

A Digital Filter-Based Method for Diagnosing Speech Comprehension Deficits

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Abstract

Objective: To improve the diagnostic efficiency of current tests for auditory processing disorders (APDs) by creating new test signals using digital filtering methods.

Methods: We conducted a prospective study from August 1, 2014, to August 31, 2019, using 3 low speech redundancy tests with novel test signals that we created with specially designed digital filters: the binaural resynthesis test and the low pass and high pass filtered speech tests. We validated and optimized these new tests, then applied them to healthy individuals across different age groups to examine how age affected performance and to children with APD before and after acoustically controlled auditory training (ACAT) to assess clinical improvement after treatment.

Results: We found a progressive increase in performance accuracy with less restrictive filters ($P < .001$) and with increasing age for all tests ($P < .001$). Our results suggest that binaural resynthesis and auditory closure mature at similar rates. We also demonstrate that the new tests can be used for the diagnosis of APD and for the monitoring of ACAT effects. Interestingly, we found that patients having the most severe deficits also benefited the most from ACAT ($P < .001$).

Conclusion: We introduce a method that substantially improves current diagnostic tools for APD. In addition, we provide information on auditory processing maturation in normal development and validate that our method can detect APD-related deficits and ACAT-induced improvements in auditory processing.

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Normal speech comprehension requires the central nervous system to constantly reconstruct meaningful messages from corrupted auditory signals, a capacity known as auditory processing.¹⁻³ Auditory processing disorders (APDs) are defined by a consistent misunderstanding of auditory information without clear neurologic damage, intellectual disability, or peripheral hearing loss.^{1,2} This term is broadly applied to symptoms that may have different etiologic underpinnings according to the patient and clinical setting.¹ Around 3% of children and 70% of elderly people exhibit these disorders, which can lead to severe impairments in learning, speech, attention, and memory.⁴⁻⁷

Auditory processing disorder is traditionally diagnosed by acoustically controlled hearing tests, such as the filtered speech tests (FSTs) and the binaural resynthesis test (BRT). They force the central nervous system to reconstruct a verbal message by reducing

information redundancy in speech signals using filtering.^{1,4,7-19} FSTs assess auditory closure (AC),^{1,8-14} which is the ability to reconstruct an acoustic message when part of its frequency range is removed; the BRT^{1,9,18} evaluates the ability to synthesize partial, simultaneous, and complementary information presented for both ears.

Auditory processing disorders can be treated by acoustically controlled auditory training (ACAT), a therapeutic protocol that consists of auditory stimuli presentations with progressively increasing difficulty while associating them with visual stimuli and executive function tasks.^{1,20-27} It is thought to induce neuroplasticity in the central auditory system, improving speech comprehension.^{1,4,23,24} FSTs and BRT have been used to compare patients with APD with healthy controls but not to evaluate their recovery after ACAT.^{10,28-30} In these cases, these tests were found to have low diagnostic sensitivity. For

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example, Musiek et al³⁰ found only an 11% difference in low pass filtered speech test (LPFST) between controls and patients with APD and 12% difference in BRT, and it had less than 20% diagnostic accuracy.

One major limitation of current FSTs likely to be partially responsible for their limited diagnostic power is that they have nearly always relied on analog filters, which results in residual acoustic information in the filtered signals. This preserved information reduces the efficiency of the test, potentially leading to diagnostic errors.^{9,28-31} In the English-language analog filtering LPFST, the maximal attenuation is 20 dB at 1 kHz, 40 dB at 2.4 kHz, and 60 dB above 4.5 kHz⁹; and in the Brazilian Portuguese LPFST, the maximum achieved attenuation is 24 dB above 0.8 kHz.^{3,32} Because of the technical limitations of analog filters, it is impossible to increase attenuation without causing phase distortion or harmonic misalignments.^{15,17,30,33,34}

The BRT, on the other hand, evaluates the effectiveness of binaural resynthesis (BR).^{1,3,18} A test voice signal is divided into 2 frequency bands (low and high) that by themselves are unintelligible but when heard, one in each ear simultaneously, must be intelligible in healthy individuals.^{9,18} Analog filtering, because of residual acoustic cues, results in a redundancy of bands presented separately for each ear, which also reduces the diagnostic efficiency of the test.^{30,31,33,34}

We reasoned that we could improve the efficacy of FSTs by applying digital filters to construct the test speech signals. Digital filtering can efficiently attenuate the desired speech frequency bands, without phase distortion or temporal misalignment, therefore allowing less redundant test signals.²⁴⁻²⁷ Here we report that using digital filtering, we achieved attenuation above 80 dB (a more than 3-fold improvement in relation to analog methods) without phase distortion or harmonic misalignment. We tested our novel method for the generation of FSTs and BRT test signals on healthy individuals distributed across different age groups and on a group of children with impaired speech comprehension, a symptom of APD, before and after ACAT.

METHODS

Participants or their parents when they were minors were instructed on the study and signed

an informed consent form. We excluded individuals with complaints suggestive of previous otorhinolaryngologic, neurologic, or psychological problems, with audiometric thresholds greater than 25 dB, with monosyllabic speech recognition below 92%, and with immittance alterations. For the tests with healthy participants, we also excluded individuals with APD, as assessed by anamnesis and audiologic tests. This study was approved by the Research Ethics Committee of the Federal University of Pará (03107912.4.0000.00180 and 03688912.0.0000.5172) and was conducted from August 1, 2014, to August 31, 2019.

