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Research Article

Common Configurations of Real-Ear Aided Response Targets Prescribed by NAL-NL2 for Older Adults With Mild-to-Moderate Hearing Loss

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Purpose: This study investigates common real-ear aided response (REAR) configurations prescribed by the NAL-NL2 algorithm for older adults with hearing loss.
Method: A data set that is representative of the older adult U.S. population with mild-to-moderate sensorineural hearing loss was constructed from the audiometric data of 934 adults (aged 55–85 years) from the National Health and Nutrition Examination Survey years 1999–2012. Two clustering approaches were implemented to generate common REAR configurations for eight frequencies (0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz) at three input levels (55, 65, and 75 dB SPL). (a) In the REAR-based clustering approach, the National Health and Nutrition Examination Survey audiograms were first converted to REAR targets and then clustered to generate common REAR configurations. (b) In the audiogram-based clustering approach, the audiograms were first clustered into common hearing loss profiles and then converted to REAR configurations. The trade-off between the number of available REAR configurations and the percentage of the U.S. population whose hearing loss could be fit by at least one of them (i.e., percent coverage) was evaluated. Hearing loss fit was defined as less than ± 5-dB difference between an individual's REAR targets and those of the clustered REAR configuration.
Results: Percent coverage increases with the number of available REAR configurations, with four configurations resulting in 75% population coverage. Overall, REAR-based clustering yielded 5 percentage points better coverage on average compared to audiogram-based clustering.
Conclusions: The common REAR configurations can be used for programming the gain frequency responses in preconfigured over-the-counter hearing aids and provide clinically appropriate amplification settings for older adults with mild-to-moderate hearing loss.

Age-related hearing loss is a substantial national problem due to its high prevalence and significant psychosocial consequences (Lin, Niparko, & Ferricci, 2011; Lin et al., 2013; PCAST, 2015). However, the adoption rate of the primary intervention of age-related hearing loss, that is, hearing aids (HAs), is quite low (15%–30%; Chien & Lin, 2012; Lin, Thorpe, et al., 2011). HA adoption rates are even poorer for people with lower incomes and for racial and ethnic minorities (Bainbridge & Ramachandran, 2014). Surveys showed that 64% of people with hearing loss reported that HAs were unaffordable, and over 75% identified financial factors as a barrier toward adopting amplification (Kochkin, 2007). In recent years, over-the-counter (OTC) HAs have been gaining popularity. In 2010, approximately 1.5 million Americans (most of them older adults with lower incomes) purchased OTC amplification devices to compensate for their impaired hearing (Kochkin, 2010).

Although OTC HAs have been regarded as an important option for promoting accessible and affordable hearing health care (Kochkin, 2010; National Academies of Sciences, Engineering, and Medicine, 2016; PCAST, 2015), current OTC HAs have limitations that preclude them from becoming part of quality hearing health care. One of these limitations is that OTC HAs do not provide a customized gain frequency response, which is the amount of amplification provided by the device at different frequencies,

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to compensate for an individual's hearing loss. Traditionally, audiologists measure a patient's hearing loss at different frequencies (i.e., audiometry) and then use the audiometric information to customize HAs' gain frequency responses to ensure that patients obtain adequate audibility across frequencies while maintaining appropriate loudness and sound quality. Since OTC HAs are distributed using a direct-to-consumer service delivery model, no professional is available to individually optimize the devices' frequency responses.

To address this limitation, OTC HAs often either allow the user some amount of control over the configuring process via a computerized user interface or are preconfigured with a limited number of gain frequency response settings, enabling the user to arrive at an HA configuration without professional input. The methods for arriving at the OTC device's final configuration can generally be broken down into three categories: (a) the "in situ audiogram" approach, which seeks to program the devices according to an established audiological prescriptive formula based on an audiogram performed outside a professional setting or in situ through the device itself; (b) the "user-driven fine tuning" approach, which allows the user to adjust the gain frequency response of their device manually (e.g., "goldilocks" search and select approach, Mackersie, 2019; "Ear Machine," Nelson et al., 2018); and (c) the "preset" approach, which offers the user a fixed number of preconfigured HA settings to choose from. Although the first two approaches are promising, recent surveys suggest that between one third and one half of potential OTC device users are uncomfortable with assessing their hearing loss and adjusting their HAs' settings on their own (Edwards, 2020). OTC HAs that use the preset approach (i.e., preconfigured HAs) address these concerns because they do not require self-administration of any tests or self-adjustment of the HA gain frequency response and they do not require any additional equipment such as a smartphone or tablet. Preconfigured HAs may have predetermined gain frequency responses that are saved in different HA memories, and users can easily try out different presets by pushing a button on the device or on a remote control. Many OTC amplification devices currently available are preconfigured devices, but their gain frequency responses are poorly designed and not appropriate for most adults with hearing loss (Chan & McPherson, 2015; Cheng & McPherson, 2000). Recently, researchers have addressed this issue by using evidence-based methods for developing OTC HA presets that are appropriate for age-related hearing loss (Urbanski et al., 2019).

One approach to creating frequency responses for preconfigured HAs is to use audiometric data from common audiogram configurations. Ciletti and Flamme (2008) retrieved audiometric data from two large publicly available health data sets—the National Health and Nutrition Examination Survey (NHANES) and the Keokuk County Rural Health Study—in order to apply cluster analysis on the included audiograms to generate a representative set of common audiogram configurations that would be generalizable to the U.S. population. The premise of cluster analysis is to group individual sets of data points into clusters that share similar characteristics. Accordingly, the cluster analysis done by Ciletti and Flamme sorted all the audiograms from both databases into groups (i.e., clusters) of audiograms such that the audiograms within a cluster were more similar to each other than they were to the audiograms of another cluster. The results show that the predominant audiometric configurations were a gentle slope (13% of population) or a negligible slope (9%) with a tendency for more severe hearing thresholds for males than for females. These common audiogram configurations derived from the cluster analysis can be input into a prescriptive formula, such as the National Acoustics Laboratory's NAL-NL2 formula (Keidser et al., 2011), to produce real-ear aided response (REAR) prescriptive targets. The resulting REAR targets represent the sound levels, expressed in dB SPL, to be produced by an amplification device at different frequencies at the level of the eardrum. Several HA configurations that match the REAR targets corresponding to common audiogram loss profiles can be saved as presets in an OTC device so as to offer appropriate amplification settings for a significant percentage of the U.S. population.

This audiogram-based clustering approach has been supported by evidence from Humes et al. (2017), who conducted a placebo-controlled clinical trial that examined the effects of service delivery and purchase price on HA outcomes for a group of adults whose HAs were fit by established audiology best practices and a group of adults fit via a simulated OTC service delivery model. For the OTC model, study participants selected their own HA settings from among several preconfigured options. To simulate preconfigured OTC HAs, the three most common audiograms identified by Ciletti and Flamme (2008) were used to configure three different memory programs in a pair of HAs, and participants could switch between the three programs to select their preferred gain frequency response, which would be used in a subsequent field trial. During the field trial, participants had access to volume controls to make manual adjustments to the overall gain of their chosen preset. The primary outcome measures of the study, the Profile of Hearing Aid Performance (Cox & Gilmore, 1990), along with speech perception testing done with both traditional HAs and the simulated OTC devices, showed the preconfigured OTC HAs generated comparable outcomes compared to HAs fitted by professionals. This study indicates the feasibility of using common audiograms to program preconfigured OTC HAs.

