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Virtual Stage Acoustics: a flexible tool for providing useful sounds for musicians

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ABSTRACT

Musicians performing on stage require an appropriate balance of sounds from all instruments and voices, including their own, to achieve a good sense of ensemble. The balance normally depends on the stage set up, properties of the instruments, and the availability of surfaces redirecting the sounds back to the musicians. It is possible, using virtual acoustics technology, to modify the balance of sounds heard by musicians and to enhance their self- and mutual audibility on stage. The paper presents the results of experiments conducted with musicians immersed in virtual acoustics receiving adjustable amounts of stage support from early, mid, and late parts of the sound field projected from multiple angles around the ensemble. The importance of the relative balance between the direct sound and reverberation, the loudness level of support and the projection angles are evaluated, including the effects of simulated stage and hall. It is conceivable to create a shared performance space where musicians and audiences experience similar auditory sensations and where communication between the artist and the audience becomes more immediate and intimate.

VIRTUAL ACOUSTICS - A SUPPLEMENT TO NATURAL ACOUSTICS

Acoustic conditions of musicians performing on stage in a hall are determined by two coupled enclosures: stage and hall. While stage acoustics dominates performance conditions, auditorium acoustics also plays an important role in performance. The coupling between stage and hall varies from separated (as in Boston Symphony Hall), to partly integrated (as in Amsterdam Concertgebouw or Leipzig Gewandhaus), to concentric (as in Berlin Philharmonie or in Elbphilharmonie Hamburg, currently under construction). Visual and auditory desire to remain close to the performance puts the stage in the midst of the surrounding audience.

Over the years researchers used different methods of testing stage acoustics with involvement of performing musicians: using natural acoustic environments and structural modifications of the stage (Berntson and Andersson, 2007); using synthetic sound fields set up in anechoic rooms (Nakayama, 1984), (Gade, 1986, 1989); and using sound fields generated by convolution set up in anechoic rooms (Ueno and Tachibana, 2003). In this current study virtual acoustics is used to support various acoustic conditions encountered by musicians performing in a natural environment. We use synthetic sound fields generated by convolution of sources with measured rooms to augment the existing natural acoustics.

Virtual acoustics can be effective in improving stage acoustics in halls where the width of the stage is too large (e.g. in fan shaped halls) and the lateral reflected energy is weak.

In this experiment, we create a wide stage and arrange a large separation between musicians to test the extreme case of low level, high latency lateral reflections. Ease of ensemble playing is difficult to achieve in large halls with large stage dimensions because of the absence of reflecting surfaces nearby that could improve mutual audibility on stage. We hope to see a positive correlation between subjective evaluations of performance and objective contributions of virtual acoustics.

EXPERIMENTAL SET UP

Two violinists take part in the experiments performing two musical duets within a large rectangular multimedia room (MMR) designed as scoring stage for film music. The MMR dimensions are 80 x 60 x 50 feet. Music A is "Bruno" by Maderna (duration 2min 15sec), Music B - "Annie" by Neuburger – 58sec. The music is well known to the performers, their sense of comfort should not change much during the tests while performing it many times over and over. The music is tightly structured requiring close synchronization. Only the first half of the music A (approximately 50 seconds) is used for the listening test since it contains more immediate musical interactions between two violinists as well as more steady rhythmic structure, both important features for our analysis. Music B is fully used in the test without any editing.

Musicians perform the pieces in the three positions with and without virtual stage support system. The set up of musicians and loudspeakers is carried out in two configurations: 'stage' & 'hall' (see Figure 1). Four line-array type full-range loudspeakers with wide horizontal and narow vertical dispersion are placed standing near the perimiter of the room to radiate real-time response from the virtual acoustics system. The sound propagation from these 2m tall vertical sources is aimed over the floor towards the players and away from the ceiling. The output level is set to be barely noticeable at the player positions; musicians cannot aurally pinpoint the speaker locations and the virtual and natural rooms are well integrated. Absorbers placed immediately behind the speakers reduce their radiation towards the nearest wall.

The 'hall' configuration setup shows the players oriented towards the narrower pair of speakers (as placed along the east wall of the MMR). A pair of numbered chairs represents each position of the musicians, with an arrow indicating the frontal orientation of the players. As can be seen on the chart, positions 2 and 3 are 3m and 6m away from position 1, respectively, creating a total distance of 13 m between players when in position 3, and 7 m distance in position 2. The sound of each instrument is collected by a cardioid microphone placed 1m away and is fed to the convolution mixer. The overall capture of two players is carried out via a spaced pair of Schoeps mk2 omnidirectional microphones, placed 2.5m from the players in their position 1 orientation. Each player signal is panned 72% towards their respective side of the speaker setup, and delays are applied to create "virtual walls"; the remaining 28% from the player's direct cardioid microphone routed to the opposite side speakers is delayed by 20ms. The 'hall' left and right front speakers (HLf & HRf), mainly reproducing mid and late reverberant energy returning from the hall, are attenuated approximately 8 dB from the level of the side speakers (HL & HR) that carry mostly early and mid reflections of the stage.

