March 2020

Fitting hearing aids with musicians

Christophe Lesimple
Barbara Simon
Julie Tantau

Active musicians using hearing aids need specific attention during the fitting of their devices. The perceived sound quality provided by their hearing aids is essential as it helps them to control the way they perform. A recent clinical study by Bernafon was performed to evaluate a fitting protocol designed to improve the perception of music for active musicians. Optimizing the music program is a challenge because the characteristics of music cover a wide range of listening situations. The results highlight the need for the active participation of the musicians during the fitting process and for the audiologist to speak a common language with hearing-impaired musicians in order to translate their feedback into fine-tuning solutions. This approach is necessary to take advantage of the full technological potential of advanced hearing aid solutions.

bernafon
Your hearing • Our passion

State-of-the art recommendations for hearing aids and music

A key requirement in the development of hearing aids is to design signal processing features and acoustical coupling to improve the perception of speech in various environments. An acoustical model of speech can be produced as the individual anatomical differences are minor, and vocal tracts have similar physical limitations. This speech model defines a frequency and dynamic range for speech upon which target signals used for the development and testing of different hearing solutions are based. Producing an acoustical model of music is much more challenging as the differences between musical instruments cover a broader frequency and dynamic range than speech (Chasin & Russo, 2004; Kirchberger & Russo, 2016). Combining these differences with the variety of performing conditions, i.e. from practicing alone up to performing in a large orchestra, produces a wide range of listening conditions that could be classified as live music.

The need for a music program is driven by the acoustical differences between speech and music and by the feedback from hearing aid users.

The need for a music program in hearing aids is therefore driven by the acoustical differences between speech and music and also by the feedback from hearing aid users who commonly report reduced sound quality especially for live music (Madsen & Moore, 2014). This additional listening program can be activated on request during the fitting of hearing aids. To improve music listening satisfaction with hearing aids, manufacturers often apply the following changes to music programs based on recommendations from the literature:

a) increasing the input dynamic range to avoid distortions of the loudest components of the incoming signal (Hockley et al., 2012);
b) adapting the bandwidth of the device, i.e. option 1: wider bandwidth for mild to moderate and flatter hearing losses for more clarity, or option 2: narrower bandwidth for severe to profound and sloping hearing losses for more comfort (Moore, 2012);
c) reducing the effect of adaptive features such as wide dynamic range compression (Croghan et al., 2014; Madsen et al., 2015; Kirchberger & Russo, 2016), feedback cancellation (Spriet et al., 2009), frequency lowering (Parsa et al., 2013; Mussoi & Bentler, 2015) as well as noise reduction or directionality as we assume that there is no detrimental signal in a music listening situation;
d) adjusting the gain and frequency response with more gain in the low frequencies (Moore et al., 2016) or reducing amplification over the entire bandwidth (D'Onofrio et al., 2019).

While there is a consensus about the first three recommendations, some questions remain for the last suggestion, i.e. how to define the desired gain and frequency response for the music program, for which music style, and in which condition? If we can't model the target signal, how can we determine the appropriate gain for optimal audibility, sound fidelity, and comfort? We assume that, in the case of active musicians, the target signal of the music program could be primarily based on the acoustical characteristics of their own instrument. However, this parameter cannot be known ahead of time and suggests that some personalized fine tuning could be beneficial when fitting hearing-impaired musicians.

The second limitation is that research is mainly based on listening experiments, i.e. researchers must select a small subset of musical excerpts, define a playback condition and assume that they can generalize the findings to music overall. This generalization cannot be ensured when the hearing aid users are actively playing music because these experiments rely on passive listening tests. This methodology is appropriate when preparing for a research investigation in the general area of music and hearing aids. However, a sound quality rating test for musicians is more complex, because their judgement is also based on what they expect, especially when they assess their own musical production.

Music amplification requirements for musicians

Musicians create a mental representation of the musical object before and while they perform.

The way musicians perceive their own musical production is essential in controlling their performance. This is based on feedforward and feedback interactions between the auditory and motor systems (Figure 1). Musicians create a mental representation of the musical object before and while they perform. This representation is mapped in the premotor cortex to plan its execution and carried out by the motor cortex and cerebellum (Zatorre et al., 2007; Héroux, 2018). The response is the sound produced by the instrument in a given situation. The perceived sound, via the auditory system, is then used to fine-tune and adjust the musical execution via the motor system to achieve the desired effect (Repp, 1999).

