface module as it appears on a computer display. It consists of 20 small windows corresponding to individuals, i.e., output sounds, from a hearing aid simulator. Each window has a button for playing its sound and five buttons for choosing a subjective fitness value in five levels from *bad* to *good* [32]–[34]. The user plays each sound and inputs his or her subjective fitness value by clicking on one of the five buttons. Three buttons at the bottom of the screen correspond to the operations of exiting the calibration, sorting individuals in descending order of fitness value, and advancing to the next generation. The display also indicates the current generation number. After the user evaluates all the sounds and confirms their rank, the user interface module sends the evaluation results directly into the optimization module and receives the parameter candidates for the next generation generated by the optimization module through the conversion module. This process is iterated until the user obtains a satisfactory sound, i.e., the best hearing aid setup.

We determined the final design of the user interface module after several trials, improving it after each trial, since it is essential to usability and the convergence of the interactive EC fitting. The most important design point is the required precision of the evaluation; if the evaluation scale is too precise, the burden of the interactive EC on the user is too great, even if the convergence is fast. Conversely, rough evaluation is easy for the user, but a larger quantization error in an evaluation scale results in slower convergence. Our preliminary experiments investigated the relationship between the EC convergence and burden on the user and the number of quantization levels used for the fitness values. Consequently, we adopted the five level evaluation scale [32], [33], [34].

Another important design point is the relativity of human evaluation; in general, it is easier for humans to evaluate something according to a relative scale. While the user may evaluate individuals relatively, however, the EC uses absolute fitness values for the selection operation. It is not easy to analyze this gap between relative and absolute scores and its influence on EC convergence. In this case, we empirically confirmed in our preliminary simulations and experiments [32] that the gap does not seriously negatively impact the EC convergence. A method used to estimate the absolute scale from relative fitness values in each generation for general interactive EC [35] can also be incorporated in interactive EC fitting, as mentioned later in the discussion section.

IV. Experimental Evaluations

In this section, we define what performance means for the interactive EC fitting, how we evaluate it, and what kind of subjects participated in our experiments. After that, we outline the experimental conditions, present our results, and discuss the effectiveness of interactive EC fitting.

A. *Experimental Design*

We evaluate our proposed interactive EC fitting using both speech sources and music sources (see Table III). One of the biggest features of the interactive EC fitting is that any sound source is acceptable for hearing aid fitting, in contrast to conventional fitting where only pure tones and bandpass noises can be used. To further expound on the benefits of this feature, we include an evaluation of the fitting using musical sounds and quantitatively demonstrated the sound quality improvement—something which is not possible with conventional fitting methods.

What is the performance of interactive EC fitting? Unlike noninteractive EC, performance cannot be determined in terms of convergence speed alone. As mentioned in Section III-A, interactive EC fitting has, in principle, the potential to realize W^3 fitting. In other words, unlike conventional fitting, it can improve both speech intelligibility and sound quality—allowing hearing-impaired people to enjoy hearing again. System usability and calibration time are also significant to any measure of performance. We therefore define the performance of the interactive EC as the synthesis of speech intelligibility, sound quality, system usability, and calibration time.

How do we evaluate the performance? To evaluate the interactive EC fitting and its specific advantages, experiments should be conducted using music in addition to speech. The experimental procedure was thus divided into two phases.

Phase One consisted of the fitting of the hearing aid.

Phase Two consisted of the evaluation of sounds output from the fitted hearing aid.

It is difficult for hearing-impaired experimental subjects to evaluate the absolute performance of an interactive EC fitting, so its relative performance was estimated by comparing its performance to the conventional fitting case and the no-processing case. We design the fitting evaluation experiments, as shown in Table III accordingly.

