The influence of room acoustic parameters on the impression of orchestral blending

Jithin Thilakan[1], Otavio Colella Gomes[1,2], Malte Kob[1]

[1]Erich Thienhaus Institut, Detmold University of Music, Germany
(jithin.thilakan@hfm-detmold.de, malte.kob@hfm-detmold.de)
[2]Müller-BBM GmbH, Planegg, Germany
(otavio.gomes@mbbm.com)

Abstract

The blending between sound sources is an important attribute relevant in current acoustic research disciplines such as evaluation of the sound field of an orchestra/ensemble in real or VR domains, and adaptation of stage/room acoustics. Recent studies reveal that the room acoustic characteristics significantly influence the blending impression. This paper investigates the relations between established room acoustic parameters and the perceived degree of blending.

A set of Spatial Room Impulse Responses (SRIRs) for a wide variety of virtual rooms were generated using geometry-based room acoustic simulation software. Perceptually rated dry recordings of two violins were auralized using these SRIRs. A listening test with expert listeners (Tonmeisters & musicians) was carried out to rate the blending between violins in these simulated environments. Potentially relevant room acoustic parameters to the orchestral blending are evaluated and discussed. The results show that the correlation of parameters such as EDT, T_{30}, and C_{80} with blend rating is observed to be influenced by the source-level blending.

Keywords: Orchestral blending, room acoustics, auralization, perceptual evaluation, virtual acoustics.

1 Introduction

While attending orchestra performances, listeners don't necessarily hear the individual instruments, instead they experience a fusion of individual sound sources that results in a blended orchestral sound impression. 'Blending' refers to the perceptual fusion of two or more concurrent sounds by losing their individual distinctiveness [1, 2, and 3] and it is often an end goal in joint musical performances. Hence, investigation of blending between sources has high relevance in many areas such as music composing, performance and recording, room/stage acoustic adaptations, orchestra sound field evaluation in real and VR, etc [4, 5]. Blending is observed to be a multi-dimensional sonic phenomenon that is highly influenced by many factors such as the music composition and performance-related attributes, the characteristics of music performance space, the position and orientation of the sources and listeners, personal skill and experience of the listener, etc.

In orchestral performance, each performer/listener experiences a different impression of blending due to acoustic and musical factors. At the same time, the choice of the desired degree of blending between sound sources is different for composers, conductors, musicians, recording engineers, and finally the listeners depending upon their taste and requirements. Recent studies show that the acoustic features of concert halls significantly influence the blending impression [6]. In the acoustic transfer path of the orchestra/ ensemble sound formation (shown in Figure 1), the influence of the feedback from the musical instrument and the acoustic environment on the musician is observed to have a high impact on the resulting sound field [7, 8]. Furthermore, to achieve a blended sound impression, it requires coordinated action and joint strategies between two or more performers in a joint performance [9]. As a result, musicians try to adjust different aspects of performance which in effect changes the overall sound field of the orchestra.

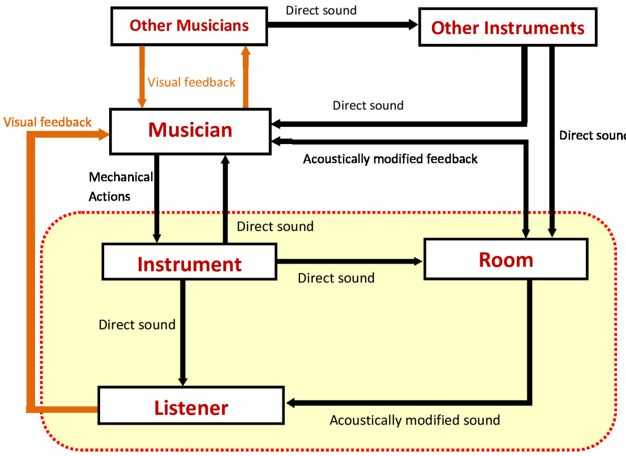

Figure 1 – Acoustic transfer path of ensemble sound formation.

Although the acoustic transfer path of the ensemble sound formation is a multi-level process, the progress of blending impression can be resolved into a three-level process: formation of blending at the source level, alteration of blending due to room acoustics, and perception of blending at listener's level. At the source level, blending is mainly influenced by the timbre of constituent instruments, and musical factors in joint performances such as pitch similarity, synchronicity in note transients and micro-modulations, formant matching, loudness adjustment, etc. The directivity of sound sources shows how the instrument excites the acoustic environment. Finally, the room acoustic environment alters the sound field of the orchestra spectrally (timbre coloration [10]) and temporally (early and late reflections [11, 12]) and thereby influence the blending impression. In addition, the seating arrangement of string sections which correlates with radiation characteristics of sound sources seems to have a high influence on the resultant blending impression [11].