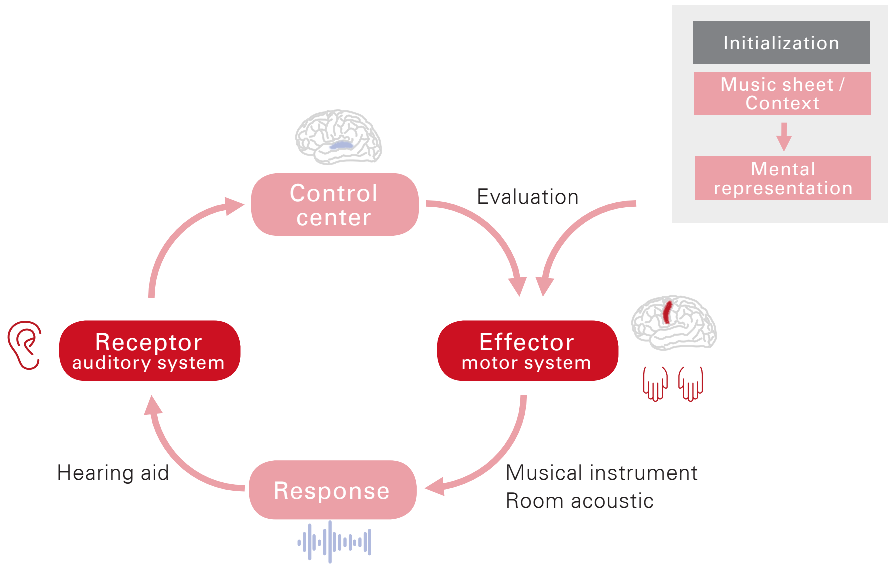


Figure 1: Auditory – motor interaction during musical performance. The mental representation produced during the initialization phase will plan and organize the execution of music. The perceived response, including the effect of the hearing aid, is compared to the expected result and used to fine-tune the performance.

The evaluation of the perceived sound, including the effect of the hearing aid, is compared to the mental representation created by the musician. This mental representation is a creative process which depends on the musical training and musical background of each musician (Héroux, 2018). There are therefore large differences in mental representations between musicians even if they play the same musical excerpts. This is a fundamental difference between active playing and experiments using listening tasks. Standard listening tasks involve comparing a stimulus to a reference, either given by the test or a mental reference of the test subject and rely on instructions from the test leader. In this standard listening condition, the test subject has no control over the stimuli production and can only respond to what is given. The subject's motivation and reference (provided or personal) during the evaluation are limited as they have no preconceived expectations of the provided stimuli. In this situation, subtle changes caused by the signal processing in a hearing aid might not be as relevant for the listener.

In contrast, changes in the hearing aid fitting might have a different effect when the listener is performing music and has actively created his own mental representation. Evaluating the effect of different hearing aid settings for musicians with only listening tests might therefore not provide a complete experimental framework that would also be externally valid. An alternative approach would require introducing changes in the tested hearing aids while the musician plays his own instrument using his own mental representation as the reference (Greasley et al., 2019).

Our hypothesis is that the standard Live Music Program (referred to as the default music program) should provide a general improvement when listening to music over the default dynamic program designed for speech in various listening environments. However, for musicians, this default music program could benefit from an optimization protocol requiring their active participation during the fitting process so that the resulting perception of sound quality comes closer to their expectations.

Tested optimization protocol for musicians

The optimization protocol was developed to fine-tune a music program with musicians and their specific instrument.

The optimization protocol was developed to fine-tune a music program with musicians and their specific instrument. The protocol starts with the default music program, and it is expected that the changes made in the fitting environment should be valid in real performing conditions. The protocol is based on an interactive and iterative process to find the best gain and frequency response and feature settings while the musician is playing. The musician is asked to play scales over the entire frequency range at different dynamics and then report if a note is not equivalent or sounds noticeably different compared to its neighbors. Different changes to the program are immediately tested until the perceived sound quality achieves satisfaction.

This protocol requires a common terminology linking musical, audiological, and acoustical concepts (Greasley et al., 2019). A basic understanding of these concepts is essential for the audiologist to understand the musician's feedback and to implement adequate changes in the fitting software. A dialog with the musician is necessary to correctly fine-tune the gain and frequency response. The musician can give the audiologist an idea about the dynamic range for a specific instrument and help them understand which frequencies will be affected by a given note. Adjustments should be made in finite steps as small changes could have large effects.

Range of sound level for acoustical live music

The sound level exposures experienced by music students (Rodrigues et al., 2015) and professional musicians (O'Brien et al., 2013) were analyzed in different situations. This information can be refined by instrument type to determine the dynamic range for a specific instrument (Table 1). O'Brien et al. (2013) recorded sound levels between 60 and 107 dB $L_{A, eq}$ with peak levels between 101 and 130 dB $L_{C, peak}$ in a sound-treated practice room during solitary practice. We can expect even louder sound levels if reverberation is added or when playing in a large orchestra.