TABLE III
Design of Evaluation Experiments

Experiment I: Evaluation for Speech

Phase One (Fitting)	**(P) Proposed Fitting**: Interactive EC Fitting using male and female speech in Japanese
	(C) Conventional Fitting: loudness category method using five octave-band-pass noises
	(N) No Processing
Phase Two (Evaluation)	**(N)** vs. **(P)** and **(N)** vs. **(C)** **(i)** Speech Intelligibility Test: syllable articulation test using 70 male VCV syllables **(ii)** Sound Quality Test: Scheffé's paired comparison using male and female speech in Japanese with/without a multi-talkers' noise

Experiment II: Evaluation for Music

Phase One (Fitting)	**(P) Proposed Fitting**: Interactive EC Fitting using an orchestral performance
	(N) No Processing
Phase Two (Evaluation)	**(N)** vs. **(P)** **(ii)** Sound Quality Test: Scheffé's paired comparison using four kinds of music

The methods and input sounds used in Phase One and Phase Two of Experiments I and II are outlined in Table III. Evaluation terms, during which subjects used their fitted hearing aids, can be divided roughly into two groups: short-term evaluations (from one to four weeks) and long-term evaluations (from six months to one year). We select the short-term evaluation for confirming the basic effectiveness of interactive EC fitting. The practical effectiveness of interactive EC fitting versus a commercial hearing aid over long-term use should be evaluated in the next stage of our research after the interactive EC fitting's fundamental effectiveness is confirmed.

In Experiment I, we select the loudness category method, which is a popular fitting method used for loudness compensation hearing aids [30], as the conventional method for Phase One. We select a syllable articulation test, a popular speech intelligibility test [2], [9], and Scheffé's paired comparison, a popular sound quality test [36] in Phase Two. We also measured the calibration time and asked the subjects some questions on system usability throughout the tests. Experiment II uses the same conditions as Experiment I, except there is no conventional fitting **(C)** or speech intelligibility test **(i)** because they are designed only for speech sounds.

We used two kinds of subjects: 1) real hearing-impaired subjects and 2) normal-hearing subjects with simulated hearing impairment (SHI). Each subject group has advantages and disadvantages.

TABLE IV
RESULTS OF THE (I) SPEECH INTELLIGIBILITY TEST IN PHASE TWO OF EXPERIMENT I. THE NUMBERS SHOW THE IMPROVED/DECLINED CASES FOR THE ARTICULATIONS OF 70 VCV SYLLABLES OF THREE HEARING-IMPAIRED SUBJECTS PER TEN TRIALS IN THREE IMPROVEMENT/DECLINATION DEGREE RANGES

Improvement/Declination from **(N)** to **(P)**

Number of Occurrences	Improvement			Declination		
	Subject ID (Impaired)					
	I-A	I-B	I-C	I-A	I-B	I-C
$20\% \leq$ Degree $< 40\%$	0	2	14	5	5	3
$40\% \leq$ Degree $< 60\%$	2	0	11	0	0	0
$60\% \leq$ Degree $< 100\%$	0	0	16	0	0	0
Sum per (70 VCV$\times$3 subjects)	45 / 210			13 / 210		

Improvement/Declination from **(N)** to **(C)**

Number of Occurrences	Improvement			Declination		
	Subject ID (Impaired)					
	I-A	I-B	I-C	I-A	I-B	I-C
$20\% \leq$ Degree $< 40\%$	1	2	10	3	10	1
$40\% \leq$ Degree $< 60\%$	1	2	8	4	7	3
$60\% \leq$ Degree $< 100\%$	1	0	13	0	13	0
Sum per (70 VCV$\times$3 subjects)	38 / 210			41 / 210		

When we evaluate fitting methods with real hearing-impaired subjects, we can obtain fitting performance results for real users. However, their reliability may not be high because of the diversity of real impairments in the subjects. When we evaluate fitting methods with normal-hearing subjects, on the other hand, we can obtain reliable experimental results under the controlled experimental conditions—but they may be less accurate at reflecting the actual benefits of the methods. For these reasons, we decided to use both groups of subjects to evaluate the total performance of the interactive EC fitting; three hearing-impaired subjects with mild or moderate impairment and eight normal-hearing subjects with simulated loudness impairment by the expanded method [37], [38] were used.