However, it is not completely sure that the presence of having a room acoustic environment always improves the blending impression. In addition, the impact of room acoustics on the blending impression for samples with different degrees of source-level blending is also unexplored. This paper investigates the influence of acoustic environment and contribution of room acoustic parameters on the impression of blending between two sources having different source-level blending.

Geometrical room acoustic modeling software is used to generate Spatial Room Impulse Responses (SRIRs) for 25 different acoustic environments. This is used for auralizing two violins and thereby determining the relationship between the blend rating and the acoustic parameters. Even though the geometrical room acoustic simulations have limitations in dealing with complex wave phenomena and are observed to have perceptual differences from real rooms [13], it possesses advantages that include estimation of SRIR for directional sources, easiness in alteration of acoustic properties of materials and geometry of rooms, lack of background noise and distortion, etc [14]. To check the impact of the acoustic environment on samples with different levels of source-level blending, a separate perceptual test is conducted on sound samples recorded with clip-on microphones attached on violins in a joint live performance, and as a result, three stimuli having good, moderate, and poor source-level blending are obtained. Using these three stimuli in the 25 simulated acoustic environments, the influence of room acoustics in the overall blending impression and its impact on stimuli with different source-level blending are estimated and presented.

2 Methodology

2.1 Simulation of SRIRs

Commercially used geometrical room acoustic modelling software, ODEON version 16 is used to simulate different acoustic environments. ODEON uses a hybrid method of image sources and a modified ray-tracing approach for the room acoustic simulation and also possesses the advantage of simulation of diffraction [15]. Four rectangular shaped rooms with an approximate volume of 500 m^3 (roughly having length × width × height as 10×10×5 m), 5000 m^3 (33×14×11 m), 10,000 m^3 (36×20×14 m), and 15,000 m^3 (36×29×14 m) respectively are simulated using ODEON. These rooms are named henceforth as 'R1', 'R2', 'R3', and 'R4' as in the above-given order. Three different variations for each particular room are generated by changing the absorption coefficients of the surfaces which result in the 'Dry', 'Normal', and 'Wet' variants. The direction of the reflections, which is a function of the room geometry in geometrical acoustics, remains the same in the three variants, but the strength of the reflections gets changed which eventually resulted in different acoustic impressions. In addition to these 12 different room acoustic simulations (4 rooms × 3 variants), an anechoic chamber version is also simulated using R1 with 100% absorbing surfaces.

Table 1 – Wall absorption coefficients of dry, normal and wet variants for different frequency bands.

Condition	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Dry	0,18	0,31	0,36	0,4	0,42	0,42	0,43	0,43
Normal	0,18	0,18	0,16	0,14	0,13	0,12	0,11	0,10
Wet	0,10	0,10	0,09	0,08	0,07	0,06	0,05	0,05

All rooms had a stage and an audience area proportional to the rooms' size and representative of realistic rooms. The stage height was 100 cm and the audience block height was 50 cm. The listener was positioned at a height of 130 cm and pointing towards the sources as shown in Figure 2. The absorption and scattering coefficients for the audience area were set as typical values for occupied rooms and these values were kept constant for the different room conditions, with the exception of the anechoic room where the audience was also set to 100% absorbing. The absorption coefficient for all other surfaces used for the different conditions are presented in table 1.

In this paper, these acoustic environments are abbreviated in the given order: the room geometry as **'R1', 'R2'**, **'R3'**, and **'R4'** – room variants as **'A', 'D', 'N', 'W'** (anechoic, dry, normal and wet) – and the listener location as **'c', 'f'** (close/near location, far location). An example: R2Wf represents the far location in the wet variant of 5000 m^3 room.