		During individual classes with students (Rodrigues et al., 2015)		During practice professional musicians ($L_{A, eq}$ in dB A) (O'Brien et al., 2013)	
		$L_{A, eq}$ dB (A)	$L_{C peak}$ dB (C)	Left ear	Right ear
Strings	Double bass	74.7 (0.8)	107.2 (2.1)	76 (1)	77 (2)
	Violin	85.1 (3.1)	118.3 (4.5)	91 (1)	87 (3)
Woodwind	Clarinet	87.1 (0.9)	116.1 (1.3)	90 (4)	90 (3)
Brass	French horn	92.0 (-)	114.7 (-)	90 (5)	93 (3)
	Trombone	92.8 (2.6)	126.1 (5.9)	94 (3)	94 (1)
Percussion		90.8 (2.5)	137.0 (5.2)	97 (-)	98 (-)

Table 1: Equivalent continuous sound level exposure (in dB A) and peak levels (in dB C) of instruments measured with music students during an individual class over a 2-week period (left column). Side effect (left and right ear) of the continuous sound level exposure (in dB A) when professional orchestra musicians are practicing technical work for 5 minutes (right column). Ranges in brackets indicate variations between individual players of the same instrument type.

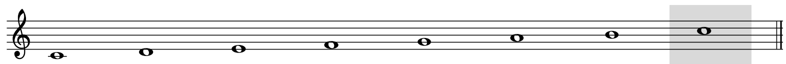
For some instruments like the violin, the interaural difference must be taken into account as violinists need clear feedback from their own instrument especially when they play in an orchestra.

The interaural difference must also be taken into account for some instruments like the violin. This difference can reach 6 dB when the sound level is measured in the orchestra (Schmid et al., 2011). It is important to preserve this difference with the hearing aid as violinists need clear feedback from their own instrument especially when they play in an orchestra.

While sound levels might also vary by the player's technical expertise, it is essential information as the fitting software allows for the adjustment of the gain curve for different input levels. Fine-tuning the gain and frequency response should focus primarily on the gain curves for the 65 dB and 80 dB input level curves in the fitting software when it comes to live music. The influence of the gain curve for 50 dB input level might have a moderate effect for live music. However, it must be adapted for the breaks between music, for example, when someone is speaking during the rehearsal.

Frequency range for acoustical live music

The other aspect of the fine-tuning process in the optimization protocol is to target the most critical frequencies for a specific note. Figure 2 shows how to link notes from a C-major scale to the first three harmonics in the frequency domain. The fundamental frequency (f1) and the first harmonics (f2 and f3) carry the most energy and should thus get the most attention when fine-tuning the gain and frequency response. The role of the harmonics is crucial as they convey important information to discriminate or distinguish between instruments. The energy ratio between the harmonics helps also to identify nuances in the timbres and dynamics (Grey & Gordon, 1978).



n=1 (Hz)	262	294	330	349	392	440	494	523
n=2 (Hz)	524	588	660	698	784	880	988	1046
n=3 (Hz)	786	882	990	1047	1176	1320	1482	1569

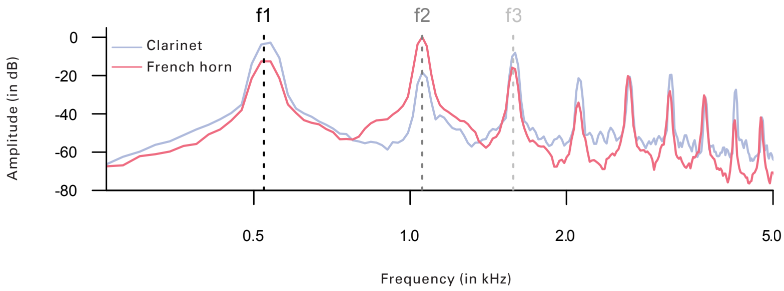


Figure 2: Relation between the musical notation of a C-major scale and the frequencies of the first three harmonics used for the optimization procedure (top). The fundamental frequency is in black while the harmonics are in gray. The same C5 (grayed note with a fundamental frequency of 523 Hz) was played by a clarinet and a french horn. The spectrums for the C5 from the clarinet (purple) and the french horn (pink) are shown on the bottom. The harmonics are aligned in frequency which gives the same pitch. The energy distribution of the harmonics allows the listener to discriminate both instruments.

A large part of the energy distribution of music is located in the lower frequency range, which has a limited frequency resolution in the fitting software.