B. Experiment I: Evaluation for Speech

1) Experimental Conditions: In Phase One, the subjects perform the proposed fitting **(P)** and the conventional fitting **(C)** , and we obtain a hearing aid calibration for each case and subject. In addition, we measure the calibration time and obtain user reports on system usability.

In the speech intelligibility test of Phase Two **(i)**, we prepare 70 vowel-consonant-vowel (VCV) syllables, such as */aka/*, */aki/*, or */aku/*, and process them with the proposed fitting **(P)**, the conventional fitting **(C)**, and with no processing **(N)**. During the test, the subjects hear each of the 70 syllables and are required to identify which syllable is being presented. For instance, a subject would select "APA" from a syllable list on a computer display when he or she hears */apa/*. All the syllables used in **(P)**, **(C)**, and **(N)** are randomly presented ten times to each subject; in other words, the number of syllables presented is: 3 subjects $\times$ 70 VCV syllables $\times$ 10 iterations $\times$ 3 hearing aids [for the characteristics (P), (C), and (N)]. Note that only the hearing-impaired subjects participated in **(i)**. Some research papers have reported that syllable articulation identification with normal-hearing subjects using SHI was quite different from the results obtained for hearing-impaired subjects [37], [38]. Normal-hearing subjects with SHI therefore did not participate in **(i)**.

In the sound quality test of Phase Two **(ii)**, we prepare male and female speech sounds with and without multiple-talker noise processed with **(P)**, **(C)**, and **(N)**. The subjects are repeatedly presented with a pair randomly selected among the speeches and required to answer which one is better. Unlike conventional fitting that aims to emphasize speech intelligibility, no restraint on the subjects' methods of evaluation are made; they comprehensively evaluate pairs based on ease of listening, preference, and speech intelligibility. All speech segments of **(P)**, **(C)**, and **(N)** are presented 15 times randomly. Note that only the hearing-impaired subjects participate in the evaluation using speech with a multiple-talker noise. This is because it is commonly known that the perception of sound quality by normal-hearing subjects with SHI for noisy sounds is quite different from that by hearing-impaired subjects.

2) Results and Discussion: The operation time of **(P)** was from between 40 to 60 minutes in Phase One. This was longer than the operation time of **(C)**, which took about 20 minutes. However, some subjects reported favorable impressions; the operation of **(P)** was more amusing and less of a burden than **(C)**, because **(P)** presented various unusual sounds.

Table IV shows the evaluation results obtained from the speech intelligibility test in Phase Two **(i)** as follows. For each of **(P)**, **(C)**, and **(N)**, we calculated the correct answer rates for each articulation of the 70 VCV syllables and each subject over ten trials. Let $\mathrm{P}[i]$, $\mathrm{C}[i]$, and $\mathrm{N}[i]$ be the articulations of 70 VCV syllables, where $1 \geq i \geq 70$. We then calculated the degrees of articulation improvement and declination by $(\mathrm{P}[i] - \mathrm{N}[i])$ and $(\mathrm{C}[i] - \mathrm{N}[i])$ for each i. As there is no space to show these data of (70 syllables $\times$ 2 differences $\times$ 3 subjects) here, and it is not easy to see the differences from so much raw data, we summed the number of improved and declined cases for three ranges of degree for each subject.

Table IV shows this data. **(P)** improved in 45 cases and declined in 13 cases, while **(C)** improved in 38 cases and declined in 41 cases. If these improved/declined cases are weighted with the score of 1, 2, and 3 for each of the three categories of degrees, then the scores for improved/declined cases of **(P)** is 90 versus 13 points, while for **(C)**, it is 77 versus 81 points. The interactive EC fitting, **(P)**, can therefore be seen to have outperformed conventional manual fitting, **(C)**, in terms of the intelligibility of 70 syllables with 3 hearing-impaired subjects.

