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Protopapas

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[54] **AURAL TRAINING METHOD AND APPARATUS TO IMPROVE A LISTENER'S ABILITY TO RECOGNIZE AND IDENTIFY SIMILAR SOUNDS**

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[73] Assignee: **Scientific Learning Corp.**, Berkeley, Calif.

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Related U.S. Application Data

[63] Continuation-in-part of application No. 09/045,279, Mar. 20, 1998.

[51] **Int. Cl.**[7] **G10L 21/02**

[52] **U.S. Cl.** **704/278**; 434/185

[58] **Field of Search** 704/278, 268, 704/269, 271; 434/185, 116, 169; 381/23.1

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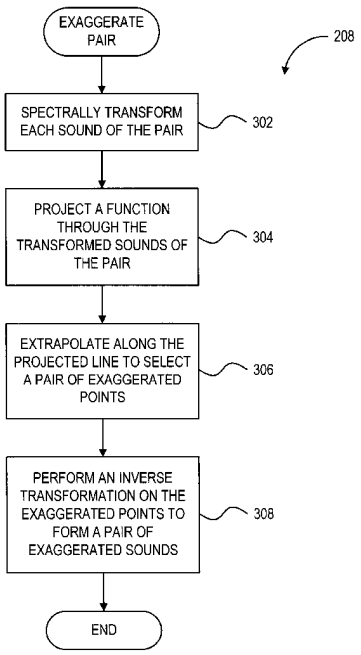
Primary Examiner—David R. Hudspeth
Assistant Examiner—Donald L. Storm
Attorney, Agent, or Firm—James D. Ivey

[57] **ABSTRACT**

A listener's ability to recognize and identify similar sounds is improved by forming exaggerated sounds which differ in spectral/temporal energy distribution from one another more than the similar sounds differ from one another and in generally the same way in which the similar sounds differ and testing the listener's ability to recognize and identify the exaggerated sounds. The exaggerated sounds are formed as follows: The similar sounds are spectrally transformed into a coordinate space and a linear function is projected between a pair of points representing the similar sounds in the coordinate space. Between the pair of points, the linear function represents a continuum of sounds between the similar sounds. To exaggerate the sounds, points are extrapolated outward from the pair of points along the linear function. An inverse transformation is applied to the extrapolated points to produce exaggerated sounds which differ from one another more than the similar sounds differ and in generally the same way that the similar sounds differ. Filtering extrapolation coefficients before extrapolating and filtering inverse transformation coefficients before applying the inverse transform provide pleasant, naturally sounding exaggerated sound.

9 Claims, 8 Drawing Sheets



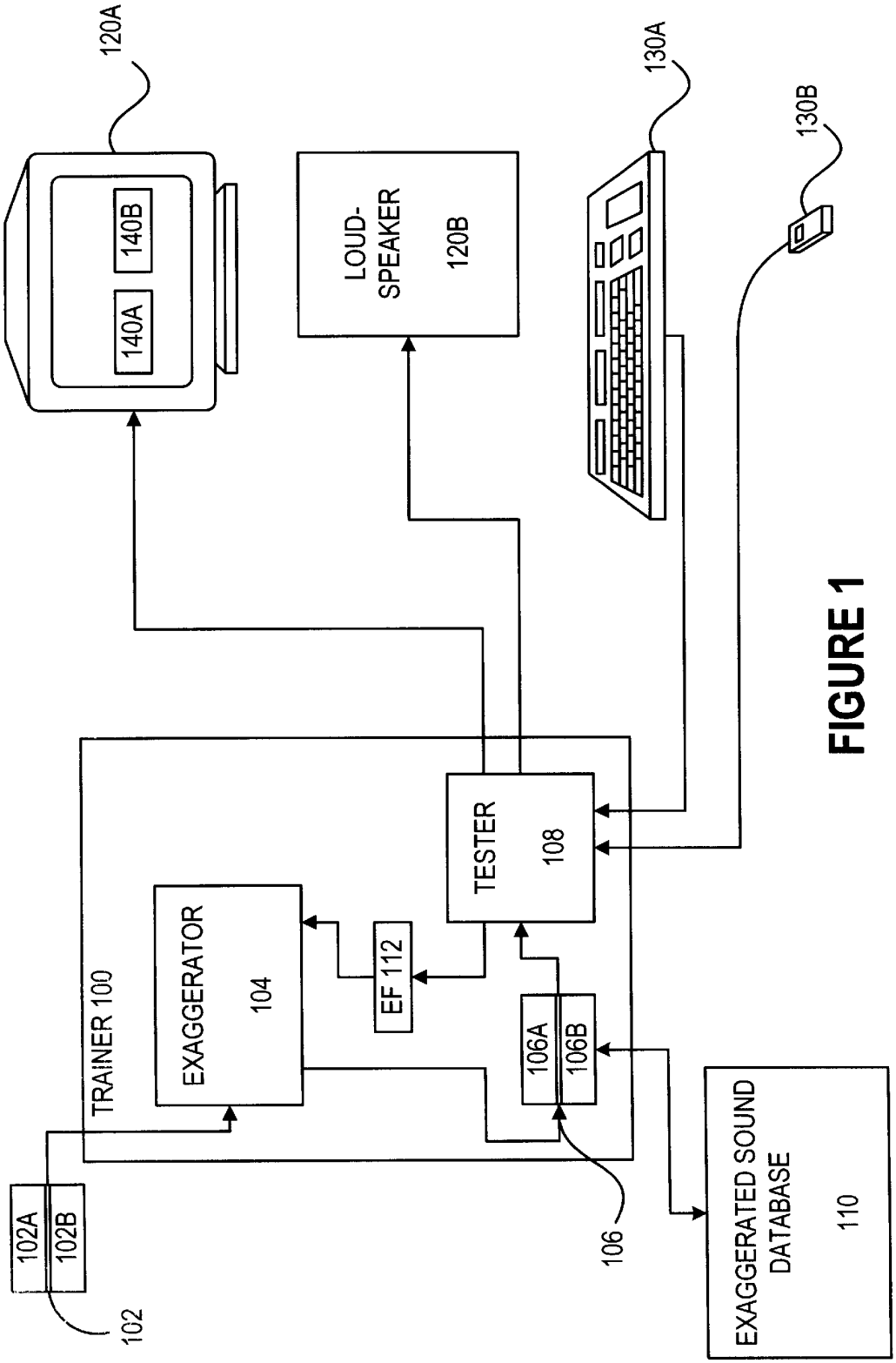

120A
140B
140A
LOUD-
SPEAKER
120B
130A
130B
TESTER
108
EXAGGERATOR
104
EF 112
TRAINER 100
106A
106B
102A
102B
102
106
EXAGGERATED SOUND
DATABASE
110