Using the audiogram-based clustering approach to configure OTC HA presets, while simple in implementation, may not be the best approach in terms of ensuring optimal population coverage (i.e., the number of people whose hearing loss could be fit by at least one available preset's REAR configuration). This is because individuals with similar audiograms may end up with significantly different prescriptive REAR targets across frequencies. Consider the two audiograms and their respective NAL-NL2 REAR targets shown in Table 1. The table indicates that, although the second audiogram's threshold at 4 kHz was lower (better) than the first audiogram by 5 dB, the prescribed REAR target of the former is 4 dB higher than that of the latter.

Table 1. Two audiograms and their prescriptive real-ear aided response (REAR) targets.

Variable	250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
Hearing thresholds (dB HL)								
Audiogram 1	30	30	30	30	35	60	70	85
Audiogram 2	30	30	35	40	45	55	70	85
Difference (dB)	0	0	5	10	10	–5	0	0
REAR targets (dB SPL)								
Audiogram 1	56	63	59	66	69	71	63	60
Audiogram 2	58	62	62	72	75	75	68	65
Difference (dB)	2	–1	3	6	6	4	5	5

Note. The REAR targets were obtained from an Audioscan Verifit 1 with the following parameters: NAL-NL2 formula, age set to adult, transducer set to headphone, nontonal language, average uncomfortable level and real-ear-to-coupler difference, binaural set to no, and a 65-dB SPL speech signal. For each audiogram, the same thresholds were entered for the left and right ear.

Due to this nonlinear relationship between audiogram and REAR targets, population coverage for presets developed via the audiogram-based clustering method is expected to be lower than it would be if the same number of presets were developed through clustering REAR targets.

This article proposes an alternative method for generating preconfigured HA settings by (a) selecting a set of REAR configurations that are representative of older adults in the United States with mild-to-moderate hearing loss and (b) applying cluster analysis to select representative REAR configurations, which may be used as the basis for preconfigured presets for OTC devices (hereafter referred to as the "REAR-based clustering approach"). The first goal of this study was to generate the representative REAR clusters and then examine the trade-off between the number of available clusters and the percentage of the population that could be fit by the REAR targets of at least one cluster using a strict fitting criterion (i.e., difference no greater than ± 5 dB across frequencies between an individual's REAR targets and those of the cluster). The performance of REAR-based clustering versus audiogram-based clustering in terms of population coverage will also be examined. The second goal is to present REAR values as a function of the number of presets to provide researchers and device manufacturers with a framework for how to program the gain frequency response of a device's presets, depending on how many presets they choose to offer.

Method

Data from the NHANES were used for this study (National Center for Health Statistics, 2006). The NHANES data set is an ongoing survey conducted by the Centers for Disease Control and Prevention every 2 years that collects data on the health status of U.S. residents and is made available to the public. Households included in the data set are selected at random from neighborhoods defined in the most recent U.S. census data, and individual NHANES participants are randomly selected from among these households. NHANES includes audiometric data for a subset of participants, along with sampling weights to assess the generalizability of the audiometric results to the noninstitutionalized U.S. civilian population. The sampling weight refers to the degree to which the NHANES individual's data can be representative of the U.S. population. Audiometric testing was performed at 0.5, 1, 2, 3, 4, 6, and 8 kHz using either TDH 39 supra-aural headphones or Etymotic EarTone 3A insert earphones when the tester thought supra-aural earphones would likely lead to ear canal collapse. The testing was performed in a mobile sound booth with instruments calibrated according to ANSI S3.6 standards (American National Standards Institute, 1996).

Data from NHANES participants from years 1999 to 2012 who were between the ages of 55 and 85 years, had normal tympanograms, and had mild-to-moderate sensorineural hearing loss were included in this study. Specifically, the NHANES participants should have a pure-tone average of 0.5, 1, and 2 kHz at ≥ 25 and ≤ 55 dB HL with no threshold poorer than 75 dB HL from 0.5 to 6 kHz. Participants with both unilateral and bilateral hearing losses were included. For each included participant, the audiometric thresholds for seven frequency bands (0.5, 1, 2, 3, 4, 6, and 8 kHz) and sampling weight were obtained from the NHANES database. Thresholds at 250 Hz were not available from the NHANES database, and the 500-Hz thresholds were duplicated as 250-Hz thresholds, so each included ear then had eight audiometric thresholds. Each set of audiometric thresholds were input into the NAL-NL2 prescriptive formula via an Audioscan Verifit with age set to adult, transducer set to headphone, nontonal language, and average uncomfortable level and real-ear-to-coupler difference (RECD). Other fitting variables, such as HA styles and dome types, were not defined because they do not affect the prescribed REAR targets. For each included audiogram, REAR targets were obtained for 55–, 65–, and 75–dB SPL input levels. REAR targets are an appropriate choice for developing clusters of HA configurations because they are more widely used in clinical settings compared to other methods like insertion gain (Bentler et al., 2016).

A total of 934 NHANES audiograms met the inclusion criteria and were used in this study (636 unilateral loss and 298 bilateral loss). Each included audiogram was categorized by the type of amplification fitting possible: (a) unilateral loss–unilateral fitting (total of 636) data correspond to participants with mild-to-moderate hearing loss in only one ear (with the other ear's thresholds outside the inclusion criteria for this study) and REAR data for a unilateral HA fitting; (b) bilateral loss–unilateral fitting (total of 298) data represent participants with mild-to-moderate hearing loss in both ears and the choice of either a left or right single unilateral fitting; and (c) bilateral loss–bilateral fitting (total of 298) corresponds to participants with mild-to-moderate hearing loss in both ears and a bilateral HA fitting for both ears. For each category of HA fitting, there are associated REAR targets for eight frequencies (0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz) across three input levels (55, 65, and 75 dB SPL), for a total of 24 REAR data points per included ear. Therefore, a given participant may have up to 96 REAR data points, depending on their fitting category (i.e., 24 for unilateral loss, 48 per ear for bilateral loss).

A hierarchical agglomerative clustering algorithm (Arabie et al., 1996) was applied to the REAR data to generate clusters of REAR values with corresponding targets for eight frequency bands across three input levels. Each cluster represents a group of included NHANES participants' REAR values that share similar configurations. The clustering algorithm works by initially treating each individual's REAR targets as separate clusters. It then analyzes the differences between all existing clusters and combines clusters to form new groups whose individual members are similar to each other. Further rounds of combining clusters follow a programmed criterion of minimizing within-cluster variance and maximizing between-clusters variance. In this method of clustering, the algorithm is implemented for a target number of total clusters, n, such that when the algorithm groups individual sets of data points into n clusters, the algorithm terminates.

The clustering algorithm was implemented 20 times to produce a target number of total clusters, ranging from one to 20. Once the clustering algorithm reached the target number of clusters (e.g., five or 10 clusters), the included sets of REAR values in each cluster were used to calculate the mean REAR targets per frequency and input level to generate representative REAR configurations for the different input levels for each cluster. The mean REAR configurations were then compared to each NHANES participant's individual REAR targets to determine whether and to what level of goodness the person's hearing loss could be fit by each cluster mean. Goodness of fit was defined as a "loose fit" if an individual's REAR targets were within ± 5 dB across all eight frequencies only for the 65-dB input level and a "tight fit" if an individual's REAR targets were within ± 5 dB across all eight frequencies for all three input levels (55, 65, and 75 dB SPL) compared to the representative cluster REAR curves. For a person to be considered fit by a cluster, their individual REAR targets must be either a loose fit or a tight fit compared to the given cluster's mean REAR configurations for that person's specific HA fitting need (i.e., unilateral or bilateral fitting). For each individual who could be fit by a cluster, their NHANES sampling weight was included in determining the percentage of the older adult U.S. population with mild-to-moderate sensorineural hearing loss that could be fit by the mean REAR configurations of the available clusters (hereafter referred to as "percent coverage").