Table V shows the evaluation results obtained in the sound quality test in Phase Two **(ii)** as follows. For each pair of **(N)** versus **(P)** and **(N)** versus **(C)**, we calculated the selection rates of **(P)**, **(C)**, and **(N)** per 15 trials for each subject. We then calculated the difference of selection rate between **(N)** and **(P)** and

TABLE V
RESULTS OF THE (II) SOUND QUALITY TEST IN PHASE TWO OF EXPERIMENT I. (X)* AND (X)** FOR THE PAIR OF (X) AND (Y) MEAN THAT (X) IS BETTER THAN (Y) AT 5% AND 1% STATISTICAL SIGNIFICANCE LEVELS, RESPECTIVELY—MEANS THAT THEIR DIFFERENCE IS NOT STATISTICALLY SIGNIFICANT

Improvement/Declination from **(N)** to **(P)**

Input Sound	Subject ID									Rate of Improvement	Rate of Declination
	Impaired			Normal with SHI							
	I-A	I-B	I-C	N-A	N-B	N-C	N-D	N-E	N-F		
Male Speech (MS)	(P)**	–	(N)**	(P)**	(P)**	(P)**	(P)**	(P)**	–	6 / 9	1 / 9
Female Speech (FS)	(P)**	–	–	(P)*	(P)**	(P)*	(P)**	(P)**	–	6 / 9	0 / 9
MS with A Multi-Talkers' Noise	(P)**	(P)*	–							2 / 3	0 / 3
FS with A Multi-Talkers' Noise	(P)**	–	(N)**							1 / 3	1 / 3
Sum per All Conditions										15 / 24	2 / 24

Improvement/Declination from **(N)** to **(C)**

Input Sound	Subject ID									Rate of Improvement	Rate of Declination
	Impaired			Normal with SHI							
	I-A	I-B	I-C	N-A	N-B	N-C	N-D	N-E	N-F		
Male Speech (MS)	–	(N)**	(N)**	–	–	(N)*	(C)*	–	(N)*	1 / 9	4 / 9
Female Speech (FS)	(N)**	(N)**	(N)**	(N)**	(N)*	(N)**	(C)**	(N)*	(N)**	1 / 9	8 / 9
MS with A Multi-Talkers' Noise	–	–	(N)**							0 / 3	1 / 3
FS with A Multi-Talkers' Noise	(N)**	(N)*	(N)**							0 / 3	3 / 3
Sum per All Conditions										2 / 24	16 / 24

between **(N)** and **(C)**. We finally conducted a sign test to estimate the statistical significance of the differences and summed the number of cases in which **(P)** or **(C)** was significantly better or worse than **(N)**.

As shown in Table V, **(P)** obviously outperformed **(C)**, again. This is because **(P)** overcame a serious problem in conventional fitting—that fitting to maximize speech intelligibility frequently causes low sound quality [39]. Therefore, it was confirmed that the interactive EC fitting is also more effective at improving sound quality than conventional fitting.

Our conclusions for Experiment I are summarized as follows. Although the interactive EC fitting takes a longer time than conventional fitting does, its operation is more interesting for hearing aid users than that of a conventional fitting, since they can listen to a variety of sounds. The interactive EC fitting also has a considerably higher performance than that of conventional fitting in terms of both speech intelligibility and sound quality.

C. *Experiment II: Evaluation for Music*

1) Experimental Conditions: The experimental conditions and procedures in Experiment II are almost the same as those in Experiment I. In Phase One, the subjects do not operate **(C)** but only the **(P)**, which, from the beginning, has not targeted musical applications. Naturally, no speech intelligibility test **(i)** is performed in Phase Two. In the sound quality test of Phase Two **(ii)**, we prepare and present an orchestral performance, a solo saxophone performance, Latin music with female vocals, and rock music with male vocals all processed with **(P)** and **(N)**.

2) Results and Discussion: We processed the raw data obtained in the sound quality test of Phase Two **(ii)** using the same procedures as those from Experiment I. As shown in Table VI, **(P)** obviously improved the sound quality over **(N)** and indicated the possibility for hearing-impaired people to enjoy listening to music using hearing aids.

In conclusion, Experiments I and II confirmed that the interactive EC fitting is effective for both speech and music.

