Evaluation of Hearing Aid Amplification on Auditory Feedback during the Production of Music for Hearing-Impaired Musicians

Christophe Lesimple[1, 2] **Julie Tantau[1]** **Barbara Simon[1]**
[1] Bernafon AG, Bern, Switzerland
[2] Bern University of Applied Sciences, Switzerland
cles@bernafon.com

ABSTRACT

Musicians use multi-sensory feedback to control their sound production. In this context, auditory feedback plays a major role in identifying changes in dynamics, pitch, duration, and timbre, which allows them to adjust motoric control to match the expected tone. Alteration of auditory feedback, e.g. with ear plugs, produces changes in dynamics and timbre while the musicians are playing. Our assumption is that hearing loss alters auditory feedback in a similar way, but by wearing hearing aids, some of these deficits might be returned. Amplification could therefore cause changes to acoustical characteristics of music while being played. Musicians with hearing loss ranging from mild to severe were recorded with and without hearing aids. The participants were asked to repeat short musical patterns with dynamics from piano to forte. Amplitude and frequency content were analyzed for each test condition. The effect of hearing loss, amount of amplification, and instrument type were included as explanatory variables in the model. Our results suggest that the dynamic range is extended, especially for the softer dynamics, with amplification. This change is directly dependent on the degree of hearing loss which determines the amount of amplification and consequently may affect the aided auditory feedback for musicians.

1. INTRODUCTION

1.1 Auditory motor interactions

Auditory-motor interactions have been identified in a wide range of vertebrates under the form of vocal-motor changes based on auditory processing [1]. Changes in speech production, triggered by auditory information, are intended to maintain a signal-to-noise ratio favorable for communication [2]. Other auditory-motor interactions have been described in the presence of music [3].

There are two different interaction patterns: a) feedforward interaction, when the auditory input drives a motor response or b) feedback interaction, when the motor response influences the auditory stimuli which is then used to adjust movements via the motor system. Feedforward interactions can be found when rhythmic patterns are identified and then predicted to produce dance steps that coordinate with the music or for a "tap to the beat" exercise [4]. Feedback interactions are present when auditory information is used to adjust the production of music, like fine-tuning pitch or dynamic when playing an instrument or singing [3]. However, these interactions can be affected by impairment of the auditory or the motor systems.

1.2 Impaired auditory feedback and speech production

The effect of hearing loss on speech production highlights the importance of auditory-motor interactions. Hearing loss acts as a filter and reduces the audibility and frequency resolution of auditory information. The relation between hearing loss degree and changes in speech production has been demonstrated [5]. Speech production of hearing-impaired speakers is altered by more nasalization [6], reduced vowel space [7], or louder voiceless sibilants [8]. These changes in speech production should compensate the sensory deficit and allow the speaker to control his voice.

The perception of auditory information can be partially restored with aural rehabilitation via hearing aids or cochlear implants. Amplification produces changes in the speech production. The extent of the changes depends on the type of hearing loss, its severity, and age of onset [9]. A person's ability to adapt to altered auditory feedback depends also on their auditory acuity demonstrated in pitch or loudness discrimination tasks [10]. The effect of altered auditory feedback has also been studied with performing musicians.

1.3 Altered auditory feedback and musicians

The role of auditory feedback has also been studied with musicians by manipulating the auditory input while they were performing. Time delay or pitch shift manipulations have been used to demonstrate the effect of altered auditory feedback on musicians [11-12]. This effect might be specific to the task; a shift in pitch affects more singing precision while adding a delay in the feedback slows down the timing and increases the error rates when playing instruments. The effect of degrading auditory or motor skills in a musical context is however dependent on the musician's experience [13]. It suggests that altered auditory feedback might be partially compensated with experience and musical training by "preexisting sensorimotor associations" [11].

The effect of hearing protection on a musician's performance provides additional evidence of the importance of auditory feedback within the auditory-motor interaction framework. Hearing protection creates a conductive hearing loss by occluding the ear canal. The degree of attenuation is usually associated with an increased sound pressure level of the produced music [14], i.e. more attenuation leads to an increase in the loudness of their own performance. Additionally, hearing protection might also reduce the dynamic range, defined as the relative contrast between soft and loud music levels, which is associated with less possibility of expression during the performance [15]. These changes could potentially explain the low use of hearing protection among musicians, as it impairs their control over their own performance and their ability to hear their colleagues [16].