This link is essential for the audiologist to translate the feedback of the musicians for a specific note into a physical scale accessible in the fitting software. It is also important to realize that the fundamental frequency of the medium A4 on a piano is only 440 Hz. This implies that a large part of the energy distribution of music is located in the lower frequency range which has a limited frequency resolution in the fitting software. Changes in the acoustical coupling (e.g. vent size or insertion depth) can also address perception issues in the lower range.

Further aspects of optimization accessible in the fitting software should also be considered beyond the fine-tuning of the gain and frequency response: a) verify if increasing the maximum power output reduces potential sound distortion at a louder dynamic without compromising comfort, b) test the effect of different frequency lowering settings on sound quality and instrument discrimination, and c) test the effect of feedback cancellation on sound stability and verify feedback risk.

All these optimization strategies are carried out in a clinical context with a controlled acoustic environment. However, these conditions won't be found in daily life that is by definition different than in the clinic, i.e. when the musician practices at home or when he performs in a group or orchestra. A clinical study was therefore needed to evaluate the significance of this optimization protocol and to answer the following research questions:

- Does the fitting protocol optimized for the hearing-impaired musician's individual needs make an audible difference compared to the standard Live Music Program?
- Is the fitting protocol optimized for the hearing-impaired musician's individual needs preferred over the standard Live Music Program?
- Does the fitting protocol optimized for a hearing-impaired musician's individual needs improve the perception of music compared to the standard Live Music Program?

Clinical trial: Optimized fitting protocol for musicians

Test protocol

The optimized protocol was evaluated during a clinical trial to answer these research questions and to gain knowledge about this specific topic. The idea was to fit the test hearing aids with a general program based on the NAL-NL2 fitting rationale (Keidser et al., 2011) as a baseline and then add two music programs to be tested in a field and lab test. One music program was based on the standard Live Music Program provided by the Oasis^{nxt} fitting software and the second music program was the result of the optimization protocol involving active participation of the test subject. The order of the music programs was randomized and blinded for the subjects. The selected test hearing aid was a Viron 9 MNR which covers a wide fitting range with different acoustical options.

The subjects were instructed to compare both music programs in situations where they were either playing or listening to music. After a two-week trial period they were asked to report their preference and the motivation for their choice. Music questionnaires were also used to evaluate the perception of some specific attributes of music with the different music programs, i.e. pleasantness and naturalness of their own instrument and for other instruments.

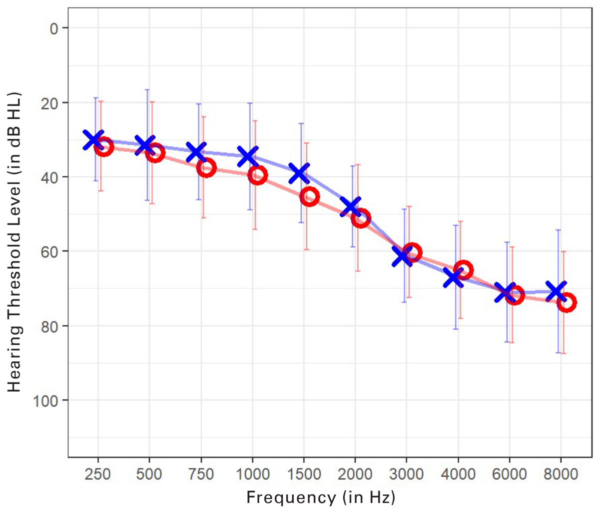
In addition to the questionnaires, a music test was completed during a lab test to evaluate the perception of small differences in music. The meter subscale from the Adaptive Music Perception (AMP) test (Kirchberger & Russo, 2015) was used to measure discrimination thresholds for level, pitch, and duration of a "trumpet like" sound played at 40 dB sensation level. These thresholds were measured in the following conditions: unaided, NAL-NL2 program, standard music program, and the optimized music program.

Participants

Inclusion criteria for the trial were defined to recruit subjects with no contra-indication to wearing a hearing aid and a hearing loss within the fitting range of the test hearing aid. The criteria also specified that subjects should play music on a regular basis in different conditions, such as daily practice, a weekly lesson, and/or in an orchestra. A further inclusion criterion was that their instrument should be transportable to the clinic.

Twenty active musicians were recruited for the trial.

Twenty active musicians with a hearing loss within the fitting range were recruited for the trial. The mean age was 68 years old ranging from 24 to 81 years and the average audiogram is shown in Figure 3. The instruments played (string, woodwind, and brass) covered the entire frequency range from the bass up to the higher register (Figure 3). Musical experience from the subjects started with 2 years of experience and ranged to professional orchestral musicians.