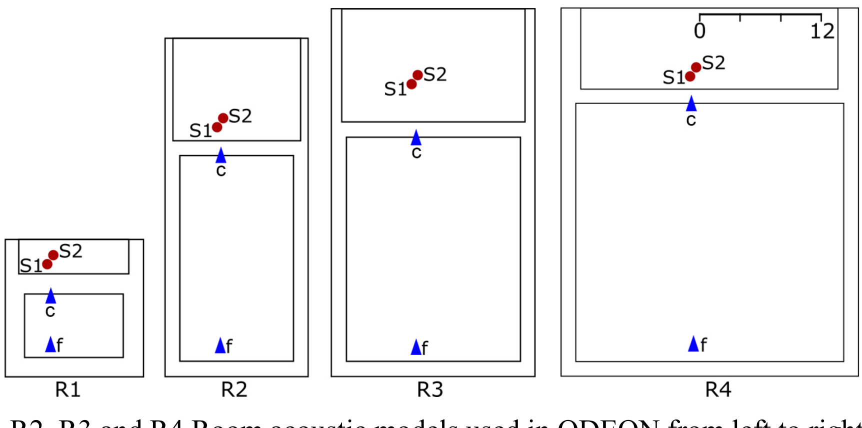

Figure 2– R1, R2, R3 and R4 Room acoustic models used in ODEON from left to right, location and orientation of sources (red) and receivers (blue)

In each simulated room, two virtual sound sources, i.e. the violins are placed slightly off-center to avoid the unwanted acoustic effects due to room symmetry. The two sources are kept at a separation of a distance of 1 meter and directed slightly towards the left side of the concert hall (see Figure 2) in all simulated rooms. The built-in directivity pattern of violin in ODEON which is averaged over 1 octave band is applied for the sound sources. Two receiver locations are chosen, one at the first row of the seating, i.e. close location (where the direct sound from the music instruments dominates), and one in far-field location of the simulated room (where the reverberant sound dominates). Similar to the sources, the listener locations are also off-center to avoid unwanted room effects (see Figure 2) in all simulated rooms. The two listeners are oriented towards the sources. The Spatial Room Impulse Responses (SRIRs) for the rooms are collected as 3rd order Ambisonics in B-format from ODEON.

2.2 Selection of sound stimuli

As mentioned earlier, studies show that it requires coordinated action and joint strategies between two or more performers to achieve a blended sound impression in a joint performance [9]. Room acoustic feedback on musicians is also observed to have an impact on their performance and thereby musicians try to adjust different aspects of performance [7]. Hence, by considering these factors into account, the best possible way to obtain a realistic and well-blended sounding impression between instruments is to record the instruments during a joint performance. But the challenge, in this case, would be to minimize the contribution of room in the recordings and reduce the microphone cross-talk.

A string ensemble consisting of 9 violins is recorded at Detmold Concert House using individual 'DPA 4099 Core Violin' clip-on microphones. From these recordings, audio samples consisting of two violins in which the constituent violins don't possess dominant cues for source segregation (such as asynchronous transients, major pitch difference, etc) in the samples are selected. A set of 50 audio samples having a length of 3 to 5 seconds are extracted and post-processed in REAPER (a Digital Audio Workstation) by applying a smooth high pass filter centered around 200 Hz to reduce the breathing and bowing noise from the player. In general, these samples had a minimal room acoustic contribution. Monophonic audio files of the samples are rendered, and a listening test has been conducted with 15 participants that include Tonmeisters, and experienced musicians to rate the degree of blending in each sample. The participants were asked to rate the blending between two violins in each sample on a scale from 1 to 10, in which a high value for a sample corresponds to a high blending impression. Since we don't know what the possible extremes in blending impression are, it was not possible to provide reference samples to the listeners at the beginning of the test which could have helped them to form their own inner-scale of blending rating.

Based on the results from the listening test, three audio samples having three different degrees of blending are chosen: '**Stimulus A**' with rating **7.9 ± 1.56** out of 10, '**Stimulus B**' with rating **5.5 ± 2.1**, and '**Stimulus C**' with rating **3.3 ± 1.87** to represent a good, moderate, and poor levels of blending. A separate pilot test with ear-trained experts validated that these selected stimuli possess reduced crosstalk in individual channels, and also the minimum level of room contribution in comparison with the other audio samples. In addition to these three samples, four other samples were also chosen for the training phase of the listening test (explained in the coming sections).

2.3 Creation of test samples

The convolution of the selected sound stimuli with the SRIRs in 3rd order (16 channel) ambisonics format is performed in REAPER using MCFX convolver [16]. For a particular acoustic environment, the two individual source signals are convolved with the two SRIRs obtained for the virtual sound sources (violins). An attenuation factor obtained from the ODEON simulation is used to adjust the gain of the individual tracks to preserve the realistic scaling between levels of different source-listening combinations for the virtual acoustic environment. To change the 3D convolved audio file into a binaural format, it is convolved with the far-field Head Related Transfer Function (HRTF) of Neumann KU 100 [17], a common standard binaural head in the field of audio recording, using SPARTA AmbiBIN plugin [18].

