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► **To cite this version:**

James Weaver, Mathieu Barthet, Elaine Chew. Filling The Space: The Impact of Convolution Reverberation Time on Note Duration and Velocity in Duet Performance. Audio Engineering Society Convention 147, Oct 2019, New York, United States. hal-03545669

**HAL Id: hal-03545669**

**<https://hal.science/hal-03545669>**

Submitted on 27 Jan 2022

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# Audio Engineering Society Conference Paper 10266

Presented at the 147th Convention  
2019 October 16 – 19, New York

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## Filling The Space: The Impact of Convolution Reverberation Time on Note Duration and Velocity in Duet Performance

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### ABSTRACT

The impact of reverberation on musical expressivity is an area of growing interest as technology to simulate, and create, acoustic environments improves. Being able to characterise the impact of acoustic environments on musical performance is a problem of interest to acousticians, designers of virtual environments, and algorithmic composers. We analyse the impact of convolution reverberation time on note duration and note velocity, which serve as markers of musical expressivity. To improve note clarity in situations of long reverberation times, we posit musicians performing in a duo would lengthen the separation between notes (note duration) and increase loudness (note velocity) contrast. The data for this study comprises of MIDI messages extracted from performances by 2 co-located pianists playing the same piece of music 100 times across 5 different reverberation conditions. To our knowledge, this is the largest data set to date looking at piano duo performance in a range of reverberation conditions. In contrast to prior work the analysis considers both the entire performance as well as an excerpt at the opening part of the piece featuring a key structural element of the score. This analysis finds convolution reverberation time is found to be moderately positively correlated with mean note duration ( $r = 0.34$  and  $p = < 0.001$ ), but no significant correlation was found between convolution reverberation time and mean note velocity ( $r = -0.19$  and  $p = 0.058$ ).

### 1 Introduction

How artificial acoustics, and in particular convolution reverberation time, impact on musical performance is a growing area of research interest. For performers, it may be intuitive that the reverberation time of a room has an impact on the way they perform a piece of music, but an ideal reverberation time (RT) for music performance is difficult to concretely ascertain, being depen-

dent on differing forms and styles of music. However, it is often the case that the musicians exert little control over the acoustic space in which they perform. Occasionally, variable acoustic spaces (for example through the use of movable panels) allow for some control over the acoustic environment, or fold back monitoring (on-stage speakers directed at the performers) provide feedback to performers so they can adapt their playing to the space. In acoustic ensembles without conductors,

the performers have to, often quickly, assess how the sound will affect their performance and whether or not it will change the 'meaning' of a piece, or cause them to not be able to work in synchronicity with each another. Based on observations in the field and on previous research, outlined below, we hypothesise that performers attempt to improve the clarity of notes in situations of long reverberation times. We posit that players would lengthen the separation between notes (note duration) and increase loudness (note velocity) contrast. However, it is not always easy to quantify the complex interaction between spatial acoustics and performance in a meaningful way.

To assess the impact of reverberation on ensemble performance, we take the MIDI data of pianists playing the same piece of music 100 times in a range of five different reverberation conditions, and analyse the note duration and velocity of the key presses both globally and in a selected segment at the beginning of the score with large variations in tempo and dynamics. With the global view, it is possible to build a broad picture of the overall changes in performance; focusing in on a part of where expressive variations is key allows us to ascertain how the acoustic environment impacts upon the constituent parts of the piece. This multi-scale approach to micro changes in expression is aimed at better understanding the expressive changes forced upon the musician by differing reverberation conditions.

We have an increased understanding of how acoustics have an effect on musical performance broadly, with research in this area growing steadily over the past thirty years; the last ten years have seen a particularly significant increase in activity in this area. This is due in part to advances in tools such as acoustic simulators and spatial audio enabling researchers to create effective representations of physical space. Much of this work concentrates on soloists, and often from a qualitative viewpoint. While this is useful, there is a growing need to understand from a quantitative viewpoint the impact of acoustic space on both solo and ensemble performance.

Early work by Gade [1] investigated the room acoustic needs of performers from a subjective viewpoint and the objective properties of the sound field in orchestra performance. This research provided an early overview of the perceptual issues affecting musical performance and presented 2 objective parameters to quantify the performer's ability to hear oneself, Support (ST) which

measures sound reflections 1 meter from the original source and Early Ensemble Level (EEL) measuring the energy of the direct sound and reflections at another position on the stage.