The clustering algorithm was similarly applied to the included NHANES participants' audiometric data to generate clusters of audiograms. Once the target number of audiogram clusters was reached (e.g., five or 10 clusters), the mean threshold values for eight audiometric frequencies (0.25, .5, 1, 2, 3, 4, 6, and 8 kHz) were computed to generate representative audiograms for each cluster. These representative audiograms were rounded to the nearest 5–dB HL increment and input into an Audioscan Verifit's NAL-NL2 prescriptive formula with the same parameters (age, transducer, nontonal, uncomfortable level, and RECD) used in the REAR-based method to generate REAR targets at three input levels (55, 65, and 75 dB SPL) for each cluster. The resulting REAR configurations from the audiogram-based clustering approach were compared to individual REAR data from the NHANES data set in a similar fashion to assess the goodness of fit for a given individual's hearing loss and HA fitting possibilities and to calculate percent population coverage.

Results

Figure 1 shows the relationship between the number of available clusters and the percent coverage for a loose fit (circles in Figure 1) and a tight fit (triangles) for the REAR-based clustering method. As the number of clusters increases, the percentage of the population that can be fit also increases, with the largest gains in coverage occurring between one and four clusters. With four available REAR-based clusters, 58% of the population can be covered with a tight fit, while 76% of the population can be covered by the less strict loose fit criteria of ± 5 dB only at average conversational sound level (65 dB SPL). Beyond four clusters, the increase in coverage for each additional cluster tapers, with smaller gains in coverage as the number of clusters increases. Figure 1 also shows percent coverage for the audiogram-based clustering method for loose fit (×s) and tight fit (squares). Coverage for audiogram-based clustering follows a similar pattern to the REAR-based method. On average, the REAR-based clustering approach yields a 5–percentage point better coverage across all target numbers of clusters than audiogram-based clustering.

The REAR configurations produced by the REAR-based clustering method for all implementations (target number of clusters from 1 to 20) are shown in Appendix A. An example of the mean REAR values generated for a clustering implementation target of 15 clusters is included in Table 2. At 15 clusters, 95% of the U.S. adult population between 55 and 85 years of age with mild-to-moderate sensorineural hearing loss can be covered with a loose fit, while 82% of the same population can be covered with a tight fit by at least one available cluster's REAR configuration.

Figure 1. Percent coverage as a function of number of available real-ear aided response (REAR) clusters for a tight fit (within ± 5 dB across eight frequencies at 55–, 65–, and 75–dB SPL input levels) and a loose fit (within ± 5 dB across eight frequencies at only 65–dB SPL input level) for REAR-based and audiogram-based clustering methods.

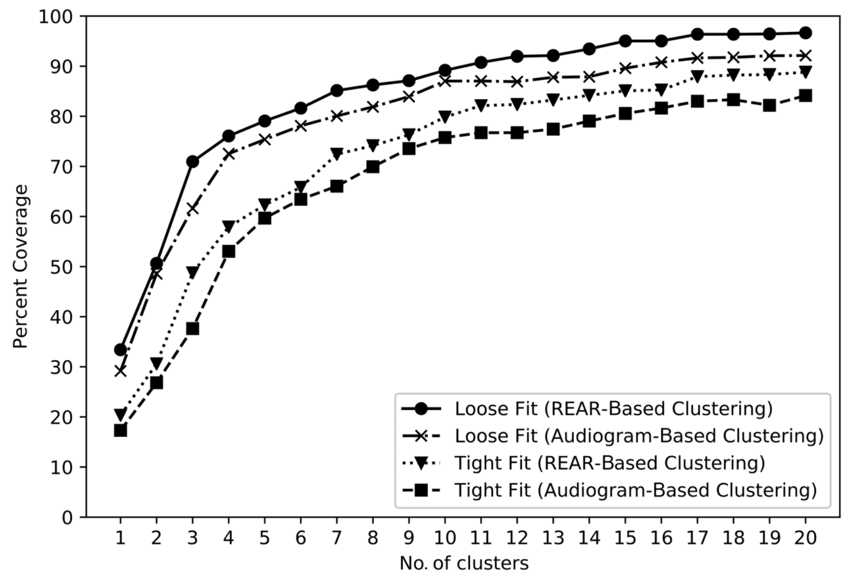


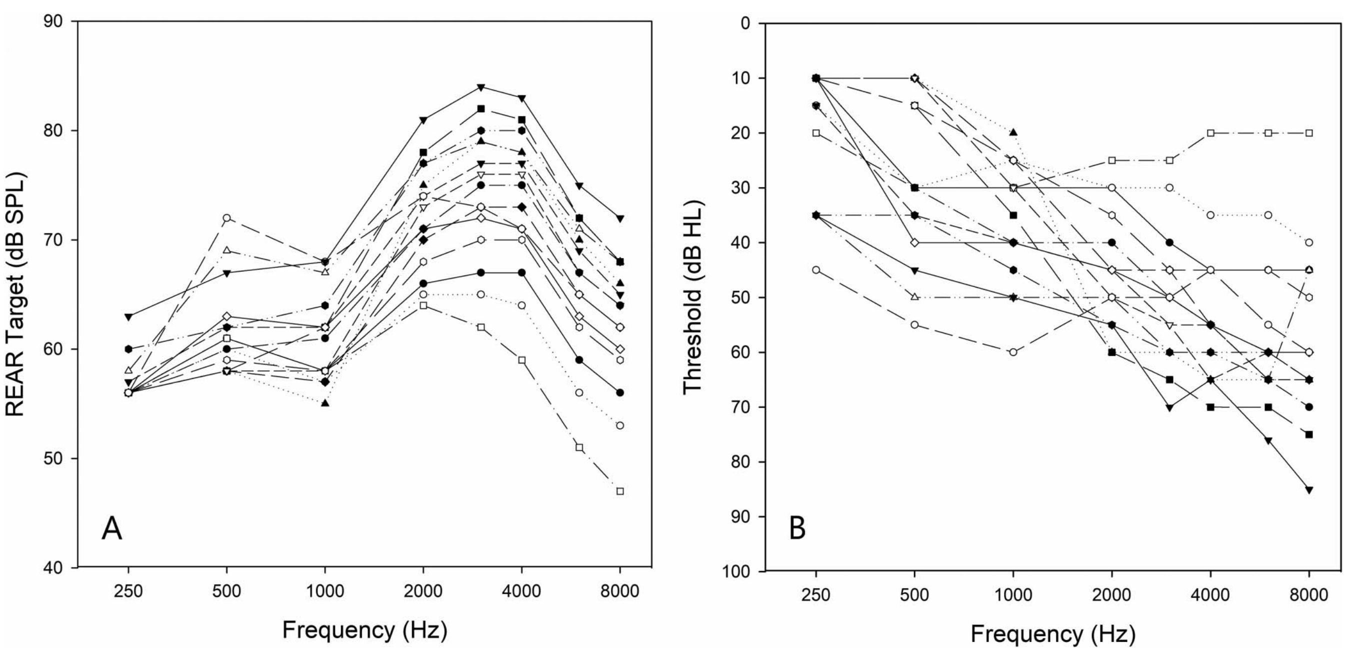
Figure 2 shows the 65-dB input-level REAR curves for the 15 example clusters reported in Table 2, and Figure 2 shows an example of 15 audiograms that would generate near-identical (within ± 1-dB deviation) REAR targets compared to the 15 example REAR clusters shown in Table 2 if the audiograms were input into a Verifit using the NAL-NL2 prescriptive formula with averaged RECD.