After rendering, the samples are cropped to avoid the reverberation tail at the end, and 0.5 second long fade-in and fade-out filters were added at the starting and ending of samples.

2.4 Listening test process

18 participants (4 female, 14 male) that includes Tonmeisters and experienced musicians participated in the listening test. Among the 18 participants, 16 of them had undergone ear-training and all of the participants had prior experience in critical listening. The listeners were aware of the objective of the test. The listening test was conducted under the platform SQUALA developed by Head Acoustics GmbH.

The Graphical User Interface (GUI) of the SQUALA platform is shown in Figure 3. A category judgement test is performed to rate the blending impression of each sample in which a 10 point scale having values from 1 to 10 represented using the categories 'Intolerable', 'severe', 'very poor'.... 'very good', 'excellent' (see Figure 3). The test was conducted individually for each listener inside a quiet and dry room. For all listeners, the binaural audio samples are played back in the test using Beyerdynamic DT 770 Pro closed-back studio headphone connected to the laptop computer using RME Babyface Pro sound card.

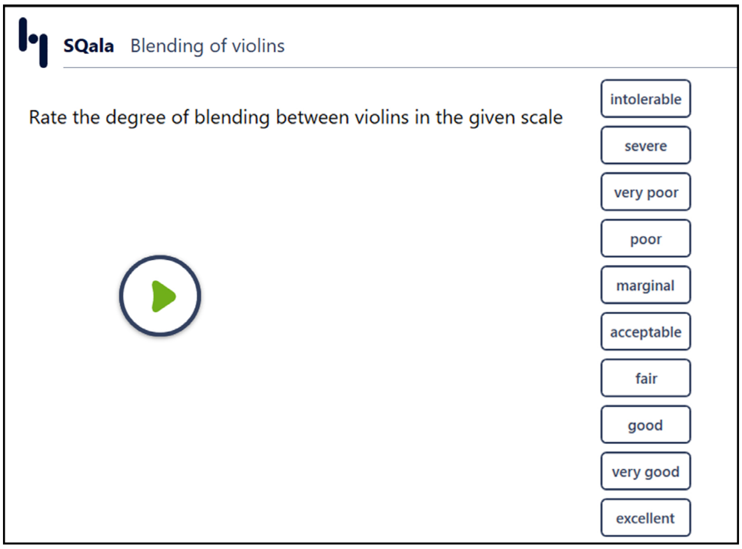

Figure 3 – Graphical user interface used for the performance of listening test.

At the beginning of the test, the goal of the experiment, definition of blending, etc were explained to the listeners to make them aware of the objective of the study. After that, the listeners had to undergo a familiarization/training phase. In this phase, the listeners were asked to rate the blending of 20 audio samples which are auralized using 4 different test stimuli (as mentioned above) in 5 different acoustic environments, to know the possible variations of acoustic environments. Since we don't know the standard examples of excellent and intolerable levels of blending (the possible extremes), the listeners used the familiarization audio samples to form their internal scale of blending based upon the possible variations of acoustic environments. As a result, this familiarisation phase helps the listeners to avoid the central biasing tendency of rating. During the familiarisation phase, the listeners were allowed to change the sound volume level according to their preference. But later, during the real test phase, the level was kept to be constant.

Once the listener completed the familiarisation phase, the real test consisting of 75 samples is started. To avoid the direct comparisons due to memory retaining effects of the brain, the convolved audio samples were randomized in a way that no two samples with the same stimulus come one after the other. Also, the acoustic environments had significant changes in the consecutive samples to reduce the sequential effects. The listeners had the choice to repeat the audio samples multiple times as they want. After each set of 20 samples, listeners were asked to take a short break of 1 to 3 minutes (up to their choice) to reduce the mental fatigue due to the test. Finally, at the end of the test, a discussion with participants about the overall impression of the test, subjective impression of blending, etc, is carried out. Altogether, the listeners took around 40 minutes to 1 hour to complete the whole test.

3 Result and Discussion

3.1 Listening test reliability

To validate the inter-rater reliability or the internal consistency between listeners, Chronbach's alpha [19] value, a commonly used coefficient of reliability value, is calculated for the listeners' ratings. The inter-rater reliability refers to the degree of agreement between the independent listeners in the rating of blending for each sample. The Chronbach's alpha is calculated to be 0.901 which denotes high reliability among the test participants on the rating of blending.