Ueno et al. [2] and Kato et al. [3, 4] presented a three-part study in performance analysis related to acoustic properties. In their study, they recorded soloists playing in a range of simulated acoustic environments. They measured the impact of these acoustic environments on the adjustment of tone, tempo, note lengths, silence between notes, articulation, dynamic level, dynamic range, harmonics strength, pitch tuning, and vibrato extent. Correlating quantitative measurements to subjective opinion, they showed agreement between objective analysis of the performance and of the statements from the musicians about their performance. The measured parameters were found to vary, with statistical significance, with room acoustic conditions.

More specifically, Kato et al. [4] examined the playing of soloists in a range of simulated acoustic environments and attempted to understand the impact of spatial acoustics on objective measurements of the adjustment of tone, tempo, the length of notes, the silence between notes, articulation, dynamic level, dynamic range, harmonic strength, pitch tuning, and/or vibrato extent. This particular study correlates the players' subjective opinion of their preferred acoustic condition with changes in the audio. The analysis showed considerable agreement between the statements from the performers between each other, and found that the above parameters all varied significantly with room acoustic conditions. In particular, it showed a reduction in tempo for short reverberation times, and for long reverberation times.

There have been a growing number of studies conducted on objective and subjective measurements of musical performance using a range of methodologies. More recent work has explored the impact of length of reverberation time on both tempo in a musical performance. Prior work by Weaver et al. [5] found highly significant changes of tempo to correlate with reverberation conditions when studying the audio signal. In particular, longer reverberation times produced slower tempos. An in preparation paper analysing the audio signal of two pianists playing over 100 performances shows significant correlation between longer reverberation time, slower tempo, and louder performance, supporting the findings of both Weaver et al. [5], and Ueno et al. [2].

Amengual [6] looked in depth at trumpet and organ players in varying simulated acoustic environments. They found that musicians consistently adjust their performance, particularly by reducing the sound level and brightness of timbre in performances in highly reverberant conditions. Furthermore, organ players modified the temporal parameters of their performance by decreasing tempo in response to increased reverberation.

For ensemble performance, Canfield-Dafilou et al. [7] studied conducted music, with twelve singers and an organ performing in a virtual sound field. While they were unable to quantify global tempo changes as the conductor attempted to keep the same tempo throughout all conditions, they did look at how reverberation time affected the performance of a piece of music composed for a certain space. They found that spatial acoustics with reverberation times longer than a full measure in the score made the music feel out of place, and reverberation times shorter than a measure caused the music to end unnaturally quickly. A decay of  $\sim 2$  beats provided natural closure to the music.

While the studies outlined above provide a good view point the study outlined in this paper presents a novel data set, which comprises of two pianists playing in the same physical space. The data set is larger in volume of performances than that previously described, and by concentrating on one piece of music providing a rich data set of 25 repetitions in each environment allowing confident assertion on the findings of this research.

This paper is organised as follows: section 2 describes the experimental design and outlines the methodology for analysis; section 3 provides analysis of the data looking at note duration and velocity in relation to changing convolution reverberation conditions; and section 4 contextualises the results within the frame of the impact of the convolution reverberation upon musical performance, looks at the limitations of this study and sets future directions for research in this area.

## 2 Methodology

The study reported in this paper refines the methodology previously employed in Weaver et al. [5], and amasses a new data set comprising of 100 two piano performances over five reverberant conditions. This data set improves on that available in previous studies, detailed above, which do not have the same amount of repetitions of the same piece of music in multiple



Fig. 1: Mozart's *Sonata for 2 Pianos in D*, K.448.

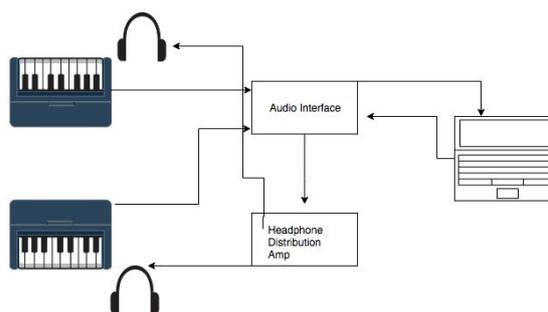


Fig. 2: System diagram of experimental setup.

conditions. The size of the data set is designed not only to give more statistical significance to quantitative evaluations, but also to future proof for any deep learning activity. The performances are captured over four sessions in order to ensure fatigue didn't factor into the data captured from the performances. Each of the four sessions consists of 25 repetitions of a two piano piece to provide consistency and reduce the physical and cognitive load on the participants.