While all subset NHANES audiograms are included in the clustering process, not all of them can ultimately be considered fit by the loose or tight fit criteria outlined in this article. For the 15 example REAR-based clusters reported, 32 audiograms (out of 934 total) could not be fit by either fitting criteria. An analysis of the NHANES sampling weights for these audiograms indicates that they account for 5% of older adults in the United States with mild-to-moderate sensorineural hearing loss. These audiograms generally fall into five configurations: (a) "rising" (31.25% of audiograms unable to be fit) with poorer low frequency thresholds rising to normal or mild loss thresholds; (b) "reverse cookie bite" (25%) with poorer low-frequency thresholds rising to normal or mild loss thresholds in mid frequencies and sloping again to poorer high-frequency thresholds; (c) "flat moderately severe" (18.75%) where thresholds across all frequencies are relatively flat and fall between

Table 2. Mean cluster real-ear aided response (REAR) targets at three input levels (55, 65, and 75 dB SPL) produced by REAR-based clustering for an implementation target of 15 total clusters.

Cluster no.	REAR targets for 3 input levels (55/65/75 dB SPL)							
	250 Hz	500 Hz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
1	46/56/60	54/61/67	52/58/69	60/66/76	61/67/76	60/67/78	53/59/63	49/56/58
2	46/56/60	53/60/66	50/57/68	58/65/75	59/65/75	58/64/76	49/56/60	45/53/55
3	49/57/60	57/62/66	57/62/72	70/74/83	72/77/85	71/77/87	63/69/72	59/65/66
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	46/56/60	50/58/66	50/57/68	65/70/80	69/73/81	68/73/83	60/65/68	56/62/63
8	47/56/60	58/63/67	56/62/71	66/71/80	66/72/80	65/71/81	58/63/66	54/60/61
9	46/56/60	48/58/66	48/55/66	70/75/84	74/79/86	74/78/88	64/70/72	60/66/66
10	46/56/60	49/58/66	52/58/68	68/73/82	72/76/84	71/76/85	62/67/70	58/64/64
11	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
12	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
13	47/56/60	55/60/66	55/61/71	66/71/81	70/75/83	69/75/85	61/67/70	57/64/64
14	46/56/60	66/72/75	63/68/76	69/74/83	68/73/82	66/71/82	59/65/68	56/62/63
15	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

Figure 2. (A) Real-ear aided response (REAR) curves for 65 dB SPL input level for the 15 example clusters reported in Table 2. (B) Audiograms that would generate near-identical (within ± 1-dB deviation) REAR targets compared to the 15 example cluster mean REAR configurations shown in Table 2 if the audiograms were input into a Verifit using the NAL-NL2 prescriptive formula with averaged real-ear-to-coupler difference.



55 and 75 dB HL; (d) "steeply sloping" (12.5%) with better low-frequency thresholds and a steep slope to poorer high-frequency thresholds; and (e) "cookie bite" (12.5%) with better low-frequency thresholds sloping to poorer thresholds at mid frequencies and rising again to better high-frequency thresholds. Examples of audiogram configurations that cannot be fit by the 15 reported example REAR configurations are shown in Figure 3 (see Appendix B for full list).

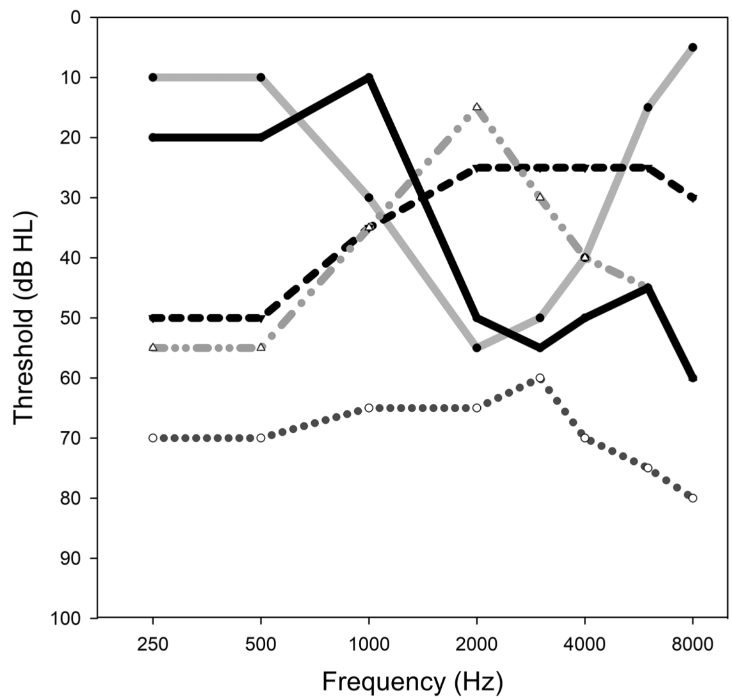
Discussion

While increasing the number of REAR configurations used to program OTC HA presets may achieve better coverage across the population, it would also increase both the difficulty and the time requirements of the preset selection process. For example, if presented with a device with four available presets to choose from, a potential user can switch between the four presets and listen to the way each preset processes sound to decide which one they prefer. Such a device with four presets that are based on the reported REAR-based clustering configurations may offer at least one acceptable amplification setting for more than 75% of the population (based on loose fit criteria). A device with 15 presets could undoubtedly reach a broader range of people and with stricter fit criteria (i.e., tight fit), but choosing a preferred preset from among the 15 would be far more time-consuming and may be unreasonably difficult without the help of specialized selection algorithms to help narrow down the available options. Increasing the number of presets beyond 20 approaches the level of a customized HA fitting, and preconfigured presets may not be the most efficient programming method. Further research is needed to investigate the relationship between the number of available presets and the time or cognitive strain required for the selection process and to develop efficient selection algorithms and user interfaces for use with high numbers of clusters. Additionally, further research is necessary to determine how many and which presets are perceivably different. Offering high numbers of presets may be inadvisable if the end user cannot perceive a difference between many of them.

Although REAR-based clustering yielded better coverage results than audiogram-based clustering (see Figure 1), it is important to note that, in the process of computing coverage for audiogram clustering, cluster mean audiograms were input into the Verifit's implementation of the NAL-NL2 prescriptive formula. The Verifit limits audiometric input to 5-dB steps, so the representative audiograms from clustering had to be rounded to the nearest 5-dB increment. This could negatively impact the resulting coverage calculations for audiogram-based clustering. Additionally, the generalizability of the REAR-based clustering approach proposed in this article is limited to the use of the NAL-NL2 prescriptive formula. An important advantage of audiogram-based clustering is that the resulting representative audiograms can be input into whichever prescriptive formula the researcher or developer chooses.

To implement the REAR clusters developed by this study, a manufacturer could configure each of their OTC

Figure 3. Examples of audiograms that cannot be fit based on loose fit or tight fit criteria by the 15 reported example clusters (i.e., the difference between the individual's real-ear aided response [REAR] targets and the mean of the cluster REAR targets is not within ± 5 dB across all frequencies). Audiogram configurations generally fall within the following types: (a) rising, (b) reverse cookie bite, (c) flat moderately severe, (d) steeply sloping, and (e) cookie bite.