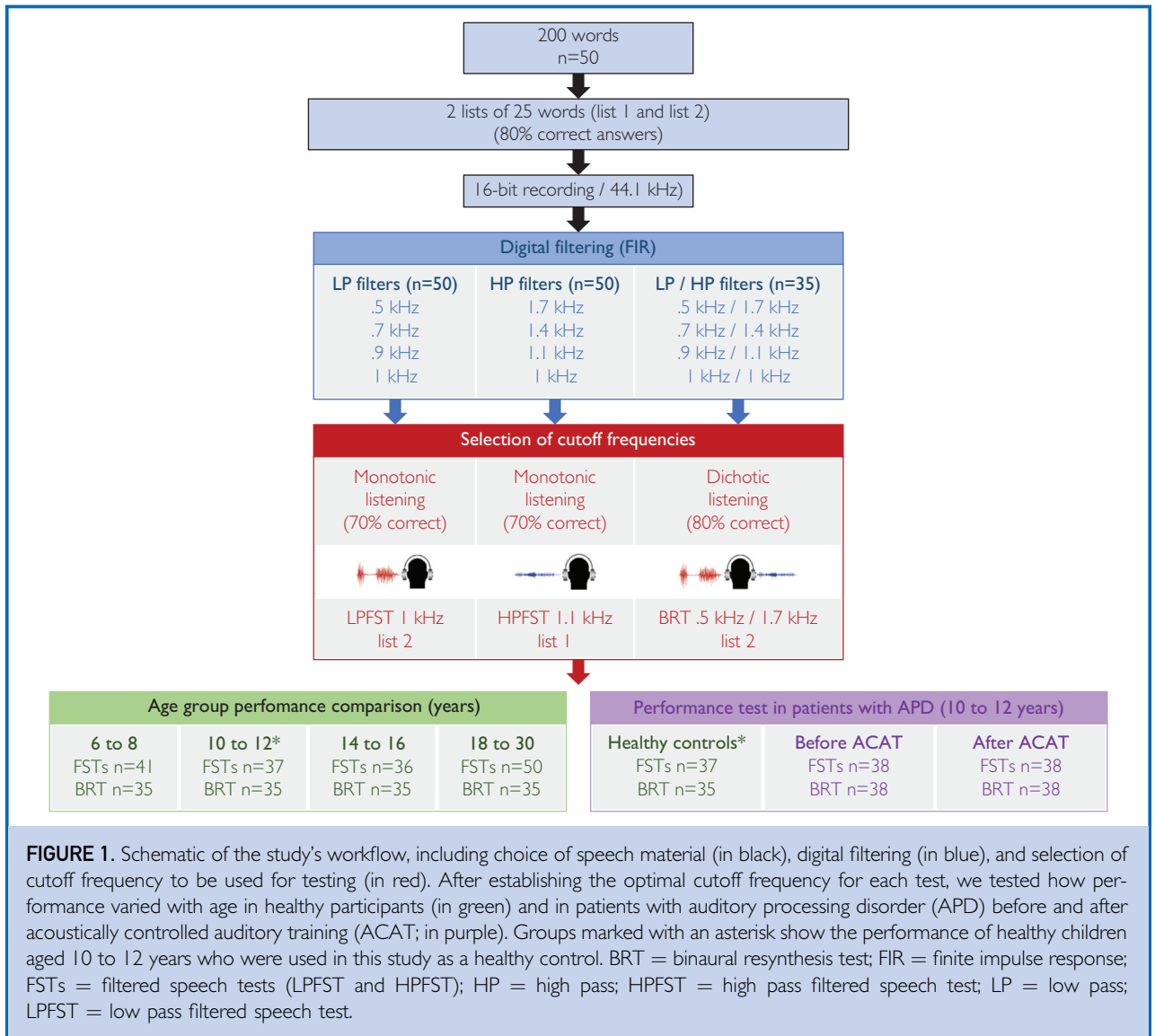
Speech Material for FSTs and BRT

The material was comprised of 200 Brazilian Portuguese³⁵ words with 2 or 3 syllables pre-selected and dictated by a healthy individual for a group of 50 literate children between 8 and 10 years old (24 boys and 26 girls). During dictation, the signal was between 15 and 20 dB above ambient noise. The 50 words with more than 80% correct answers in dictated writing were chosen to form the speech material (Supplemental Table, available online at <http://www.mayoclinicproceedings.org>).

Digital Filtering and Recording

The selected words were separated into two 25-word lists, list 1 (L1) and list 2 (L2). These were recorded in a soundproof studio with a professional microphone at 44.1 kHz/16 bits and filtered (both high pass [HP] and low pass [LP]) with Hamming window finite impulse response digital filters, with double filtering of 2048 orders, one from the beginning to end and the other from the end to beginning, corresponding to a 4096 orders null phase filter with 80 dB attenuation. This was applied to effectively reduce any perceived acoustic residues above the cutoff frequency for LP filters and below the cutoff frequency for HP filters (Figures 1 and 2).

The cutoff frequencies of the LP filters were 0.5, 0.7, 0.9, 1.0, and 1.4 kHz; for the HP filters, they were 1.7, 1.4, 1.1, 1.0, and 0.9 kHz (Figure 2). The interval between the filtered test words was set at 6 seconds. Words in each list were randomized to avoid any learning bias. Routines for filtering and



recording the test signals were developed in MATLAB (R2014a; MathWorks).