1.4 Research question

Degraded auditory feedback might also originate from hearing loss, which affects the discrimination of sound level, pitch, and timbre [17]. Hearing loss might be problematic in situations where auditory feedback is necessary to fine tune the music dynamic and intonation especially when playing in a group or an orchestra [18]. Musical performance might therefore rely on the quality of the information provided by the auditory system with or without amplification.

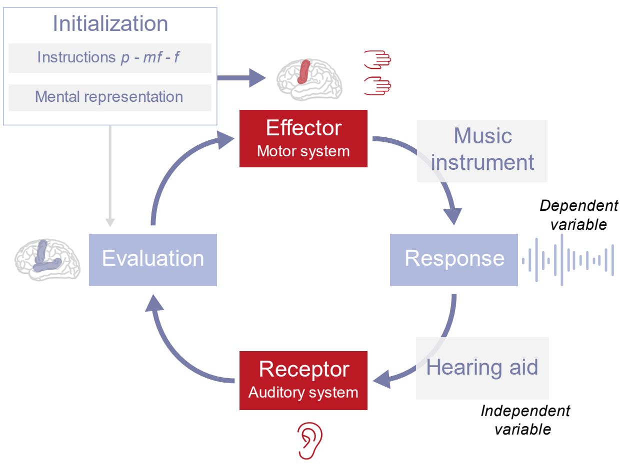

Figure 1. Effect of hearing aid amplification on auditory-motor interactions. First, the initialization phase produces a mental representation of what is expected to be heard. This representation is used to plan and execute the performance. The motor system then produces the response, a sound stimulus, which is perceived by the auditory system. The evaluation compares the input from the auditory system with the mental representation and initiates changes in the motor system for fine adjustments. This study investigates changes in the motor response as a function of amplification via hearing aid and expected musical dynamic.

It is assumed that the amplification provided by hearing aids will create changes to the auditory input and it is expected that, as with speech, these changes can be measured in the production of music by hearing impaired musicians (Fig. 1). This study was designed to evaluate the effect of amplification during musical performance.

2. METHODS

2.1 Participants

Recordings were obtained from nineteen hearing aid users actively playing music. The age of the participants ranged from 24 to 81 years (M = 67.6 years). The mean degree of hearing loss, defined as the hearing threshold average of 0.5, 1, 2, and 4 kHz, was 47.2 dB HL (SD = 16.5 dB HL) on the right side and 45.2 dB HL (SD = 16.1 dB HL) on the left side. Participant's musical experience ranged from 2-year amateurs up to professional musicians. Their instruments were portable as required for the recording purposes and encompassed 5 brass (trumpet, horn, trombone), 6 strings (violin, viola, and cello), and 8 woodwinds (clarinet, saxophone, and bassoon).

Auditory acuity was measured with the Adaptive Music Perception Test [17]. This test uses an adaptive procedure (two-down one-up rule) to estimate the level and pitch discrimination thresholds for each listening condition. The test stimulus is presented at a supra-threshold level of 40 dB SL. The average level discrimination threshold was 1.6 dB for the aided condition and 1.8 dB for the unaided conditions (within subject SD 0.8 dB). The average pitch level discrimination threshold was 1.3 Hz for the aided condition and 1.8 Hz for the unaided condition (within subject SD 0.7 Hz).

Participants were fitted with receiver-in-the-ear hearing aids (Bernafon Viron 9 MNR), and the initial gain calculation was based on the NAL-NL2 fitting rationale [19]. The hearing aid fitting was optimized and fine-tuned while the participant played his instrument to obtain a transparent and balanced response. The acoustical coupling was chosen based on the hearing loss and the fitting software recommendations (Oasis^{nxt}, version 2019.2).

2.2 Procedure

Recordings were made in a sound-isolated double-walled room (6.4 x 5.8 x 2.3 m) with an acoustical treatment to ensure a low reverberation time (from 0.28 s at 100 Hz to 0.08 s at 2.5 kHz). Participants were placed in the center of the room at 1 meter from an AKG CK 91 cardioid microphone with a SE 300 B microphone pre-amplifier. They were instructed to stay in the same position during the entire recording session. The recordings were stored in a wave file sampled at 44,100 Hz with 16-bit resolution.