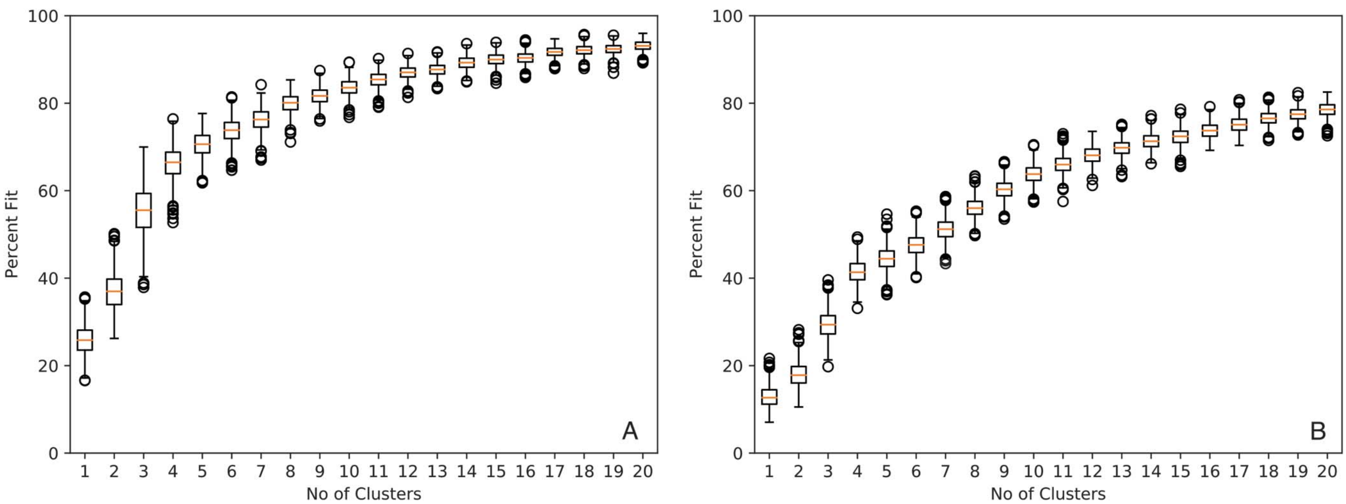
HA presets to generate an aided response on a manikin's ear (e.g., KEMAR: Knowles Electronics Manikin for Acoustic Research) that matches the corresponding cluster mean REAR targets according to the total number of presets the device will offer. However, if an end user chooses a different method of coupling (e.g., open vs. closed domes) than the coupling used by the manufacturer to configure the device, the actual REAR in the user's ear could be different than what was measured on the manikin. This inconsistency in coupling method could render an otherwise appropriate HA preset unusable. Another factor that could affect the actual REAR on the user's ear is if their RECD differs significantly from the average adult RECD used to develop the REAR clusters. See below for more discussion about RECD. Regardless of the method used to program an OTC device (e.g., in situ audiogram, user-driven fine tuning, or presets), a continued limitation of all OTC devices is the aided response in the end user's ear would likely remain unknown and unverified without a professional's input. Additionally, the configurations of audiograms that could not be fit by the 15 reported example clusters fall into categories for which an OTC device and its associated coupling concerns would likely not be appropriate. While increasing the number of available presets beyond 15 may offer REAR configurations that could theoretically fit less common hearing losses (e.g., rising, reverse cookie bite, flat moderately severe, steeply sloping, and cookie bite), individuals with these types of hearing losses would benefit from the input of a professional who can combine both a customized gain frequency response with earmold coupling considerations to achieve appropriate audibility across the frequency spectrum and to resolve any HA feedback concerns.

An analysis of the shape of the mean REAR curves from clustering reveals that, in lower frequencies (250–1000 Hz), there is comparatively less variation in targets across clusters compared to high frequencies. For the 15 example clusters reported, the average variation of REAR values across three input levels for 250–1000 Hz is between 6 and 14 dB, while the variation of REAR targets at 3–8 kHz is 21–25 dB. This suggests that the primary driver of differences in amplification needs for older adults lies in the amount of high-frequency gain needed. An OTC device designed to allow for greater numbers of presets would require greater precision and flexibility in its programming for higher frequency bands than for low-frequency bands, and this may influence the design of certain signal processing parameters like filter cutoffs and center frequencies.

Limitations

First, actual percent coverage may be lower than reported in this study due to differences between the set of REAR targets from clustering and the ability of a given

Figure 4. Ranges of percent coverage as a function of number of available clusters where each cluster went through 1,000 simulations of ± 2 dB added random noise to cluster mean real-ear aided response (REAR) targets to simulate differences between desired cluster REAR targets and real-world hearing aid programming limitations. (A) Coverage according to loose fit criteria (difference between individual's REAR targets and cluster mean REAR targets within ± 5 dB across all frequencies at the 65 dB SPL input level). (B) Coverage according to strong fit criteria (difference within ± 5 dB across all frequencies at 55–, 65–, and 75–dB SPL input levels).



device to be programmed to match those targets. In the real world, HAs with limited gain frequency response programming flexibility may be unable to match targets accurately and would add significant error to the reported coverage estimates. To simulate the possible differences between desired cluster REAR targets and the gain frequency response limitations of a real-world device, random noise of ± 2 dB was added to the cluster mean REAR values of each cluster, and percent coverage was recalculated. For each implementation of the clustering algorithm (target number of clusters from one to 20), this added noise simulation was run 1,000 times, and the resulting ranges of population coverage are shown in Figures 4A (loose fit criteria) and 4B (tight fit criteria). Results show that mean coverage estimates with added noise simulations are between 8 and 14 percentage points lower than when coverage is calculated purely based on clustered mean REAR targets. Fewer numbers of clusters also yielded significantly more variability in percent coverage estimates. This suggests that, in the real world, a device may require additional REAR configurations to achieve population coverage comparable to what is reported in this article.

Second, both clustering approaches (REAR-based and audiogram-based) used in this study used averaged adult RECD values as an input parameter for the NAL-NL2 prescription formula because the NHANES database did not include RECD information for individual participants. Variations in the size and shape of a person's ear canals change the frequency response at the level of the eardrum and would therefore require frequency-specific corrections to be applied to the REAR targets to account for this variation. Including individual RECD values with the audiometric data used for clustering would yield more accurate representative clusters for both clustering methods, but the issue of an unknown RECD for the end user would remain and would affect the goodness of fit regardless of the method used for programming the device unless the device itself and some sort of user interface could guide the user through measuring their own RECD. Third, the implementation of the NAL-NL2 algorithm in the Verifit system includes specific limitations not found in other manufacturers' implementations or in the full version of the NAL-NL2 software. For example, the Verifit system does not account for gender or HA experience when determining REAR targets for a given hearing loss. The Verifit was chosen to simulate a common clinical setting for an HA fitting; however, a different implementation of the NAL-NL2 formula may yield different results.

Finally, the data set used to generate representative REAR clusters was also used to calculate percent coverage, and the reported coverage may therefore be overestimating the percentage of the U.S. population that can be fit by these clusters. In future research, a more robust validation method would be to compare cluster REAR values to those generated by audiometric data from different data sets or from a broader range of included years of NHANES data.