FSTs Cutoff Frequency Selection

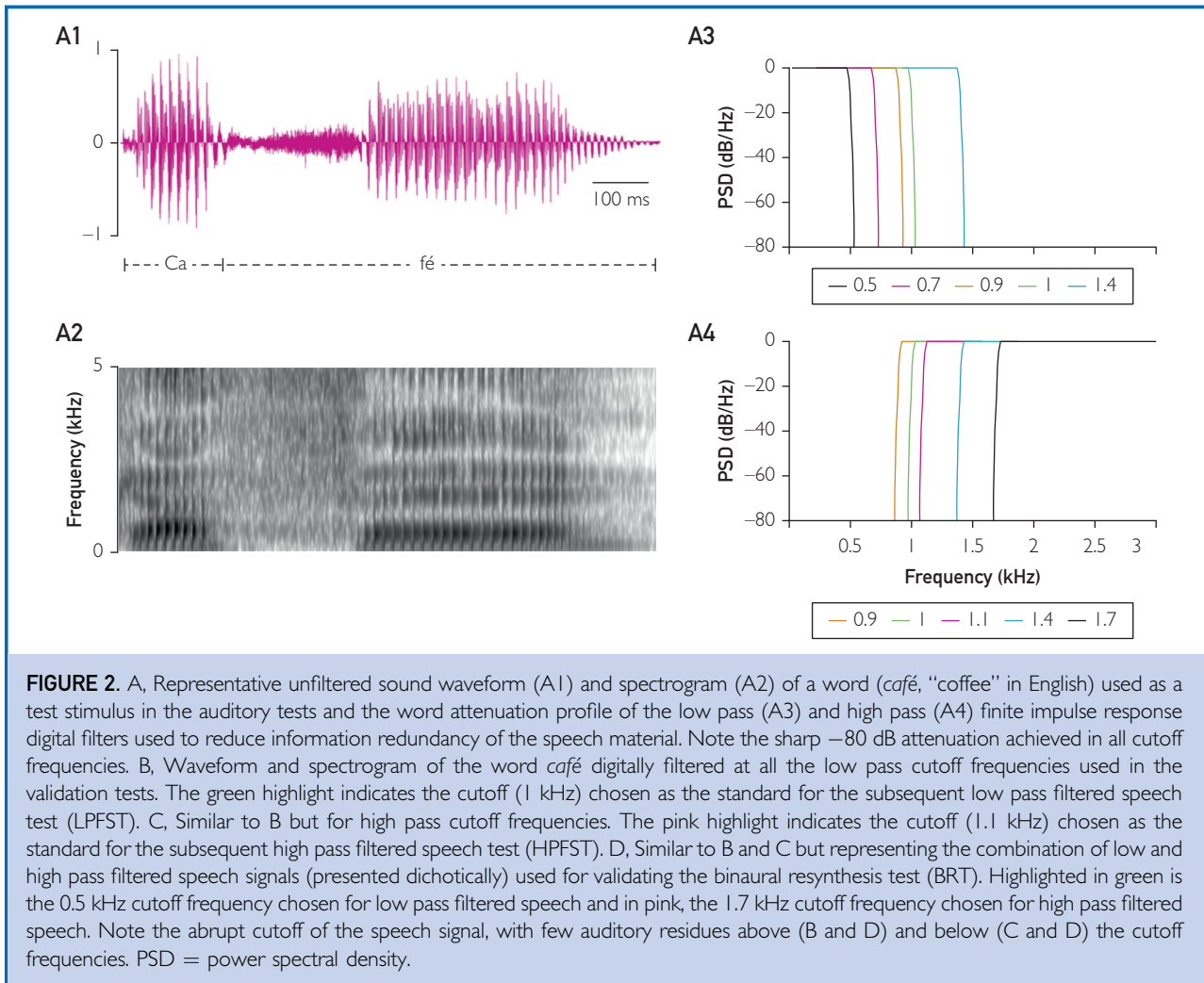
Recorded L1 and L2 were reproduced on a 2-channel audiometer and presented monotonically (filtered speech heard in one ear) in an acoustic booth with a headset calibrated to the specifications of the American National Standards Institute (ANSI 3.1-1991) to 50 healthy individuals (18 men and 32 women) ranging in age from 18 to 30 years. The display intensity was 30 dB above the 3-tonal average for the LPFST and 40 dB

above the 3-tonal average for the high pass filtered speech test (HPFST).

Participants were instructed to write what they understood from L1 and L2, first with HP filtering, then followed by LP filtering, at all cutoff frequencies for each and finally without any filtering. On the basis of this, the FST intelligibility percentage for each cutoff frequency was established, with 70% (moderate execution difficulty) set as the standard threshold of normal AC performance³² (Figure 2).

BRT Cutoff Frequency Selection

L1 and L2 were reproduced on a 2-channel audiometer and presented dichotically



(different auditory information presented in each ear) to 35 healthy individuals (10 men and 25 women) between 18 and 30 years of age who also wrote what they understood from the heard material.