FIGURE 1

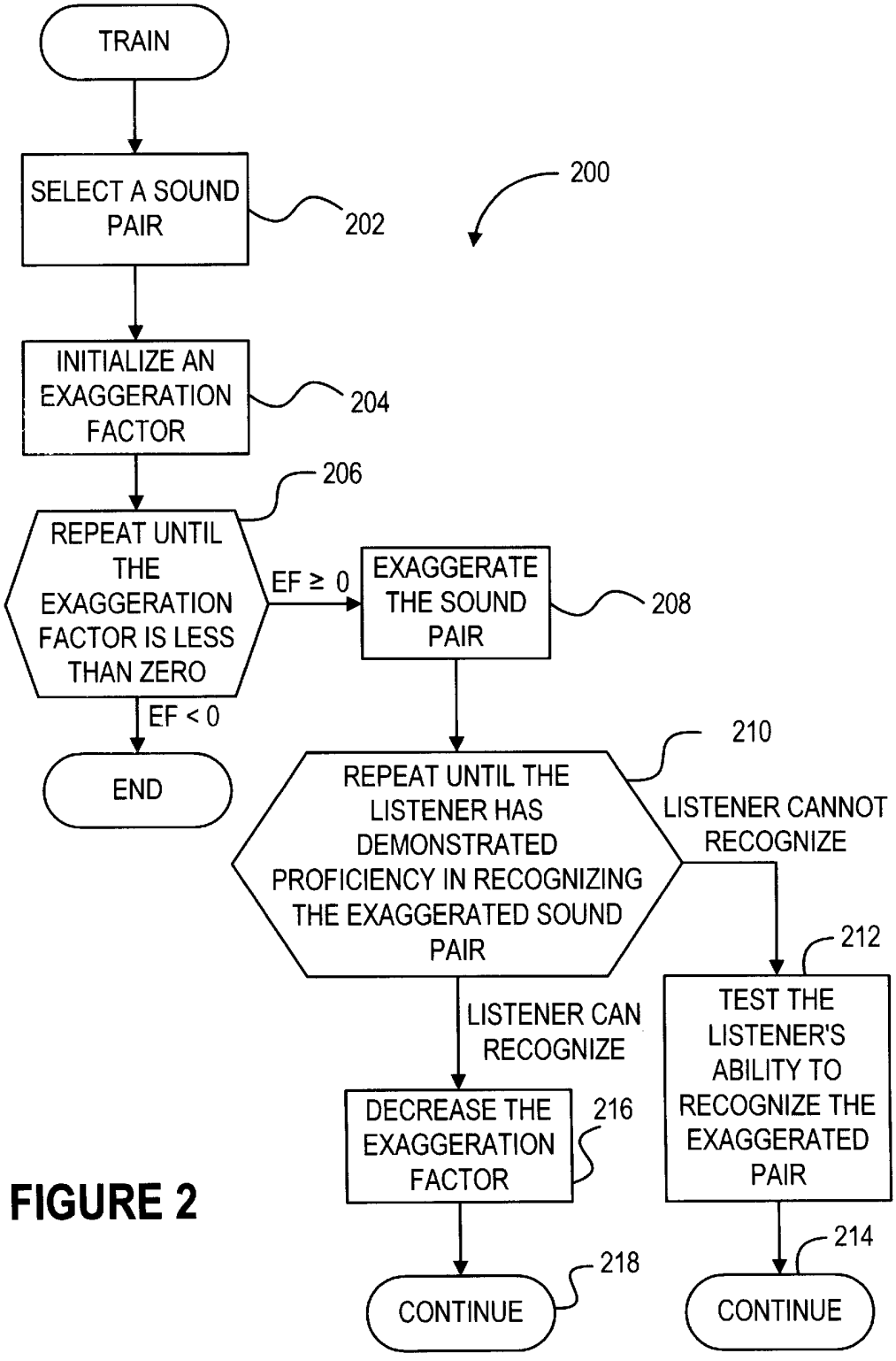

TRAIN
SELECT A SOUND PAIR
202
200
INITIALIZE AN EXAGGERATION FACTOR
204
206
REPEAT UNTIL THE EXAGGERATION FACTOR IS LESS THAN ZERO
EF ≥ 0
EXAGGERATE THE SOUND PAIR
208
EF < 0
END
210
REPEAT UNTIL THE LISTENER HAS DEMONSTRATED PROFICIENCY IN RECOGNIZING THE EXAGGERATED SOUND PAIR
LISTENER CANNOT RECOGNIZE
212
TEST THE LISTENER'S ABILITY TO RECOGNIZE THE EXAGGERATED PAIR
LISTENER CAN RECOGNIZE
DECREASE THE EXAGGERATION FACTOR
216
214
CONTINUE
218
CONTINUE

FIGURE 2

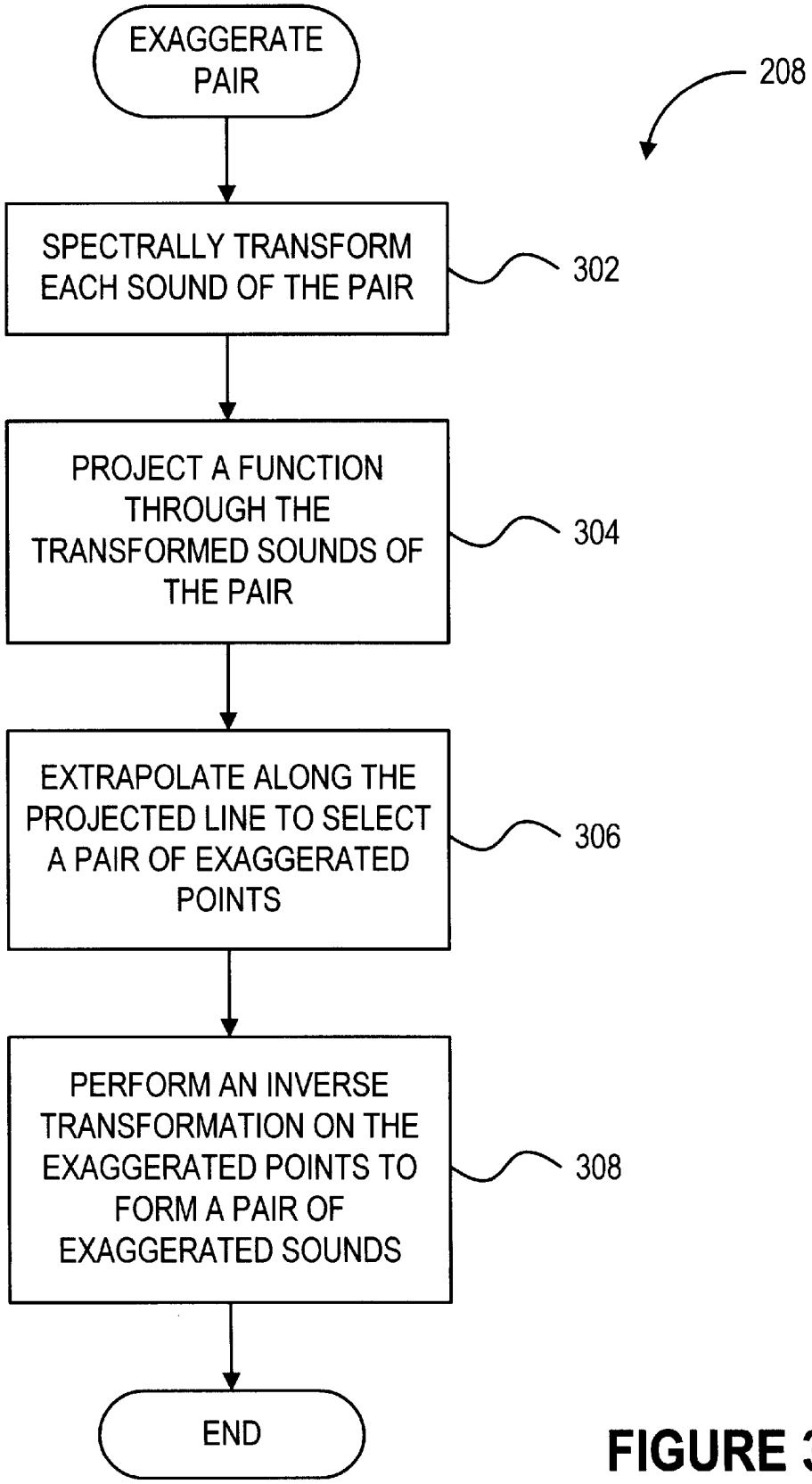

EXAGGERATE PAIR
208
SPECTRALLY TRANSFORM EACH SOUND OF THE PAIR
302
PROJECT A FUNCTION THROUGH THE TRANSFORMED SOUNDS OF THE PAIR
304
EXTRAPOLATE ALONG THE PROJECTED LINE TO SELECT A PAIR OF EXAGGERATED POINTS
306
PERFORM AN INVERSE TRANSFORMATION ON THE EXAGGERATED POINTS TO FORM A PAIR OF EXAGGERATED SOUNDS
308
END