Conclusion

The results of this study indicate that a clustering approach to generating presets for an OTC HA can offer at least one appropriate gain frequency response setting for large percentages of the older adult U.S. population with mild-to-moderate sensorineural hearing loss. A device with four presets based on the reported REAR configurations can provide a clinically appropriate HA fitting for 75% of this population, while a device with 15 available presets can cover up to 95%. Increasing the number of available configurations can lead to greater population coverage with stricter HA fitting criteria. Overall, REAR-based clustering yielded 5 percentage points better coverage, on average, compared to audiogram-based clustering.

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Appendix A (p. 1 of 6)

Tables of Real-Ear Aided Response (REAR) Targets for Eight Frequencies (0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz) at Each of Three Input Levels (55, 65, and 75 dB SPL) for Each Cluster for All Implementations of the Clustering Algorithm (From Cluster No. 1 to Cluster No. 20)

1 Cluster

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	48/57/60	54/61/66	54/60/70	66/71/81	69/74/82	68/73/84	59/65/68	55/62/63

2 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/61/67	51/58/69	59/65/76	59/65/75	57/64/76	49/56/61	46/53/55
2	48/57/60	54/61/66	55/60/70	68/73/82	71/76/84	70/76/86	62/68/70	58/64/65

3 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/61/67	51/58/69	59/65/76	59/65/75	57/64/76	49/56/61	46/53/55
2	51/58/60	57/62/67	59/63/72	72/77/86	75/80/87	74/79/89	65/71/74	61/68/68
3	46/56/60	52/59/66	52/58/69	66/71/80	68/73/81	68/73/83	59/65/68	56/62/63

4 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/61/67	51/58/69	59/65/76	59/65/75	57/64/76	49/56/61	46/53/55
2	51/58/60	57/62/67	59/63/72	72/77/86	75/80/87	74/79/89	65/71/74	61/68/68
3	46/56/60	51/58/66	52/58/68	67/72/81	71/75/83	70/75/85	61/67/70	57/64/64
4	46/56/60	54/61/66	53/59/70	64/69/79	66/71/79	65/70/81	57/63/66	53/60/61

5 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/61/67	51/58/69	59/65/76	59/65/75	57/64/76	49/56/61	46/53/55
2	50/58/60	56/61/66	58/63/72	72/76/85	74/79/87	73/79/89	65/71/73	61/67/68
3	46/56/60	51/58/66	52/58/68	67/72/81	71/75/83	70/75/85	61/67/70	57/64/64
4	46/56/60	54/61/66	53/59/70	64/69/79	66/71/79	65/70/81	57/63/66	53/60/61
5	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

6 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/60/66	51/58/69	59/65/76	60/66/76	59/65/77	51/58/62	48/55/57
2	50/58/60	56/61/66	58/63/72	72/76/85	74/79/87	73/79/89	65/71/73	61/67/68
3	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
4	46/56/60	51/58/66	52/58/68	67/72/81	71/75/83	70/75/85	61/67/70	57/64/64
5	46/56/60	54/61/66	53/59/70	64/69/79	66/71/79	65/70/81	57/63/66	53/60/61
6	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

(*table continues*)

Appendix A (p. 2 of 6)

Tables of Real-Ear Aided Response (REAR) Targets for Eight Frequencies (0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz) at Each of Three Input Levels (55, 65, and 75 dB SPL) for Each Cluster for All Implementations of the Clustering Algorithm (From Cluster No. 1 to Cluster No. 20)

7 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/60/66	51/58/69	59/65/76	60/66/76	59/65/77	51/58/62	48/55/57
2	50/58/60	56/61/66	58/63/72	72/76/85	74/79/87	73/79/89	65/71/73	61/67/68
3	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
4	46/56/60	51/58/66	52/58/68	67/72/81	71/75/83	70/75/85	61/67/70	57/64/64
5	47/56/60	59/64/68	57/63/72	67/71/81	67/72/80	65/71/81	58/63/66	54/60/62
6	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
7	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

8 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/60/66	51/58/69	59/65/76	60/66/76	59/65/77	51/58/62	48/55/57
2	49/57/60	57/62/66	57/62/72	70/74/83	72/77/85	71/77/87	63/69/72	59/65/66
3	51/58/60	56/61/66	58/63/72	73/78/87	75/80/88	74/80/90	66/72/74	62/68/69
4	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
5	46/56/60	51/58/66	52/58/68	67/72/81	71/75/83	70/75/85	61/67/70	57/64/64
6	47/56/60	59/64/68	57/63/72	67/71/81	67/72/80	65/71/81	58/63/66	54/60/62
7	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
8	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

9 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/60/66	51/58/69	59/65/76	60/66/76	59/65/77	51/58/62	48/55/57
2	49/57/60	57/62/66	57/62/72	70/74/83	72/77/85	71/77/87	63/69/72	59/65/66
3	51/58/60	56/61/66	58/63/72	73/78/87	75/80/88	74/80/90	66/72/74	62/68/69
4	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
5	47/56/60	52/59/66	53/59/69	66/71/80	69/74/82	69/74/84	60/66/69	57/63/64
6	47/56/60	59/64/68	57/63/72	67/71/81	67/72/80	65/71/81	58/63/66	54/60/62
7	46/56/60	48/58/66	50/57/67	69/74/83	73/77/85	72/77/86	63/68/71	59/65/65
8	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
9	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

10 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/60/66	51/58/69	59/65/76	60/66/76	59/65/77	51/58/62	48/55/57
2	49/57/60	57/62/66	57/62/72	70/74/83	72/77/85	71/77/87	63/69/72	59/65/66
3	52/60/60	59/64/67	60/64/73	73/77/86	75/80/87	74/79/89	66/71/74	62/68/69
4	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
5	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
6	47/56/60	52/59/66	53/59/69	66/71/80	69/74/82	69/74/84	60/66/69	57/63/64
7	47/56/60	59/64/68	57/63/72	67/71/81	67/72/80	65/71/81	58/63/66	54/60/62
8	46/56/60	48/58/66	50/57/67	69/74/83	73/77/85	72/77/86	63/68/71	59/65/65
9	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
10	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

(*table continues*)

Appendix A (p. 3 of 6)

Tables of Real-Ear Aided Response (REAR) Targets for Eight Frequencies (0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz) at Each of Three Input Levels (55, 65, and 75 dB SPL) for Each Cluster for All Implementations of the Clustering Algorithm (From Cluster No. 1 to Cluster No. 20)

11 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/60/66	51/58/69	59/65/76	60/66/76	59/65/77	51/58/62	48/55/57
2	49/57/60	57/62/66	57/62/72	70/74/83	72/77/85	71/77/87	63/69/72	59/65/66
3	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
4	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
5	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
6	47/56/60	52/59/66	53/59/69	66/71/80	69/74/82	69/74/84	60/66/69	57/63/64
7	47/56/60	59/64/68	57/63/72	67/71/81	67/72/80	65/71/81	58/63/66	54/60/62
8	46/56/60	48/58/66	50/57/67	69/74/83	73/77/85	72/77/86	63/68/71	59/65/65
9	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
10	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
11	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

12 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/61/67	52/58/69	60/66/76	61/67/76	60/67/78	53/59/63	49/56/58
2	46/56/60	53/60/66	50/57/68	58/65/75	59/65/75	58/64/76	49/56/60	45/53/55
3	49/57/60	57/62/66	57/62/72	70/74/83	72/77/85	71/77/87	63/69/72	59/65/66
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	47/56/60	52/59/66	53/59/69	66/71/80	69/74/82	69/74/84	60/66/69	57/63/64
8	47/56/60	59/64/68	57/63/72	67/71/81	67/72/80	65/71/81	58/63/66	54/60/62
9	46/56/60	48/58/66	50/57/67	69/74/83	73/77/85	72/77/86	63/68/71	59/65/65
10	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
11	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
12	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