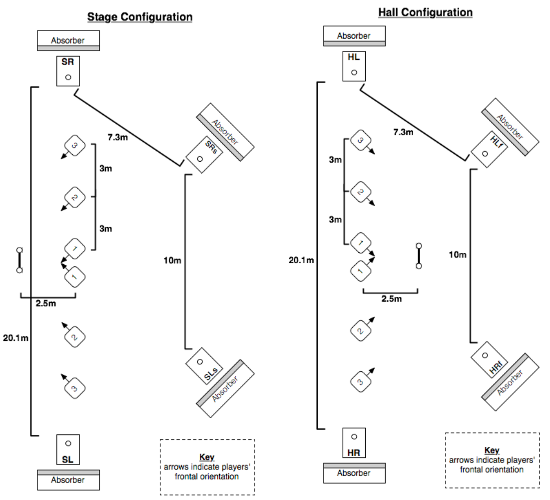


Figure 1. 'Stage' and 'hall' configurations showing distances between two violinists and between four line-array loudspeakers providing virtual acoustics support

The stage configuration places two speakers behind the player in order to create a sense of stage back wall. As with the hall configuration, each player's signal is panned 41 % towards their closest speakers, creating virtual reflecting walls near that player. The stage rear speakers (SLs & SRs) are also attenuated 9.6 dB from the front/side speakers (SL & SR). This stage configuration aims to generate an immersive experience for the players, supporting them virtually from 180°, just as they would experience it on a concert stage.

Virtual support consists of three distinct segments of an eight-channel impulse response measured in L'eglise de Saint-Benoit in Mirabel, QC, Canada. The floor plan of the church is presented in Figure 2. The three time segments of the impulse response are: 10-80ms (early), 80-380ms (mid), and 380ms-1.2s (late), based on previous study (Woszczyk, 2009).

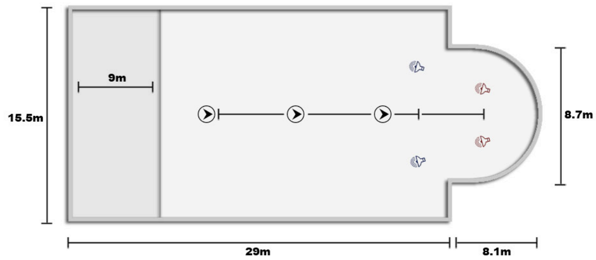


Figure 2. Layout of L'eglise de Saint-Benoit in Mirabel, QC.

The block diagram of signal interconnections is presented in Figure 3. Microphone signals are recorded on a workstation permitting subsequent instant recall and evaluation of musical duet performances within different acoustic conditions. Each convolution engine delivers a component of the acoustic support; thereby scenarios with early, mid, and/or late field support, as well as no support, can be created instantly.

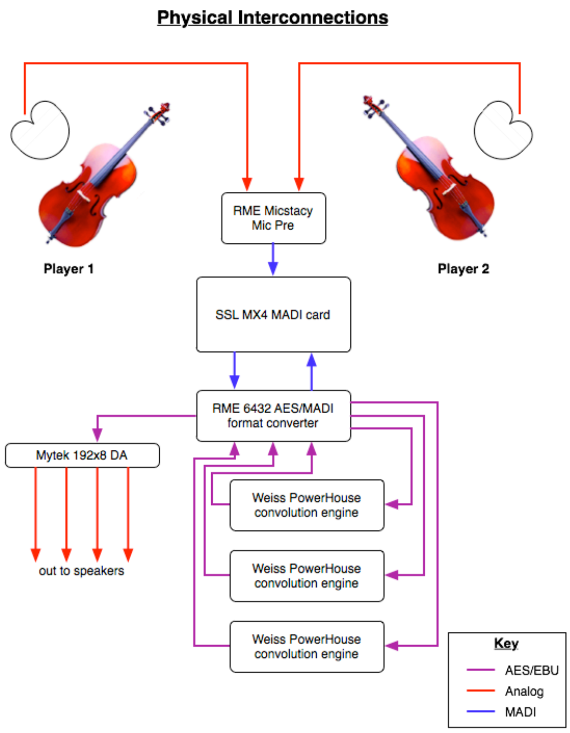


Figure 3. Equipment and interconnections used to generate high-resolution virtual acoustics based on convolution

EVALUATION OF MUSICAL PERFORMANCES

On a large stage there is an auditory 'disconnect' between musicians due to large distances separating them plus poor quality of reflected sound. The goal of using virtual acoustics is to compensate for low sound levels between distant players to ease auditory communicaton on stage while playing. Narrow and high stage enclosures provide sufficient acoustic support level through reflected sound (Dammerud and Barron, 2008), therefore virtual acoustics could be used to generate higher level of reflected sounds on stages that are too wide and deep. Wide stages usually require musicians to be farther apart which reduces the level of direct sound received between them. Support of musicians' own sound is weak when reflecting surfaces are far away, and the masking by loud sources present nearby dominates the auditory balance.