	Bass	Medium	High
String	Cello (1)	Viola (2)	Violin (3)
Woodwing	Bassoon (1)	Saxophone (2)	Clarinet (5)
Brass	Trombone (1)	Horn (3)	Trumpet (1)
Other		Harp (1)	

Figure 3: Mean hearing threshold levels for the left (blue) and right (red) ears. Error bars indicate one standard deviation. Instrument distribution by type and range is shown in the table.

Results

Preferences between music programs after the field test are summarized in Figure 4. Each subject could indicate which blinded program he preferred and if it was a slight or clear preference. If no difference or no preference was found between the programs, then he could use the "no preference" option. Beyond the preference, it is also important to understand what the motivation for a given music program is. If a music program was preferred, then the subject could choose different reasons for his preference among the following possibilities: overall loudness, instrument timbre, follow a melody, follow a harmony, less feedback, intonation, listening effort, comfort, or other.

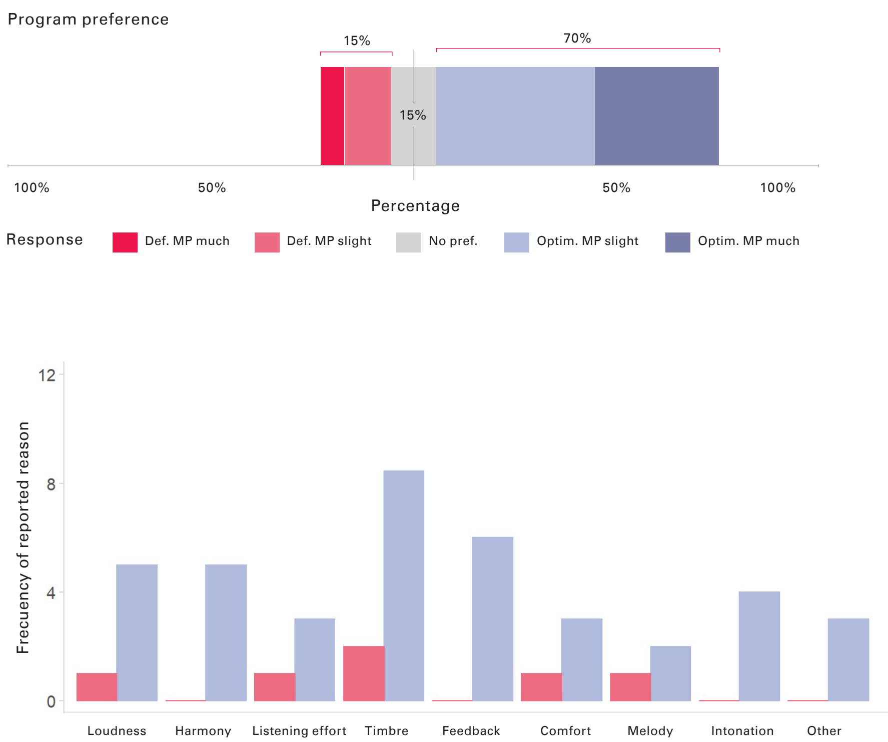


Figure 4: Preference for a specific music program after the field trial for 20 hearing-impaired musicians (top) and the frequency of reported reasons for each preference (bottom). The default music program (MP) is shown in red while the optimized music program is in light purple.

70% of the subjects preferred the optimized music program.

After the field trial, 70% of the subjects preferred the optimized music program, 15% had no preference, and 15% preferred the default music program. The preference for the optimized music program is significant ($p = 0.01$, effect size $r = -0.54$). This result suggests that optimization made for music in the clinic is also positively experienced at home and in various performing conditions.

The optimized music program is preferred because of improved timbre, less acoustical feedback, better loudness, harmony, and intonation.

The main reasons for preferring the optimized music program are the improved timbre, less acoustical feedback, better loudness, harmony, and intonation. The instrument's timbre as a motivation is a good indication that changes in the gain and frequency response can achieve an improvement in perceived sound quality. Beside this major finding, it is also important to understand how the perception of music changed in a lab and controlled test.

The meter subscale from the AMP test measures the smallest detectable difference in level (in dB), pitch (in Hz), and duration (in ms). These measures should reflect the ability to perceive small details in music. The distributions of the measured discrimination thresholds are shown in Figure 5 for each subscale and listening condition. The results with the NAL-NL2 fitting rationale are consistent across the three subscales compared to the unaided conditions. Using a fitting rationale designed for a speech signal increases the unaided discrimination threshold level by 0.6 dB, pitch by 0.5 Hz, and duration by 29 ms. This performance degradation might be explained by the dynamic compression defined by the fitting rationale which reduces differences in level at the output of the hearing aid.