FIGURE 3

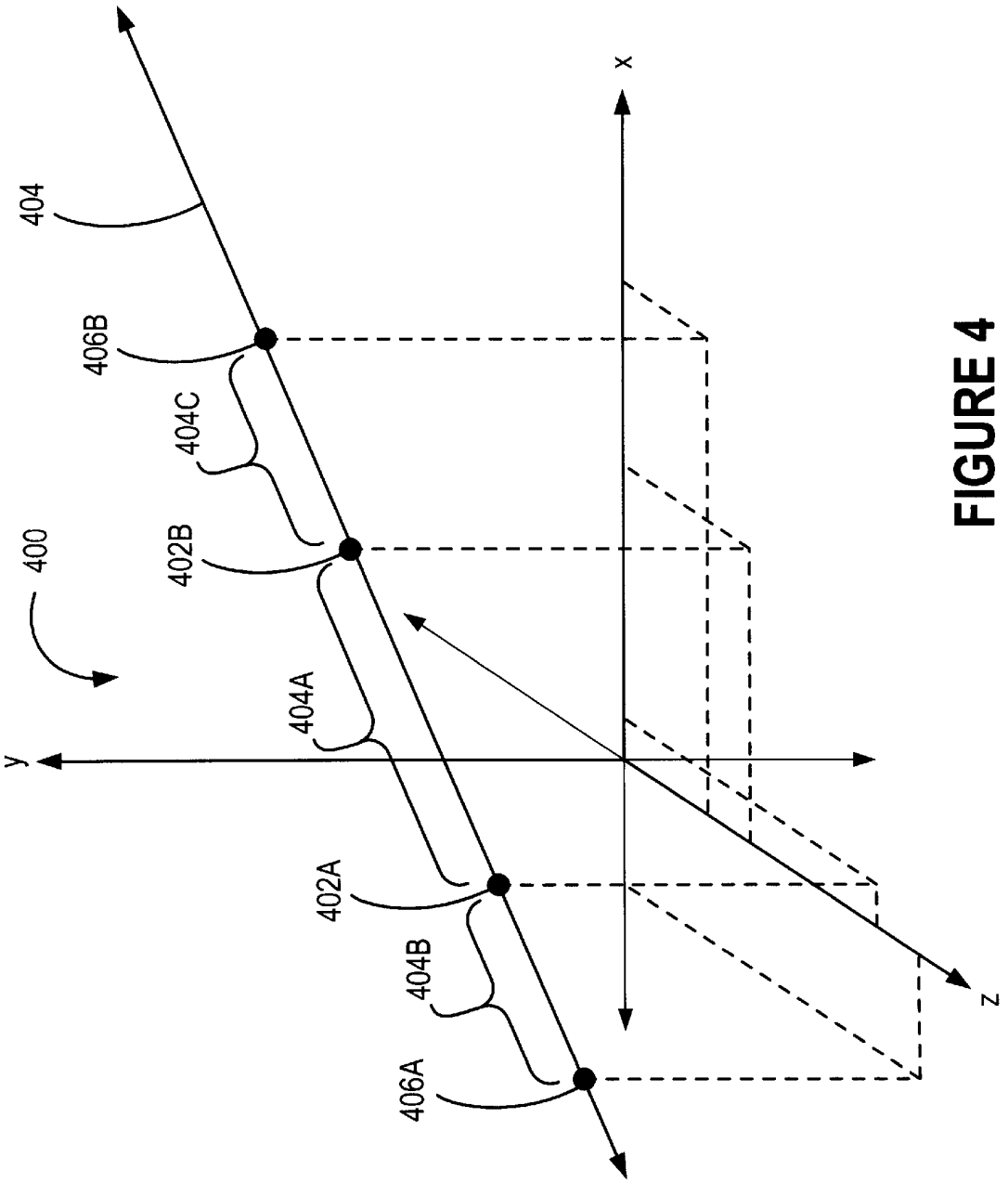
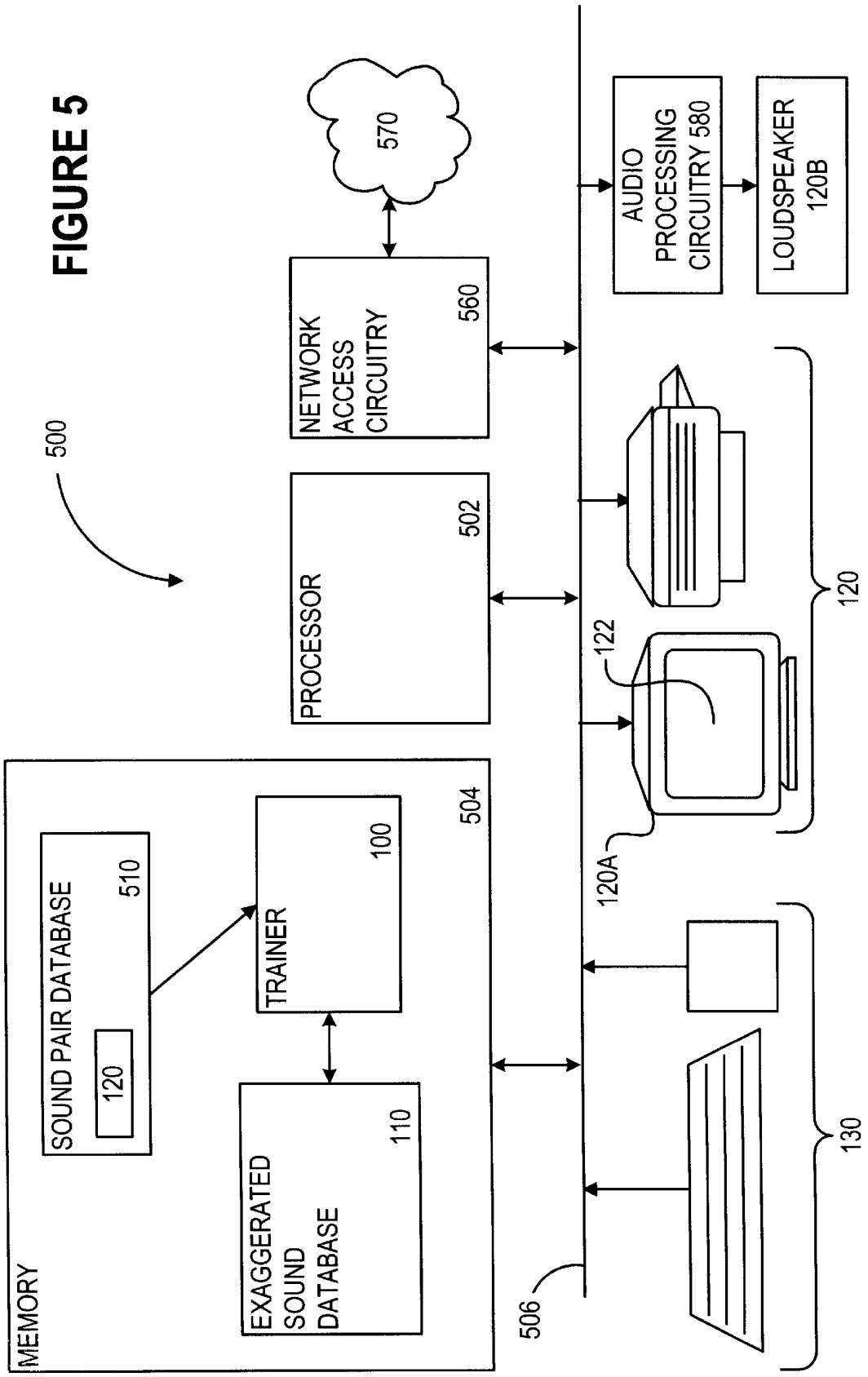


FIGURE 4

FIGURE 5


500
MEMORY
504
SOUND PAIR DATABASE
510
120
TRAINER
100
EXAGGERATED SOUND DATABASE
110
PROCESSOR
502
NETWORK ACCESS CIRCUITRY
560
570
AUDIO PROCESSING CIRCUITRY 580
LOUDSPEAKER 120B
506
120A
122
120
130

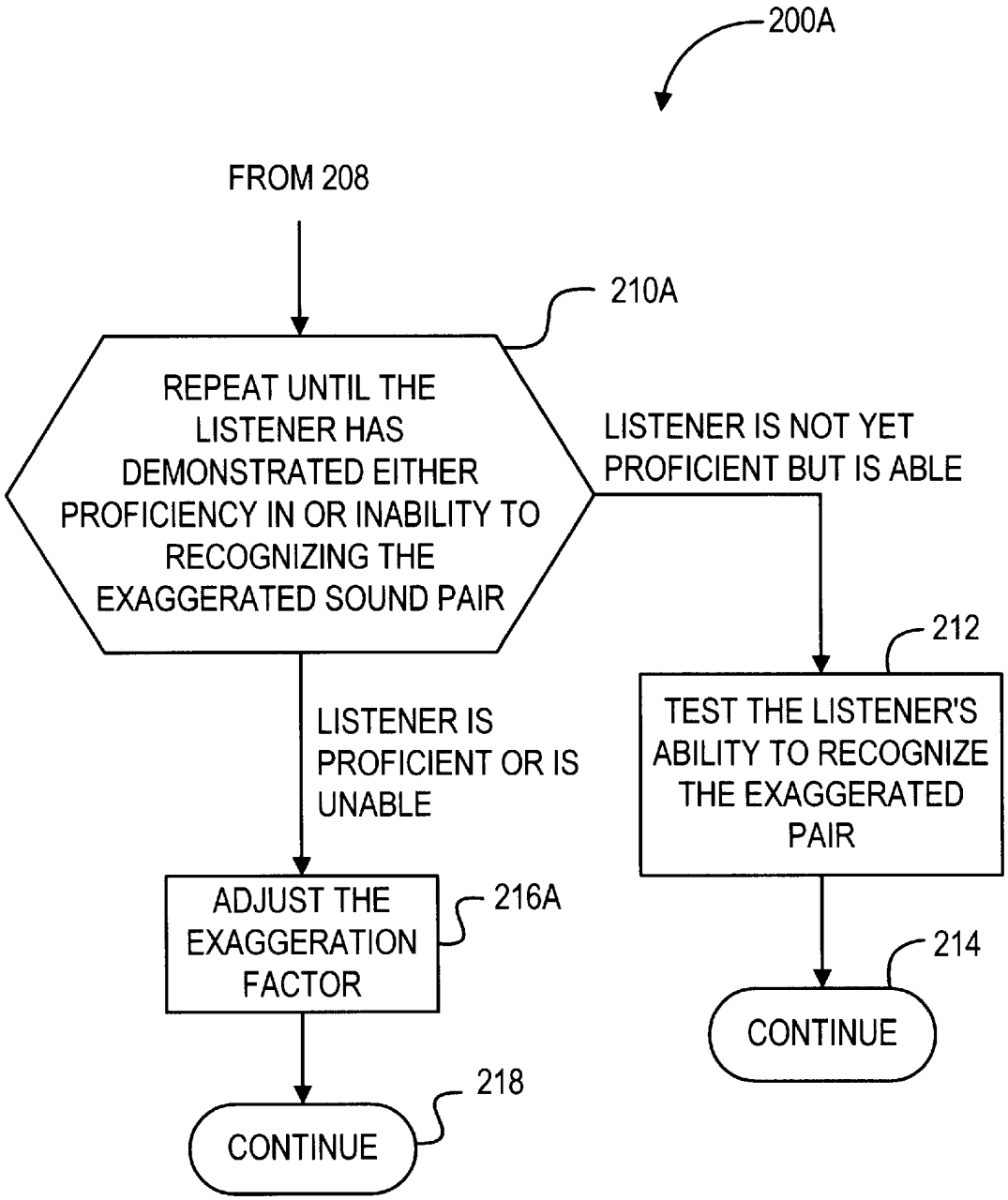

200A
FROM 208
210A
REPEAT UNTIL THE LISTENER HAS DEMONSTRATED EITHER PROFICIENCY IN OR INABILITY TO RECOGNIZING THE EXAGGERATED SOUND PAIR
LISTENER IS NOT YET PROFICIENT BUT IS ABLE
212
TEST THE LISTENER'S ABILITY TO RECOGNIZE THE EXAGGERATED PAIR
LISTENER IS PROFICIENT OR IS UNABLE
216A
ADJUST THE EXAGGERATION FACTOR
214
CONTINUE
218
CONTINUE

