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Study on effect of room acoustics on timbral brightness of clarinet tones. Part II: an acoustic interpretation and synthesis of analytical results

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ABSTRACT

It is often heard that musicians and acoustic engineers are interested in understanding how tonal quality is related to the acoustics of a room, for a musical performance. This study is the second of two works that investigate the dependency of the timbre of musical tones on room acoustic condition. In the previous paper (Part I), the subjective effect of room acoustics on the timbral brightness of clarinet tones was examined through a listening experiment. The results revealed that room acoustic condition significantly affects the timbral brightness of clarinet tones. Further, the room acoustic effect differs according to the produced note and dynamic level (e.g., *piano* or *forte*). In order to investigate these results objectively, temporal and spatial parameters were measured from binaural room impulse responses (*BRIR*s), and the spectral centroid (f_c) of semi-anechoic and reverberant signals were analyzed acoustically. The results of a linear regression analysis, which involved varying the f_c*_scaled* (f_c values as scaled by the range of f_c within the nine stimuli with the same note) factor and inputting nine combinations of perceived brightness (three dynamic levels × three produced notes) for each room acoustic condition, indicated that perceived brightness linearly increases with f_c*_scaled*. This result is in accordance with previous studies on the timbral brightness of musical tones. Further, the results suggest that each of the regression constants correlates with certain room acoustic parameters.

INTRODUCTION

This is the second report on timbral brightness perception of musical sounds in rooms. In the first report (Part I), a listening test was conducted to investigate the dependency of the timbre of musical tones on room acoustic condition (*room*). The listening experiment demonstrated that the *room* significantly affects the timbral brightness of clarinet tones. Further, the effect of the *room* differs according to the produced note and dynamic level (e.g., *piano* or *forte*). These findings call for further objective examination of the interaction between performing style and the *room* on the brightness of clarinet tones.

It is well known that timbral brightness correlates with increased power at high frequencies. The distribution in the power spectrum can be simply quantified by spectral centroid, f_c. For a power spectrum with components A_i (f_i), f_c is defined as $\Sigma f_i A_i / \Sigma A_i$, where f_i is a frequency. Some researchers have shown that brightness positively correlates with either f_c (Marozeau *et al.*, 2003; Shubert and Wolfe, 2006; Marozeau and Cheveigé, 2007) or the ratio of f_c to the fundamental frequency (i.e., f_c/F_0) (Kendall and Carterette, 1996; Kendall, 2002; Disley and Howard, 2004). However, the effect of the *room* on the perception of brightness has received little examination and is not well understood.

Disley and Howard (2004) reported that a more reverberant pipe organ sound was perceived as less bright. They speculated that this might be caused by the reduction in f_c/F_0. A useful implication of their study is that the perception of brightness of sound in rooms can be described simply by a single parameter, f_c (or f_c/F_0), of the reverberant signal.

However, it is natural to suppose that the *room* not only affects f_c of a reverberant signal, but also other acoustic attributes. Some of the temporal and spatial parameters of the *room*, such as reverberation time and/or interaural cross correlation (*IACC*), may also contribute, in a complex manner, to the perception of timbral brightness of musical sounds in rooms.

In this study, the following hypotheses were designed and tested in three steps to objectively describe perceived brightness of clarinet sound in rooms:

- The perceived brightness of clarinet tones in each *room* can be described by a linear equation, for which the f_c of each sound signal for a given *room* is set;

- either the linear or constant term, for each linear equation, differs with the *room*;

- each of the linear and constant term, for each linear equation, correlates with some of the acoustic parameters of the *room*, as extracted from the measured binaural room impulse responses (*BRIR*s).

MATERIALS AND METHOD

Semi-anechoic stimuli and reverberant stimuli for acoustic analysis

Nine semi-anechoic natural clarinet tones, produced at three different dynamic levels (*F*, *M*, and *P*) (see Table 1) and at three different notes (A3 ≈ 220 Hz, A4 ≈ 440 Hz, and A5 ≈ 880 Hz), and eighteen reverberant stimuli, as used for the listening experiment conducted in Part I, were used for the acoustic analysis. The duration of each semi-anechoic stimulus was between 2.1 s and 3.1 s, as listed in Table 2.

The reverberant stimuli were generated by convolving each semi-anechoic tone with two different *BRIR*s, which had been collected at different seat positions in two different, medium-sized concert halls (see Table 3). Figure 1 and Table 4 list the acoustic parameters of each *room*.

