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# DOES VIRTUAL CONCERT HALL COLOR AFFECT LOUDNESS?

Yuxiao Chen<sup>1</sup>

Densil Cabrera<sup>1</sup>

<sup>1</sup> School of Architecture, Design and Planning, The University of Sydney, Australia  
yuxiao.chen@sydney.edu.au

## ABSTRACT

Being a multi-sensory experience, the perception of a musical performance can be affected by many factors, especially auditory and visual ones. Studies have found connections between various visual factors and room acoustic perception, notably for spatial attributes like room size and source distance. The influence of color on perceived loudness has been found in studies of vehicle noise. To examine whether the same effect happens in concert halls, this study used a virtual reality model of a small concert hall (or recital hall) of various colors to present visual and auditory scenes, and participants rated the loudness and reverberance of an auralized string quartet. Results indicate that the effect of color on loudness and reverberance ratings is very weak in comparison to varying gain by up to 3 dB, or varying reverberation time by up to 50%.

## 1. INTRODUCTION

Going to a music performance at an auditorium is never just about the music. It is affected by many factors, and apart from the sound itself, the visual scene is the most important influence on the perception of sound [1]. The cross-sensory influence between visual and auditory modalities in auditoria has been studied in many ways. It has been found that the presence of visual stimuli can affect perceived loudness [2] and auditory perceived distance [3]; different visual distances can affect perceived loudness [4-9], auditory perceived distance [7], and other auditory parameters including apparent source width and listener envelopment [10]; and different visual room dimensions can affect auditory perceived room size [11].

Of particular interest for this study, colors have been found to affect perceived loudness for vehicles or trains [12-14]. Among the colors tested, red or pink usually yielded greatest loudness ratings, while green or blue usually yielded the quietest. However, another study on the influence of train color on loudness found no significant effect [15]. As concert hall is a place where visual scenes have already proven to have various influence on auditory perception, whether or not different colors have significant effect on loudness perception may provide supplementary evidence for this controversial question. That leads to the research question: does the color of a concert hall affect loudness? Further, reverberance as another basic room acoustics attribute is partly associated with loudness [16-17]. Therefore it is also included in this study. A subjective test was used to investigate the effect of concert hall color on perceived loudness and reverberance.

## 2. METHOD

### 2.1 Experiment Model

In order to control variables, virtual reality and digital audio playback were used in the experiment.

#### 2.1.1 Visual Stimuli

A 3D computer model of a base concert hall (Verbruggen Hall, Sydney Conservatorium of Music) was presented via an HTC Vive virtual reality headset through the software Unity (Fig. 1). The VR headset provides an immersive virtual environment with built-in headtracking.



Figure 1. Visual scene example in the experiment

Colors were controlled in the experiment using the Hue-Saturation-Value (HSV) (or HSB for Hue-Saturation-Brightness) system (Tab. 1). Red, yellow, green and blue scenes, were achieved by varying hue, while keeping saturation and value of the relevant architecture elements constant. For the neutral (grey) scene, saturation was set to 0 while the value of each architectural element is the same as other scenes.

Color	Hue	Saturation and Value			
		Carpet	Seats	Side walls	Stage wall
Red	0°	S: 50% V: 60%	S: 70%	S: 40%	S: 20%
Yellow	60°		V: 70%	V: 90%	V: 100%
Green	120°				
Blue	240°				
Neutral	NA (S: 0%)	V: 60%	V: 70%	V: 90%	V: 100%

Table 1. Color settings used in the experiment in HSB.

The texture mapping and scale of each architectural element was the same in all scenes. To keep the scenes looking reasonably realistic, some colors and textures remain the same in all scenes (e.g. wooden texture for the stage floor, black steel texture for the railings).

### 2.1.2 Auditory Stimuli

The audio used in the experiment was an anechoic recording of a string quartet [18] from an excerpt in Antonio Vivaldi's Four Seasons (Summer, III. Presto) convolved with measured and manipulated impulse responses from the base auditorium.