Participants were asked to play a short sequence with their instrument in a range where it's not expected for them to have any technical difficulties. There were no constraints for the chosen notes; participants should just be able to easily repeat the sequence at different dynamics with and without hearing aids. As an example, it was suggested to play an arpeggio, which is a chord broken into a sequence at a slow pace, e.g. 1 note per second, with a clear articulation between each note. The sequence should be repeated with the following dynamics: piano, mezzo-forte, and forte. The recoding condition order, i.e. with or without amplification, was randomized and balanced in a permuted block. A warm-up period was allowed before the recording session to tune the instrument and to get used to the room acoustics.

2.3 Signal Analysis

Each participant produced 6 recordings, combining 3 dynamics (piano, mezzo-forte, and forte) with 2 conditions (unaided and aided). Within each recorded sequence, individual notes were separated, and the attack and release period of each note were removed. The remaining steady part of the note was then used to extract different features describing the produced signal in terms of sound level and frequency content.

Level estimation was based on the root mean square of the signal for each note. Small between-subject variations, due to changes in the distance between the microphone and the musician, and to individual technical skills, were removed by normalizing the average level by participant.

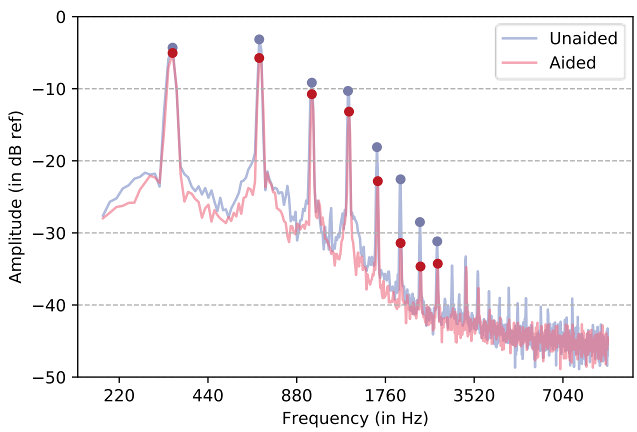

Figure 2. Spectral representation of the same note (E4) played piano with a French horn with (red) and without (blue) hearing aid. Extracted peaks are represented with a dot for the fundamental frequency and the first 7 overtones.

The spectrum was computed for each note and used to extract information in the frequency domain, i.e. harmonic peaks and spectral centroid. The spectral centroid is a summary of the static spectral energy distribution or the frequency where the energy of the spectrum is centered upon [20]. The spectrum can also be used to extract the magnitude and frequency of each peak (Fig. 2). Extracted harmonics were limited to the 5 first peaks for the analysis. These peaks represent the fundamental frequency (f1) and the corresponding overtones (f2 to f5).

The analysis of the extracted feature will be split into two stages, one with broadband features (level and spectral centroid) and a second with the amplitude of the harmonic peaks. Feature extraction was made with scipy (1.3.1) and librosa (version 0.6.3) libraries within Python (version 3.7.4).

2.4 Data Analysis

Data describing the notes and the participants were combined for the analysis. Changes in the response variable were modelled with mixed-effect regression. This model permits further reflection of the data structure, in which different notes, with the same label, are nested within each participant.

Fixed effects were defined by the experimental design as either explanatory variables (listening condition, dynamic, and their interaction) or as control variables describing the note (fundamental frequency), the participant (hearing aid gain, level and pitch discrimination thresholds), or the instrument (instrument type and range). The instrument type variable was recoded in a categorical variable with two levels (wind or string instrument) to reduce the complexity of the fitted model. Continuous fixed effects were centered and scaled to better compare their effect on the outcome variable. Categorical variables were releveled so that the intercept of the model is estimated for the unaided and piano condition.

As amplification is individually defined by the hearing loss, it is not expected to have the same effect of listening condition for all the participants. These differences were considered by adding a fixed-effect condition as varying slope by-participant.