FIGURE 6

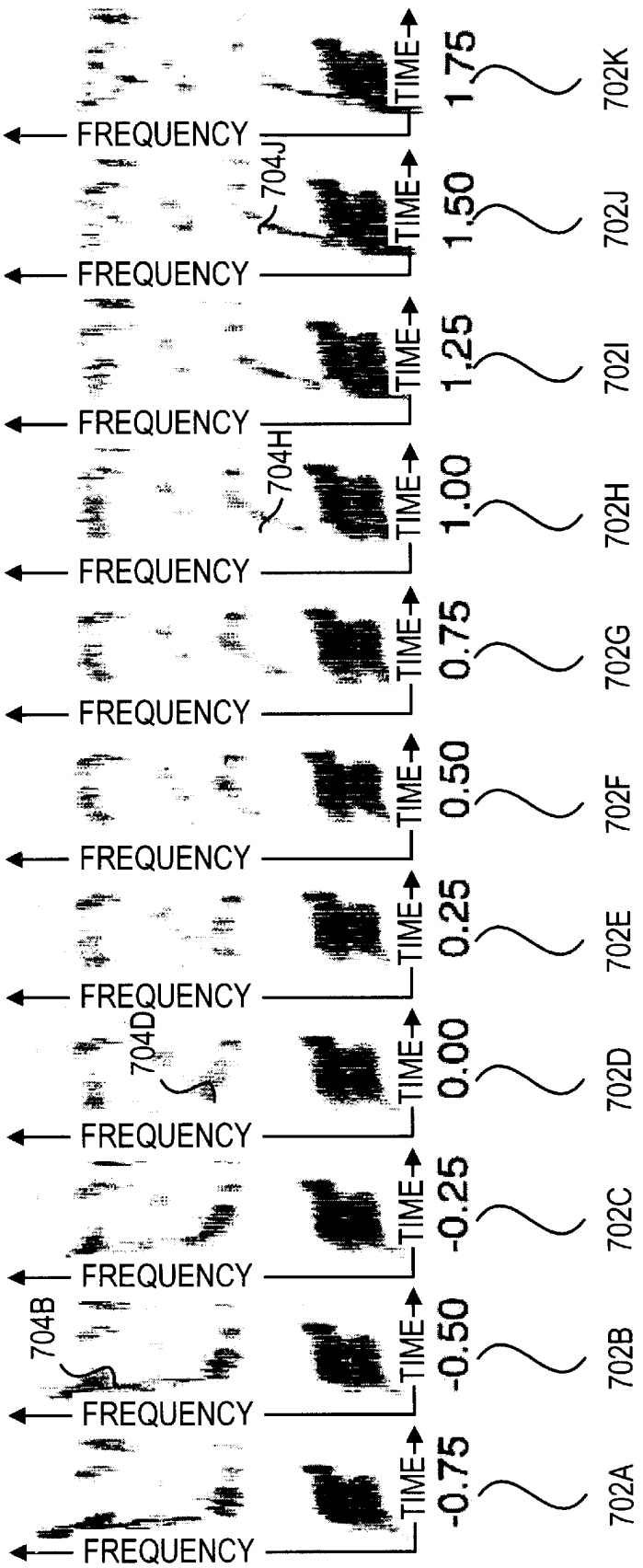

FREQUENCY
TIME
-0.75
-0.50
-0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
702A
702B
702C
702D
702E
702F
702G
702H
702I
702J
702K
704B
704D
704H
704J
106B
102B
102A
106A

FIGURE 7

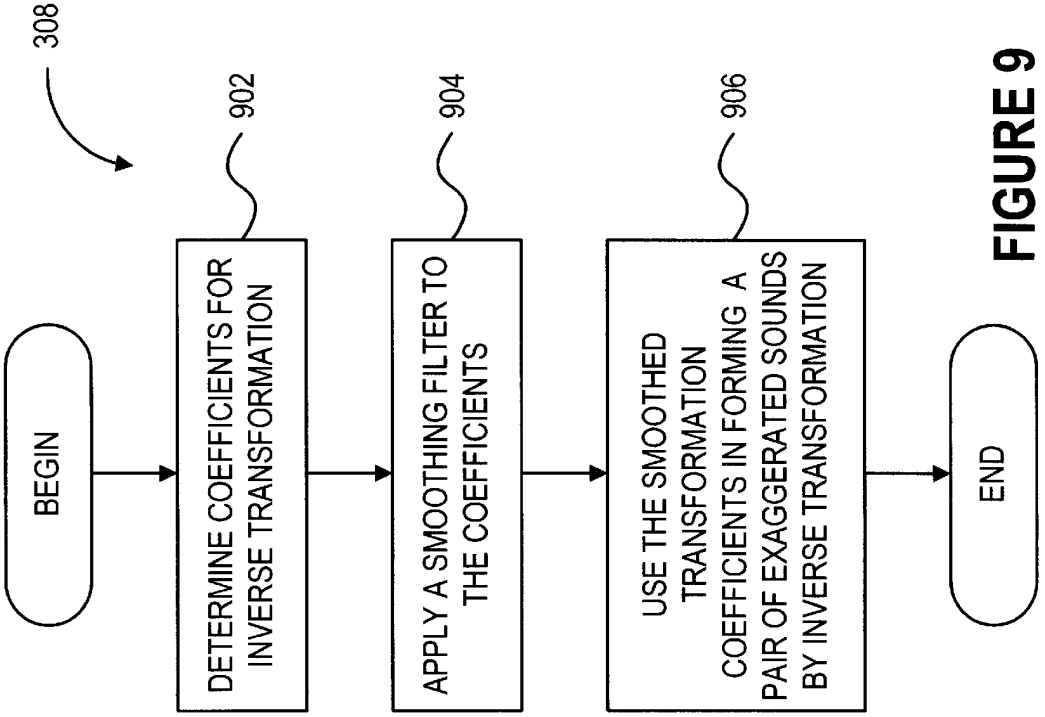


FIGURE 9

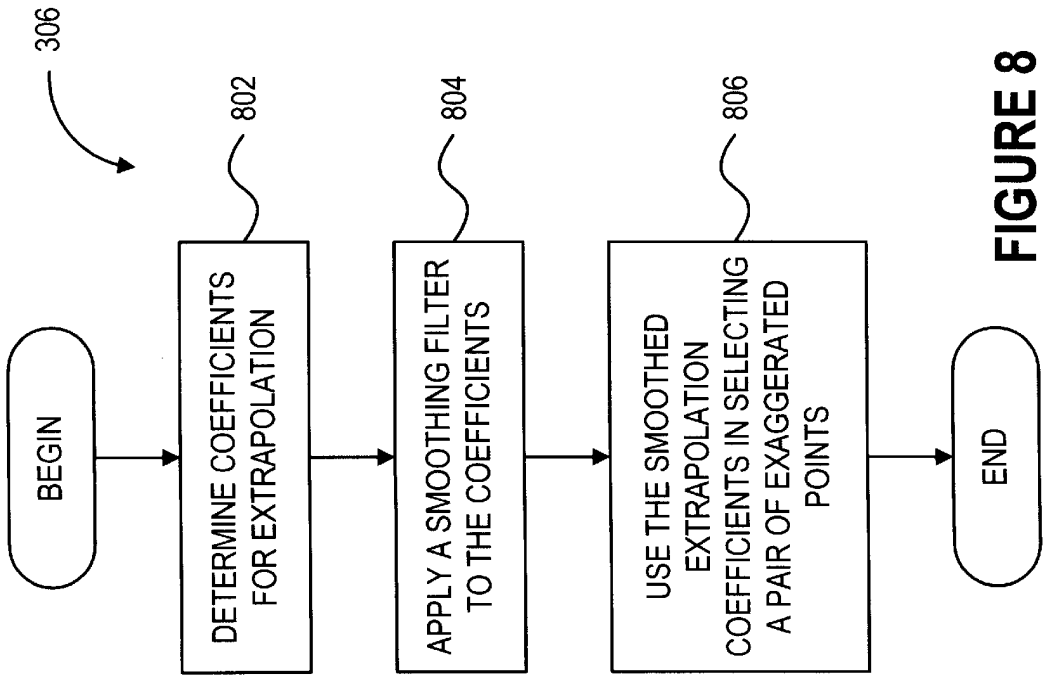


FIGURE 8

AURAL TRAINING METHOD AND APPARATUS TO IMPROVE A LISTENER'S ABILITY TO RECOGNIZE AND IDENTIFY SIMILAR SOUNDS

SPECIFICATION

This is a continuation-in-part of co-pending U.S. patent application Ser. No. 09/045,279 filed Mar. 20, 1998.

FIELD OF THE INVENTION

The present invention relates to computer-assisted training systems and, in particular, to a particularly effective mechanism for training listeners to identify and recognize similar sounds.

BACKGROUND OF THE INVENTION

One of the more significant difficulties in learning a second language is the inability to recognize and identify some sounds, distinguishing the sounds from one another, when the distinction is not a component of a listener's native language. One example is the inability of a number of people who are native speakers of certain non-English languages, e.g., Japanese, to distinguish the sounds of the English language pertaining to the letters "r" and "l. " Such people have great difficulty in distinguishing such words as (i) "rock" and "lock," (ii) "rake" and "lake," and (iii) "right" and "light." Other distinctions of the English language which are difficult for some non-native English speakers include distinctions between "b" and "v," between "f" and "t," and between "f" and "p." Such non-native English speakers would have difficulty distinguishing, or be unable to distinguish, "bat" from "vat" or "theses" or "pieces" from "feces." Such inability makes comprehension of a second language particularly difficult and hinders such a person's ability to speak in the second language. The result is often a heavy accent which is difficult for native speakers of the second language to comprehend.

Such difficulty in perceiving similar but distinct sounds of spoken language are not limited to people attempting to learn a second language. Some people have specific impairments, such as language-learning impairments, in which some distinctions between similar sounds are not perceptible.

What is needed is a mechanism by which a listener can be trained to perceive subtle differences in similar sounds which sound identical to the listener.

SUMMARY OF THE INVENTION

In accordance with the present invention, each of a pair of sounds which are indistinguishable to a listener are exaggerated in such a way that the listener can distinguish the exaggerated sounds and such that the difference in spectral/temporal energy distribution between the pair of sounds is exaggerated. Specifically, the exaggerated sounds are more different from each other than are the original pair of sounds and differ in generally the same way, albeit to a greater degree, that the original pair of sounds differ. Since the exaggerated sounds differ more than the original pair of sounds differ, the listener can distinguish the exaggerated sounds. In addition, distinguishing the exaggerated sounds from one another helps the listener develop the ability to distinguish and recognize each of the original pair of sounds since the exaggerated sounds differ from one another in generally the same way that the original sounds differ from one another. The following example is illustrative.