V. FURTHER DISCUSSION AND PROSPECTS FOR THE FUTURE

A. *Practicality*

We experimentally confirmed that the interactive EC fitting works well for both speech and music when a loudness compensation type of hearing aid [30] was the target of fitting. Loudness compensation is one of the latest hearing compensation techniques and has many more parameters to be adjusted—from between 20 and 40—than the majority of common hearing aids do (5 to 10). Combined with interactive EC fitting's New Feature 4, that is easily applicable to various hearing aids (see Section III-A), it appears reasonable to suggest that interactive EC fitting is effective for other types of hearing aids as well. In that case, is interactive EC fitting really practical? Unfortunately, there are two issues that impede the practical use of interactive EC fitting: operating fatigue of

TABLE VI

RESULTS OF THE **(II)** SOUND QUALITY TEST IN PHASE TWO OF EXPERIMENT II. (X)* AND (X)** FOR THE PAIR OF (X) AND (Y) MEAN THAT (X) IS BETTER THAN (Y) WITH 5% AND 1% STATISTICAL SIGNIFICANCE LEVELS, RESPECTIVELY—MEANS THAT THEIR DIFFERENCE IS NOT STATISTICALLY SIGNIFICANT

Improvement/Declination from **(N)** to **(P)**

	Subject ID							
	Impaired			Normal with SHI			Rate of	Rate of
Input Sound	I-A	I-B	I-C	N-A	N-B	N-C	Improvement	Declination
Orchestral Performance	(P)**	–	(P)**	(P)**	(P)**	(P)**	5 / 6	0 / 6
Solo Saxophone Performance	(P)**	–	(P)**	(P)**	(P)**	(P)**	5 / 6	0 / 6
Latin Music with A Female Vocal	–	–	(P)**	(P)**	(P)**	(P)**	4 / 6	0 / 6
Rock Music with A Male Vocal	–	(N)**	(P)**	(P)**	(P)**	(P)**	4 / 6	1 / 6
						Sum per All Conditions	18 / 24	1 / 24

hearing aid users and low reliability of fitting outcomes. Here, we discuss how they these problems might be solved.

The difficulty of operation and long calibration time required by interactive EC fitting may impose substantial user fatigue. Although some subjects enjoyed operating the interactive EC fitting, others felt it troublesome, and its operating time—from 40 to 60 minutes—was considerably longer than the 20 minutes required by the conventional fitting. All the subjects participating in the evaluation experiments who were operating the interactive EC fitting for the first time got confused. This was because the operation of the interactive EC fitting was entirely different from the conventional fittings that they were accustomed to. We expect that this difficulty of operation would decrease gradually as users became increasingly experienced with the interactive EC fitting method. Furthermore, research into interactive EC user interface design has increased [32], [34], [40]–[43], [35], and we believe that introducing these research results can further reduce the problem of user fatigue.

In the meantime, the following solutions provide clear methods for reducing the calibration time. The first is to use possibly desirable search points as initial individuals in the EC instead of a random initialization. The second is to evolve the individuals forcibly by generating a large number of individuals and killing obviously bad ones automatically. The third is to narrow the search area by fixing parameters as specified by a user. These methods are all based on *a priori* knowledge of the user's auditory characteristics, such as an audiogram, which would be comprised of premeasured audible ranges for each frequency.

In the worst case, the fitting outcomes of an interactive EC fitting might be unstable or even harmful. To evaluate the stability of fitting outcomes, we conducted additional experiments in which the subjects operated the interactive EC fitting twice and compared their fitting outcomes. Since similar fitting outcomes were obtained, stability was confirmed—at least under our experimental conditions. This result is supported by some literature that reports stability in user responses [12]. We will conduct additional case studies to confirm stability and also compile an operational manual for the interactive EC fitting to ensure consistent, stable user responses.