The initial model is justified by the experimental design and by the identification of potential control variables from the literature. However, this complexity might challenge the optimization algorithm or show collinearity between some fixed effects. Collinearity was considered to play a negligible role if the variance inflation factor was below 3 [21]. Model complexity was reduced by removing control variables, those with only a minor effect on the outcome, if the optimization algorithm could not converge toward a solution.

The effect of fixed and random variables was tested with a likelihood ratio test that compared both a model with and without the target variable. Tests of the fixed effect were limited to the explanatory variables based on the test design, i.e. the condition and the interaction condition by dynamic.

The distribution of the residuals was visually inspected with a histogram and a quantile-quantile plot to check the normal distribution as well as a residual plot to verify independent distribution. Data preparation, analysis and graphics were made with R software (version 3.6.2) using lme4 [22] and ggplot2 [23] packages.

3. RESULTS

3.1 Sound Level from RMS

The effect of amplification by dynamic and instrument type is shown in Figure 3. While there are differences between instrument type, the effect of amplification is quite constant across the different combinations of dynamic and instrument type. This first observation supports the hypothesis that amplification provided by hearing aids modifies the auditory feedback and consequently influenced the musician's control over the instrument. Results in Fig.3 suggest that there is also a quantitative interaction between condition and dynamic, i.e. participants play softer with the hearing aid especially at softer dynamics.

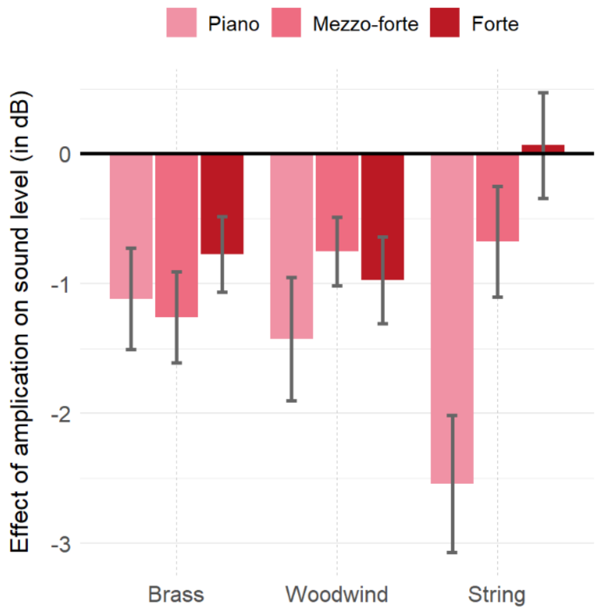

Figure 3. Average effect of amplification in dB (y axis) within each note on the sound level by instrument type (x axis) and by dynamic (color). Error bars represent one standard error.

Collinearity issues between variables representing similar traits were identified in the initial model. The condition variable was kept instead of hearing aid gain as it is easier to interpret a binary nominal variable. The fundamental frequency was preferred over the instrument range (3 levels categorical variable) because there is an overlap between the categorical possibilities (bass, medium, and high). Pitch discrimination threshold was also dropped as it showed collinearity with the level discrimination threshold.

The effect of amplification is significant (χ^2 (1) = 11.4, p = 0.001), i.e. the same note is played softer within the aided condition. The interaction between condition and dynamic was also significant (χ^2 (2) = 7.4, p = 0.025), meaning that participants played softer especially for a piano dynamic in the aided condition. The marginal R^2 (variance explained by the fixed effects) was 0.57 and the conditional R^2 (variance explained by the fixed and random effects) 0.83.

3.2 Spectral centroid

The effect of amplification on the spectral centroid by dynamic and instrument type is shown in Figure 4. The centroid increases at a piano dynamic with the aided condition; this effect is more notable for strings than for wind instruments. However, the centroid is lowered for louder dynamics. The direction (positive or negative) and the magnitude of the effect of amplification is not constant across the instrument type and dynamic. This observation suggests that there is a qualitative interaction between the condition and the dynamic.