Suppose that a non-native speaker of the English language cannot distinguish the respective sounds of the consonant "r" and the consonant "l." It should be noted that each of the consonant sounds are, in actuality, a class of sounds. For example, an English "r" can be uttered slightly different and still be recognized by native English speakers as an "r." For native English speakers, the class of sounds that are recognized as an "r" is distinct from the class of sounds that are recognized as an "l." An non-native English speaker or a person with a language learning impairment might not recognize those classes as distinct. Instead, that person recognizes the sounds as belonging to a single, indistinguishable class "r/l" of sounds whether an "r" or an "l" is spoken. According to the present invention, the "r" sound is exaggerated to form a new sound, referred to as "r++," and the "l" sound is exaggerated to form another new sound, referred to as "l++." While it's possible that "r" doesn't sound much like "r," "r++" sounds more different from "l" than does "r," and "r++" sounds more different from "l" in generally the same way that "r" sounds different from "l." Similarly, it's that possible that "l++" doesn't sound much like "l." However, "l++" sounds more different from "r" than does "l," and "l++" sounds more different from "r" in generally the same way that "l" sounds different from "r."

Even if the listener cannot recognize a sound as belonging to either an "r" class or an "l" class, the listener can recognize "r++" and "l++" as belonging to different classes of sound since "r++" and "l++" are more different than are "r" and "l." In accordance with the present invention, a trainer presents either the "r++" sound or the "l++" sound to the listener and asks the listener to identify the presented sound. Repeatedly doing so builds in the listener the ability to recognize "r++" and "l++" as sounds belonging to distinct classes which can be identified by the listener. By comparison, repeatedly asking the listener to identify a particular sound as either "r" or "l" would produce no results since the listener perceives the sounds as belonging to the same class of sounds.

Since "r++" and "l++" differ from one another in generally the same way that "r" and "l" differ from one another, building the ability of the listener to recognize "r++" and "l++" as distinct sounds establishes a perceptual distinction in approximately the place that a perceptual distinction between "r" and "l" should exist in the perception of the listener. As the listener becomes proficient in recognizing and identifying "r++" from "l++," the degree to which "r" and "l" are exaggerated is decreased. For example, "r" can be exaggerated to a smaller degree to form an exaggerated sound "r+." Similarly, "l" can be exaggerated to a smaller degree to form an exaggerated sound "l+." The listener is then asked to recognize and identify "r+" and "l+." Again, the perceptual distinction is in approximately the place that a perceptual distinction between "r" and "l" should exist in the perception of the listener since "r+" differs from "l+" in generally the way that "r" differs from "l."

The degree to which the sounds are exaggerated diminishes over time such that the exaggerated sounds recognized and identified by the listener are ever closer to the original sounds which were originally indistinguishable to the listener.

In accordance with the present invention, the exaggerated sounds are formed as follows. The original sounds of the pair are spectrally transformed into a coordinate space having one or more dimensions. The transformation can be, for example, a known vocal tract equivalent transformation. The transformation results in each sound of the pair being represented by a respective point in the coordinate space. A

function is fit between the points of the pair of sounds. The function can be linear. Between the points of the pair, the function represents a continuous interpolation between the sounds of the pair. A pair of extrapolated points is determined by extrapolating along the function from each point of the pair away from the other point of the pair by a predetermined distance. By extrapolating along the projected function away from the pair of original points, the extrapolated points differ from one another by more than the difference between the original pair of points and differ along the same function. Filtering extrapolation coefficients prior to extrapolation provides particularly good results. The exaggerated sounds are formed by performing the inverse of the transformation upon the extrapolated points. Filtering inverse transformation coefficients prior to application of the inverse transformation provides particularly naturally sounding exaggerated sounds and provides particularly good results and a more pleasant experience for the listener. The exaggerated sounds differ more than do the original sounds of the pair and that difference is exaggerated. The difference is exaggerated in that the difference is greater in degree and substantially the same in type. For example, the difference between "r++" and "l++" is an exaggeration of the difference between "r" and "l" since "r++" and "l++" differ from one another more than do "r" and "l" and the way in which "r++" and "l++" differ from one another is generally the same as the way in which "r" and "l" differ from one another.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a trainer in accordance with the present invention.

FIG. **2** is a logic flow diagram illustrating the training of a listener by the trainer of FIG. **1** in accordance with the present invention.

FIG. **3** is a logic flow diagram of the exaggeration of a pair of sounds by an exaggerator of the trainer of FIG. **1** in accordance with the present invention.

FIG. **4** is a representation of a pair of sounds and corresponding exaggerated sounds spectrally transformed into a multi-dimensional space in accordance with the present invention.

FIG. **5** is a block diagram of a computer system within which the trainer of FIG. **1** executes.

FIG. **6** is a logic flow diagram illustrating a part of the training of a listener by the trainer of FIG. **1** in accordance with an alternative embodiment of the present invention.

FIG. **7** is a collection of spectrograms illustrating exaggeration of the difference in spectral/temporal energy distribution between sounds to form exaggerated sounds in accordance with the present invention.

FIG. **8** is a logic flow diagram of the extrapolation along the spectrally transformed sound of FIG. **4** according to a step in FIG. **3**.

FIG. **9** is a logic flow diagram of the inverse transformation of the extrapolated sounds of FIG. **4** according to a step of FIG. **3**.

DETAILED DESCRIPTION

In accordance with the present invention, differences in spectral/temporal energy distribution between similar sounds are exaggerated to facilitate improvement of a listener's ability to recognize and distinguish the sounds. In particular, a trainer **100** (FIG. **1**) retrieves a pair **102** of similar sounds **102**A–B, forms therefrom a pair **106** of exaggerated sounds **106**A–B, and tests the listeners ability to recognize and identify each of exaggerated sounds **106**A–B. As the listener's ability to recognize and identify each of exaggerated sounds **106**A–B improves, the amount by which exaggerated sounds **106**A–B differ from sounds **102**A–B is diminished to thereby further challenge the listener's ability to distinguish the sounds.

In this illustrative embodiment, trainer **100** is all or part of one or more computer processes. The processing of trainer **100** is shown in greater detail as logic flow diagram **200** (FIG. **2**). Processing according to logic flow diagram **200** begins in step **202** in which trainer **100** (FIG. **1**) selects pair **102** from a number of pairs of similar sounds. Examples of such pairs can include (i) "rock" and "lock," (ii) "bat" and "dat," (iii) "sip" and "chip," (iv) "fat" and "pat," and (v) "shoe" and "chew." In step **204** (FIG. **2**), a tester **108** (FIG. **1**) of trainer **100** initializes an exaggeration factor **112** to represent an initial degree of exaggeration. Tester **108** is that portion of trainer **100** which presents exaggerated sounds to the listener in the manner described below and which measures the listener's ability to distinguish between the exaggerated sounds in the manner described below.

Loop step **206** and continue step **218** define a loop in which trainer **100** (FIG. **1**) repeatedly performs steps **208** (FIG. **2**) through **216** until exaggeration factor **112** (FIG. **1**) is less than zero. In step **208** (FIG. **2**), an exaggerator **104** (FIG. **1**) of trainer **100** forms pair **106** of exaggerated sounds **106**A–B from sounds **102**A–B. Processing by exaggerator **104** in step **208** (FIG. **2**) is shown in greater detail as logic flow diagram **208** (FIG. **3**).

In step **302**, exaggerator **104** (FIG. **1**) spectrally transforms each of sounds **102**A–B such that sounds **102**A–B can be represented in a coordinate space having one or more dimensions. For example, after such transformation in step **302** (FIG. **3**), sounds **102**A–B (FIG. **1**) are represented by points **402**A–B (FIG. **4**), respectively, in a coordinate space **400**. Many such spectral transformations are known. In general, any spectral transformation of sounds **102**A–B can produce acceptable results. Exemplary spectral transformations include transformations using (i) linear predictive coding (LPC) filter coefficients, (ii) LPC partial correlations (PARCOR) coefficients, (iii) perceptual linear predictive (PLP) coefficients, (iv) vocal tract equivalent log area ratio coefficients, (v) Fourier spectral magnitude, (vi) Fourier Spectrum complex coefficients, (vii) filterbank output envelope, (viii) ceptsral magnitude coefficients, and (ix) complex cepstrum coefficients. For reasons described more completely below, vocal tract equivalent modeling transformations produce particularly good results.

In step **304** (FIG. **3**), exaggerator **104** (FIG. **1**) projects a function **404** (FIG. **4**) through points **402**A–B in coordinate space **400**. In this illustrative embodiment, function **404** is linear. In other, alternative embodiments, function **404** is non-linear. For example, function **404** can be exponential or logarithmic. A portion of **404**A of function **404** between points **402**A–B represents a continuous spectrum of sound between sounds **102**A–B (FIG. **1**). The length of portion **404**A (FIG. **4**), i.e., the distance between points **402**A–B along function **404**A, represents an amount of difference between sounds **102**A–B (FIG. **1**).