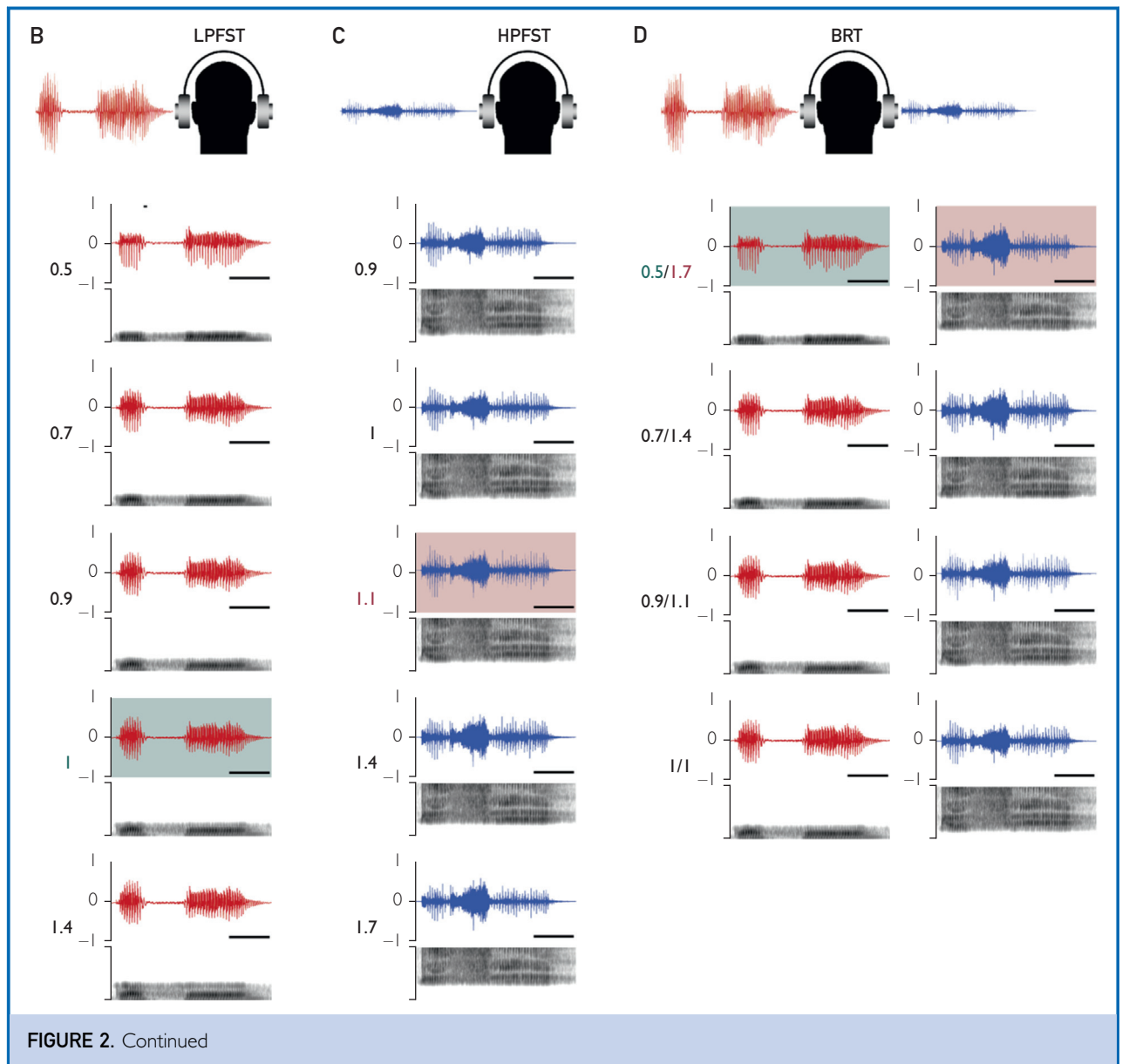
LP-filtered L1 words were presented in the right ear simultaneously with their HP-filtered counterparts in the left ear. The cutoff frequencies used were LP 0.5 kHz and HP 1.7 kHz, LP 0.7 kHz and HP 1.4 kHz, LP 0.9 kHz and HP 1.1 kHz, and LP 1 kHz and HP 1 kHz (Figure 2). Participants then heard the unfiltered signals. The same procedure was adopted for L2. The diagnostic standard for distinguishing effective BR capabilities was set at 80% correct answers (moderate execution difficulty)^{1,32} (Figure 2).

Test Performance by Age Group

After establishing the optimal cutoff frequency for each test, we tested how performance varied with age in healthy participants. We tested 164 individuals on the FSTs and 140 individuals on the BRT, divided in the following 4 age groups (Figure 1): 6 to 8 years (FSTs, $n=41$; BRT, $n=35$), 10 to 12 years (FSTs, $n=37$; BRT, $n=35$), 14 to 16 years (FSTs, $n=36$; BRT, $n=35$), and 18 to 30 years (FSTs, $n=50$; BRT $n=35$). Tests were performed under the same conditions used in the selection of frequencies.

Test Performance in Patients With APD Before and After ACAT

We tested 38 children (27 boys and 11 girls), aged 10 to 12 years and previously diagnosed



with an APD, on the LPFST, HPFST, and BRT procedures before and after rehabilitation with ACAT. The ACAT was conducted in 12 intensive and personalized sessions, as described previously.^{1,36-40} Auditory processing behavioral tests, including the tests proposed in this paper, were applied 15 to 30 days after ACAT treatment. The results obtained before and after ACAT were compared with the healthy 10- to 12-year age group in the

previously described experiment, which served as a control group (Figure 1).

Statistical Analyses

Because data distribution in most groups was non-Gaussian (Shapiro-Wilk test), comparisons between performances with different cutoff frequencies were performed with the Friedman test and Dunn multiple comparisons tests. The Kruskal-Wallis test was used

to compare test performance at different age groups. The Wilcoxon matched pairs signed rank test was used to compare performance in patients with APD before and after ACAT, and the Mann-Whitney test was used to compare the patients with the control group. Spearman correlation coefficient (r) was used to assess correlations between variables, and linear regressions were used to compare these

associations across groups. Statistical significance threshold was set at $P < .05$, and analyses were performed using GraphPad Prism (GraphPad Software Inc).