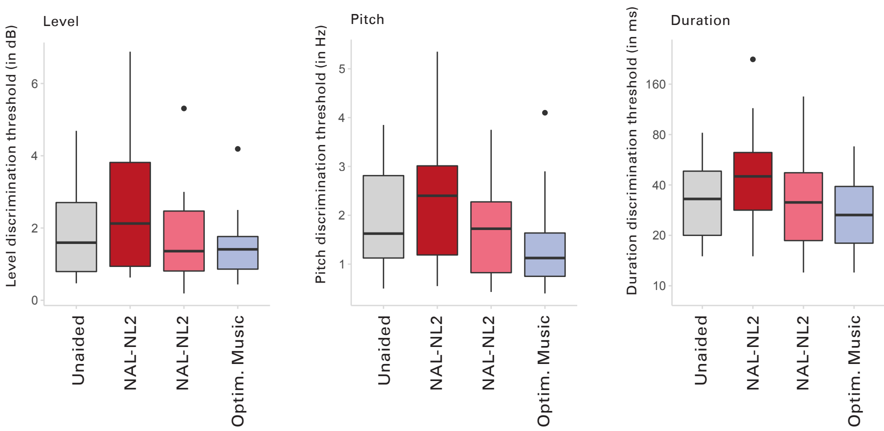


Figure 5: Results distribution from the AMP test for discrimination thresholds of level (in dB – left), pitch (in Hz – middle), and duration (in ms – right) in the unaided condition (gray), default fitting rationale NAL-NL2 (red), default music program (pink), and optimized music program (light purple). Better discrimination is shown with lower thresholds.

The analysis of the aided conditions was performed with a planned contrast to first compare the NAL-NL2 program with the music programs and then compare the default music program with the optimized music program. The unaided performance as well as the music experience are used as explanatory variables in the regression model.

The effects of planned contrasts and covariates are shown in Table 2 for each subscale.

	Level (in dB)		Pitch (in Hz)		Duration (in ms)	
Predictors	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*
NAL-NL2 vs. music programs	-0.32	**<0.001**	-0.26	**<0.001**	-6.27	**0.012**
Default vs. optimized music prg.	-0.11	0.346	-0.21	0.075	-3.80	0.381
Unaided performance	0.59	**0.007**	0.56	**0.001**	11.17	**0.018**
Music experience	0.25	0.258	0.11	0.536	8.19	0.083
Marginal R^2 / Conditional R^2	0.317/ 0.720		0.335/ 0.597		0.246/ 0.392	

Table 2: Regression models for the discrimination thresholds of level, pitch, and duration. The marginal R^2 describes the proportion of variance explained by the predictors alone while the conditional R^2 describes the proportion of variance explained by the fixed (predictors) and random (subjects) effects.

The use of a music program proved to be beneficial as it significantly reduced the discrimination thresholds to detect a change in level, pitch, and duration. The differences between both tested music programs are not significant even if the average scores obtained with the optimized program were better than with the default music program. Because the optimized music program uses the default music program as a baseline, differences between both music programs should be smaller than with the NAL-NL2 listening program.

Explaining the differences between these three aided conditions might be more complex. A single and isolated test captures some aspects of the differences, but it might not fully explain a potential preference. The expressed preference could be the sum of different attributes that can be directly measured (lab test with controlled but unrealistic conditions) or indirectly evaluated (questionnaire after the field test with realistic but uncontrolled conditions).

Measures from different tests are defined in a multidimensional space where they may convey redundant information. A principal component analysis (PCA) can be used to simplify and visualize the information carried by different test results. Results are projected on new dimensions maximizing the amount of information, i.e. with the highest variance. The PCA applied to the results from the AMP test in the lab and from the questionnaire from the field test are shown in Figure 6.