Acoustic analysis and hypothesis models

The f_c of clarinet tones in the *room*s was analyzed acoustically for A-weighted amplitude spectrum A_i (f_i). In this study, f_c was defined as $10^{(\Sigma f_i A_i / \Sigma A_i)}$, where A_i is the absolute value of the amplitude spectrum and f_i is a frequency in logarithmic scale, respectively.

The relationship between perceived brightness in rooms and measured f_c was investigated by testing the following hypotheses in three steps:

- The scale values of the brightness of clarinet tones (*brightness*) in each *room* can be described by a linear equation, setting f_{c_scaled} as a factor, as shown in equation (1).

$$brightness(i,j,k) = a_0(j) + a_1(j)\{f_{c\_scaled}(i,j,k)\} \qquad (1),$$

where

$$f_{c\_scaled}(i,j,k) = \frac{\log f_c(i,j,k) - \overline{\log f_c(k)}}{\log f_{c\_range}(k)} \qquad (2),$$

$$\log f_{c\_range}(k) = Max\{\log f_c(i,j,k)\} - \min\{\log f_c(i,j,k)\} \qquad (3),$$

$$\overline{\log f_c(k)} = \frac{1}{3\times 3}\sum_{i}^{3}\sum_{j}^{3}\log f_c(i,j,k) \qquad (4),$$

$$\log f_c(i,j,k) = \{\log_{10} f_{c,left}(i,j,k) + \log_{10} f_{c,right}(i,j,k)\}/2 \qquad (5),$$

i = dynamic level (*P*, *M*, and *F*) (6),

j = *room* (*A*, *K*, and *T*) (7),

k = produced note (A3, A4, and A5) (8),

$a_0(j)$ is the constant term for *room j*, and $a_1(j)$ is the liner coefficient for *room j*. Further,

- either $a_0(j)$ or $a_1(j)$ in equation (1) varies with the *room*;

- each of $a_0(j)$ and $a_1(j)$ correlates with some of the acoustic parameters of the *room*.

Table 1. Produced dynamic levels and their abbreviations

Dynamic level	Abbreviation
Piano	*P*
Mezzo	*M*
Forte	*F*

Table 2. Duration of each semi-anechoic stimulus

Note	Dynamic level	Duration [s]
A3	*P*	2.5
	M	3.1
	F	2.4
A4	*P*	2.4
	M	2.8
	F	2.1
A5	*P*	2.2
	M	2.6
	F	2.4

Table 3. Abbreviations of various room acoustic conditions

Room acoustic condition	Abbreviation
Semi-anechoic	*A*
Kirishima International Concert Hall (15th row, seat number 7)	*K*
Tsuyama Music Hall (5th row, seat number 9)	*T*

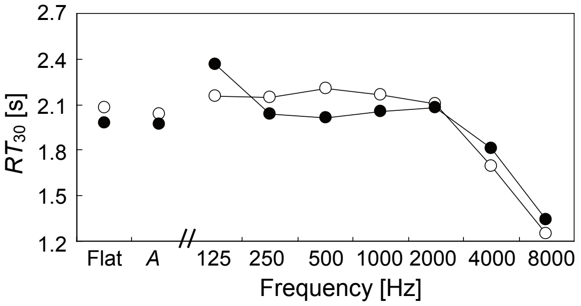

Figure 1. Reverberation time (RT_{30}) in 1/1 octave bands for conditions *K* (●) and *T* (○).

Table 4. Room acoustic measures for conditions *K* and *T*. *A*: A-weighted. *ITDG*: Initial time delay gap between direct sound and first reflection. *EDT*: Early decay time. RT_{30}: Reverberation time. *IACC*: Interaural cross correlation. τ_{IACC}: Interaural time difference. W_{IACC}: Width of interaural cross correlation. *A*-value: Total amplitude of reflections.