RESULTS

We found higher percentages of correct responses with less restrictive cutoff frequencies for both lists in all tests ($P < .001$) (Figure 3). Multiple comparison tests did not reveal performance differences in LP (Figure 3A) and HP (Figure 3B) AC between immediately adjacent tested cutoff frequencies, except for the 0.5 kHz LP, which had more errors than all other tested thresholds. Aiming to compose a test with moderate execution difficulty, we chose L2 with a cutoff of 1 kHz for the LPFST and L1 with a cutoff of 1.1 kHz for the HPFST as standard tests lists as they resulted in intelligibility levels of approximately 70% in healthy subjects.

For the BRT (Figure 3C), there was a significant difference across the chosen cutoff frequencies ($P < .001$), except for 0.5/1.7 kHz vs 0.9/1.1 kHz, 0.7/1.4 kHz vs 0.9/1.1 kHz,

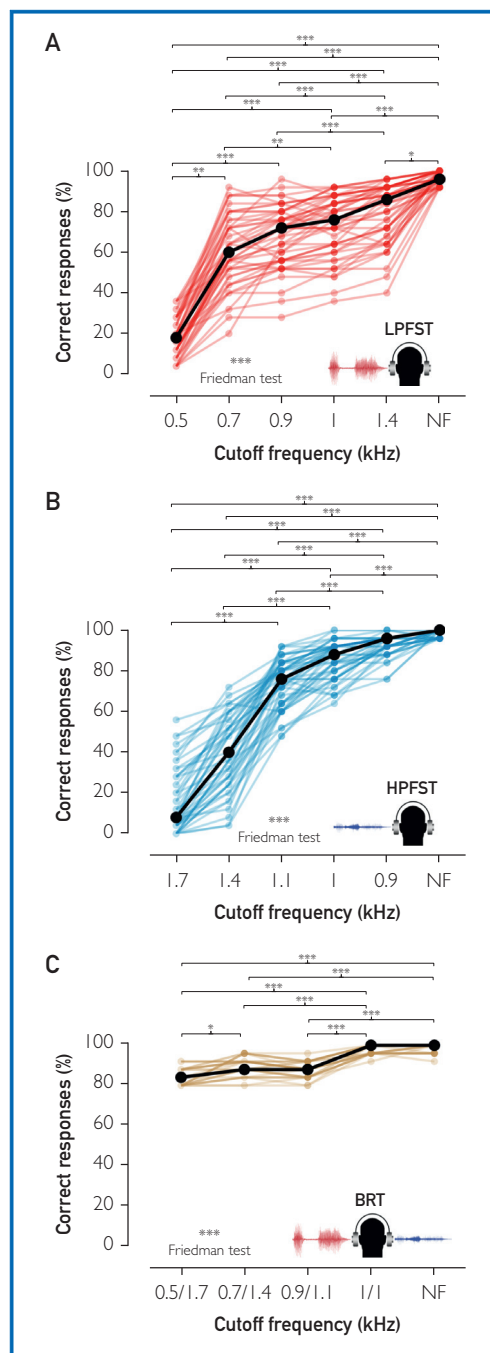


FIGURE 3. Proportion of correct responses (ie, answers that accurately identified the presented stimuli) given by healthy adults presented with digitally filtered spoken words. Black dots indicate the median value of each group; individual data points are represented by colored symbols. A, Performance in the low pass filtered speech test (LPFST) with several cutoff frequencies. Note the decrease in performance with lower cutoffs and that the 1 kHz cutoff results in a median response accuracy of around 70%. B, Performance in the high pass filtered speech test (HPFST) with several cutoff frequencies; the 1.1 kHz cutoff results in a median response accuracy of around 70%. Note the decrease in performance with higher cutoffs. C, Performance in the binaural resynthesis test (BRT) with several combinations of low pass and high pass filter cutoff frequencies, presented dichotically. Note the decrease in performance with more restrictive cutoff ranges and that the 0.5/1.1 kHz combination results in a median response accuracy of around 80%. Also note that the low pass and high pass filter cutoffs, when applied monotonically in the LPFST and the HPFST, result in median accuracy levels of less than 20%. NF = not filtered. Friedman test: * $P = .05$; ** $P = .01$; *** $P < .001$.