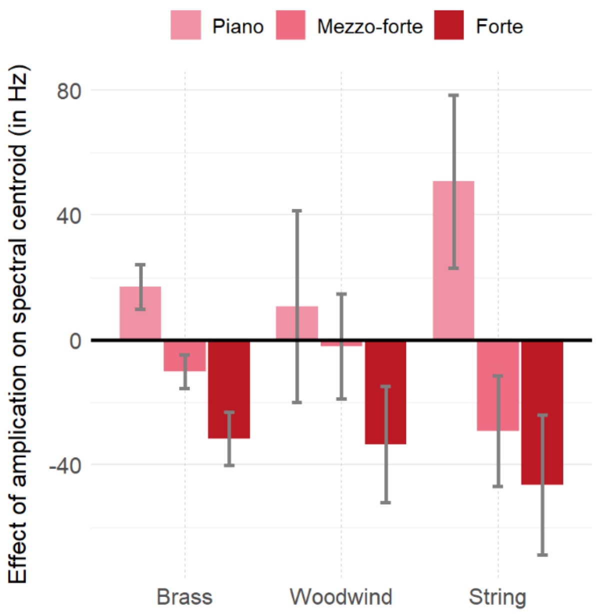

Figure 4. Average effect of amplification in Hz (y axis) within each note on the spectral centroid by instrument type (x axis) and by dynamic (color). Error bars represent one standard error.

The effect of amplification is not significant (χ^2 (1) = 2.6, p = 0.36) as well as the interaction between condition and dynamic (χ^2 (2) = 2.0, p = 0.11). The marginal R^2 was 0.46 and the conditional R^2 0.88.

Interpretation of the regression's coefficients for the final model are discussed in section 4 for the sound level and the spectral centroid.

3.3 Peak amplitude of harmonics

The peak of the extracted harmonics is computed for each note in each condition. The average effect of amplification (aided minus unaided peak) is summarized by dynamic and by instrument type (string or wind) in Figure 5.

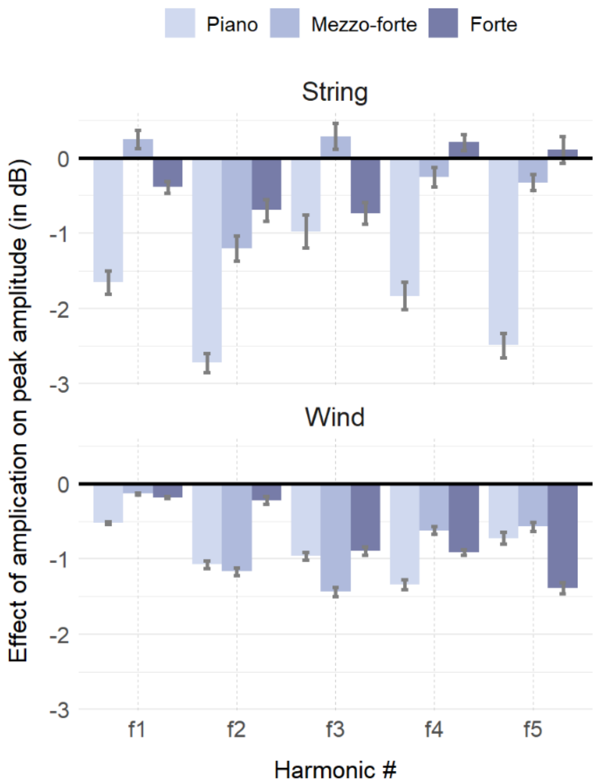

Figure 5. Average effect of amplification in dB (y axis) within each note on the extracted peaks by harmonic number (x axis), by dynamic (color) for the string (top) and for the wind (bottom) instruments. Error bars represent one standard error.

The outcome for the regression model was defined as the difference in dB between the aided and unaided conditions for each extracted peak. Predictors were harmonic number, dynamic, instrument type, and the interaction between instrument type and dynamic (Table 1). The intercept of the model represents the effect of amplification for the fundamental frequency (f1), at a piano dynamic and with a string instrument ($\beta 0$ = -1.6 dB). As the condition term is already present in the outcome and removed from the predictors, it is not possible to use the likelihood ratio test to evaluate the effect of amplification. However, it is possible to test if the intercept is different from 0. The degree of freedom needed to compute the Welch's t-test can be estimated with the Satterthwaite method. This method is also used to test all the listed fixed effects.