13 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/61/67	52/58/69	60/66/76	61/67/76	60/67/78	53/59/63	49/56/58
2	46/56/60	53/60/66	50/57/68	58/65/75	59/65/75	58/64/76	49/56/60	45/53/55
3	49/57/60	57/62/66	57/62/72	70/74/83	72/77/85	71/77/87	63/69/72	59/65/66
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	46/56/60	50/58/66	50/57/68	65/70/80	69/73/81	68/73/83	60/65/68	56/62/63
8	47/56/60	59/64/68	57/63/72	67/71/81	67/72/80	65/71/81	58/63/66	54/60/62
9	46/56/60	48/58/66	50/57/67	69/74/83	73/77/85	72/77/86	63/68/71	59/65/65
10	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
11	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
12	47/56/60	55/60/66	55/61/71	66/71/81	70/75/83	69/75/85	61/67/70	57/64/64
13	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

(*table continues*)

Appendix A (p. 4 of 6)

Tables of Real-Ear Aided Response (REAR) Targets for Eight Frequencies (0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz) at Each of Three Input Levels (55, 65, and 75 dB SPL) for Each Cluster for All Implementations of the Clustering Algorithm (From Cluster No. 1 to Cluster No. 20)

14 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/61/67	52/58/69	60/66/76	61/67/76	60/67/78	53/59/63	49/56/58
2	46/56/60	53/60/66	50/57/68	58/65/75	59/65/75	58/64/76	49/56/60	45/53/55
3	49/57/60	57/62/66	57/62/72	70/74/83	72/77/85	71/77/87	63/69/72	59/65/66
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	46/56/60	50/58/66	50/57/68	65/70/80	69/73/81	68/73/83	60/65/68	56/62/63
8	47/56/60	58/63/67	56/62/71	66/71/80	66/72/80	65/71/81	58/63/66	54/60/61
9	46/56/60	48/58/66	50/57/67	69/74/83	73/77/85	72/77/86	63/68/71	59/65/65
10	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
11	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
12	47/56/60	55/60/66	55/61/71	66/71/81	70/75/83	69/75/85	61/67/70	57/64/64
13	46/56/60	66/72/75	63/68/76	69/74/83	68/73/82	66/71/82	59/65/68	56/62/63
14	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

15 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/61/67	52/58/69	60/66/76	61/67/76	60/67/78	53/59/63	49/56/58
2	46/56/60	53/60/66	50/57/68	58/65/75	59/65/75	58/64/76	49/56/60	45/53/55
3	49/57/60	57/62/66	57/62/72	70/74/83	72/77/85	71/77/87	63/69/72	59/65/66
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	46/56/60	50/58/66	50/57/68	65/70/80	69/73/81	68/73/83	60/65/68	56/62/63
8	47/56/60	58/63/67	56/62/71	66/71/80	66/72/80	65/71/81	58/63/66	54/60/61
9	46/56/60	48/58/66	48/55/66	70/75/84	74/79/86	74/78/88	64/70/72	60/66/66
10	46/56/60	49/58/66	52/58/68	68/73/82	72/76/84	71/76/85	62/67/70	58/64/64
11	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
12	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
13	47/56/60	55/60/66	55/61/71	66/71/81	70/75/83	69/75/85	61/67/70	57/64/64
14	46/56/60	66/72/75	63/68/76	69/74/83	68/73/82	66/71/82	59/65/68	56/62/63
15	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

16 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	54/61/67	52/58/69	60/66/76	61/67/76	60/67/78	53/59/63	49/56/58
2	46/56/60	53/60/66	50/57/68	58/65/75	59/65/75	58/64/76	49/56/60	45/53/55
3	46/56/60	59/64/67	58/63/72	68/73/82	71/76/85	71/77/87	63/69/72	60/66/67
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	46/56/60	50/58/66	50/57/68	65/70/80	69/73/81	68/73/83	60/65/68	56/62/63
8	47/56/60	58/63/67	56/62/71	66/71/80	66/72/80	65/71/81	58/63/66	54/60/61
9	46/56/60	48/58/66	48/55/66	70/75/84	74/79/86	74/78/88	64/70/72	60/66/66
10	46/56/60	49/58/66	52/58/68	68/73/82	72/76/84	71/76/85	62/67/70	58/64/64
11	51/58/60	55/60/66	57/62/71	71/75/84	72/77/85	71/76/86	63/68/71	59/65/65
12	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
13	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
14	47/56/60	55/60/66	55/61/71	66/71/81	70/75/83	69/75/85	61/67/70	57/64/64
15	46/56/60	66/72/75	63/68/76	69/74/83	68/73/82	66/71/82	59/65/68	56/62/63
16	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

(*table continues*)

Appendix A (p. 5 of 6)

Tables of Real-Ear Aided Response (REAR) Targets for Eight Frequencies (0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz) at Each of Three Input Levels (55, 65, and 75 dB SPL) for Each Cluster for All Implementations of the Clustering Algorithm (From Cluster No. 1 to Cluster No. 20)

17 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	53/60/66	51/58/69	60/66/76	61/67/76	61/67/78	53/59/63	49/56/58
2	46/56/60	53/60/66	50/57/68	58/65/75	59/65/75	58/64/76	49/56/60	45/53/55
3	46/56/60	59/64/67	58/63/72	68/73/82	71/76/85	71/77/87	63/69/72	60/66/67
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	46/56/60	50/58/66	50/57/68	65/70/80	69/73/81	68/73/83	60/65/68	56/62/63
8	47/56/60	58/63/67	56/62/71	66/71/80	66/72/80	65/71/81	58/63/66	54/60/61
9	46/56/60	48/58/66	48/55/66	70/75/84	74/79/86	74/78/88	64/70/72	60/66/66
10	46/56/60	49/58/66	52/58/68	68/73/82	72/76/84	71/76/85	62/67/70	58/64/64
11	46/56/60	60/67/72	57/63/73	62/67/77	60/66/76	59/65/77	52/58/62	49/56/58
12	51/58/60	55/60/66	57/62/71	71/75/84	72/77/85	71/76/86	63/68/71	59/65/65
13	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
14	46/56/60	52/59/66	51/58/68	62/68/78	65/70/79	65/70/81	57/62/65	53/59/60
15	47/56/60	55/60/66	55/61/71	66/71/81	70/75/83	69/75/85	61/67/70	57/64/64
16	46/56/60	66/72/75	63/68/76	69/74/83	68/73/82	66/71/82	59/65/68	56/62/63
17	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