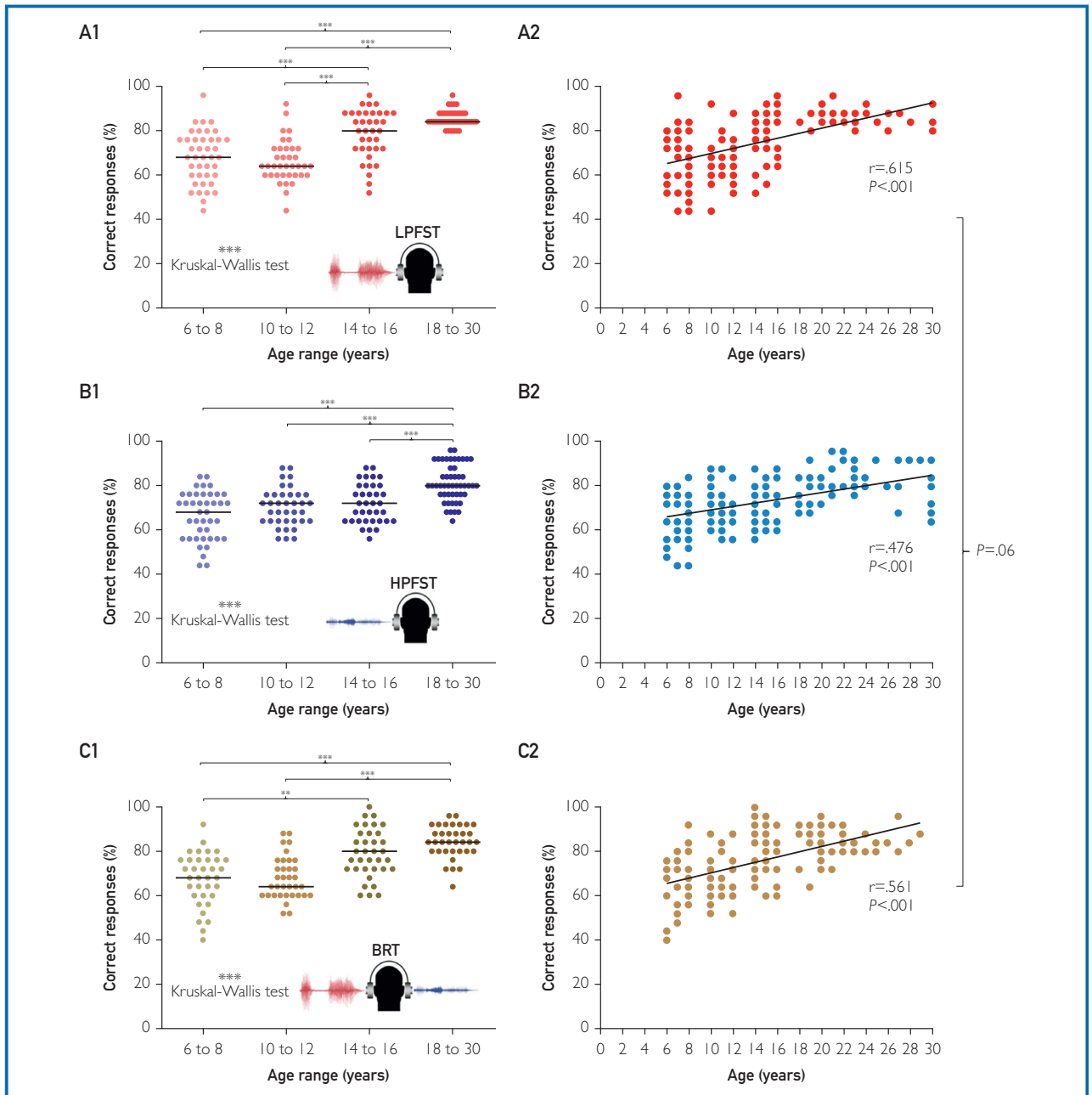


FIGURE 4. Proportion of correct responses in the filtered speech tests given by participants of different ages. Black lines indicate the median value of each group; individual data points are represented by colored symbols. Note that performance improved with age in all tests. A, Results on the low pass filtered speech test (LPFST) across separate age groups (A1) and the correlation between age and performance (A2). Note that when different age groups are segregated (A1), there is no significant difference between the 14- to 16-year and the 18- to 30-year age groups ($P = .06$). Also, there is a significant correlation between age and performance (A2). B, Results on the high pass filtered speech test (HPFST) across separate age groups (B1) and the correlation between age and performance (B2). Note the significant correlation between age and performance (B2). C, Results on the binaural resynthesis test (BRT) across separate age groups (C1) and the correlation between age and performance (C2). Note that as with the LPFST, when different age groups are segregated (C1), there is no significant difference between the 14- to 16-year and the 18- to 30-year age groups ($P = .23$). Also, there is a significant correlation between age and performance (C2). Importantly, there was no significant difference in the slopes of the linear regression curves between age and performance for all three tests ($P = .06$), that is, the correlation between age and performance was similar for all tests. Kruskal-Wallis test: ** $P = .01$; *** $P < .001$.