The music, performed by two experienced pianists, consists of bars 1 - 33 of Mozart's *Sonata for Two Pianos in D Major*, K.448 / 375a— (Figure 1) shows the initial bars. The piece was chosen because it provides an appropriate degree of expressive variation in terms of tempo and dynamics, with relatively few explicit score instructions (markings), and has significant detail for analysis due to interlocking melodies which are exchanged between the performers. Two rehearsal sessions allowed the participants to further discuss and explore the piece. During the rehearsals, the pianists perform without any simulated reverberation.

In order to make a replicable study, easily available commercial equipment is sourced. Two digital pianos—a Yamaha CP300 and Yamaha P80—are used as the performers were familiar with these instruments and they also provide faculty to record detailed MIDI data

alongside audio. Both digital pianos have zero reverberation at source. In order to capture the data from the performances a Motu 828 Mk III audio interface is used, as it provides both audio with built in preamps and MIDI recording capability. Recordings are made using an Apple MacBook Air laptop running the Ableton 9 (Suite) Digital Audio Workstation (DAW), this was chosen as the lead author is an advanced user of this DAW and it utilises the freely available Convolution Pro Reverb Device developed in MAX/MSP. This particular device provides natural sounding simulation of acoustic environments.

The convolved signal is relayed to the participants through Beyer Dynamic 150 Headphones, routed through the audio interface and a Behringer Powerplay Pro XL headphone distribution amplifier, allowing the lead author to monitor the performance. Using this set up enables capture of audio signal and MIDI Data for each individual player’s performances, and their combined performances, allowing multiple analysis points and a manipulable data set for future study.

Latency in the system was measured at 10ms which is in line with that of a live performance, and consistent with the optimal delay discussed in Bartlette and Bocko [8], Chafe [9], which placed the ‘sweet spot’ for ensemble interaction at 11.5ms. This baseline system delay together with the introduction of reverberation smooths any rough edges in the sound heard by the performers. The latency and volume level was deemed acceptable by the participants and investigator after a sound check. It was essential to ensure this latency would not impact upon the performance of the participants, and was exactly the same for both participants.

RT <sub>60</sub> Name	500Hz (s)
R8	0.58
Conrad	1.28
R17	1.38
St Albans	5.74
York Minster	7.19

**Table 1:** Reverberation times at 500Hz.

The Room Impulse Responses (RIR) for the study are selected from the OpenAir Library [10], and chosen to represent a wide range of acoustic conditions which could be used for performance. The list of locations are presented in Table 1 with their associated reverberation

times (RT<sub>60</sub>) for tones at 500Hz. The chosen frequencies are selected to cover the range of a typical musical performance; the reverberation conditions here are arranged in ascending order based on the RT<sub>60</sub> times for the 500Hz tone. During the study we presented the conditions randomly to prevent order based learning influencing the results.

MIDI data was extracted using Midi Toolbox [11] functions augmented by code developed by the lead author in MATLAB.

### 3 Results

We examine the impact of reverberation on note duration and note velocity by analysing MIDI data captured from 100 performances. We study the performance as a whole, and focus on the opening 30 beats of the piece to obtain a detailed view.