To obtain an indication of the audibility on stage between two musicians in varied conditions of virtual support, evaluation of musical performance is conducted using the following methods: interview with musicians immediately following the performance, evaluation of close microphone recordings by musicians in aspects of ensemble and musicality, objective evaluation of tempo and intensity level, measurement of temporal spread (lack of synchronicity). Analysis of waveform envelopes from close microphones allows us to assess the temporal spread in places that should be performed together and cumulative temporal mismatch is measured in 3 places. Poor mutual audibility affects confidence and risk-taking and will result in safe, careful playing, indicated by slower tempo and lower level of sound intensity.

Performers' evaluation of ensemble experience

In the interview, the two musicians confirm that sitting far apart creates problems with ensemble playing. They cannot hear the other person well enough and they are not sure when to play a note to be together. There is not enough sound from other player in comparison to the masking presence of their own sound near the ear. With the virtual acoustics added (early and mid) in the 'stage' configuration set up, the players report better audibility of each other and a stronger sense of self-sound. They declare to be playing better, enjoying it more, and requiring less effort to monitor their ensemble playing, matching the other musician. The virtual support helps them in all distances between them (at all 3 positions).

In the 'hall' configuration setting (musicians switched the sides and turned in the opposite direction), the musicians report difficulty in playing together with the large separation (position 3) blaming too much of the late sound (delays) and not enough early essential parts in what they hear. In the mid-distance separation setting (position 2), the presence of late-reverberation is not a problem because early and direct sounds are strong enough. With close distance separation, the large amount of reverberation is not detrimental or distracting and in fact is appreciated for its dramatic effect giving musicians a sense of powerful performance. This setting helps them shape the dynamics, articulation and expression of playing. It is an enjoyable and useful (not detrimental) sound setting.

Normally musicians use gestures, body motion, eye contact, and facial expressions to keep mutual contact while playing. In this experiment, musicians are asked to only use acoustic cues without looking at the other person. They report it is difficult to abandon the usual habit to look for visual cues during performance.

Subjective evaluation of 'musicality' and 'ensemble' in the recordings

Seven trained violinists participate in the listening evaluations of the recorded performances. All participants are violin major undergraduate and graduate students in the Schulich School of Music of McGill University. The results are presented in Figures 4 and 5. Only close microphones are used and the playback balance is adjusted not to reveal to the test participants the different acoustic conditions present during the performances.

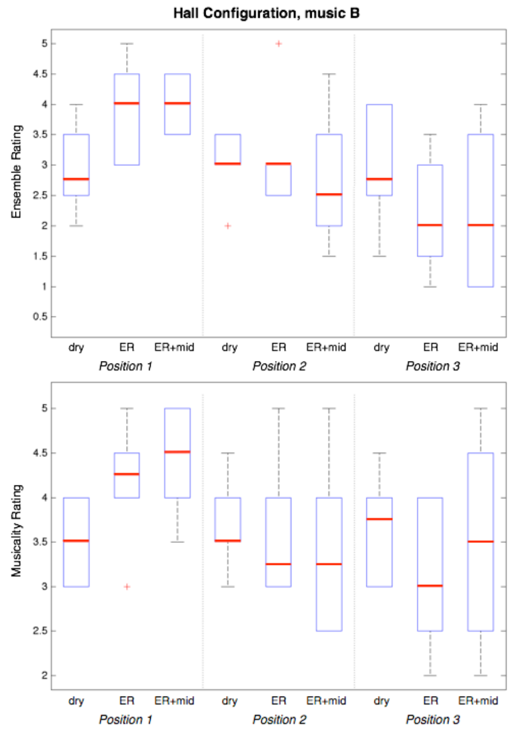


Figure 4. Subjective ratings, delivered by seven musicians, of 'ensemble' and 'musicality' for the violin duet performances recorded in the 'Hall Configuration'

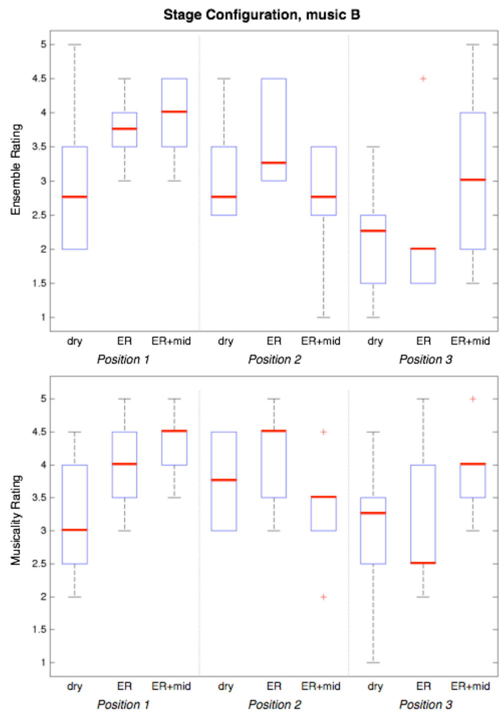


Figure 5. Subjective ratings, delivered by seven musicians, of 'ensemble' and 'musicality' for the violin duet performances recorded in the 'Stage Configuration'

Figure 4 shows both 'musicality' and 'ensemble' ratings for the 'hall configuration' performance of music B. Position 1 shows a marked increase in the subjective rating of both musicality and ensemble as the system is turned on and again as the mid reverberation is added to the virtual acoustic environment. It is of note that the highest mean ratings in both ensemble and musicality for all possible conditions are achieved with the addition of early reflections and late reverberation with the players situated in position 1. In both positions 2 and 3, however, the mean musicality and ensemble ratings drop below those of the dry condition. It is also of note that the mean ratings for both ensemble and musicality for the dry condition remain fairly consistent across all positions. The ensemble ratings for positions 2 and 3 seem to drop off as the system is turned on, while the musicality ratings for positions 2 and 3 are somewhat less clear.