The effect of the harmonic number on the change in peak amplitude is not clear. It seems that the second harmonic is more affected by amplification especially when considering the instrument type. For string instruments, dynamic plays a major role on the effect of amplification on the peak amplitude. The peaks are attenuated by 1.9 dB (SD 4.4 dB) for piano, 0.2 dB (SD 4.2 dB) for mezzo forte, and 0.3 dB (SD 3.6 dB) for the forte dynamic. For the wind instrument, the effect of dynamic is less pronounced for the piano dynamic, as the peaks are attenuated with amplification by 0.9 dB (SD 4.7 dB) for piano, 0.8 dB (SD 4.3 dB) for mezzo, and 0.7 dB (SD 4.2 dB) for forte. This difference is reflected by the significant interaction terms between instrument type and dynamic.

	Change in peak amplitude (in dB)
Intercept	**-1.6**, t = -3.0**
From f1 to	
f2	**-0.6**, t = -2.0*
f3	**-0.6**, t = -1.8
f4	**-0.5**, t = -1.6
f5	**-0.5**, t = -1.6
Dynamic from piano:	
To mezzo-forte	**1.7**, t = 3.3**
To forte	**1.6**, t = 3.1**
Instrument type from string to wind	**1.1**, t = 2.0*
Interactions: Wind x Mezzo	**-1.5**, t = -2.6**
Wind x Forte	**-1.4**, t = -2.4*
Note:	*p<0.05; **p<0.01; ***p<0.001

Table 1. Summary of the fixed effects for the change in peak amplitude of the extracted harmonics. Welch's t-test uses Satterthwaite's method.

4. DISCUSSION

The final model with all the fixed effects is shown for the level and the spectral centroid in Table 2. The coefficient's interpretation gives some additional information about changes in the outcome variable.

4.1 Effect of amplification on level

For the sound level model, amplification reduces the level by 1.6 dB when all the other variables are kept constant for the reference situation (piano, string instrument and average continuous predictors). Changing from piano to mezzo-forte increases the level an average of 5.1 dB and changing from piano to forte increases the level an average of 8.7 dB. These observations make sense as participants played louder when they were asked to increase the dynamic.

The interaction terms have positive coefficients; when a participant plays louder, the effect of amplification, which should reduce the level, is less important. Amplification provided by the hearing aid is based on a non-linear function to provide more gain for softer input levels [19]. Additionally, hearing-loss changes the loudness growth function especially for softer sound levels [24]. The effect of amplification might therefore be more important for the piano dynamic. For louder input levels, the hearing aid reduces the gain and the proportion of direct sound over amplified sound becomes more important [25]. In this case, it is expected that amplification should have less impact on the perceived sound and the auditory feedback loop. This non-linear behavior could potentially explain the interaction term between recording condition and dynamic. Playing under the aided condition should increase the dynamic range.

	Dependent variable:	
	Sound level (in dB ref)	Spectral centroid (in Hz)
Intercept	**-39.0***** (0.5)	**1,047***** (70)
Condition		
Unaided to Aided	**-1.6***** (0.4)	**-8** (15)
Dynamic		
Piano to Mezzo-forte	**5.1***** (0.3)	**43**** (14)
Piano to Forte	**8.7***** (0.3)	**180***** (14)
Fund. frequency	**0.7**** (0.2)	**66*****(14)
Level discr. thresh.	**0.4** (0.2)	**10** (8)
Instrument type		
String to Wind	**-0.5** (0.6)	**-465***** (76)
Interaction		
Aided x Mezzo	**0.8*** (0.4)	**0** (20)
Aided x Forte	**1.0****(0.4)	**-25** (20)
Note:	*p<0.05; **p<0.01; ***p<0.001	

Table 2. Summary of the fixed effects for the model of sound level (left column) and spectral centroid (right column). The standard error is shown in brackets.

Additional sources of variation should be discussed as they might provide more information about the model. The recruited participants do not form a homogeneous group of musicians. Technical abilities vary between participants and might explain different dynamic ranges. Experienced musicians will control their instrument better especially for soft dynamics [26]. An outlier was detected while verifying the distribution of the residuals. All the residuals were in a range of ± 6 dB, expect one value, that had an error of - 17 dB compared to the prediction of the model. This observation was the highest note played piano by a professional clarinetist. This musician possessed extreme control over the instrument so that this piano note was 28 dB softer than the same note played mezzo-forte. However, estimating and including a value representing technical abilities is challenging, as it combines musical experience, education, perceptual musical skills, motoric capacities and more [26].