	Room			
	K		*T*	
	All (Flat)	All (*A*)	All (Flat)	All (*A*)
ITDG [ms]	37		52	
EDT [s]	1.8	1.9	2.0	2.0
RT_{30} [s]	2.0	2.0	2.1	2.0
IACC	0.12	0.09	0.11	0.10
τ_{IACC} [ms]	0.083	0.063	0.000	0.000
W_{IACC} [ms]	0.058	0.055	0.052	0.071
A-value	5.9	5.2	3.7	3.4

RESULTS

Figure 2 shows the log of the measured f_c, as formulated in equation (5). Log f_c ranged between 2.6 and 3.1 for note A3, between 2.7 and 3.2 for note A4, and between 2.9 and 3.2 for note A5. It is apparent that, in each *room*, log f_c increases with the dynamic level. It is also apparent that the log f_c of reverberant signals was either lower or higher than that of its semi-anechoic source signal.

Table 5 lists the results of a linear regression, setting f_{c_scaled} as a factor, subject to nine conditions of *brightness* (three different dynamic levels × three different produced notes) in each *room* (see equation (1)). These models are also illustrated in Fig. 3. In each model, a clear linear relationship was observed, with a coefficient of determination (R^2) ranging between 0.96 and 0.99. These results show that *brightness* in each *room* linearly increases with f_{c_scaled}. This supports our first hypothesis that the perceived brightness of clarinet tones in each *room* can be described by a linear equation, for which the f_c of each sound signal for a given *room* is set.

Table 5 also shows that both the constant and linear terms of the regression constants vary with the *room*. Further, each of measured constant and linear terms of the regression constants for the reverberant *room*s *K* and *T* were larger than those for the semi-anechoic *room A*. These results support our second hypothesis that either the linear or constant term, for each linear equation, differs with the *room*. Further, the constant term for the *room K* was larger than that for the *room T*, while the linear term for the *room K* was similar to that for the *room T*.

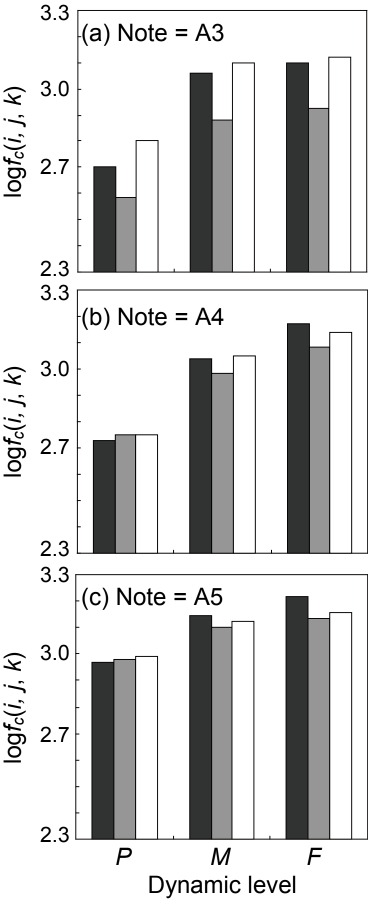

Figure 2. Comparison of effect of room acoustic condition on log f_c. ■: room *A*, ■: room *K*, and □: room *T*.

Table 5. Single variable linear regression for each *room*. Variables $a_0(j)$ and $a_1(j)$ are regression constants; the constant term and linear term, respectively. R^2: coefficient of determination.

Room	$a_0(j)$	$a_1(j)$	R^2
A	-0.32	+1.81	0.99
K	+0.29	+2.51	0.96
T	+0.06	+2.67	0.97

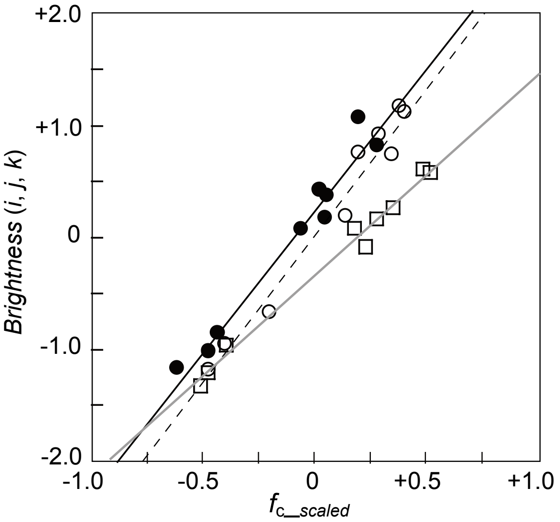

Figure 3. Relationship between f_{c_scaled} and measured scale values of brightness for each *room*. Each regression line depicts equation (1) with regression constants listed in Table 5. □ gray regression line: *room A*; ● solid line: *room K*; ○ dashed line: *room T*.