The 'stage configuration' (Figure 5) shows similar trends in the ratings of position 1. Once again, the highest ratings for both musicality and ensemble are received with the virtual acoustic system reproducing early reflections and mid reverberation with the players situated in position 1. This early reflections and mid reverberation condition also shows great promise in position 3. In both ensemble and musicality ratings for position three, while ratings decreased from the dry condition to the early reflection condition, the presence of early reflections and mid reverberation surpassed even the dry condition. Position 2 favors the addition of only early reflections in both categories.

Objective evaluation of performance

Duration (tempo) analysis

Fritz Winckel (Winckel, 1962) found that minimum values of performance duration (fastest tempo) occur in halls having particularly good hearing conditions, while maximum values occur in auditoriums that are not designed for music performance. The dynamic range of music performance is also dependent on acoustic conditions and is influenced by the noise level of the room and on the quality of sound diffusion.

Performance duration (length of the recording) is measured for all acoustic conditions in 'stage' and 'hall' configurations. The results for Music A (Figure 6) show that in most cases the tempo is faster when virtual acoustics is added to the natural acoustics. This indicates increased confidence of musicians, presumably from better acoustic conditions, when the support is used.

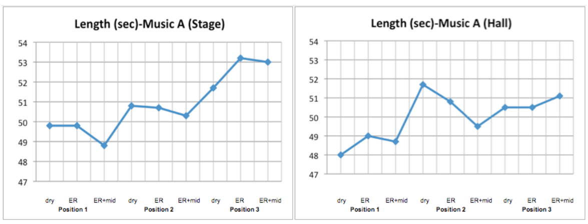


Figure 6. Changes in the duration of performance of the same piece of music when different acoustic conditions exist within the 'Stage' and the 'Hall' configurations

Synchronicity (temporal alignment)

It is difficult to achieve tight synchronicity in ensemble playing when musicians sit far apart, 13m (42 feet), at position 3. Figure 7 shows the method of calculating the accumulated time mismatch between the players using the alignment of waveform envelopes in the recordings. Figure 8 indicates that in a few rare cases tighter performance is achieved with the system on, but in general sitting further apart reduces rhythmic accuracy. Playing tightly together to a large extent relies on the availability of direct sound with low latency.

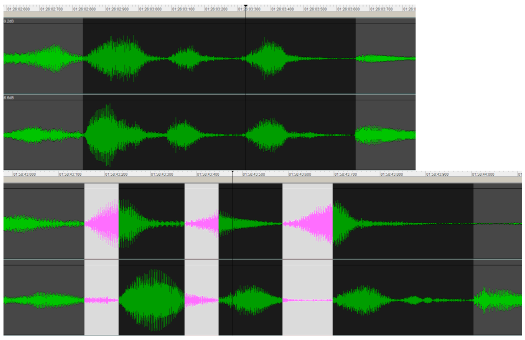


Figure 7. Synchronicity during performance measured as temporal misalignment at 3 notes that should be performed together. Top - position 1 where the musicians are close to each other, bottom - position 3 where the musicians are 13m apart. Highlighted area shows the time gap between two musicians for each note.

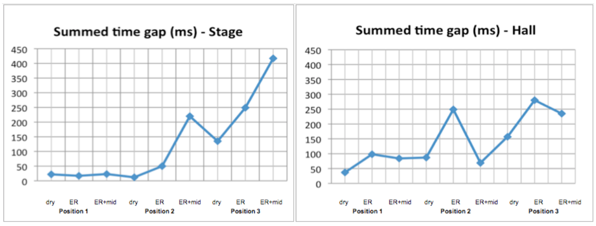


Figure 8. Timing asynchronicities in performance between two violinists at 3 notes required as unison in part of Music A example. 'Stage' and 'Hall' configurations, three positions and varied acoustic conditions are shown. The values show the accumulated mismatch at all 3 notes.

Average differences in sound pressure level

Improved acoustic conditions on stage typically result in a more confident (less tentative) execution of the piece. This should be reflected in a slight increase of the sound level generated by each player indicating best acoustic conditions. The graphs in Figures 9 compare variations in players' output level through the different conditions and positions. The RMS level of the entire excerpt is calculated for each player and then those RMS levels are averaged (simple arithmetic mean) between players. The 0 dB reference is set by the measurements of position 1, dry. This serves as a "control" of sorts, as it represents a normal player configuration and spacing with no virtual acoustic support, and therefore is used as a baseline for the comparison of the virtual acoustic conditions. Looking at the RMS analysis of the 'hall configuration', there is a clear trend of increased player level as the system is added. When the system reproduces early reflections, there is a marked increase in level in both positions 1 and 2, but only a small increase in position 3. In all positions, though, there is a distinct increase in level when mid reverberation is added to the early reflections being reproduced virtually. The starting level for each position (i.e. the dry performance) is decreased from that of the previous position indicating worsening acoustic conditions due to the increased distance. The addition of early reflections in position 2 returns the lowered level to approximately that of the original dry performance in position 1. With large amount of direct sound available in position 1, virtual acoustics support shows considerable improvement in confidence of playing. The musicians faithfully follow the instruction to always execute the piece with the best of their ability.