3.2 Variation of blending with room acoustic parameters

The acoustic parameters for individual RIR from a particular source with the directivity of violin to the listener position are obtained from ODEON. For one particular acoustic environment, the value of acoustic parameters is estimated by averaging the values obtained from the two RIRs for the frequency bands 500 – 1000 Hz. As the source directivity was not omni directional, the values presented are not in agreement with the ISO 3382-1 [20]. However, the parameters are still representative of the acoustic sound field in the different environments and comparisons within this experiment are possible.

The parameters Early Decay Time (EDT), Reverberation Time (T_{20}, T_{30}), Clarity (C_{80}), Definition (D_{50}), Strength (G_{early} calculated for 0 to 80 ms, G_{late} for 80 ms onwards, and $G_{5\text{-}80}$ for 5 to 80 ms particularly meant for early reflections), Direct Sound Pressure Level (SPL_{direct}), and Lateral fraction (LF, LFC) are estimated referring to ISO 3382-1. A correlation analysis between the mean values of ratings of each stimulus in the 25 acoustic environments with its corresponding room acoustic parameters is carried out, and the Pearson correlation coefficients are provided in Table 2. It is to be noted that the anechoic room simulation is excluded from the 25 acoustic environments for the correlation with C_{80}, $G_{5\text{-}80}$ and G_{late} due to the non-physical values of these parameters in the anechoic chamber.

Table 2 – Pearson correlation coefficients between mean value of blend ratings for three stimuli in different acoustic environments and its corresponding room acoustic parameters (for 500- 1000 Hz octave bands)

Sound Stimulus	EDT	T_{30}	C_{80}	G_{early}	$G_{5\text{-}80}$	G_{late}	SPL_{direct}	LF
Stimulus A	**0.53****	**0.56****	**-0.41***	**-0.48***	**-0.51***	-0.15	**-0.50***	0.00
Stimulus B	**0.65****	**0.69****	**-0.70****	**-0.42***	-0.30	0.13	**-0.57****	0.36
Stimulus C	**0.75****	**0.79****	**-0.78****	**-0.53****	**-0.42***	0.14	**-0.56****	0.10

* Correlation is significant at p-value < 0.05 level
** Correlation is significant at p-value < 0.01 level

In general, the correlation analysis shows that the blending rating impression is significantly correlated with room acoustic parameters such as EDT, T30, C_{80}, G_{early}, and SPL_{direct}. The Early Decay Time (EDT) which better reflects the perception of reverberation [21] possesses a high correlation with T_{30} (**0.982****) and C_{80} (**-0.85****). Similarly, the G_{early} and SPL_{direct} are also observed to have a high correlation (**0.80****) among themselves. For these simulated environments, the Lateral Fraction parameter which shows the influence of early side reflections seems to have no correlation with the impression of blending for the three different stimuli. A similar behaviour is also observed for G_{late}.

Considering the influence of source-level blending into account, it is observed that, when the source level blending gets poorer (from stimulus A to C), the correlation of the blending impression with EDT, T_{30}, and C_{80} increases whereas the correlation remains almost the same for G_{early}, and SPL_{direct}. This shows that although the above described room acoustic factors contribute to the blending impression, the influence of EDT, T_{30}, and C_{80} changes with the source level blending while the other parameters such as G_{early}, and SPL_{direct} do not exhibit such systematic changes.

The variation of blend rating with EDT is represented in Figure 4 (the acoustic environment corresponding to the EDT value is represented on the upper x-axis). It shows that the order and relative spacing between dry stimuli (7.8/10, 5.5/10, and 3.3/10 for the stimulus A, B, and C respectively) persists for spatially distributed sources under anechoic condition (4.6/10, 3.3/10, and 2.0/10 for stimulus A, B, C). It is to be noted that the perceptual scale of blending to rate the source level blending is developed on the basis of dry recordings with minimal room contribution. This perceptual scale developed by the listeners is different when it comes to the auralized samples in virtual rooms.