#### 3.1 Note Duration

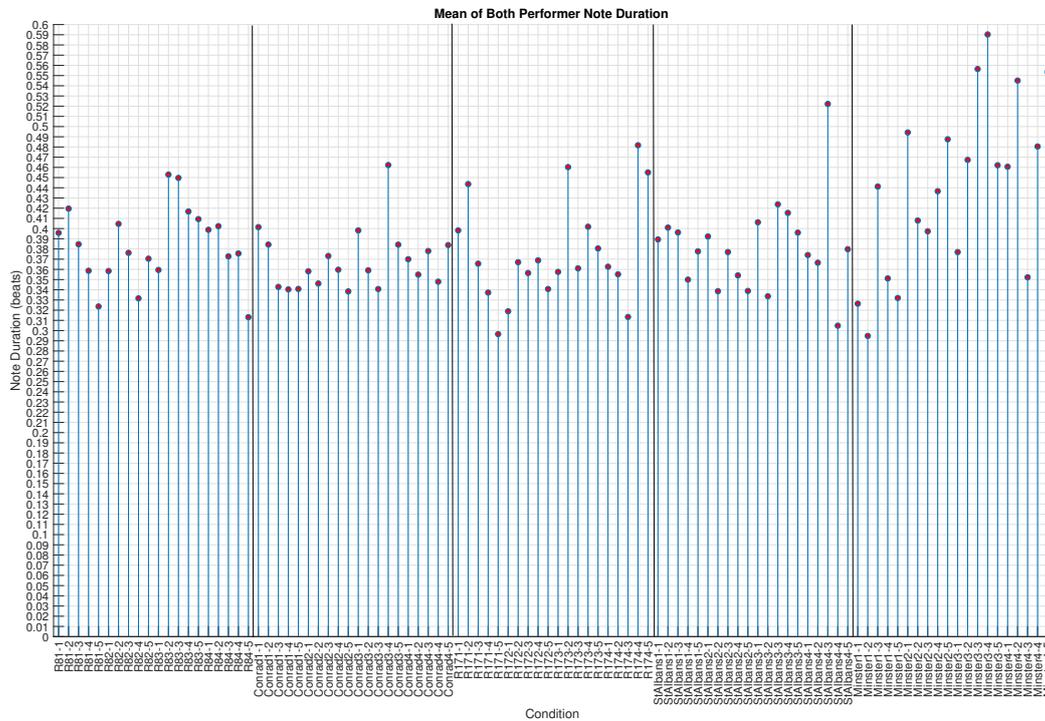
Note duration is a measure of note articulation in a performance. By comparing note durations of the same piece performed under different reverberation conditions, we can get a sense of how this impacts performance.

Part	r	p-value
Piano 1	0.2107	0.0353
Piano 2	0.4089	$2.4038 \times 10^{-5}$
Both Pianos	0.3409	$5.1947 \times 10^{-4}$

**Table 2:** r and p values of the Pearson correlation between note duration and RT<sub>60</sub>.

Figure 3 shows the mean, maximum and minimum note duration for each performance, segregated by performer (Piano 1 at the top, and Piano 2 bottom). The duration, extracted using the Midi Toolbox function, ‘Duration’, is given in units of the average quarter beat length. To evaluate the impact of reverberation time on performance, we perform a Pearson correlation test on the mean note duration and reverberation time. Table 2 presents the results of the correlation test reported for each performer separately, and for both performers combined. The test gives insight into the effect of reverberation time on note duration (articulation). In addition, the profile of the individual player note duration provides a view of the synchronicity of the performers’ responses to the different reverberant conditions.





**Fig. 4:** Mean note duration for both pianos combined in each performance - Presented from left to right in ascending order of  $RT_{60}$ .

be a useful marker of how reverberation impacts upon expressivity in musical performance.

In Figure 6 we show the Mean, minimum and maximum note velocity for each performer, performance, and reverberation condition. Extracted using the MIDI Toolbox function 'Velocity' is given in steps of 0 - 127, which is the standard MIDI format with 0 being the smallest and 127 the largest value.

A Pearson correlation test of mean note velocity vs. reverberation time, given in Table 3, shows limited correlation between velocity and reverberation time for the individual performers. When combining the performers' data and taking their mean note velocity (see Figure 7), we see negative correlation, but the result is not significant ( $r = -0.1899$ ,  $p = 0.058$ ).

Beats 1 – 30 show variation in the initial part of the performance, evidenced in figure 8. In this opening section, there is evidence of higher velocity during the longest reverberation condition, but combined note velocity is negatively correlated ( $r = -0.1754$ ) with  $p = 0.0809$  meaning it is not statistically significant.

Part	r	p-value
Piano 1	-0.1433	0.1550
Piano 2	-0.2413	0.0156
Both Pianos	-0.1899	0.058

**Table 3:** r and p values of the Pearson correlation between note velocity and  $RT_{60}$ .

## 4 Discussion and conclusions

This study analysed the MIDI data from 100 performances of Mozart's *Sonata for 2 Pianos in D Major*, K.448 / 375a, in five different convolution reverberation conditions. By analysing the note duration and velocity we built further knowledge about the effect of artificial reverberation tools on musical performance.