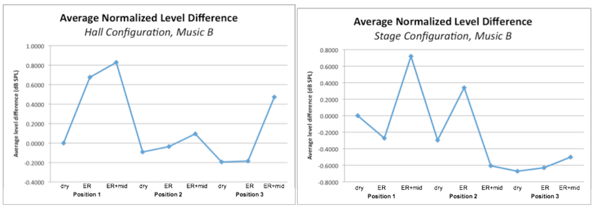


Figure 9. Differences in the average level of sound output from the musicians in the 'hall' (left) and 'stage' (right) configurations

The 'stage configuration' is somewhat puzzling. In position 1, there is a drop in the level when the early reflections are added, but a drastic increase in the level with the addition of mid reverberation. This pattern is reversed in the second position, however, where the addition of early reflections triggers an increase in player level, and mid reverberation causes a decrease. The decrease in starting level at each position, as seen in the hall configuration analysis, still holds true. Position 3 shows an interesting trend, though; it seems that the addition of early reflections and the subsequent addition of mid reverberation causes a gradual increase in player level, trending back towards the original position 1 dry performance level.

EVALUATION OF SOUND FIELD CONDITIONS

Sound field conditions closely approximating those found at the ears of performing musicians are measured using sweep sine techniques pioneered by Gade (Gade, 1982). B&K head and torso simlulator is placed in each seat occupied by the musician whereas a PMC IB2 loudspeaker radiating the sweep is placed in the seat of the partner musician. Binaural transfer function and impulse response are measured at each of the three positions, in the 'hall' and 'stage' set ups, with and without virtual acoustic support added in steps. Figure 10 shows the measurement of binaural IR and the playback environment for assessing recorded performances. The presence of the violin next to the left ear of the player holding it is not included in the measurement. The goal is to measure the structural contribution of virtual acoustics to the total reflected sound.

Figure 10. Source/receiver set up for measuring binaural impulse responses in position 1 (left); and listening environment for evaluating recorded performances (right)

The relative contributions of the early, mid, and late virtual field components to the total ambient sound are small compared to those generated by the MMR room. Figure 11 shows the impulse response measured in position 3 with the system off (upper) and on (lower) for the stage and hall configurations. There seems to be a little change between conditions with and without virtual components. The reverberation time RT60 = 1.5s does not change when the system is on or off.

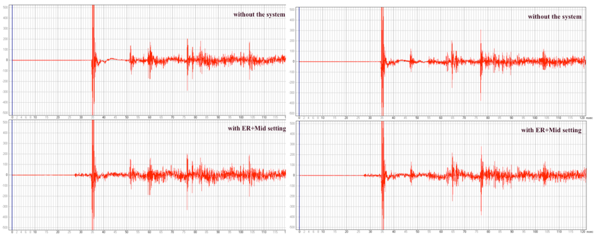


Figure 11. Impulse response measured in position 3 with the system 'off ' (upper) and 'on' (lower) for the 'stage' (left) and the 'hall' (right) configurations

However, the contribution of virtual acoustic support is not insignificant. Figure 12 shows the output magnitude response of the convolution system (signal supplied to the loudspeakers) and the signal recorded via fixed dummy head ears. Head movements collect an average of many magnitude responses.

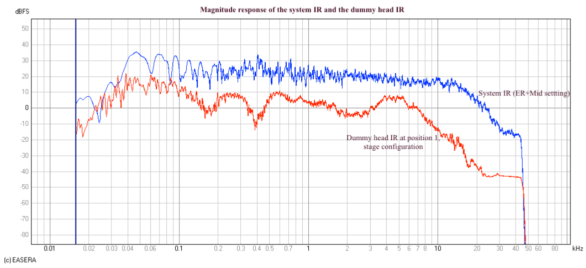


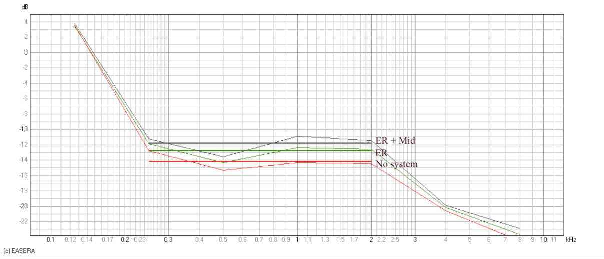
Figure 12. Magnitude response of ch-1 of virtual system IR 'ER+Mid' (upper) compared to the dummy-head ipsilateral-ear IR (lower) measured at position 1 in 'stage' configuration

Support ST measurements

Support quantities ST1 and ST2 indicate the degree to which the room supports musicians by supplying reflections from the room response. In this case, reflections are generated naturally by the MMR as well as virtually in real-time by L'eglise de Saint-Benoit in Mirabel radiated by the loudspeakers. The ST1 and ST2 values are typically measured on the stage with an omnidirectional microphone at a distance of 1m from an omnidirectional sound source (ISO 3382-1:2009(E), (Barron, 2005). The source/receiver interval of 1m simulates the separation between two musicians.