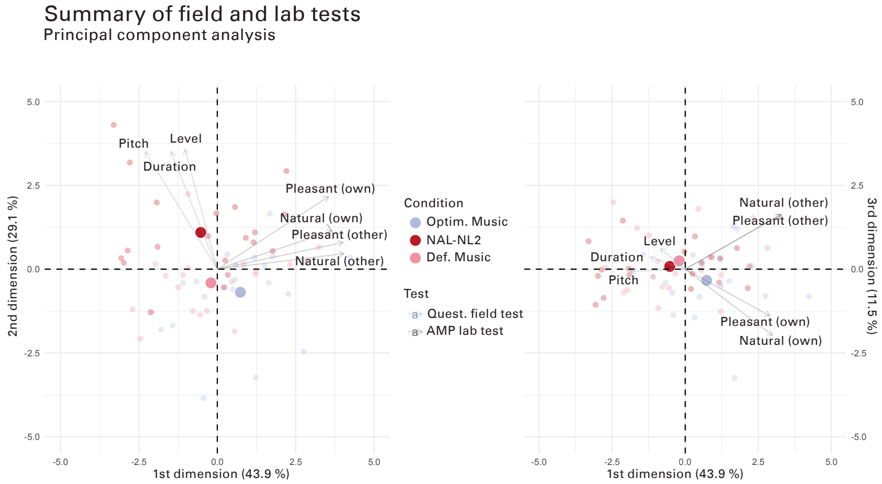


Figure 6: Principal component analysis with the projection of individual points and averages by test condition. The projection of factors on the dimensions 1 and 2 (left) and on the dimensions 1 and 3 (right). Results with NAL-NL2 are in red, with the default music program in pink, and with the optimized program in light purple. The arrows represent the influence of different tests on each dimension from the PCA.

The PCA results fall into three main dimensions, which explain 84.5% of the variance: a) dimension 1 (43.9%) is dominated by the field test questionnaire, b) dimension 2 (29.1%) embraces the discrimination threshold from the AMP test, and dimension 3 (11.5%) is related to the evaluation of which instrument is rated in the field test, i.e. their own or the other instruments.

The preference for the optimized music program is the sum of different attributes that can be directly measured in the lab or indirectly evaluated after the field test.

These findings suggest that the results from the AMP test and the feedback collected after the field test are almost independent. The first dimension indicates that the difference between the default and optimized music program is supported by the field test evaluation. The second dimension reflects the results from the AMP test, i.e. the music programs decrease the discrimination thresholds of the three subscales compared to the NAL-NL2 based listening program. The third dimension highlights the difference when the subjects are evaluating the sound of their own instrument or when someone else is playing.

The protocol designed to fine-tune the music program was preferred over the default solution. It improves the perceived sound quality of the instrument.

Conclusions

While the default music program improves the perception of subtle details of music over the NAL-NL2 based listening program, there is room left to improve the perception of music for musicians. The protocol designed to fine-tune the music program was preferred over the default solution as it improved different aspects reflecting the perceived sound quality of their own instrument. Evaluating the sound quality of their own instrument was more important than when the musicians were listening to other musicians.

Providing hearing aids with more dynamic range, larger frequency bandwidth, and low distortion is the starting point for good sound quality. The optimization process also needs hearing aid technology with enough fine-tuning options to find the best solution for a specific situation: a hearing aid user playing a specific instrument. The fine-tuning protocol points out the role of the audiologist in the fitting process, i.e. the audiologist needs to understand some acoustical aspects of music and develop a common language with the musicians to provide a custom solution.

This custom approach provides an additional benefit by helping hearing-impaired musicians to continue to actively play music. Beyond the personal interest of playing music, research has shown the positive effect of active music-making for a) improving cognition, b) stimulating motoric performance, and c) enhancing social well-being (Creech et al., 2013; Creech, 2019; MacRitchie et al., 2020). The key to this life-changing approach requires advanced hearing aid technology combined with audiological knowledge.

References

Chasin, M., & Russo, F. A. (2004). Hearing Aids and Music. T*rends in Amplification, 8*(2), 35–47. https://doi.org/10.1177/108471380400800202

Creech, A., Hallam, S., McQueen, H., & Varvarigou, M. (2013). The power of music in the lives of older adults. *Research Studies in Music Education, 35*(1), 87–102. https://doi.org/10.1177/1321103x13478862

Creech A. (2019). Using Music Technology Creatively to Enrich Later-Life: A Literature Review. *Frontiers in psychology, 10,* 117. https://doi.org/doi:10.3389/fpsyg.2019.00117

Croghan, N. B. H., Arehart, K. H., & Kates, J. M. (2014). Music Preferences with Hearing Aids. *Ear and Hearing, 35*(5), e170–e184. https://doi.org/10.1097/aud.0000000000000056

D'Onofrio, K. L., Gifford, R. H., & Ricketts, T. A. (2019). Musician and Nonmusician Hearing Aid Setting Preferences for Music and Speech Stimuli. *American Journal of Audiology, 28*(2), 333–347. https://doi.org/10.1044/2019_aja-18-0125

Greasley, A. E., Crook, H. & Beeston, A. V. (2019). *Hearing Aids for Music: Findings and recommendations for hearing aid users, audiologists, manufacturers and researchers.* Final report of the AHRC-funded Hearing Aids for Music Project. 25 April 2019.