We found reverberation time to be significantly correlated to mean note duration, both globally and at a key point in the score with high expressive variability. Extended duration is found in longer reverberation conditions. We hypothesised that this is a result of the

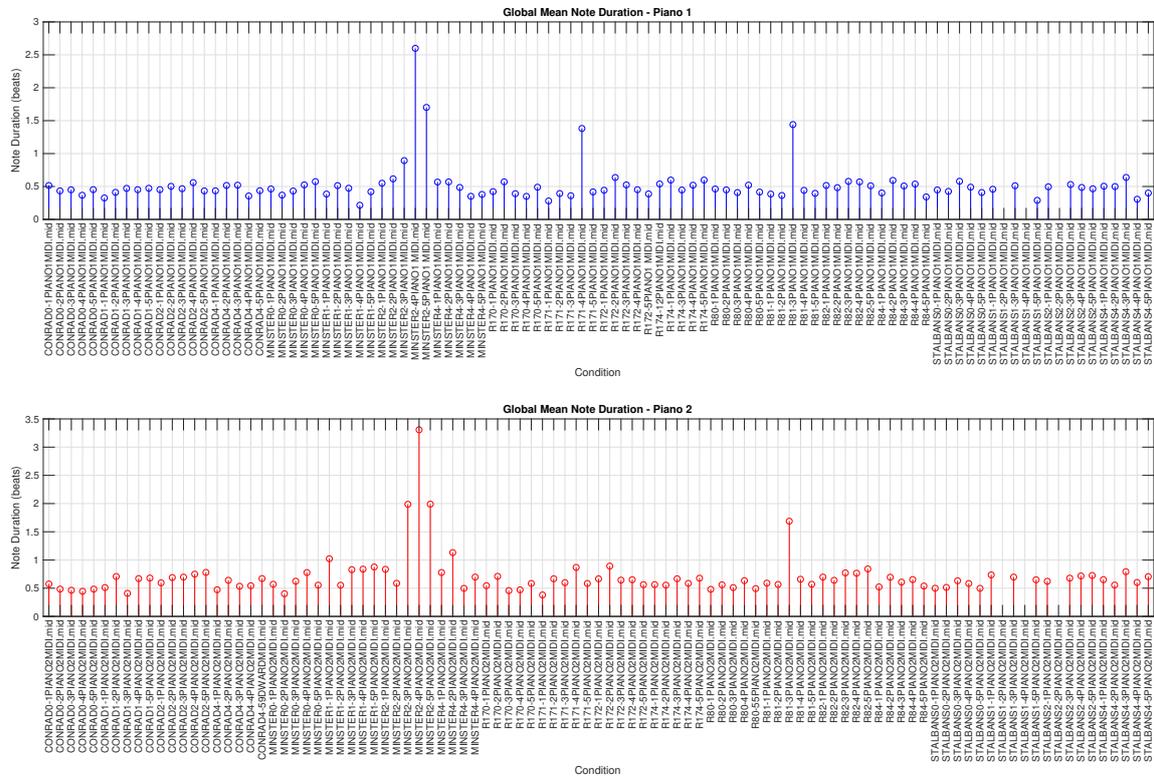


Fig. 5: Mean note duration by performer for beats 1 – 30 (Piano 1 top, Piano 2 bottom).

performers looking to counteract an imbalance in the reverberation and direct sound, which decreases the definition of the notes. When examining the opening bars of the performance where the performers have to adjust most starkly to the acoustic conditions, it is particularly evident that the longest reverberation time corresponded to longer mean note duration, which is consistent with a slower global tempo. We propose that this is due not just to stylistic interpretation, but represents a conscious adjustment by the performer to increase note clarity.

Slowing the performance tempo, as described in [5], and articulating individual notes with longer duration allows for stronger delineation between note onsets. The direct sound and reverberant sound of an extremely long reverberation time cause the note onsets to overlap, so by increasing the time between notes a performer is attempting to override and to tame the balance between the reverberation and the direct sound.

With this in mind it would stand to reason that the mean note velocity would increase in an effort to accentuate the note onsets in longer reverberation ties. However, analysis of note velocity is considerably less conclusive. The note velocity is not significantly influenced by longer reverberation time, which indicates that loudness is not as significant a factor that is varied to clarity in the stimulus used. In preliminary research using the same corpus, which is yet to be published, it was found when analysing the audio signal of the performances there is correlation between louder audio with longer reverberation time. However, in this analysis of the note velocity, we cannot conclusively link the loudness and longer reverberation time. While there are subtle variations in the velocity, it cannot be clearly said that the velocity is correlated with the reverberation time. This holds true when looking at smaller sections of the performance as well.