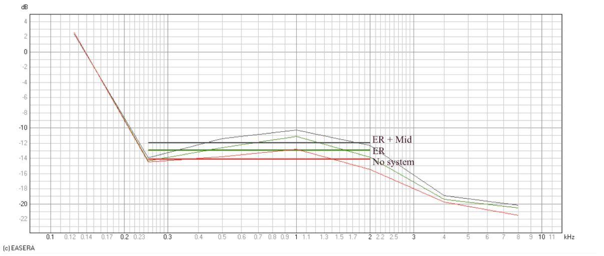
Usual ST values are –15dB to –12dB in concert halls. For comparison, several measurements of ST quantities are made to give an indication of the magnitude of reflections when the virtual support system is on and off. In positions 1, the source and receiver are 1 m apart, however, the source is unidirectional at higher frequencies and receiver is binaural, with only one ear signal used for calculation. Figure 13 shows ST2 measurement at position 1 with 'stage configuration' (ipsilateral ear signal) in 3 different spatial conditions of support. Clearly, adding early reflections (ER: 20-80ms) and early+mid reverberation (ER+MID: 20-380ms) increases the level of reflected sound in the receiver (listener) position.

ST2 values measured at position 1 with 'hall configuration' (ipsilateral signal) in 3 different spatial conditions of support are presented in Figure 14. Again, there is a clear evidence of contribution from the virtual acoustics supporting the musicians with additional reflected sound.



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	250Hz-2kHz	500Hz-4kHz
Stage_dry	3.5	-12.8	-15.3	-14.4	-14.5	-20.6	-24.5	-14.2	-16.2
Stage_ER	3.4	-11.9	-14.3	-12.4	-12.6	-20.1	-23.7	-12.8	-14.9
Stage_ER+MID	3.7	-11.3	-13.6	-10.9	-11.4	-19.9	-22.9	-11.8	-14
Average	3.6	-12	-14.4	-12.5	-12.8	-20.2	-23.7	-12.9	-15

Figure 13. ST2 measurement at position 1 with 'stage' configuration (ipsilateral ear signal) in 3 different spatial conditions of support



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	250Hz-2kHz	500Hz-4kHz
Hall_dry	2.6	-14.5	-13.8	-12.8	-15.5	-19.7	-21.5	-14.1	-15.4
Hall_ER	2.5	-14.3	-12.6	-11.1	-13.9	-19.4	-20.5	-13	-14.2
Hall_ER+MID	2.3	-13.9	-11.4	-10.3	-12.3	-18.9	-20.2	-12	-13.2
Average	2.5	-14.3	-12.6	-11.4	-13.9	-19.3	-20.7	-13	-14.3

Figure 14. ST2 measurement at position 1 with 'hall' configuration (ipsilateral ear signal) in 3 different spatial conditions of support

In positions 2 and 3 at greater distances from the source (e.g. violin 1), the receiver (violinist 2) receives a higher level of reflected sound relative to the direct sound because direct component is lower in level. Figure 15 shows the relative displacement of ST1 values for all three source/receiver positions. It may be worthwhile to agree on a few recommended source/receiver positions so that a wider set of ST values can be compared. Typical as well as extreme distances found between musicians on stage should be included. This expanded range of ST measurements helps one to visualize the acoustic properties of the room, such as the room radius, in octave frequency bands.

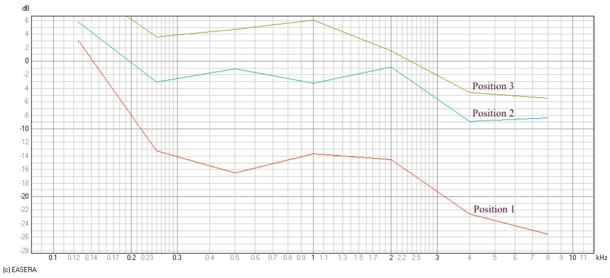


Figure 15. ST1 values measured at all 3 positions with 'stage' configuration. Ipsilateral signal with ER+Mid setting.

The directional properties of the source-loudspeaker and receiver-microphone affect the results of ST measurements. They should correspond more or less exactly to the actual directional characteristics of musical instruments and human listeners. Some directional characteristics would therefore be worthwhile to include in the evaluations of acoustic support. Binaural directivity of head & torso can be used as a model of human receiver. Figure 16 shows the relationships between ST1 and ST2 values in 'stage' configuration when quantities measured at ipsilateral and contralateral ears are averaged, compared to only ipsilateral ear values. The averaged values of two ears combined can be said to approximate, with reservations, the omnidirectional characteristics.