Because the interactive EC fitting has a medical purpose, it is essential that harmful fitting outcomes be avoided. We cannot prove the safeness of interactive EC fitting from the first trial's experiments at this time. However, although the confirmation and proof of safeness remain a target of our future research, we will enumerate here some conceivable countermeasures to harmful fittings. The first is to search only in a safe area, as estimated based on *a priori* knowledge of the auditory characteristics of the user. Another is to embed a function for the supervision by a human fitting expert, which the expert can use to monitor the acoustical characteristics of the hearing aid and intervene in the fitting. The latter approach may help to reduce the social novelty—and corresponding unacceptability—of interactive EC fitting, whose operation is so different from conventional, accepted, fitting methods.

B. Differences From Other New Fitting Methods

Investigations into hearing-aid fitting methods that reflect users' comprehensive hearing have attracted a lot of attention recently. Here, we compare the interactive EC fitting with other new methods.

APHAB is one new method that is widely used [2]. APHAB uses a questionnaire for self-assessment in which a user reports the amount of trouble he or she is having with communication and/or noises that are troublesome in daily situations. The results of APHAB are useful for addressing users' comprehensive hearing and for fine-tunning their hearing aids accordingly. The results are not directly reflected in the fittings, however; fitting experts must interpret APHAB results and manually adjust users' hearing aids based on their interpretations.

Modeling users' hearing preferences using neural networks (NN) was investigated in another trial [44], [45], [13]. An NN learns the mapping between the acoustical characteristics of a fitted hearing aid and the subjective evaluation results as determined by the user. The NN can then be used for evaluating fitting outcomes as a substitute for the user. This is remarkable as a novel application of computational intelligence techniques to fitting. However, a difficult problem is proposed in that an NN requires sufficient training data for precise learning, while the

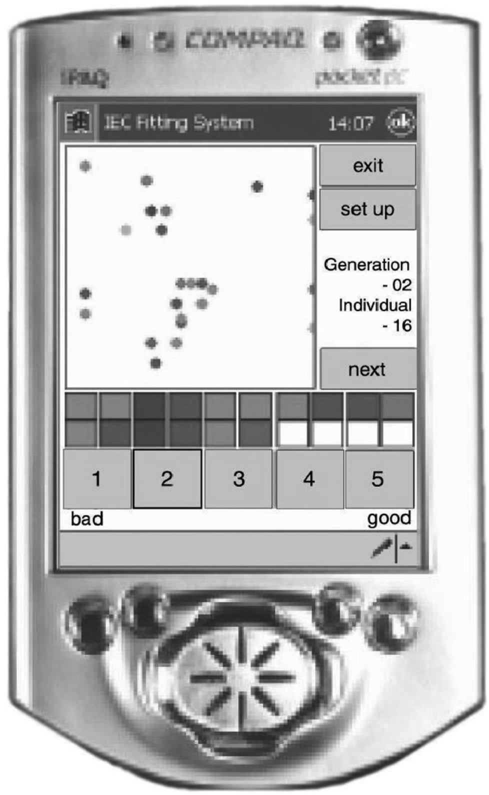

Fig. 7. Interactive EC fitting with visualized interactive EC on a PDA.

number of subjective evaluation results that can be provided by a single user is strictly limited.

Consequently, it is likely to learn the common tendency of users having similar hearing and is unlikely to reflect the subtle differences between them.

Compared with these methods, interactive EC fitting has several attractive advantages. First, in contrast to APHAB, it directly reflects the comprehensive hearing of a user in the calibration of signal processing parameters. Second, in contrast to a pseudohuman approach with an NN, it does not request additional measurements for NN training, which results in less human fatigue for fitting.

Conversely, APHAB or NN-based methods possess some advantages over interactive EC fitting. Therefore, it seems likely that the cooperative combination of those methods with interactive EC fitting provides the most likely route to advance fitting performance and satisfy the needs of both users and fitting experts. One of our future aims is to explore these potential combinations.