Second-order Ambisonics impulse responses for four source locations on stage corresponding to the 4 instruments of a string quartet were measured in the real auditorium with the receiver at one selected seat. The original measured impulse responses were manipulated using the reverberation time changing function in AARAE [19-20]. Three levels of reverberation time were used in the experiment: the measured original *RT*, and manipulated *RT* with relative factors of 0.8 and 1.2. Compared to the shortest reverberation time, the longest reverberation time has an increase of 50%.

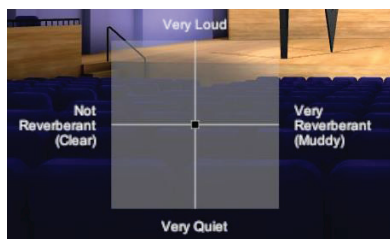
The audio was played to the participants via Sennheiser HD 800 Headphones using the software Max/MSP/Jitter. For each level of reverberation time, the impulse responses were convolved with each anechoic recording and added together to an Ambisonics audio file at the selected seat, which was rendered binaurally with real-time head movement data sent from Unity to Max/MSP/Jitter through Open Sound Control portal.

The gain of the audio was changed by applying gain factors in Max/MSP/Jitter. Four levels of Gain were used in the experiment, with the gain factors of 0.6, 0.8, 1.0, and 1.2 respectively (corresponding to -2.2, -0.9, 0 and +0.8 dB respectively). The difference between the smallest and largest gain was 3 dB.

Hence, a total of 60 stimuli were generated, comprising all combinations of the 12 audio stimuli (4 levels of Gain  $\times$  3 levels of RT) and the 5 visual scenes.

### 2.1.3 Participant input

The input for subjective evaluation was done with HTC Vive Controllers. Two 2D sliders were presented to the participants. Each 2D slider contains two subjective attributes: Loudness and Reverberance; Visual Preference and Auditory Preference. Only the results from the first slider (loudness and reverberance) (Fig. 2) are included in this paper.



**Figure 2.** Subjective response interface for Loudness and Reverberance.

## 2.2 Experiment Setting

30 participants over 18 years old with normal color sight and normal hearing took part in the study. The 60 scenes were presented to each participant in one of 4 different randomly generated orders. Every participant went through an induction at the beginning to get used to the system. To prevent cybersickness and fatigue, there was a 10-15 minutes rest after the first 30 scenes.

## 3. RESULTS AND ANALYSIS

### 3.1 ANOVA results

#### 3.1.1 Using Original Scores

ANOVA was used to test the effect of controlled variables and individual influence on the of subjective loudness (Tab. 3) and reverberance (Tab. 4).

Effect	<i>Df</i>	<i>F</i> value	Significance	Eta sq
Gain	3	544.5	***	0.427
RT	2	80.6	***	0.042
Color	4	3.1	*	0.003
Participant ID	29	9.0	***	0.068
* $p < .05$ ** $p < .01$ *** $p < .001$				

**Table 3.** ANOVA results for original score of Loudness.

Effect	<i>Df</i>	<i>F</i> value	Significance	Eta sq
Gain	3	34.9	***	0.048
RT	2	76.8	***	0.070
Color	4	1.6	0.178	0.003
Participant ID	29	6.1	***	0.080
* $p < .05$ ** $p < .01$ *** $p < .001$				

**Table 4.** ANOVA results for original score of Reverberance.

The results indicate that individual difference significantly influenced both the results of Loudness and Reverberance, of which its effect on Reverberance was more obvious because of the relatively small effect of the independent various on Reverberance. In order to eliminate this effect, the results for each evaluation parameter of each participant were standardized to *z*-scores (with a mean of 0 and a standard deviation of 1).

#### 3.1.2 Using Standardized Scores

The same ANOVA tests were conducted for the standardized scores, and no effect was found for Participant ID. The rest of the results are shown in Tab. 5 and Tab. 6. It can be seen that the effects of independent variables were slightly bigger for the standardized scores compared to original scores.