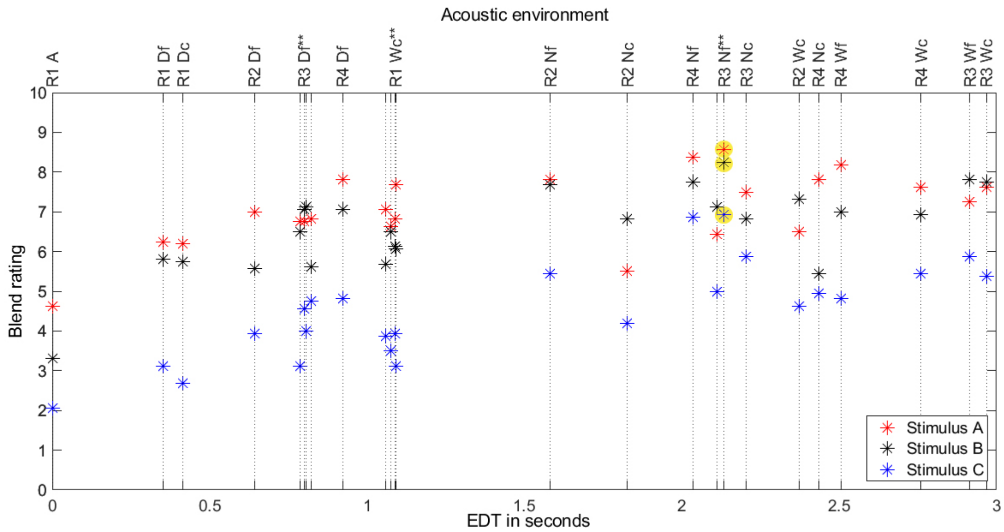

Figure 4 – Variation of blend rating with Early Decay Time (** on upper x-axis denotes closely spaced samples, i.e. multiple acoustic environments with close EDT values).

The samples of three stimuli from anechoic environments are observed to have the lowest possible blend ratings. Hence, the presence of having a room acoustic environment seems to improve the blending impression. Interestingly "R3 Nf", the far-field location in 10,000 m^3 room with normal acoustics (represented with yellow circle in Figure 4, 5, and 6), is observed to have the highest blend rating for the three stimuli irrespective of the source-level blending. Although some exceptional acoustic environments which degrade the blending are observed, the order of source-level blending for the stimuli persists in general. The degrading of blending for some samples may likely be due to the influence of other room acoustic parameters. In general, the Stimulus C seems to be linearly varying with the EDT up to roughly around 2.2 s compared to the other two stimuli which do not exhibit such a strong behaviour. This variation is reflected in the high correlation value for the Stimulus C with a poor source-level blending. This trend is consistent for T_{20} and T_{30} plots as well.

Figure 5 shows the variation of blending with C_{80} (the anechoic condition is excluded due to the infinite value of C_{80}). The general trend shows that the blending rating decreases with an increase in C_{80}. The C_{80} variation plot likely seems to be an inverted version of EDT variation which is consistent with a high negative correlation value between EDT and C_{80}. Similar to the earlier case, Stimulus C reflects a linear relationship with C_{80} in the range of -1 to 14 dB whereas this behaviour is not seen for the other stimuli. The same trend is observed in plotting the Definition (D_{50}) values as well.

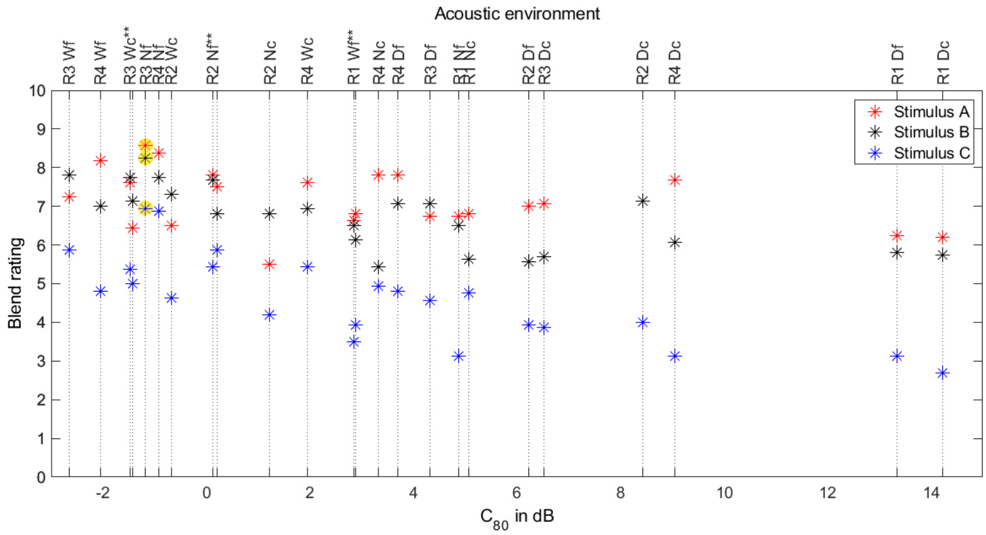

Figure 5 – Variation of blend rating with C80 (** on upper x-axis denotes closely spaced samples)

The variation of blend rating with G_{early} is shown in Figure 6. Unlike the previous cases, the three stimuli behave almost in a similar manner irrespective of their differences in source-level blending. Considering Figure 6 and the correlation value between G_{early} and blend rating, the contribution of G_{early} to the blending impression seems to be independent of the source level blending.

