Multimodal Perception of Auditoria: Influence of Auditory and Visual Factors on Preference

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Declaration

This is to certify that to the best of my knowledge, the content of this thesis is my own work.

This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

The studies described in Chapters 3 to 7 were conducted as per the University of Sydney Human Research Ethics Committee (HREC) guidelines. The experiment described in Chapter 3 were approved by the HREC under the project number [2019/814], the experiments described in Chapters 4 to 6 were approved by the HREC under the project number [2020/449], and the questionnaire survey described in Chapter 7 were approved by the HREC under the project number [2020/800].

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Abstract

The enjoyment of a music performance is a multisensory experience, of which auditory and visual senses play the most important parts in conveying the content of the concerts. This thesis investigates the effects of and relationships between various auditory and visual factors on subjective preference, with an emphasis on the rarely-studied visual preference. The thesis includes four subjective evaluation experiments (all using head-mounted virtual reality display and headphones audio playback, 30 to 33 volunteers each) and one online survey (153 responses). The experimental method of virtual reality display and digital audio playback allows each factor to be individually controlled and tested, which was never possible with traditional methods, but still provides a reasonable sense of space and realism. Auditory factors considered in the thesis include sound pressure level and reverberation time, while visual factors include interior design colour, distance from the stage, lateral angle from the concert hall mid-plane, vertical angle from stage level, and visual obstruction. The effects of factors were studied using orthogonal control, and verified with realistic models and alternative methods with larger sample. Results include a prediction model that accounts for the effects and relationships of all investigated factors, and a practical tool for design/evaluation of auditorium seating layout.

The first chapter reviews and summarizes the current state-of-the-art regarding auditory and visual preference in auditoria. In the field of auditorium acoustics, auditory preferences have been rather well-studied and many acoustic attributes including sound strength, reverberation time, lateral energy fraction, etc. have been found to affect subjective preferences. But visual preferences are relatively less studied with few established results. However, it is found that visual preferences play a very important part in, and can sometimes contribute more to, overall preferences. In addition, visual and auditory preferences are found to influence each other, but the interaction has also not been studied thoroughly. Therefore, this thesis tries to fill in the gaps and investigate the relationship between subjective preferences and objective factors in both auditory and visual aspects, and their relationships, using subjective evaluation study.

The second chapter gives details of the overall methodology of all the virtual-reality subjective experiments included in this thesis. Computer models of static orchestras and auditoria were rendered in head-mounted virtual reality display, and spatial audio signals were decoded binaurally with real-time head-rotation information and presented via headphones. As an innovative adaptation to COVID-19 restrictions, parts of the experiments were conducted remotely with the volunteers' own equipment outside the laboratory. To operationalize this new method, user-interactions from game design were integrated in the experiments.

The third chapter investigates the effect of concert hall colour on auditory and visual preference, together with loudness and reverberance, through the first laboratory-based subjective experiment. The same audio clips with four distinct sound pressure levels and three distinct reverberation times were paired with the same concert hall of five different interior colours. Thirty participants provided subjective evaluation of loudness, reverberance, visual preference, and auditory preferences, for each of the sixty combinations of stimuli. Results show that auditory preference was significantly affected by sound pressure level but not by reverberation time, and visual preference was significantly affected by colour. For different

interior colours, red was the most favourable while green was the least. A positive correlation was found between the preferences for each colour and the number of existing auditoria of that colour. In addition, auditory preferences and visual preferences have positive correlations. The perception of loudness and reverberance were only found to be influenced by the two auditory factors.

The fourth chapter describes the second experiment with orthogonally controlled factors investigating the effect of visual seat location, including distance, lateral angle, and vertical angle on overall preference, with the effect of audio gain level as a reference. No auditorium was rendered beyond the stage with static musician models, hence this experiment was mostly concerned with stage-view quality. Thirty-six visual locations, containing six different values for each factor including a three-by-three-by-three orthogonal matrix, were examined together with four different audio gain levels. Thirty-three volunteers participated in the experiment remotely. Results show that people prefer smaller distance to the stage, smaller lateral angle from the centreline of the auditorium, vertical angle around 20° above stage plane, and higher audio gain level. No interaction was found between the factors. The prediction model derived from the results was validated with previous case studies and online survey results.