While the experimental design is now established, there

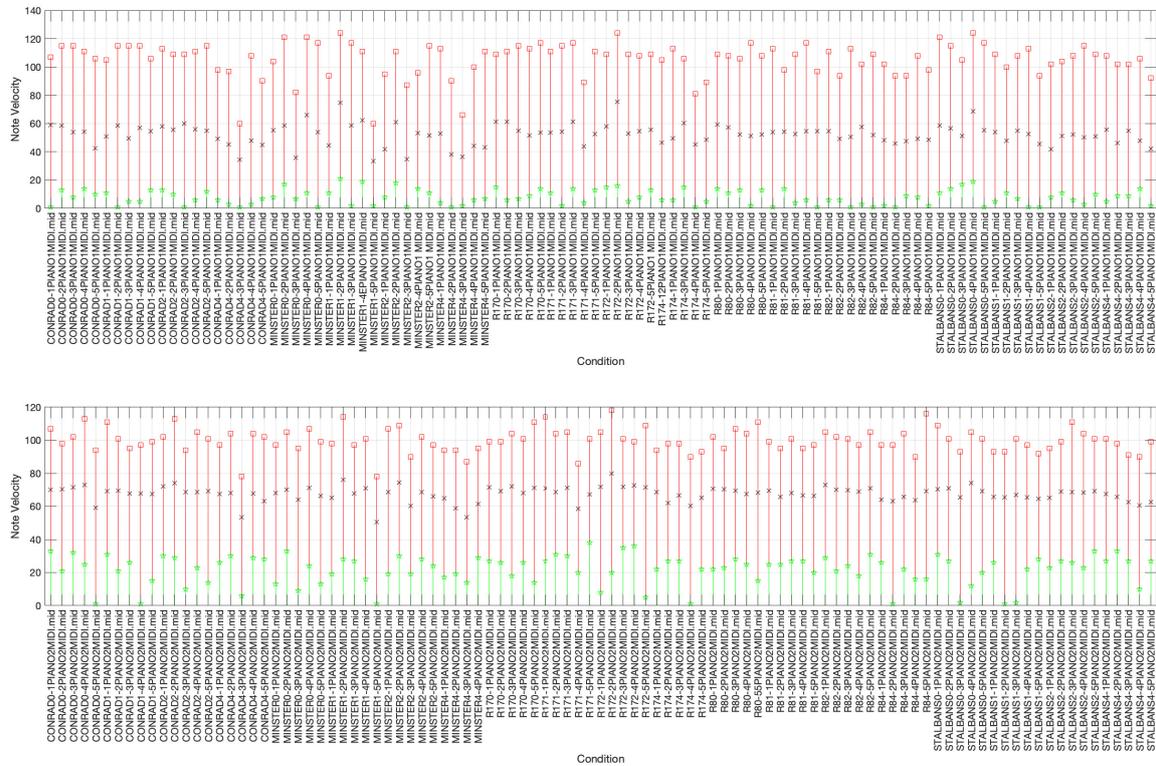


Fig. 6: Mean (x), max (square) & min (star) note velocity - Piano 1 top, Piano 2 bottom - in all performances.

exist some limitations that are worth pointing out. Firstly, The audio conditions were presented via headphones. While many studies use a speaker array, the headphone option was chosen as it would be closest to that used in a conventional rehearsal, or online performance. Secondly, While many more performances have been captured than in previous studies only 1 piece of music has been used, so we cannot generalise the results to other types of music or instrumentation at this stage. Future work will involve using multiple stimuli with similar quantities of performances. There is also scope to extend this to other MIDI enabled instrumentation in order to generalise the data. Finally, While the RIR used in this study are high quality, they were not spatialised as the performers were static. Future studies may include instrumentation that provides freedom of movement (e.g. guitar or violin) that would necessitate spatialised audio in order to create an ecologically valid working environment. This would provide an opportunity to show how the musicians adjust their physical

proximity in various reverberant conditions.

In summary the analysis presented here is particularly useful for musicians working in simulated acoustic environments, and also for people developing plausible algorithmic music compositions as detailed in Hallström et al. [12]. Planned work will involve using a Deep Learning Model using the feature set available in the MIDI data to augment algorithmically composed music that adapts to different reverberation conditions.