These results were also obtained for a solo recording. When playing in a group (band, chamber music or orchestra), music dynamic becomes a relative concept. The musician must adapt his musical performance to the environment on top of the indicated dynamic. We can only assume that if the task is to play piano, that the hearing aid provides the correct amount of amplification to allow them to play softer. The test design does not allow for generalization of these findings to a group performance and to know if the changes in the auditory feedback path caused by amplification improve musicians' ability to blend in with a group. This additional information would give a qualitative indication; does the measured change have a positive impact on the way musicians play? It is an important focus, because playing music with a soft dynamic has been identified as a challenge for hearing impaired musicians [27].

4.2 Effect of amplification on spectral centroid

For the spectral centroid, the interpretation is less straightforward, because the coefficient for the instrument type is the largest. The spectral centroid is estimated to be 465 Hz lower for the wind than for the string instruments. The dynamic has also an influence on the spectral shape of the note, with higher spectral centroids for louder dynamics. The spectral centroid also increases with the fundamental frequency as expected. This coefficient is expected as higher notes have higher harmonics and the centroid of the spectrum will be by default increased.

The effect of amplification with the hearing aid is small compared to other variables and it might be partially confounded by the change in level. If the spectral centroid changes with the dynamic and if musicians play louder without their hearing aids, then the estimated effect of condition might be explained more by the change in dynamic than by amplification.

5. CONCLUSION

The comparison of recordings from hearing impaired musicians with and without hearing aids was used to evaluate the effect of amplification on the auditory feedback loop. Changes in sound level indicate that amplification might provide more auditory information so that musicians reduce the level of the produced notes especially for piano or a softer dynamic. This effect was not observed for the spectral centroid which might be more affected by the dynamic than by amplification.

These results suggest that hearing loss alters auditory feedback and that by wearing hearing aids, some of these deficits might be returned. These results are however obtained in a controlled environment without the need for the musician to adapt his performance to a group or orchestra. This aspect requires further investigation to generalize the results to more realistic performing conditions.

6. REFERENCES

[1] J. Luo, S. R. Hage, and C. F. Moss, "The Lombard Effect: From Acoustics to Neural Mechanisms," *Trends in Neurosciences*, vol. 41, no. 12, pp. 938–949, Dec. 2018.

[2] H. Lane and B. Tranel, "The Lombard Sign and the Role of Hearing in Speech," *Journal of Speech and Hearing Research*, vol. 14, no. 4, pp. 677–709, Dec. 1971.

[3] R. J. Zatorre, J. L. Chen, and V. B. Penhune, "When the brain plays music: auditory–motor interactions in music perception and production," *Nature Reviews Neuroscience*, vol. 8, no. 7, pp. 547–558, Jul. 2007.

[4] E. W. Large and C. Palmer, "Perceiving temporal regularity in music," *Cognitive Science*, vol. 26, no. 1, pp. 1–37, Jan. 2002

[5] M. A. Selleck and R. T. Sataloff, "The Impact of the Auditory System on Phonation: A Review," *Journal of Voice*, vol. 28, no. 6, pp. 688–693, Nov. 2014.

[6] K. N. Stevens, R. S. Nickerson, A. Boothroyd, and A. M. Rollins, "Assessment of Nasalization in the Speech of Deaf Children," *Journal of Speech and Hearing Research*, vol. 19, no. 2, pp. 393–416, Jun. 1976.

[7] Y.-C. Hung, Y.-J. Lee, and L.-C. Tsai, "Vowel production of Mandarin-speaking hearing aid users with different types of hearing loss," *PLOS ONE*, vol. 12, no. 6, p. e0178588, Jun. 2017.

[8] A. L. Pittman, A. Daliri, and L. Meadows, "Vocal Biomarkers of Mild-to-Moderate Hearing Loss in Children and Adults: Voiceless Sibilants," *Journal of Speech, Language, and Hearing Research*, vol. 61, no. 11, pp. 2814–2826, Nov. 2018.

[9] A. C. Coelho, D. M. Medved, and A. G. Brasolotto, "Hearing Loss and the Voice," in *Update On Hearing Loss*, InTech, 2015.