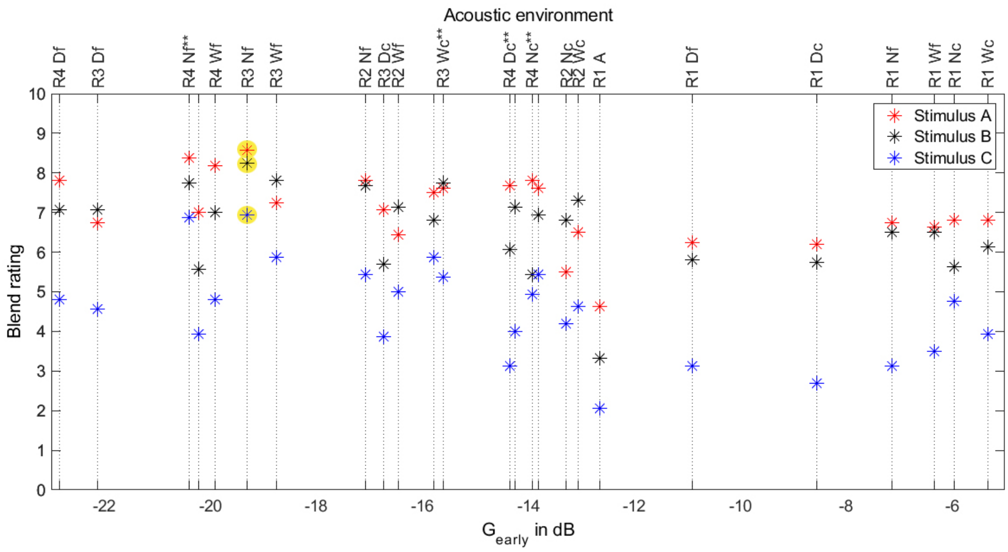

Figure 6 – Variation of blend rating with G_{early} (** on upper x-axis denotes closely spaced samples)

4 Conclusion

The influence of room acoustic features on the impression of blending is analysed using perceptually rated spot microphone recordings of two violins in different simulated room acoustic environments. SRIRs of 25 different acoustic environments are generated using ODEON simulation software and used to auralize three pairs of dry violins signals having good, moderate, and poor impression of source-level blending. A perceptual test with 18 trained listeners is conducted to rate the blending in different acoustic environments using virtual acoustic methods, and the resultant ratings are correlated with corresponding room acoustic parameters obtained from the simulation.

The results show that the simulated room acoustic environments generally contribute to the improvement of the impression of blending, and the conventional room acoustic factors such as EDT, T_{30}, C_{80}, G_{early}, etc possess a high correlation with the blend ratings. Although the three stimuli had different source-level blending characteristics, the maximum blending rating was reported for the same acoustic environment in the three cases. The impact of parameters EDT, T_{30}, and C_{80} on blend ratings seem to be influenced by the source level blending while the other parameters such as G_{early}, and SPL_{direct} do not exhibit such systematic behaviour. The blending impression is observed to be a function of multiple inter-correlated variables. Also, the geometry-based room acoustic simulations can have limitations on simulating more complex wave phenomena. Hence, more studies using multivariate analysis which includes SRIRs measured from real rooms with variable geometries would be needed to have a generalized solution showing the individual contribution of room acoustic parameters on the blending impression.

Acknowledgements

The authors thank the students the listening test participants for their kind and immense cooperation. Thanks to Dr. Isabel Schiller and Dr. Timo Grothe for the discussion on listening test planning, Nils Meyer-Kahlen for the support on creation of audio samples. This work has been performed within the project VRACE (Virtual Reality Audio for Cyber Environments) which has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska Curie actions (grant agreement number 812719).

References

[1] Lembke, Sven-Amin & Narmour, Eugene & Mcadams, Stephen. (2013). Predicting blend between orchestral timbres using generalized spectral-envelope descriptions. *The Journal of the Acoustical Society of America*. 133. 3449. 10.1121/1.4806105.