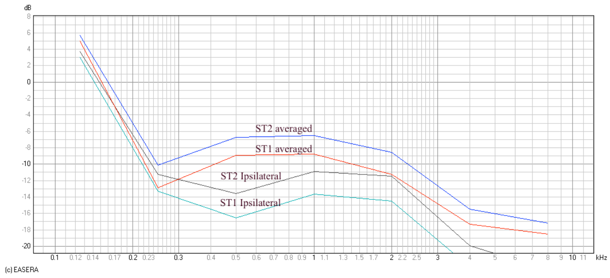


Figure 16. ST1 and ST2 values measured at position 1 in stage configuration with ER+Mid. 'Averaged' values are derived by averaging ipsilateral and contralateral signals.

Evaluation of directional aspects of virtual acoustic support by means of correlation analysis

Directivity of dummy head and torso helps to evaluate directional emphasis in reflected and partly diffused soundfield. This is important because acoustic support for musicians should provide directional cues confirming the locations of musical sources. Figure 17 illustrates the correlation between the impulse response applied to each speaker in the virtual acoustics system and the signal received at the player's ears. The measure indicates whether virtual reflections are aligned with the direct sound path from the other instrument, or not. Direct sound component is removed from the measurement. For each correlation graph in the 'hall configuration', the ipsilateral ear is closer to the other player/sound source. While all of the correlation measures are quite small, the correlation of the early reflection condition to the player's ears shows a distinct correlation between the right (ipsilateral) ear and HLf. HR is also prominent in both ears, as it is the main source of reflections from the other player. There is a significant drop in correlation in the contralateral ear through all conditions. With the addition of mid reverberation (lower graph), we see HR becoming the prominent channel, with a strong negative correlation from HLf.

When in the 'stage configuration', correlation is somewhat more predictable. The ipsilateral ear is relatively correlated to SL, the speaker responsible for the majority of the other player's reflected energy. In the case of the early reflection condition, the secondary support speaker for the other player (SLs) is seen as somewhat correlated as well. Once again, the contralateral ear is decorrelated from all individual channels. In the case of the early reflections with mid reverberation, the speakers closest to the receiver (SR and SRs) begin to show increased correlation, especially in the contralateral ear. The correlation values are admittedly small since only a small part of the acoustic energy is correlated. However, they are sufficient to create a blurred localized auditory image of a source within the diffuse soundfield (Blauert, 1996).

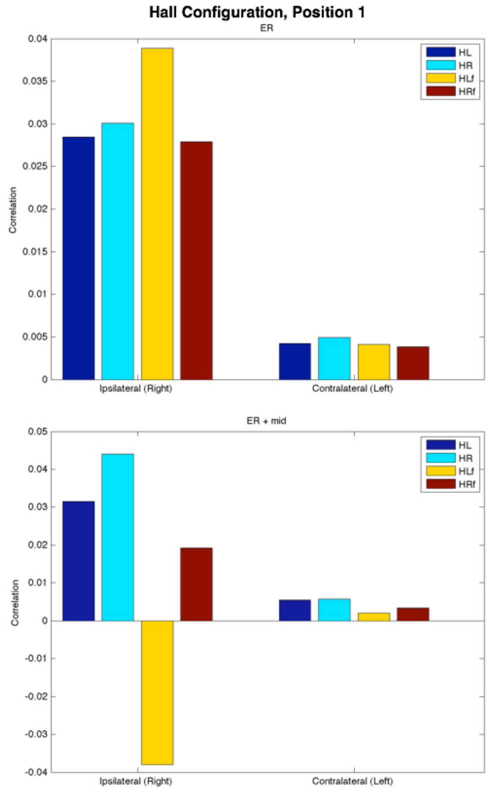


Figure 17. Correlation between the impulse response applied to each speaker in the virtual acoustics system and the signal received at the player's ears for "Hall" configuration when ER (upper) and ER+Mid (lower) signals are applied

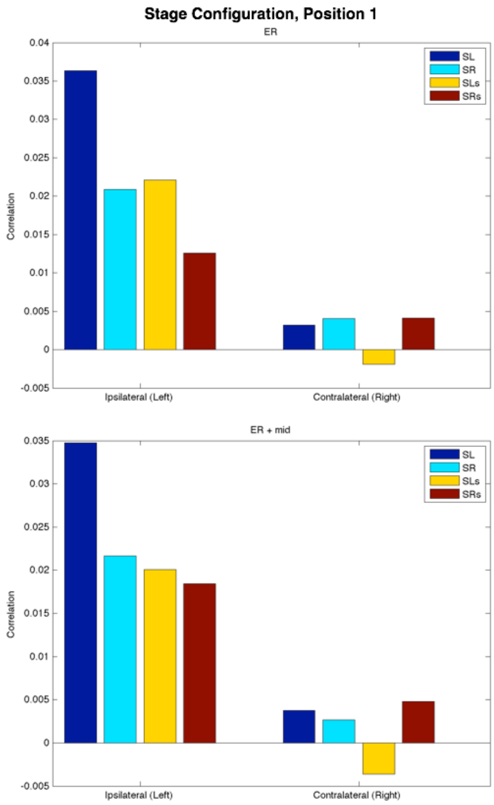


Figure 18. Correlation between the impulse response applied to each speaker in the virtual acoustics system and the signal received at the player's ears for "Stage" configuration when ER (upper) and ER+Mid (lower) signals are applied