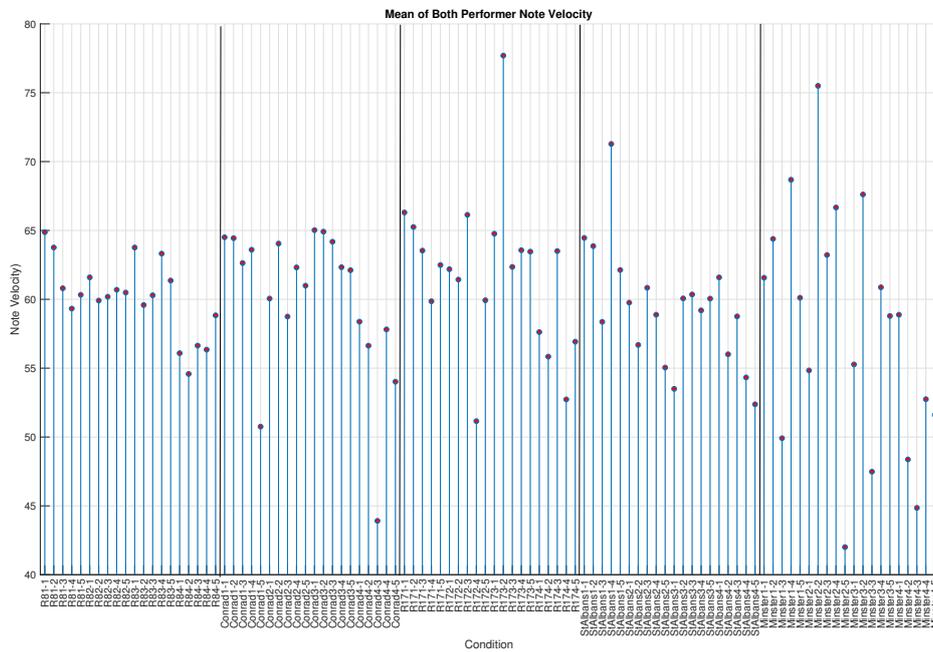


Fig. 7: Mean note velocity for both pianos combined in each performance - Presented from left to right in ascending order of  $RT_{60}$ .

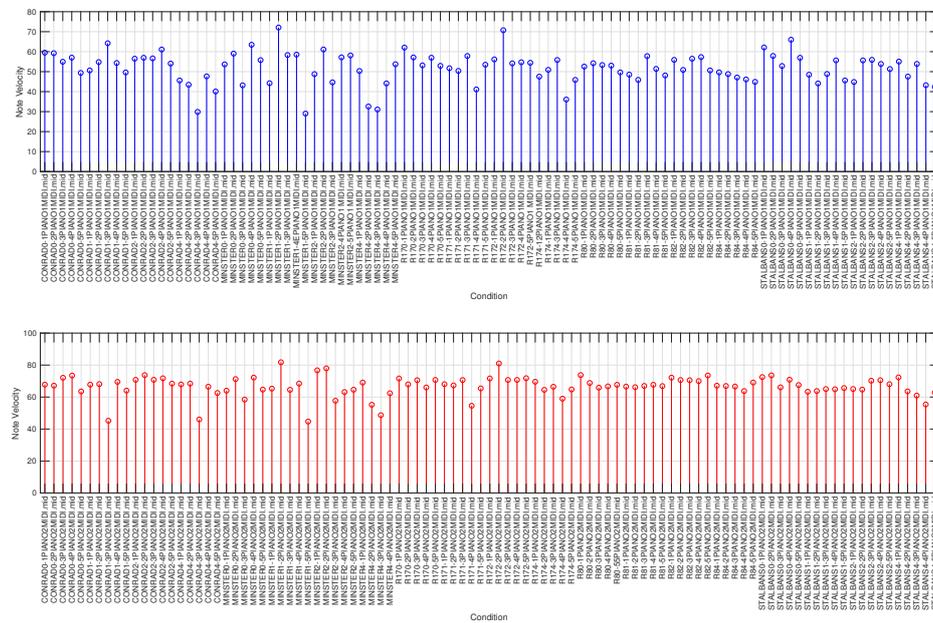


Fig. 8: Mean note velocity by performer: Beats 1 – 30 (Piano 1 Top, Piano 2 Bottom).

## 5 Acknowledgements

The authors wish to thank Edward Hall and Elaine Chew for their performances, Vanessa Pope for insights into the analysis, and C4DM studio manager Giulio Moro for help with sourcing equipment for the experimental setup.

This work was supported in part by the EPSRC and AHRC Centre for Doctoral Training in Media and Arts Technology (EP/L01632X/1).

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