[2] Sandell, G. J. (1991). Concurrent timbres in orchestration: a perceptual study of factors determining blend. PhD thesis, Northwestern University.

[3] Roger A. Kendall & Edward C. Carterette (1993) Identification and blend of timbres as a basis for orchestration, *Contemporary Music Review*, 9:1-2, 51-67, DOI: 10.1080/07494469300640341.

[4] Ioannou, Stefanos & Kob, Malte. (2019). Investigation of the Blending of Sound in a String Ensemble, *Proceedings of ISMA 2019*, Detmold, Germany.

[5] Kob, Malte & Francisco, Martha & Rivest, Jean-François & Traube, Caroline. (2019). ODESSA - Orchestral Distribution Effects in Sound, Space and Acoustics: an interdisciplinary symphonic recording for the study of orchestral sound blending, *Proceedings of ISMA 2019*, Detmold, Germany.

[6] D. Lincke, "Instrumental Blending in Concert Halls," Master thesis, Technische Universitat Berlin Institut, 2020. Available at: https://www.ak.tu-berlin.de/menue/master_theses/

[7] Amengual Garí, Sebastià & Kob, Malte & Lokki, Tapio. (2019). Analysis of trumpet performance adjustments due to room acoustics, *Proceedings of International Symposium on Room Acoustics 2019*, Amsterdam.

[8] Amengual Garí, Sebastià & Lachenmayr, Winfried & Kob, Malte. (2015). Study on the influence of room acoustics on organ playing using room enhancement, *Proceedings of Third Vienna Talk on Music Acoustics,* Vienna.

[9] Lembke, Sven-Amin & Levine, Scott & Mcadams, Stephen. (2017). Blending Between Bassoon and Horn Players: An Analysis of Timbral Adjustments During Musical Performance. *Music Perception: An Interdisciplinary Journal*. 35. 144-164. 10.1525/mp.2017.35.2.144.

[10] P. J. Goad and D. H. Keefe, "Timbre Discrimination of Musical Instruments in a Concert Hall," *Music Perception*, vol. 10, no. 1, pp. 43-62, 1992.

[11] J. Meyer, *Acoustics and the Performance of Music*, Springer, 2009

[12] Lokki, T., Pätynen, J., Tervo, S., Kuusinen, A., Tahvanainen, H., & Haapaniemi, A. (2015). The secret of the Musikverein and other shoebox concert halls. *Ninth International Conference On Auditorium Acoustics*, Paris, France, October 29-31 Institute of Acoustics.

[13] Brinkmann, Fabian & Aspöck, Lukas & Ackermann, David & Lepa, Steffen & Vorländer, Michael & Weinzierl, Stefan. (2019). A round robin on room acoustical simulation and auralization. *The Journal of the Acoustical Society of America*. 145. 2746-2760. 10.1121/1.5096178.

[14] Christensen, Claus & Koutsouris, George & Rindel, Jens. (2013). The ISO 3382 parameters: Can we simulate them? Can we measure them?. *International Symposium on Room Acoustics*, Toronto, 2013.

[15] C. L. Christensen, ODEON Room Acoustics Software, Version 12, User Manual, Kgs. Lyngby: Odeon A/S, 2013

[16] MCFX Plugin. https://github.com/kronihias/mcfx

[17] Christoph Pörschmann, Johannes M. Arend, Raphael Gillioz. How wearing headgear affects measured head-related transfer functions. *EAA Spatial Audio Signal Processing Symposium*, Sep 2019, Paris, France.

[18] Mc Cormack, L., & Politis, A. (2019). SPARTA & COMPASS: Real-Time Implementations of Linear and Parametric Spatial Audio Reproduction and Processing Methods. *AES International Conference on Immersive and Interactive Audio Audio Engineering Society* 2019. http://www.aes.org/e-lib/browse.cfm?elib=20417

[19] Cronbach, L.J. Coefficient alpha and the internal structure of tests. *Psychometrika* 16, 297–334 (1951). https://doi.org/10.1007/BF02310555

[20] ISO 3382-1. Acoustics - Measurement of room acoustic parameters - Part 1: Performance spaces, Geneva: nternational Organization for Standardization, 2009.

[21] W. Lachenmayr, "Perception and Quantification of Reverberation in Concert Venues," Ph.D. dissertation, Detmold Univ. of Music, 2016.