Effect	Df	F value	Significance	Eta sq
Gain	3	627.7	***	0.487
RT	2	89.7	***	0.046
Color	4	3.2	*	0.003
* $p < .05$ ** $p < .01$ *** $p < .001$				

**Table 5.** ANOVA results for standardized score of Loudness.

Effect	Df	F value	Significance	Eta sq
Gain	3	30.3	***	0.045
RT	2	77.5	***	0.076
Color	4	1.6	0.166	0.003
* $p < .05$ ** $p < .01$ *** $p < .001$				

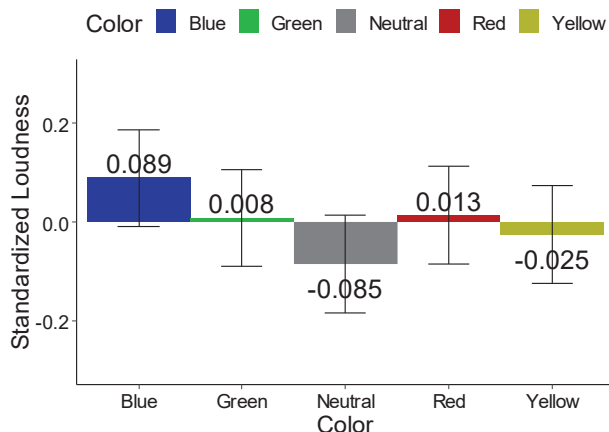
**Table 6.** ANOVA results for standardized score of Reverberance.

Loudness was significantly affected by Gain, RT, and Color. However, the  $F$ -value, significance level, and effect size (eta squared) for Color are much smaller than those of Gain or RT. RT also has a much smaller effect than Gain. Although the effect of Color is significant, the effect size is negligible.

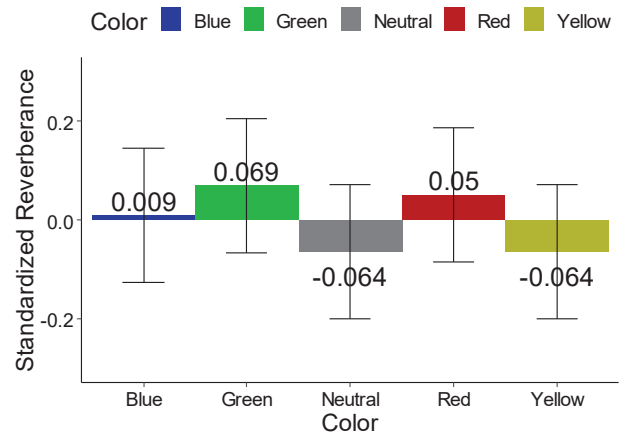
Reverberance was only significantly affected by Gain and RT, but not significantly affected by Color. RT has a bigger effect than Gain. However, the effect of RT on Reverberance is much smaller than the effect of Gain on Loudness.

### 3.2 Visualization

Even though the total effect of color on loudness and reverberance was negligible, the mean values of each color (with the effects of *Gain* and *RT* eliminated) may still be of interest, and are shown in Fig. 3 and Fig. 4.



**Figure 3.** Mean and 95% confidence interval of standardized Loudness for the five visual scenes



**Figure 4.** Mean and 95% confidence interval of standardized Reverberance for the five visual scenes

Blue scenes corresponded to the highest loudness judgement, contrary to Fastl's finding that red had the highest loudness [13]. Overall, the effect of color on Loudness and Reverberance were both very weak compared to changing auditory stimuli, and had relatively high error rates. The findings in this study are effectively consistent with the null hypothesis that color is likely to have no noticeable effect on perceived loudness [15].

## 4. CONCLUSIONS

Five different interior colors were applied to a concert hall in virtual reality, in which thirty participants evaluated perceived loudness and reverberance of a music excerpt with various audio gain and reverberation time. Results show that color scarcely influences perceived loudness and reverberance, with negligible effects compared to the changes in auditory stimuli. The effect of each individual color on loudness did not show the same trend as observed by Fastl.

The results reported here (along with subjective preference, not reported here) are further developed in [21].

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