[10] C. D. Martin et al., "Online Adaptation to Altered Auditory Feedback Is Predicted by Auditory Acuity and Not by Domain-General Executive Control Resources," *Frontiers in Human Neuroscience*, vol. 12, Mar. 2018.

[11] P. Q. Pfordresher, "Musical training and the role of auditory feedback during performance," *Annals of the New York Academy of Sciences*, vol. 1252, no. 1, pp. 171–178, Apr. 2012.

[12] T. A. Pruitt and P. Q. Pfordresher, "The role of auditory feedback in speech and song.," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 41, no. 1, pp. 152–166, 2015.

[13] B. Kleber, A. G. Zeitouni, A. Friberg, and R. J. Zatorre, "Experience-Dependent Modulation of Feedback Integration during Singing: Role of the Right Anterior Insula," *Journal of Neuroscience*, vol. 33, no. 14, pp. 6070–6080, Apr. 2013

[14] E. Kozłowski, J. Żera, and R. Młyński, "Effect of Musician's Earplugs on Sound Level and Spectrum During Musical Performances," *International Journal of Occupational Safety and Ergonomics*, vol. 17, no. 3, pp. 249–254, Jan. 2011.

[15] V. Rawool and R. Buñag, "Levels of Music Played by Caucasian and Filipino Musicians with and without Conventional and Musicians' Earplugs," Journal of the American Academy of Audiology, vol. 30, no. 1, pp. 78–88, Jan. 2019.

[16] K. Huttunen, V. Sivonen, and V. Pöykkö, " Symphony orchestra musicians′ use of hearing protection and attenuation of custom-made hearing protectors as measured with two different real-ear attenuation at threshold methods," *Noise and Health*, vol. 13, no. 51, p. 176, 2011.

[17] M. J. Kirchberger and F. A. Russo, "Development of the Adaptive Music Perception Test," *Ear and Hearing*, vol. 36, no. 2, pp. 217–228, 2015.

[18] J. M. Vaisberg, A. T. Martindale, P. Folkeard, and C. Benedict, "A Qualitative Study of the Effects of Hearing Loss and Hearing Aid Use on Music Perception in Performing Musicians," Journal of the American Academy of Audiology, vol. 30, no. 10, pp. 856–870, Nov. 2019.

[19] G. Keidser, H. R. Dillon, M. Flax, T. Ching, and S. Brewer, "The NAL-NL2 prescription procedure," *Audiology Research*, vol. 1, no. 1S, May 2011.

[20] J. M. Grey and J. W. Gordon, "Perceptual effects of spectral modifications on musical timbres," The *Journal of the Acoustical Society of America*, vol. 63, no. 5, pp. 1493–1500, May 1978.

[21] A. F. Zuur, E. N. Ieno, and C. S. Elphick, "A protocol for data exploration to avoid common statistical problems," *Methods in Ecology and Evolution*, vol. 1, no. 1, pp. 3–14, Nov. 2009.

[22] D. Bates, M. Mächler, B. Bolker, and S. Walker, "Fitting Linear Mixed-Effects Models Usinglme4," Journal of Statistical Software, vol. 67, no. 1, 2015.

[23] H. Wickham, *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York, 2016.

[24] B. C. J. Moore, "The Perception of Loudness*," An introduction to the psychology of hearing* (6th ed.). Academic Press, 2003, p. 163.

[25] A. Winkler, M. Latzel, and I. Holube, "Open Versus Closed Hearing-Aid Fittings: A Literature Review of Both Fitting Approaches," *Trends in Hearing*, vol. 20, p. 233121651663174, Feb. 2016.

[26] S. Weinzierl, S. Lepa, F. Schultz, E. Detzner, H. von Coler, and G. Behler, "Sound power and timbre as cues for the dynamic strength of orchestral instruments," *The Journal of the Acoustical Society of America*, vol. 144, no. 3, pp. 1347–1355, Sep. 2018.

[27] L. N. C. Law and M. Zentner, "Assessing Musical Abilities Objectively: Construction and Validation of the Profile of Music Perception Skills," *PLoS ONE*, vol. 7, no. 12, p. e52508, Dec. 2012.