In step **306** (FIG. **3**), exaggerator **104** (FIG. **1**) forms points **406**A–B (FIG. **4**) which are representative of exaggerated points **106**A–B (FIG. **1**) in coordinate space **400** (FIG. **4**). In particular, exaggerator **104** (FIG. **1**) extrapolates a point **406**A (FIG. **4**) along function **404** from point **402**A in a direction away from point **402**B. As a result, point **406**A is further from point **402**B than is point **402**A is the same

direction that point **402**A is from point **402**B. Since point **406**A represents exaggerated sound **106**A (FIG. **1**), exaggerated sound **106**A differs from sound **102**B more than sound **102**A differs from sound **102**B and in generally the same way that sound **102**A differs from sound **102**B. Similarly, exaggerator **104** (FIG. **1**) extrapolates a point **406**B (FIG. **4**) along function **404** from point **402**B in a direction away from point **402**A. As a result, point **406**B is further from point **402**A than is point **402**B is the same direction that point **402**B is from point **402**A. Since point **406**B represents exaggerated sound **106**B (FIG. **1**), exaggerated sound **106**B differs from sound **102**A more than sound **102**B differs from sound **102**A and in generally the same way that sound **102**B differs from sound **102**A.

The distance of portion **404**B (FIG. **4**) along function **404** from point **402**A to extrapolated point **406**A as determined by exaggerator **104** (FIG. **1**) is controlled by exaggeration factor **112**. In one embodiment, the distance of portion **404**B (FIG. **4**) is relative to the distance of portion **404**A between points **402**A and **402**B and exaggeration factor **112** (FIG. **1**) represents a ratio between the respective distances of portions **404**B (FIG. **4**) and **404**A. Similarly, the distance of a portion **404**C along function **404** between extrapolated point **406**B and point **402**B as determined by exaggerator **104** (FIG. **1**) is controlled by exaggeration factor **112** which represents a ratio between the respective distances of portions **404**C (FIG. **4**) and **404**A. In this illustrative embodiment, exaggeration factor **112** (FIG. **1**) is initialized in step **204** (FIG. **2**) to represent a ratio of 0.5 and is decreased in step **216**, as described more completely below, in decrements of 0.05. It is appreciated that other initial values and decrements for exaggeration factor **112** (FIG. **1**) can also provide relatively good results.

In step **308** (FIG. **3**), exaggerator **104** (FIG. **1**) performs the inverse of the transformation of step **302** (FIG. **3**) upon extrapolated points **406**A–B FIG. **4**) to form exaggerated sounds **106**A–B, respectively. As a result, exaggerated sound **106**A differs from sound **102**B more than sound **102**A differs from sound **102**B and, importantly, in generally the same way that sound **102**A differs from sound **102**B. In addition, exaggerated sound **106**B differs from sound **102**A more than sound **102**B differs from sound **102**A and in generally the same way that sound **102**B differs from sound **102**A.

Consider the example in which sounds **102**A–B are "rock" and "lock," respectively. Point **402**A (FIG. **4**) represents "rock" in coordinate space **400**, and point **402**B represents "lock" in coordinate space **400**. Extrapolated point **406**A is formed by extrapolation along function **404** from point **402**A in a direction away from point **402**B, and exaggerated sound **106**A is formed by performing an inverse transformation upon point **406**A. It is appreciated that exaggerated sound **106**A may sound very little lie "rock." However, exaggerated sound **106**A sounds more different from "lock" than does "rock" and sounds more different than "lock" in generally the same way that "rock" sounds different from "lock." Analogously, exaggerated sound **106**B is an exaggeration of "lock" and sounds more different from "rock" than does "lock" and sounds more different than "rock" in generally the same way that "lock" sounds different from "rock." Such is true even if exaggerated sound **106**B sounds very little like "lock."

The manner in which exaggerated sounds **106**A–B exaggerate differences between sounds **102**A–B is shown in FIG. **7**. Specifically, exaggerated sounds **106**A–B exaggerated the difference in spectral/temporal distribution of energy of sounds **102**A–B. In spectrograms **702**A–K, energy in the form of sonic amplitude is plotted along time and frequency axes. Amplitude is shown as darker areas within the axes of time and frequency. The time domain shown is 265 milliseconds in duration, and the range of frequencies shown is 0–5.5 kHz. Below each of spectrograms **702**A–K is an index identifying a point along function **400** (FIG. **4**). Spectrogram **702**D (FIG. **7**) has an index of 0.0 and represents sound **102**B, e.g., "lock" Spectrogram **702**H (FIG. **7**) has an index of 1.0 and represents sound **102**A, e.g., "rock." Spectrograms **702**E–G have indices between 0.0 and 1.0 and represent sounds interpolated between sounds **102**A–B. Spectrograms **702**D and **702**H show a difference in spectral/temporal energy distribution between sounds **102**A–B, namely, an energy peak **704**D which is relatively constant in frequency over time with only slight downward sweeping which is different from an energy peak **704**H which sweeps dramatically from low frequency to generally the same relatively high frequency of energy peak **704**D.

Exaggerated sound **106**A is represented by spectrogram **702**J, and exaggerated sound **106**B is represented by spectrogram **702**B. To exaggerate the difference between sounds **102**A–B, exaggerated sound **106**A has an energy peak **704**J which starts at a lower frequency than does energy peak **704**H and sweeps upward more dramatically, i.e., more quickly over time, that does energy peak **704**H. In addition, exaggerated sound **106**B has an energy peak **704**B which starts higher and sweeps downward more dramatically that does energy peak **704**D and therefore exaggerates the difference between sounds **102**A–B. Specifically, exaggerated sounds **106**A–B are formed by redistributing energy of sounds **102**A–B, respectively, in a spectra/temporal space as shown in spectrograms **702**A–K to emphasize differences between sounds **102**A–B.

The result is thus a pair **106** (FIG. **1**) of exaggerated sounds **106**A–B that differ from one another more than do sounds **102**A–B and in generally the same manner that sounds **102**A–B differ from one another. The fact that exaggerated sounds **106**A–B sound more different from one another than do sounds **102**A–B enables the listener to recognize and identify exaggerated sounds **106**A–B as distinct from one another. Such is so even if the listener is incapable of recognizing and identifying sounds **102**A–B as distinct from one another. The fact that exaggerated sounds **106**A–B differ from one another in generally the same way that sounds **102**A–B differ from one another leverages, from the listener's ability to recognize and identify exaggerated sounds **106**A–B, improvement in the listener's ability to recognize and identify sounds **102**A–B.

As described briefly above, vocal tract equivalent modeling transformations produce particularly good results. Vocal tract equivalent modeling transformations are known but are described herein briefly for completeness. Vocal tract equivalent modeling transformations approximate the shape of the vocal tract of a human speaker forming a particular sounds with discrete, joined tubes which are represented mathematically. Extrapolation of a vocal tract equivalent model for sound **102**A away from a vocal tract equivalent model for sound **102**B involves accentuating differences between such vocal tract equivalent models. The resulting extrapolation is itself a vocal tract equivalent model and therefore approximates the shape of a vocal tract. Vocal tract modeling produces sounds which are generally of the same order and properties as natural speech. Accordingly, the result of inverse transformation of the extrapolated vocal tract equivalent is frequently a sound that theoretically can be produced by a human speaker. Waveforms produced by inverse vocal tract equivalent modeling transformations tend

to have energy peaks in patterns and relations which are known to exist and are expected in oral speech. Thus, while exaggerated sounds **106**A–B can be artificial in that they are not representative of any sounds made in an actual spoken language, using vocal tract equivalent modeling transformation to form exaggerated sounds **106**A–B tends to ensure that exaggerated sounds **106**A–B still sound like human speech. Such assists the listener in distinguishing nuances of human speech and sounds more natural and pleasing to the listener.

Once exaggerator **104** forms exaggerated sounds **106**A–B in step **208** (FIG. **2**), processing transfers to loop step **210** which, in conjunction with continue step **214**, defines a loop in which tester **108** (FIG. **1**) repeatedly performs step **212** until the listener has demonstrated proficiency in recognizing and identifying exaggerated sounds **106**A–B (FIG. **1**). In step **212** (FIG. **2**), tester **108** (FIG. **1**) presents either of exaggerated sounds **106**A–B to the listener through a loudspeaker **120**B and receives response signals generated by the listener through physical manipulation of user input devices **130**A–B which identify one of exaggerated sounds **106**A–B. In one embodiment, tester **108** displays buttons **140**A–B in a computer display device **120**A and associates buttons **140**A–B with exaggerated sounds **106**A–B, respectively. Tester **108** plays one of exaggerated sounds **106**A–B though loudspeaker **120**B, and the listener identifies one of exaggerated sounds **106**A–B by clicking on one of buttons **140**A–B using conventional user interface techniques and physical manipulation of user input devices **130**A–B. If the sound identified by the user-generated signals is the sound presented by tester **108**, the listener has successfully recognized and identify the presented one of exaggerated sounds **106**A–B. If the sound identified by the user-generated signals is not the sound presented by tester **108**, the listener has failed to recognize and identify the presented one of exaggerated sounds **106**A–B.

Tester **108** can determine whether the listener has demonstrated proficiency in recognizing and identifying exaggerated sounds **106**A–B in a number of ways. In one embodiment, tester **108** determines that the listener has demonstrated such proficiency when the listener has responded correctly to 80% of thirty (30) consecutive sounds. In an alternative embodiment, tester **108** determines that the listener has demonstrated such proficiency when the listener has responded correctly to three (3) consecutive sounds. When the listener has demonstrated proficiency in distinguishing exaggerated sounds **106**A–B, processing transfers from loop step **210** (FIG. **2**) to step **216**.