18 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	53/60/66	51/58/69	60/66/76	61/67/76	61/67/78	53/59/63	49/56/58
2	46/56/60	53/60/66	50/57/68	58/65/75	59/65/75	58/64/76	49/56/60	45/53/55
3	46/56/60	59/64/67	58/63/72	68/73/82	71/76/85	71/77/87	63/69/72	60/66/67
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	49/56/60	51/58/65	56/62/71	73/78/88	76/82/90	75/81/91	66/72/75	62/68/69
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	46/56/60	50/58/66	50/57/68	65/70/80	69/73/81	68/73/83	60/65/68	56/62/63
8	47/56/60	58/63/67	56/62/71	66/71/80	66/72/80	65/71/81	58/63/66	54/60/61
9	46/56/60	48/58/66	48/55/66	70/75/84	74/79/86	74/78/88	64/70/72	60/66/66
10	46/56/60	49/58/66	52/58/68	68/73/82	72/76/84	71/76/85	62/67/70	58/64/64
11	46/56/60	60/67/72	57/63/73	62/67/77	60/66/76	59/65/77	52/58/62	49/56/58
12	51/58/60	55/60/66	57/62/71	71/75/84	72/77/85	71/76/86	63/68/71	59/65/65
13	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
14	46/56/60	55/61/66	52/59/70	61/66/77	65/70/79	65/71/82	57/63/66	53/60/61
15	47/56/60	55/60/66	55/61/71	66/71/81	70/75/83	69/75/85	61/67/70	57/64/64
16	46/56/60	50/58/66	50/57/68	63/68/78	65/70/79	65/70/80	56/62/65	52/59/60
17	46/56/60	66/72/75	63/68/76	69/74/83	68/73/82	66/71/82	59/65/68	56/62/63
18	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

(*table continues*)

Appendix A (p. 6 of 6)

Tables of Real-Ear Aided Response (REAR) Targets for Eight Frequencies (0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz) at Each of Three Input Levels (55, 65, and 75 dB SPL) for Each Cluster for All Implementations of the Clustering Algorithm (From Cluster No. 1 to Cluster No. 20)

19 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	53/60/66	51/58/69	60/66/76	61/67/76	61/67/78	53/59/63	49/56/58
2	46/56/60	53/60/66	50/57/68	58/65/75	59/65/75	58/64/76	49/56/60	45/53/55
3	46/56/60	59/64/67	58/63/72	68/73/82	71/76/85	71/77/87	63/69/72	60/66/67
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	47/56/60	50/58/65	55/60/70	72/77/87	76/81/89	74/80/90	65/71/74	61/67/68
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	46/56/60	50/58/66	50/57/68	65/70/80	69/73/81	68/73/83	60/65/68	56/62/63
8	47/56/60	58/63/67	56/62/71	66/71/80	66/72/80	65/71/81	58/63/66	54/60/61
9	46/56/60	48/58/66	48/55/66	70/75/84	74/79/86	74/78/88	64/70/72	60/66/66
10	46/56/60	49/58/66	52/58/68	68/73/82	72/76/84	71/76/85	62/67/70	58/64/64
11	46/56/60	60/67/72	57/63/73	62/67/77	60/66/76	59/65/77	52/58/62	49/56/58
12	51/58/60	55/60/66	57/62/71	71/75/84	72/77/85	71/76/86	63/68/71	59/65/65
13	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
14	46/56/60	55/61/66	52/59/70	61/66/77	65/70/79	65/71/82	57/63/66	53/60/61
15	47/56/60	55/60/66	55/61/71	66/71/81	70/75/83	69/75/85	61/67/70	57/64/64
16	46/56/60	50/58/66	50/57/68	63/68/78	65/70/79	65/70/80	56/62/65	52/59/60
17	51/57/60	53/59/66	58/63/72	75/80/89	78/83/91	76/82/92	67/73/76	63/69/70
18	46/56/60	66/72/75	63/68/76	69/74/83	68/73/82	66/71/82	59/65/68	56/62/63
19	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

20 Clusters

	REAR targets for 3 input levels (55/65/75 dB SPL)							
Cluster no.	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
1	46/56/60	53/60/66	51/58/69	60/66/76	61/67/76	61/67/78	53/59/63	49/56/58
2	47/56/60	51/59/66	49/56/68	60/66/77	60/66/76	59/65/76	50/57/61	45/53/55
3	46/56/60	59/64/67	58/63/72	68/73/82	71/76/85	71/77/87	63/69/72	60/66/67
4	48/58/61	66/69/71	64/67/75	73/77/85	74/79/86	73/78/88	65/71/73	62/68/68
5	47/56/60	50/58/65	55/60/70	72/77/87	76/81/89	74/80/90	65/71/74	61/67/68
6	47/56/60	54/61/67	51/58/70	57/64/75	55/62/73	52/59/72	43/51/56	38/47/50
7	46/56/60	50/58/66	50/57/68	65/70/80	69/73/81	68/73/83	60/65/68	56/62/63
8	47/56/60	58/63/67	56/62/71	66/71/80	66/72/80	65/71/81	58/63/66	54/60/61
9	46/56/60	48/58/66	48/55/66	70/75/84	74/79/86	74/78/88	64/70/72	60/66/66
10	46/56/60	49/58/66	52/58/68	68/73/82	72/76/84	71/76/85	62/67/70	58/64/64
11	46/56/60	60/67/72	57/63/73	62/67/77	60/66/76	59/65/77	52/58/62	49/56/58
12	51/58/60	55/60/66	57/62/71	71/75/84	72/77/85	71/76/86	63/68/71	59/65/65
13	46/56/60	56/62/67	50/58/69	56/62/74	57/64/74	56/63/75	48/55/60	45/52/55
14	53/60/60	57/62/66	59/64/72	73/77/86	75/80/88	74/80/90	66/72/74	62/68/69
15	46/56/60	55/61/66	52/59/70	61/66/77	65/70/79	65/71/82	57/63/66	53/60/61
16	47/56/60	55/60/66	55/61/71	66/71/81	70/75/83	69/75/85	61/67/70	57/64/64
17	46/56/60	50/58/66	50/57/68	63/68/78	65/70/79	65/70/80	56/62/65	52/59/60
18	51/57/60	53/59/66	58/63/72	75/80/89	78/83/91	76/82/92	67/73/76	63/69/70
19	46/56/60	66/72/75	63/68/76	69/74/83	68/73/82	66/71/82	59/65/68	56/62/63
20	56/63/63	64/67/69	64/68/76	77/81/90	79/84/92	78/83/93	69/75/78	65/72/73

Appendix B

Table of Audiograms That Cannot Be Fit by Either the Loose Fit or Tight Fit Criteria by the 15 Reported Example Real-Ear Aided Response (REAR) Configurations from REAR-Based Clustering

250 Hz	500 Hz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
10	10	30	55	50	40	15	5
15	15	15	55	55	50	15	10
20	20	45	45	30	20	20	45
15	15	35	40	45	55	30	25
50	50	35	45	40	65	60	70
55	55	45	65	60	60	65	80
60	60	50	45	50	55	75	100
55	55	50	50	70	75	75	75
50	50	45	60	55	65	70	75
70	70	65	65	60	70	75	80
50	50	35	30	30	35	55	75
45	45	25	10	15	20	15	25
40	40	40	30	15	20	30	70
65	65	45	40	30	30	45	70
50	50	35	25	25	25	25	30
45	45	50	70	25	15	20	25
45	45	30	35	30	20	25	65
40	40	20	15	10	10	25	40
55	55	40	25	40	15	25	40
45	45	40	30	20	20	25	20
40	40	45	50	35	35	20	25
70	70	50	15	–5	–5	35	40
55	55	35	15	30	40	45	60
55	55	40	25	20	30	50	65
50	50	35	30	20	20	40	80
50	50	35	15	15	50	70	75
45	45	30	45	15	30	45	55
55	55	40	45	30	30	45	60
20	20	10	50	55	50	45	60
20	20	5	50	55	60	75	80
10	10	15	55	50	55	30	30
15	15	15	45	40	45	40	40