Grey, J. M., & Gordon, J. W. (1978). Perceptual effects of spectral modifications on musical timbres. *The Journal of the Acoustical Society of America, 63*(5), 1493–1500. https://doi.org/10.1121/1.381843

Héroux, I. (2018). Creative Processes in the Shaping of a Musical Interpretation: A Study of Nine Professional Musicians. *Frontiers in Psychology, 9*. https://doi.org/10.3389/fpsyg.2018.00665

Hockley, N. S., Bahlmann, F., & Fulton, B. (2012). Analog-to-Digital Conversion to Accommodate the Dynamics of Live Music in Hearing Instruments. *Trends in Amplification, 16*(3), 146–158. https://doi.org/10.1177/1084713812471906

Keidser G, Dillon H, Flax M, Ching T, & Brewer, S. (2011). The NAL-NL2 prescription procedure. *Audiology Research,* 1:e24.

Kirchberger, M. J., & Russo, F. A. (2015). Development of the Adaptive Music Perception Test. *Ear and Hearing, 36*(2), 217–228. https://doi.org/10.1097/aud.0000000000000112

Kirchberger, M., & Russo, F. A. (2016). Dynamic Range Across Music Genres and the Perception of Dynamic Compression in Hearing-Impaired Listeners. *Trends in Hearing, 20*. https://doi.org/10.1177/2331216516630549

MacRitchie, J., Breaden, M., Milne, A. J., & McIntyre, S. (2020). Cognitive, Motor and Social Factors of Music Instrument Training Programs for Older Adults' Improved Wellbeing. *Frontiers in Psychology, 10*. https://doi.org/10.3389/fpsyg.2019.02868

Madsen, S. M. K., & Moore, B. C. J. (2014). Music and Hearing Aids. *Trends in Hearing, 18*. https://doi.org/10.1177/2331216514558271

Madsen, S. M. K., Stone, M. A., McKinney, M. F., Fitz, K., & Moore, B. C. J. (2015). Effects of wide dynamic-range compression on the perceived clarity of individual musical instruments. *The Journal of the Acoustical Society of America, 137*(4), 1867–1876. https://doi.org/10.1121/1.4914988

Moore, B. C. J. (2012). Effects of Bandwidth, Compression Speed, and Gain at High Frequencies on Preferences for Amplified Music. *Trends in Amplification, 16*(3), 159–172. https://doi.org/10.1177/1084713812465494

Moore, B. C. J., Baer, T., Ives, D. T., Marriage, J., & Salorio-Corbetto, M. (2016). Effects of Modified Hearing Aid Fittings on Loudness and Tone Quality for Different Acoustic Scenes. *Ear and Hearing, 37*(4), 483–491. https://doi.org/10.1097/aud.0000000000000285

Mussoi, B. S. S., & Bentler, R. A. (2015). Impact of frequency compression on music perception. *International Journal of Audiology, 54*(9), 627–633. https://doi.org/10.3109/14992027.2015.1020972

O'Brien, I., Driscoll, T., & Ackermann, B. (2013). Sound exposure of professional orchestral musicians during solitary practice. *The Journal of the Acoustical Society of America, 134*(4), 2748–2754. https://doi.org/10.1121/1.4820900

Parsa, V., Scollie, S., Glista, D., & Seelisch, A. (2013). Nonlinear Frequency Compression. *Trends in Amplification, 17*(1), 54–68. https://doi.org/10.1177/1084713813480856

Repp, B. H. (1999). Effects of Auditory Feedback Deprivation on Expressive Piano Performance. *Music Perception: An Interdisciplinary Journal, 16*(4), 409–438. https://doi.org/10.2307/40285802

Rodrigues, M. A., Amorim, M., Silva, M. V., Neves, P., Sousa, A., & Inácio, O. (2015). Sound Levels and Risk Perceptions of Music Students During Classes. *Journal of Toxicology and Environmental Health, Part A, 78*(13–14), 825–839. https://doi.org/10.1080/15287394.2015.1051174

Schmidt, J.H., Pedersen, E.R., Juhl, P.M., Christensen-Dalsgaard, J., Andersen, T.D., Poulsen, T., Baelum J. (2011). Sound Exposure of Symphony Orchestra Musicians. *The Annals of Occupational Hygiene, 55*(8), 893–905. https://doi.org/10.1093/annhyg/mer055

Spriet, A., Moonen, M., and Wouters, J. (2009). *Objective evaluation of feedback reduction techniques in hearing aids*. 17th European Signal Processing Conference, Glasgow, pp. 1859-1863.

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: auditory–motor interactions in music perception and production. *Nature Reviews Neuroscience, 8*(7), 547–558. https://doi.org/10.1038/nrn2152

World Headquarters

Switzerland
Bernafon AG
Morgenstrasse 131
3018 Bern
Phone +41 31 998 15 15
Fax +41 31 998 15 90

2020-02-10/UK/subject to change