Table 6 presents the correlation matrix of variables $a_0(j)$, $a_1(j)$ and the room acoustic measures, as listed in Table 4. It can be seen that either *EDT*, RT_{30}, or *A-value* correlates well ($r \geq 0.91$) with $a_0(j)$, while either *ITDG*, *EDT*, RT_{30}, *IACC*, or W_{IACC} correlates well ($r \geq 0.98$) with $a_1(j)$. These results support our third hypothesis that each of the linear and constant term, for each linear equation, correlates with some of the acoustic parameters of the *room*, as extracted from the measured binaural room impulse responses (*BRIR*s).

Table 6. Correlation matrix of variables $a_0(j)$, $a_1(j)$ and room acoustic measures listed in Table 4. In bold face: $r > 0.90$.

	$a_0(j)$	$a_1(j)$	*ITDG*	*EDT*	RT_{30}	*IACC*	τ_{IACC}	W_{IACC}	*A-value*
$a_0(j)$	**1**	0.85	0.79	**0.91**	**0.93**	0.89	0.78	0.83	**1.00**
$a_1(j)$		**1**	**1.00**	**0.99**	**0.98**	**1.00**	0.33	**1.00**	0.85
ITDG			**1**	**0.97**	**0.96**	**0.98**	0.24	**1.00**	0.79
EDT				**1**	**1.00**	**1.00**	0.46	**0.99**	**0.92**
RT_{30}					**1**	**1.00**	0.50	**0.98**	**0.93**
IACC						**1**	0.42	**0.99**	**0.90**
τ_{IACC}							**1**	0.30	0.78
W_{IACC}								**1**	0.83
A-value									**1**

DISCUSSION

In the past, many researchers have suggested that the timbral brightness of musical sounds positively correlates with either f_c or f_c/F_0 (Kendall and Carterette, 1996; Kendall, 2002; Marozeau *et al*., 2003; Shubert and Wolfe, 2006; Marozeau and Cheveigé, 2007; Disley and Howard, 2004). Similar to the results of these previous studies, an acoustic analysis in this study showed that *brightness* in rooms linearly increases with f_{c_scaled} (see Table 5 and Fig.3). This suggests that we can interpolate the *brightness* of clarinet sounds simply by analyzing the f_c of signals recorded there, as far as the *room* is constant. This may be a useful result for researchers, sound engineers and/or musicians who are interested in the timbre of musical sounds in a given *room*. However, it should be noted that these results may be limited to the specific conditions of this study.

Considering Table 5 and Fig.3 again, our acoustic analysis also showed that both the constant and linear terms of the regression line varied with the *room*. This suggests that the *brightness* in a *room* can be described not only by f_{c_scaled}, but also by the other acoustic cues of the *room*.

In Table 6, it is suggested that one parameter among *EDT*, RT_{30}, and *A-value* correlates with the constant term, while one parameter among *ITDG*, *EDT*, RT_{30}, *IACC*, and W_{IACC} correlates with the linear term of the regression line. However, it is still unclear exactly which cues contribute to the brightness perceived in rooms. This calls for further detailed parametric investigations.

Disley and Howard (2004) reported that the value of f_c/F_0, for a reverberant pipe organ sound is lower than that of other less reverberant pipe organ sounds. In this study, the measured $\log f_c$ of reverberant signals was either lower or higher than that of its semi-anechoic source signal (see Fig.2). However, the f_c of the convolved signal may depend on the interaction between the distribution in the power spectrum of the musical sound source and the frequency-response characteristic of *BRIR*s. This is an issue that we plan to address in a future work.

CONCLUSIONS

In this study, in order to objectively examine the timbral brightness of clarinet tones as perceived in rooms, a linear regression analysis, in which f_c*_scaled* was set as a factor and that was subject to various conditions of *brightness*, was conducted for each *room*. The results showed that *brightness* increases linearly with f_c*_scaled*.

Further, the results suggested that each of the regression constants for the linear regression analysis correlates with certain room acoustic parameters. It was observed that one parameter among *EDT*, RT_{30}, and *A-value* correlates well ($r \geq 0.91$) with the constant term, while one parameter among *ITDG*, *EDT*, RT_{30}, *IACC*, and W_{IACC} correlates well ($r \geq 0.98$) with the linear term.

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