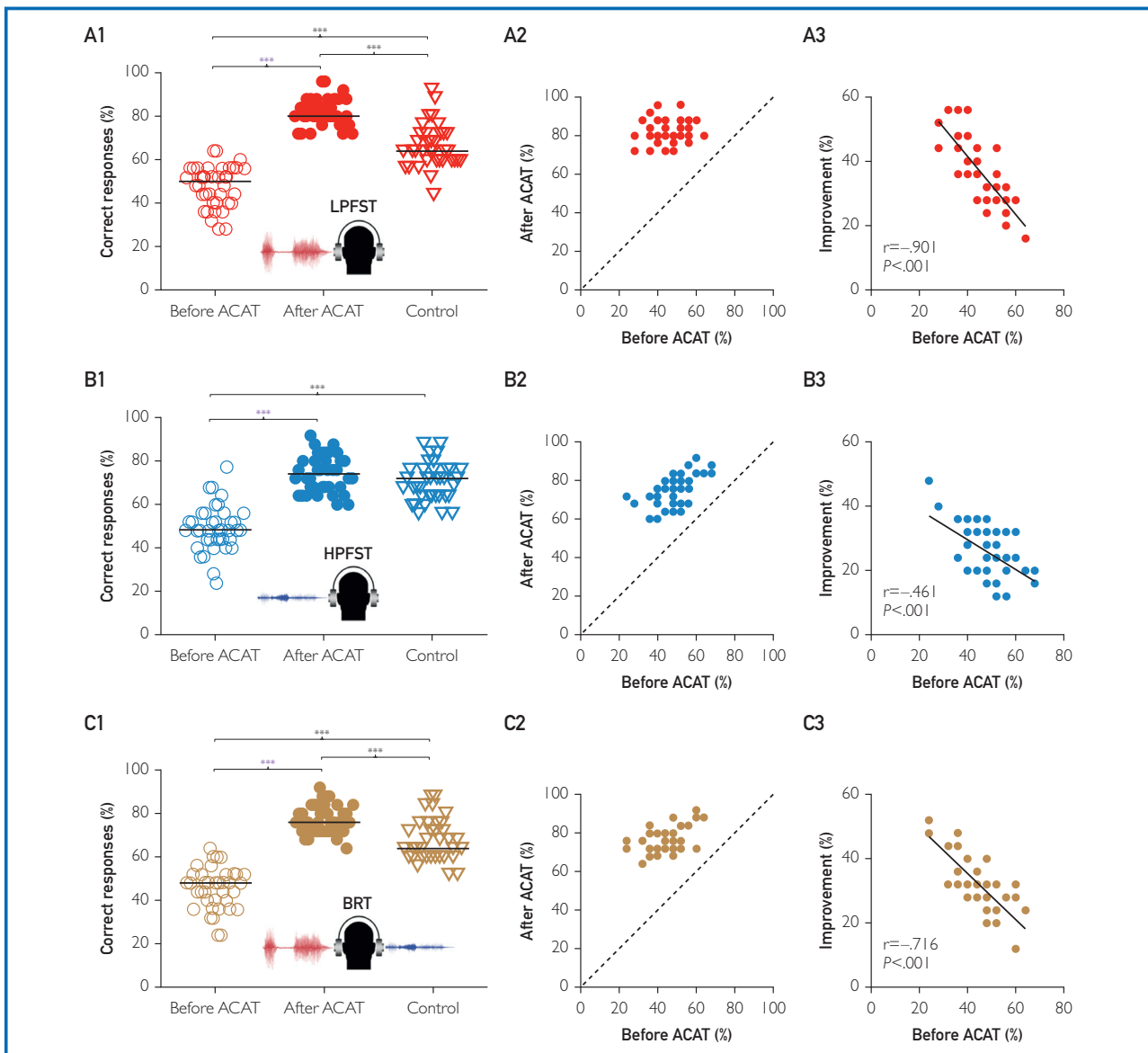


FIGURE 5. Proportion of correct responses in the filtered speech tests given by patients diagnosed with auditory processing disorder (APD) before and after acoustically controlled auditory training (ACAT) and age-matched healthy controls. Black lines indicate the median value of each group; individual data points are represented by colored symbols. A, Performance in the low pass filtered speech test (LPFST). A1 shows the data for patients with APD before (empty circles) and after (full circles) ACAT and for the controls (empty triangles). Note that patients with APD scored significantly lower than controls before ACAT but then scored significantly higher after the treatment. A2 shows the identity plot for each patient before and after treatment. A3 shows the correlation between performance before ACAT and improvement (performance after ACAT – performance before ACAT). B, Similar to A but for the high pass filtered speech test (HPFST). Note that unlike for the LPFST and binaural resynthesis test (BRT), patients did not score higher than the controls after ACAT, even though they were worse before the treatment. Nevertheless, there still was no significant difference between performance after ACAT and controls ($P=.06$), indicating that the patients achieved normal levels of performance. C, Similar to A and B but for the BRT. As for the LPFST, patients scored significantly lower than controls before ACAT but then scored significantly higher after the treatment. Importantly, note that every single patient falls above the identity line for every filtered speech test applied, indicating that performance improved across all tested auditory skills after ACAT treatment. Also note that there was a significant inverse correlation between initial performance and improvement, demonstrating that patients with the worse initial symptoms benefited disproportionately more from ACAT. Wilcoxon matched pairs signed rank test (paired, in purple): *** $P<.001$. Mann-Whitney test (unpaired, in black): *** $P<.001$).

and 1/1kHz vs not filtered. We chose L2 with 0.5/1.7 kHz LP and HP limits as the standard for the BRT, with intelligibility close to 80%.

We then used these standard lists to evaluate how intelligibility varied with age. Performance increased with age across all tests (Figure 4). Post hoc statistics showed that in the LPFST and BRT, there were no more significant improvements in performance after 14 to 16 years of age (Figure 4, A1 and C1), whereas in the HPFST (Figure 4, B1), there was still a significant difference between the 14- to 16-year and 18- to 30-year age groups. This suggested that the development of LP vs HP AC abilities could follow different time courses. To test this, we examined the correlation between age and performance across all tests (Figure 4, A2, B2, and C2). If there was indeed a difference in the developmental time course of different auditory skills, we would expect the slope of the correlations to significantly differ between the groups. However, although there was a significant correlation between age and performance for all tests (Figure 4, A2, B2 and C2), there was no significant difference between the slopes of these correlations ($P=.06$), rejecting this hypothesis.

We then evaluated the clinical improvement of patients with APD after ACAT treatment. Patients with APD had a lower initial percentage of correct responses in all tests in relation to controls ($P<.001$); after ACAT, the same patients had a stark increase in performance across all tests ($P<.001$) and even had better performances, on average, in the LPFST and BRT than healthy controls ($P<.001$) (Figure 5, A1, B1, C1). Identity plots of the performances of these patients before and after ACAT show that every patient improved after the treatment (Figure 5, A2, B2, C2). Importantly, we found that the lower the initial performance of the patient, the greater the improvement after the treatment (Figure 5, A3, B3, C3; $P<.001$ for all correlations).