C. New Prospects

Finally, we discuss the two new prospects of interactive EC fitting, which we have partially achieved. One prospect is the development of real W^3 fitting. We implemented an interactive EC fitting system on a personal digital assistant (PDA) that is compact enough to carry around, as shown in Fig. 7. We added a function for visualizing the interactive EC [41] to improve the usability, and also made some refinements to make the system operate well with less computer memory. Now, we are testing the usability and performance of the system and expect that it realizes a W^3 fitting that is both easy-to-use and precise due to iterative daily refinement.

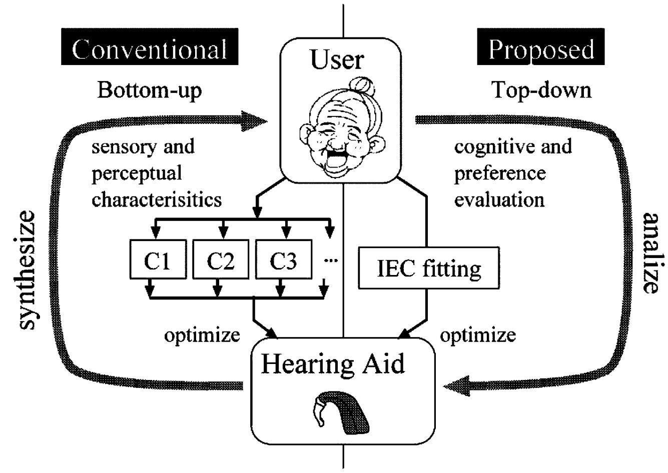

Fig. 8. Approaches to hearing characteristic research. The conventional bottom-up approach appears on the left, and the proposed top-down approach is on the right.

The other prospect opened up by interactive EC fitting is that of a new approach to research on auditory systems. The conventional approach has been based on reductionism, as shown on the left side of Fig. 8; it tries to understand and model an auditory system by synthesizing its primitive sensory and perceptual responses. To suppress the extraneous factors that accumulate through the synthesis, it requires well-controlled artificial conditions and precise equipment for measurement. For instance, absolute thresholds of hearing must be measured using pure tones via standardized circumaural headphones in a highly soundproofed chamber. Although research using this bottom-up approach has achieved important results, the approach has some problems; it is fundamentally difficult to examine the mutual effect among the responses due to their combinatorial interaction, the individuality of each person due to the lack of data, and the relation between the characteristics in the sensory and perceptual levels and those in the cognitive and preference ones.

In response to the problems, we propose a top-down approach based on the interactive EC fitting, as shown on the right side of Fig. 8. Our idea is as follows: the interactive EC fitting fits a hearing aid to the comprehensive hearing of a user, while treating his or her auditory system as a black box. The analysis of the calibration will then let us discover new knowledge about auditory systems such as mutual effects, individuality, and relationships, which cannot be discovered from the bottom-up approach. In fact, we have already conducted research using the top-down approach to examine the difference between loudness characteristics for bandpass noises and daily life sounds [46]. In the future, we will apply the top-down approach to other hearing characteristic research.

VI. Conclusion

We proposed an application of interactive EC techniques in hearing aid fitting and showed its high potential quantitatively through three evaluation tests for speech intelligibility, speech quality, and music quality. There must be hearing aid fitters whose capabilities are higher or lower than the fitters in our experiments, and the fitting performance of the conventional fittings used in this paper must, of course, have differed according to the fitters. One of the advantages of our proposed method is that it improves this real-world uneven fitting quality by automatically realizing fittings based on users' unique hearing. It also solves the fundamental fitting problem, that of fitting by nonusers, by introducing an interactive EC technique. We believe this marks a breakthrough in the history of hearing aid fitting technology. Furthermore, thanks to its ability to fit based on hearing, the interactive EC fitting has no restrictions on the sounds that may be used; users can use any sounds from their daily lives— something which is impossible with conventional hearing aid fitting.

Although human fatigue remains a problem in interactive EC, research addressing this issue is very active and we expect it will gradually become a less serious problem. A hearing aid company now in collaboration with us is evaluating interactive EC fitting using their commercial hearing aids and we hope that our proposed method will become a pioneer of practical interactive EC applications in the welfare field.

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