In step **216**, tester **108** (FIG. **1**) decreases exaggeration factor **112**. Processing transfers from step **216** (FIG. **2**) through continue step **218** to loop step **206** in which steps **208**–**216** are repeated until exaggeration factor **112** (FIG. **1**) is less than zero. Accordingly, exaggerator **104** again forms exaggerated sounds **106**A–B from sounds **102**A–B in the manner described above with respect to logic flow diagram **208** (FIG. **3**) and FIG. **4**. However, since tester **108** (FIG. **1**) decreases exaggeration factor **112** in step **216** (FIG. **2**), exaggerated sounds **106**A–B are now a little closer to one another than they were in the previous iteration of the loop of steps **206**–**218** (FIG. **2**). Accordingly, the listener's ability to recognize and identify exaggerated sounds **106**A–B (FIG. **1**) is challenged to a greater degree and is therefore improved. In addition, exaggerated sounds **106**A–B are also a little closer to sounds **102**A–B, respectively. Therefore, as the listener develops the ability to distinguish sounds which are ever closer to sounds **102**A–B, the listener eventually develops the ability to distinguish sounds **102**A–B themselves.

FIG. **6** shows steps **210**A and **216**A of a logic flow diagram **200**A which is otherwise analogous to logic flow diagram **200** (FIG. **2**). Steps **210**A (FIG. **6**) and **216**A correspond to steps **210** (FIG. **2**) and **216** in an alternative embodiment of tester **108**. In loop step **210**A (FIG. **6**), tester **108** determines (i) whether the listener has demonstrated proficiency in recognizing and identifying exaggerated sounds **106**A–B (FIG. **1**) in the manner described above with respect to loop step **210** (FIG. **2**) or (ii) whether the listener is unable to recognize and identify exaggerated sounds **106**A–B (FIG. **1**) with exaggeration factor **112** at its current setting. In step **216**A (FIG. **6**), tester **108** (FIG. **1**) adjusts exaggeration factor **112** by an incremental amount. If the listener has demonstrated proficiency, tester **108** decrements exaggeration factor **112** in the manner described above with respect to step **216** (FIG. **2**). Conversely, if the listener has demonstrated inability, tester **108** FIG. **1**) increments exaggeration factor **112** by the incremental amount. Accordingly, the difference between exaggerated sounds **106**A–B is increased to make recognition and identification of exaggerated sounds **106**A–B a little easier for the listener and to avoid frustrating the listener.

In the final iteration of the loop of steps **206**–**218** (FIG. **2**), tester **108** (FIG. **1**) has decreased exaggeration factor **112** to zero such that exaggerated sounds **106**A–B are equivalent to sounds **102**A–B, respectively. When the listener demonstrated proficiency in recognizing and identifying exaggerated sounds **106**A–B in the loop of steps **210**–**214** (FIG. **2**), the listener has demonstrated proficiency in recognizing and identifying sounds **102**A–B (FIG. **1**) and tester **108** decreases exaggeration factor **112** to a value less than zero. Accordingly, the loop of steps **206**–**218** (FIG. **2**) and logic flow diagram **200** completes.

It should be noted that at the completion of logic flow diagram **200**, the listener has demonstrated proficiency in recognizing and identifying sounds **102**A–B (FIG. **1**) as distinct from one another which the listener could not do prior to commencement of processing according to logic flow diagram **200** (FIG. **2**). Of course, the training of the listener according to logic flow diagram **200** can be divided among several sessions over a period of multiple days so as to avoid exhausting the attention and stamina of the listener. In addition, processing of pair **102** (FIG. **1**) by trainer **100** can be concurrent and interleaved with processing by trainer **100** of other pairs in a directly analogous manner. For example, in one embodiment, tester **108** can test the listener's ability to recognize as distinct and identify exaggerated sounds corresponding to the pair of sounds "rock" and "lock" for a period of time and test the listener's ability to distinguish exaggerated sounds corresponding to a different pair of sounds before resuming training with respect to distinguishing "rock" and "lock."

Tester **108** can retrieve pair **102** and other pairs of similar sounds from a sound pair database **510** (FIG. **5**) which is described more completely below. In one embodiment, sounds of pairs stored in sound pair database **510** are stored in a transformed state and are represented by data specifying a transformed point in coordinate space **400** (FIG. **4**).

In addition, groups of pairs of sounds which are trained together can be organized according to the specific difference between sounds. For example, trainer **100** can intermingle training with respect to distinguishing sounds which differ only in the consonant "r" and the consonant "l." Trainer **100** can inter-mingle processing according to logic flow diagram **200** (FIG. **2**) of the pair of sounds "rock" and "lock" with processing according to logic flow diagram **200** of the following additional pairs of sounds, (i) "right" and

"light," (ii) "rake" and "lake," (iii) "rot" and "lot," and (iv) "rap" and "lap." In this illustrative embodiment, trainer **100** proceeds to pairs of sounds which differ from one another in ways other than the consonants "r" and "l" when the listener has shown proficiency in recognizing as distinct and identifying sounds of the "r/l" pairs listed above.

As described above, the tester **108** (FIG. **1**) tests the listener's ability to recognize exaggerated sounds **106**A–B as distinct from one another. In an alternative embodiment, tester **108** tests the listener's ability to recognize one of exaggerated sounds **106**A–B as distinct from a complementary one of sounds **102**A–B. For example, tester **108** tests the listener's ability to recognize exaggerated sound **106**A as distinct from sound **102**B and to recognize exaggerated sound **106**B as distinct from sound **102**A. In this embodiment, each of sounds **102**A–B serves as a reference sound to which to compare exaggerated sounds **106**B and **106**A, respectively. In the embodiment described further above, each of the exaggerated sound **106**A–B serves as a reference sound for the other of exaggerated sounds **106**A–B.

In addition, exaggerator **104** of trainer **100** can form exaggerated pair **106** with various degrees of exaggeration specified by exaggeration factor **112** and can store multiple instances of exaggerated pair **106** in an exaggerated sound database **110**. Accordingly, much of the processing required to form various instances of exaggerated pair **106** can be performed prior to the interacting testing of the listener by tester **108** in the manner described above. Tester **108** can retrieve a particular instance of exaggerated pair **106** corresponding to a particular degree of exaggeration represented by exaggeration factor **112** from exaggerated sound database **110**.

Further improvements in the listener's ability to comprehend a particular language can be realized by following training as described above with language comprehension training as described in co-pending U.S. patent application Ser. No. 08/982,189 filed Dec. 17, 1997, now U.S. Pat. No. 5,927,988 by William M. Jenkins et al. and entitled "Method and Apparatus for Training of Sensory And Perceptual Systems in LLI Subjects" and that description is incorporated herein by reference. Such language comprehension training can be subsequent to and/or concurrent with training to recognize and identify distinct sounds in the manner described above.

Filtering to Improve Exaggerated Sounds

As described above, results in improving the ability of the listener to recognize similar sounds as distinct are better if exaggerated sounds **106**A–B (FIG. **1**) sound like sounds made by human speech. In addition, the listener's overall experience with trainer **100** is more pleasant when exaggerated sounds **106**A–B seem more natural to the listener, as if exaggerated sounds **106**A–B were indeed spoken by a human being. While extrapolation using vocal tract modeling in the manner described above provides relatively natural sounding exaggerated sounds, further improvements can be made as shown in logic flow diagrams **306** (FIG. **8**) and **308** (FIG. **9**).

Logic flow diagram **306** (FIG. **8**) shows step **306** (FIG. **3**) in greater detail. Briefly, application of a smoothing filter to coefficients used in extrapolating along function **400** (FIG. **4**) in the manner described above produces smoother, more natural sounding exaggerated sounds. Specifically, trainer **100** (FIG. **1**) determines the particular coefficients by which extrapolation along function **404** (FIG. **4**) is to be performed in step **802** (FIG. **8**). In step **804**, trainer **100** (FIG. **1**) applies a smoothing filter to the extrapolation coefficients. In one embodiment, the smoothing filter is a five-point Hamming window smoothing filter. In step **806** (FIG. **8**), trainer **100** (FIG. **1**) uses the filtered extrapolation coefficients to determine extrapolated points **406**A–B (FIG. **4**) in the manner described above. As a result of filtering in step **804** (FIG. **8**), extreme, undesirable exaggerated sounds **106**A–B (FIG. **1**) are avoided. The result is that exaggerated sounds **106**A–B, which are determined from extrapolated points **406**A–B (FIG. **4**) in the manner described above, sound more natural.

Logic flow diagram **308** (FIG. **9**) shows step **308** (FIG. **3**) in greater detail. Briefly, application of a smoothing filter to coefficients used in performing the inverse transformation of extrapolated points **406**A–B (FIG. **4**) to form exaggerated sounds **106**A–B also makes exaggerated sounds **106**A–B more natural sounding. Specifically, trainer **100** (FIG. **1**) determines the particular coefficients used for such inverse transformation in step **902** (FIG. **9**). In step **904**, trainer **100** (FIG. **1**) filters the transformation coefficients using a smoothing filter. In one embodiment, the smoothing filter is a five-point Hamming window smoothing filter. Trainer **100** uses the filtered transformation coefficients to perform the inverse transformation of extrapolated points **406**A–B. (FIG. **4**) in step **906** (FIG. **9**). As a result of filtering the transformation coefficients in step **904** is that exaggerated sounds **106**A–B have a more smooth, natural sound. The result is pleasing to the listener and provides particularly good results in improving the listener's ability to recognize similar sounds as distinct from one another.

Good results can be achieved using the filtering of either of logic flow diagrams **306** (FIG. **8**) and **308** (FIG. **9**) alone or using the filtering of both logic flow diagram **306** (FIG. **8**) and **308** (FIG. **9**).

Implementation of Trainer **100** in a Computer System

Trainer **100** executes within a server computer **500** which is shown in FIG. **5**. Computer **500** includes a processor **502** and memory **504** which is coupled to processor **502** through an interconnect **506**. Interconnect **506** can be generally any interconnect mechanism for computer system components and can be, e.g., a bus, a crossbar, a mesh, a torus, or a hypercube. Processor **502** fetches from memory **504** computer instructions and executes the fetched computer instructions. In addition, processor **502** can fetch computer instructions through a computer network **570** through network access circuitry **560** such as a modem or ethernet network access circuitry. Processor **502** also reads data from and writes data to memory **504** and sends data and control signals through interconnect **506** to one or more computer display devices **120** and receives data and control signals through interconnect **506** from one or more computer user input devices **130** in accordance with fetched and executed computer instructions.