DISCUSSION

We introduced, validated, and applied a novel method for creating test stimuli for the LPFST, HPFST, and BRT, diagnostic tests used to identify APDs.^{1,3,8,9,32} Using digital filters, we achieved 80 dB attenuation across all

frequencies without creating distortions in the signal compared with frequency-specific attenuations in the range of 20 to 60 dB currently used in current clinical practice.^{1,3,9,32-34}

We first tested how different cutoff frequencies in each test affected performance to select parameters that had moderate difficulty in healthy adults and could be used as a standard for further tests. As expected, we found a progressive improvement in the percentage of correct responses the larger the applied frequency range.^{1,41-44} FSTs with very restrictive cuts, removing important portions for speech intelligibility, prevented hearing closure in filtering with LP 0.5 kHz, HP 1.7 kHz, and HP 1.4 kHz, for which intelligibility was less than 50% even in healthy patients, making these filters unsuitable for clinical practice.⁴¹⁻⁴⁴ The chosen cutoff frequencies of 1 kHz for the LPFST and 1.1 kHz for the HPFST produced, on average, a response accuracy of around 70% and as such have optimal sensitivity for clinical application. In the BRT, there was a similarly progressive but smaller improvement in intelligibility with widening frequency ranges, probably due to the greater preservation of acoustic cues.^{9,15,43,44} In comparing the results of the LPFST and HPFST with the BRT, especially at the 0.5/1.7 kHz range that we chose as the standard, we confirm that BR allows the correct perception of words even though the components presented in each ear are by themselves unintelligible.^{9-11,42,43} We point out that by choosing the 0.5/1.7 kHz range as a standard, we are specifically testing the capacity to perform BR as even healthy individuals are mostly unable to identify words based on the filtered stimuli by themselves.

We found that intelligibility in all tests increased with age across childhood and adolescence, which was expected as AC and BR are skills that evolve with central nervous system maturation.⁴⁵⁻⁵³ An initial analysis across groups divided by age range suggested that peak performance in the HPFST was achieved later than in LPFST or BRT. However, linear regression analyses across the full range of sampled participants revealed that this was only a nonsignificant trend. It is interesting that different abilities of auditory comprehension seem to mature at a similar

speed, which could be due to shared neural substrates.^{12,26,27,39,40} Importantly, these results demonstrate that age-related adjustments in normal performance standards for clinical practices can be done across tests for each age range.

Finally, we applied our tests to patients with APD before and after ACAT treatment and compared performance of age-matched healthy controls. We found that ACAT improved the performance of all patients in all tested measures, demonstrating that our method has the sensitivity to detect clinically relevant improvements in AC and BR skills.^{1,38-40} In the HPFST, patients were able to reach average performance levels similar to those of controls. In the LPFST and BRT, the average performance of the trained group even exceeded that of the controls. Similar results have been reported with other auditory tests.⁵⁴

To the best of our knowledge, this is the first study to evaluate AC and BR performance before and after ACAT with FSTs and BRT methods. Previous studies, using other performance tests, have also observed significant improvement in patients with APD after ACAT. For example, Zalcman and Schochat,⁵⁴ using the nonverbal dichotic test, reported a nearly 2-fold performance improvement in patients with APD after ACAT, which is similar to the effect sizes we observed in our study. Our study establishes that digital FSTs and BRT can also be used for the diagnosis of APD and especially for monitoring the therapeutic effects of ACAT.

A potential confound was that patients with APD tested after ACAT had previous experience with the test, whereas the controls did not. This raises the possibility that performance increases might be attributable to an exposure effect. We believe this is unlikely because there was an intertest interval of at least 15 days, making it difficult to recall specific stimuli from memory; the order of stimuli presentation was randomized, precluding memorization based on presentation sequence; and the material used for ACAT training did not contain the words used as test stimuli. The most parsimonious explanation is that ACAT produces a generalized improvement of speech comprehension in patients with APD.

An interesting novel finding was that clinical improvement was higher for patients with more severe deficits; that is, the more a patient is affected by APD, the more the patient can benefit from ACAT. Here there is the potential confound of a ceiling effect on ACAT-induced improvements. However, this is unlikely, given that for the HPFST and the BRT performances, there is still a notable inclination of the data clusters in the identity plots (Figure 5, B2 and C2), indicating that patients with the worst initial performances still were at the lower range for detectable improvement compared with better initial performers. Even then, patients with more severe initial symptoms benefited disproportionately from ACAT.

A promising perspective is to investigate how digital filtering can affect intelligibility in other languages as peculiarities of each language might lead to differing results.⁵⁵⁻⁵⁷ Another important issue is the testing of senior citizens (>60 years of age). This population has the highest incidence of APD,^{5,7} and it could be crucial to quantify how performance in the tests described here progresses in advanced age as well as quantifying the benefits of therapeutic procedures such as ACAT in older individuals.

CONCLUSION

We introduced novel test parameters for diagnostic tests of APD. Using digital filters, we propose a new set of standards for the LPFST, HPFST, and BRT. We validated our methods by examining how cutoff frequencies affect performance and which ranges are optimal for clinical practice. Performance in the tests increased with age, at the same rate across all tests. Our tests were able to detect APD in children and to show improvement after ACAT. We found that patients having the most severe deficits also benefited the most from ACAT.

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SUPPLEMENTAL ONLINE MATERIAL

Supplemental material can be found online at <http://www.mayoclinicproceedings.org>. Supplemental material attached to journal articles has not been edited, and the authors take responsibility for the accuracy of all data.

Abbreviations and Acronyms: **AC** = auditory closure; **ACAT** = acoustically controlled auditory training; **APD** = auditory processing disorder; **BR** = binaural resynthesis; **BRT** = binaural resynthesis test; **FST** = filtered speech test; **HP** = high pass; **HPFST** = high pass filtered speech test; **L1** = list 1; **L2** = list 2; **LP** = low pass; **LPFST** = low pass filtered speech test

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