DISCUSSION

Only one performance of the two musical pieces was recorded at each of the varying acoustical conditions. An individual performance might be affected by the moment (attention, interest, pleasure or discomfort, mood, distractions, etc.). However, recording multiple performances in each acoustic condition might also introduce unwanted effects such as overlearning, accumulation of experience, predictive error correction due to memorization of performance artifacts, compensation of auditory conditions with memorization of experience, etc. To prevent these types of errors, we would need to record the same piece of music 'afresh' with a considerable time in between to erase the memory of recent experience, or to record a different piece each time while introducing different type of errors and performance metrics. This would essentially amount to recording and analyzing an accumulated experience of performance over a long period of time. A single recording presents only one case and this interpretation should be used with caution.

The perception of the soundfield by the two violinists will be largely affected by the masked threshold of audibility of indirect sound dependent on the angle of incidence, and on the proximity and the angle of the masking source. Meyer (Meyer, 1986) showed the difference in sound pressure level between the left and right ears of instrumental musicians. For violinists, the near field sound pressure difference between the two ears is more than 10dB above 1000 Hz. This will no doubt affect the violinists' ability to hear various soundfield components; it also explains the value of head movements.

CONCLUSIONS

This study was conducted in the natural acoustics of a large scoring stage studio enhanced by virtual acoustics from a convolution based room simulator radiated by four line-array loudspeakers (see Figure 19). It is important to use loudspeakers with wide horizontal dispersion in order for the sound radiation to reach the ears of all musicians spread across the stage with minimal coloration; narrow vertical dispersion ensures that little energy is sent towards the ceiling and balconies where it becomes considerably delayed and less useful.

Figure 19. The arrangement of two musicians in the scoring stage of MMR studio with the virtual acoustics support added via four line-array loudspeakers. Musicians are seated at position 3 (13 m apart) in the 'Hall' configuration.

The strategy for supplying virtual acoustic support must consider the angles (directions) from which the support is radiated to the musicians. Taking into consideration the positive results in stages arranged vertically (e.g. Vienna's Musikvereinsaal, or Amsterdam's Concertgebouw), one should consider projecting support information from above, both in front and behind the musicians, and from angles directly above. The frontal direction (straight ahead and above) is the return path from the hall, and is usually unobstructed. This is the direction musicians are facing so there their binaural hearing acuity is high. Parts of the proscenium and the hall enclosure could radiate useful information back to the orchestra. The surfaces behind the musicians, like in stages with staggered multiple risers, are also used for supplying early energy. Areas above are totally open (without obstructions and absorption) and musicians are used to listen to the hall ambient response there. We plan to assess the role of virtual acoustics applied from the areas above in our future study. Side horizontal angles of support may need to be slightly elevated to project the sound above the heads and bodies of musicians, to penetrate better into the middle of the ensemble, away from the absorbing bodies of the players.

Altogether it seems that the delivery of acoustic support should be diverse and from many directions allowing musicians to find any desired sound quickly. However, it is important to project supporting sounds from the directions corresponding to the locations of respective instruments and sections. This will inform the players about the expected locations of other musicians without confusion.

Virtual acoustic support should generally not be used for reinforcement of direct sound as this creates errors in localization for different positions on stage. The goal is to create a reinforcement of diffused sound while supporting the general location of each source or group with early reflections. Certain amount of late reverberation may help musicians in controlling their intonation, tempo and dynamics. Reverberation returns a valuable feedback to the players from the hall, therefore virtual acoustics should reintroduce the presence of the hall onto the stage. This can be equivalent to virtually moving the stage into the middle of the hall, as is the case in some highly regarded concert halls (Berlin Philharmonie).

The output power of virtual acoustic support should track accurately the dynamic variations of sound power produced by musicians on stage. In particular it is important that with the increasing loudness on stage, virtual acoustic power grows proportionally in magnitude and also expands in volume, expanding in space as if the entire stage is returning the sound, not just a few directions designated by loudspeakers. This type of dynamic multisource pulsation requires a large number of loudspeakers covering the entire stage enclosure. At the same time, the balance between early, mid, and late sound needs to be carefully proportioned.

Proper choices need to be made about the magnitude of support contributed by each group or instrument. While it is important for all musicians to hear each other on stage, it is most important for all orchestra players to hear the strings. String players provide the most reliable reference of pitch and tempo because string sections play almost all the time and are spread across the stage reaching to most distant musicians. Providing sufficient audibility of strings to all players is a key factor in maintaining good ensemble conditions on stage. Strings players also need to hear each other to secure good intonation and ensemble so acoustic support must also be channelled to them.

The level of own playing when the level of other musicians is fixed governs the sound ratio of 'myself' to 'others'. A player is not able to hear other musicians if own sound is masking the sound of others. Therefore, all musicians should try to play softer when then have hard time hearing everyone else. It is possible then, using virtual acoustics technology, to modify the balances of sounds heard by musicians and to enhance their self- and mutual audibility on stage.

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