Memory **504** can include any type of computer memory and can include, without limitation, randomly accessible memory (RAM), read-only memory (ROM), and storage devices which include storage media such as magnetic and/or optical disks. Memory **504** includes trainer **100** which is all or part of one or more computer processes which in turn executes within processor **502** from memory **504**. A computer process is generally a collection of computer instructions and data which collectively define a task performed by computer **500**.

Each of computer display devices **120** can be any type of computer display device including without limitation a printer, a cathode ray tube (CRT), a light-emitting diode (LED) display, or a liquid crystal display (LCD). Each of computer display devices **120** receives from processor **502** control signals and data and, in response to such control

signals, displays the received data. Computer display devices **120**, and the control thereof by processor **502**, are conventional.

In addition, loudspeaker **120**B can be any loudspeaker and can include amplification and can be, for example, a pair of headphones. Loudspeaker **120**B receives sound signals from audio processing circuitry **580** and produces corresponding sound for presentation to the listener. Audio processing circuitry **580** receives control signals and data from processor **502** through interconnect **506** and, in response to such control signals, transforms the received data to a sound signal for presentation through loudspeaker **120**B.

Each of user input devices **130** can be any type of user input device including, without limitation, a keyboard, a numeric keypad, or a pointing device such as an electronic mouse, trackball, lightpen, touch-sensitive pad, digitizing tablet, thumb wheels, or joystick. Each of user input devices **130** generates signals in response to physical manipulation by the listener and transmits those signals through interconnect **506** to processor **502**.

As described above, trainer **100** executes within processor **502** from memory **504**. Specifically, processor **502** fetches computer instructions from trainer **100** and executes those computer instructions. Processor **502**, in executing trainer **100**, retrieves pair **102** from sound pair database **510**, forms exaggerated pair **106**, and tests a listener's ability to recognize and identify exaggerated sounds **106**A–B of exaggerated pair **106** in the manner described above.

The above description is illustrative only and is not limiting. The present invention is limited only by the claims which follow:

1. A method for training a listener to recognize and identify as distinct a first sound and a second sound, the method comprising:

forming an exaggerated sound by:

applying a transformation to the first sound to map the first sound to a first point in a coordinate space having one or more dimensions;

applying the transformation to the second sound to map the second sound to a second point in the coordinate space;

fitting a function between the first and second points in the coordinate space;

determining extrapolation coefficients for extrapolating along the function from the second point away from the first point by a distance to locate a third point in the coordinate space;

filtering the extrapolation coefficients to form filtered extrapolation coefficients;

extrapolating using the filtered extrapolation coefficients to determine the third point; and

applying an inverse of the transformation to the third point to form the exaggerated sound;

presenting one or more stimulus sounds to the listener wherein the stimulus sounds are each selected from a group consisting of the exaggerated sound and a reference sound which is representative of the first sound; and

receiving response signals generated by the listener which identify each of the stimulus sounds as a perceived one of the sounds of the group consisting of the exaggerated sound and the reference sound.

2. A method for training a listener to recognize and identify as distinct a first sound and a second sound, the method comprising:

forming an exaggerated sound by:

applying a transformation to the first sound to map the first sound to a first point in a coordinate space having one or more dimensions;

applying the transformation to the second sound to map the second sound to a second point in the coordinate space;

fitting a function between the first and second points in the coordinate space;

extrapolating along the function from the second point away from the first point by a distance to locate a third point in the coordinate space;

determining inverse transformation coefficients for transforming the third point to form the exaggerated sound;

filtering the inverse transformation coefficients to form filtered inverse transformation coefficients; and

applying an inverse of the transformation to the third point using the filtered inverse transformation coefficients to form the exaggerated sound;

presenting one or more stimulus sounds to the listener wherein the stimulus sounds are each selected from a group consisting of the exaggerated sound and a reference sound which is representative of the first sound; and

receiving response signals generated by the listener which identify each of the stimulus sounds as a perceived one of the sounds of the group consisting of the exaggerated sound and the reference sound.

3. The method of claim **2**, wherein extrapolating comprises:

determining extrapolation coefficients for extrapolating along the function from the second point away from the first point by a distance to locate a third point in the coordinate space;

filtering the extrapolation coefficients to form filtered extrapolation coefficients; and

extrapolating using the filtered extrapolation coefficients to determine the third point.

4. A computer readable medium usefull in association with a computer which includes a processor and a memory, the computer readable medium including computer instructions which are configured to cause the computer to train a listener to recognize and identify as distinct a first sound and a second sound by:

forming an exaggerated sound by:

applying a transformation to the first sound to map the first sound to a first point in a coordinate space having one or more dimensions;

applying the transformation to the second sound to map the second sound to a second point in the coordinate space;

fitting a function between the first and second points in the coordinate space;

determining extrapolation coefficients for extrapolating along the function from the second point away from the first point by a distance to locate a third point in the coordinate space;

filtering the extrapolation coefficients to form filtered extrapolation coefficients;

extrapolating using the filtered extrapolation coefficients to determine the third point; and

applying an inverse of the transformation to the third point to form the exaggerated sound;

presenting one or more stimulus sounds to the listener wherein the stimulus sounds are each selected from a group consisting of the exaggerated sound and a reference sound which is representative of the first sound; and

receiving response signals generated by the listener which identify each of the stimulus sounds as a perceived one

of the sounds of the group consisting of the exaggerated sound and the reference sound.

5. A computer readable medium useful in association with a computer which includes a processor and a memory, the computer readable medium including computer instructions which are configured to cause the computer to train a listener to recognize and identify as distinct a first sound and a second sound by:

forming an exaggerated sound by:

applying a transformation to the first sound to map the first sound to a first point in a coordinate space having one or more dimensions;

applying the transformation to the second sound to map the second sound to a second point in the coordinate space;

fitting a function between the first and second points in the coordinate space;

extrapolating along the function from the second point away from the first point by a distance to locate a third point in the coordinate space;

determining inverse transformation coefficients for transforming the third point to form the exaggerated sound;

filtering the inverse transformation coefficients to form filtered inverse transformation coefficients; and

applying an inverse of the transformation to the third point using the filtered inverse transformation coefficients to form the exaggerated sound;

presenting one or more stimulus sounds to the listener wherein the stimulus sounds are each selected from a group consisting of the exaggerated sound and a reference sound which is representative of the first sound; and

receiving response signals generated by the listener which identify each of the stimulus sounds as a perceived one of the sounds of the group consisting of the exaggerated sound and the reference sound.

6. The computer readable medium of claim **5** wherein extrapolating comprises:

determining extrapolation coefficients for extrapolating along the function from the second point away from the first point by a distance to locate a third point in the coordinate space;

filtering the extrapolation coefficients to form filtered extrapolation coefficients; and

extrapolating using the filtered extrapolation coefficients to determine the third point.

7. A computer system comprising:

a processor;

a memory operatively coupled to the processor; and

an authentication module (i) which executes in the processor from the memory and (ii) which, when executed by the processor, causes the computer to train a listener to recognize and identify as distinct a first sound and a second sound by:

forming an exaggerated sound by:

applying a transformation to the first sound to map the first sound to a first point in a coordinate space having one or more dimensions;

applying the transformation to the second sound to map the second sound to a second point in the coordinate space;

fitting a function between the first and second points in the coordinate space;

determining extrapolation coefficients for extrapolating along the function from the second point away from the first point by a distance to locate a third point in the coordinate space;

filtering the extrapolation coefficients to form filtered extrapolation coefficients;

extrapolating using the filtered extrapolation coefficients to determine the third point; and

applying an inverse of the transformation to the third point to form the exaggerated sound;

presenting one or more stimulus sounds to the listener wherein the stimulus sounds are each selected from a group consisting of the exaggerated sound and a reference sound which is representative of the first sound; and

receiving response signals generated by the listener which identify each of the stimulus sounds as a perceived one of the sounds of the group consisting of the exaggerated sound and the reference sound.

8. A computer system comprising:

a processor;

a memory operatively coupled to the processor; and

an authentication module (i) which executes in the processor from the memory and (ii) which, when executed by the processor, causes the computer to train a listener to recognize and identify as distinct a first sound and a second sound by:

forming an exaggerated sound by:

applying a transformation to the first sound to map the first sound to a first point in a coordinate space having one or more dimensions;

applying the transformation to the second sound to map the second sound to a second point in the coordinate space;

fitting a function between the first and second points in the coordinate space;

extrapolating along the function from the second point away from the first point by a distance to locate a third point in the coordinate space;

determining inverse transformation coefficients for transforming the third point to form the exaggerated sound;

filtering the inverse transformation coefficients to form filtered inverse transformation coefficients; and

applying an inverse of the transformation to the third point using the filtered inverse transformation coefficients to form the exaggerated sound;

presenting one or more stimulus sounds to the listener wherein the stimulus sounds are each selected from a group consisting of the exaggerated sound and a reference sound which is representative of the first sound; and

receiving response signals generated by the listener which identify each of the stimulus sounds as a perceived one of the sounds of the group consisting of the exaggerated sound and the reference sound.

9. The computer system of claim **8** wherein extrapolating comprises:

determining extrapolation coefficients for extrapolating along the function from the second point away from the first point by a distance to locate a third point in the coordinate space;

filtering the extrapolation coefficients to form filtered extrapolation coefficients; and

extrapolating using the filtered extrapolation coefficients to determine the third point.

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