The fifth chapter contains the third experiment, which tests and corrects the prediction model from the orthogonal experiment in more realistic audio-visual virtual reality concert hall environments with simulated first-order Ambisonic audio. The visual and auditory models of two size variations of a concert hall were simulated and presented under both matching and unmatching conditions. Thirty-three volunteers, including fifteen laboratory-based participants and eighteen remote participants, evaluated the seat preference at eighteen locations in each of the four combinations of visual and auditory auditorium models. Results show that both visual and auditory auditorium model affect preference, obstructions of the stage view negatively affect preference, and the effect of distance is slightly larger than in the prediction model when visual environment of the auditorium is present. The prediction model was modified accordingly. However, no other acoustic parameter was found to have significant effect in addition to the modified prediction model. No significant difference was found between the results of laboratory-based and remote participants.

The sixth chapter contains the fourth experiment that is a visual-only laboratory-based experiment. It investigates several unanswered questions from the previous chapters by examining and comparing the effect of various visual factors of auditorium, including the presence of visual environment, size, occupancy, and colour, on visual seat preference and hall preference. Thirty participants evaluated six locations each in twelve visual variations of an auditorium, and their overall preference for each variation. Results show that auditorium size, occupancy, and colour all affect preference of the halls. Colour also affects seat preference to a smaller extent. When using visual stimuli only, seat preference is much more affected by visual obstruction than when using combined audiovisual stimuli. The prediction model proposed in Chapter 5 experiment fits the results well when taking into the account the additional effect of visual obstruction. View obstructions caused by other audience members are more tolerated than obstructions caused by architectural elements.

The seventh chapter examines the evaluated importance and relationships of various factors on concert enjoyment and decision making through an online survey. The investigated factors include the visual and auditory factors examined in the experiments, and those related to other aspects of concert-going, including performance, price, comfort, architectural design, and social aspects. From 153 valid responses, it was found that the most important factors are related to performance, acoustics, and view; but price, comfort, and social factors are also moderately important. Performance and acoustic factors, comfort and view, social aspects and architectural design were closely linked in the judgements. Backgrounds of participants, including commitment in concert-attending and professional backgrounds in music, acoustics, audio engineering and architectural design, were found to influence their evaluation.

The eighth chapter analyses the view quality at all seat locations in 56 music auditoria in the world using the prediction model derived from this thesis, and examines the relationships between view quality and acoustic quality, size, and architectural form of the auditoria. Halls with the best acoustics have less varied stage view qualities compared to others. When the acoustic qualities are in the same category, rectangular halls generally have the best view qualities. Smaller halls have both better acoustics and better view qualities (in terms of proportion) compared to larger halls. In terms of the providing the largest number of seats with "good" view quality, there is an optimal size of auditorium at around 2000 to 2500 seats.

In summary, this thesis evolves around the topic of subjective preference in music auditoria, with emphases on visual factors and seat preference, to fill in gaps in the current literature. Findings confirmed and quantified the effects of various factors. Prediction models were derived from the results which can be used to evaluate any given auditorium.

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Chapter 1 Introduction

1.1 Overview

Going to a music concert is a very complex, multi-sensory activity.

The psychological context of going to a concert has great influence on the experience, from the activity prior to going to a concert, the price of the ticket, and the social companions one goes to a concert with, to the fame, the history, and one's knowledge of the concert hall, the musicians and the repertoire. Even during a concert, various factors including the comfort of the seat, the thermal comfort of the surrounding environment, and one's own physical and psychological conditions could all affect the watching and listening process.

However, for most audiences, the primary purpose of going to a concert is still to watch and listen to the musicians playing music. Therefore, the content of the performance is conveyed to the audiences through two main sensory modes: auditory and visual. How to improve the quality of the sound and sight for the audiences has been a long-studied topic since auditoria for performance art came to existence.

"Quality" is a subjective term in this context, and every person has his or her own definitions. But in modern times, an auditorium is built for all audiences instead of just one person, and the best it can do is to fit the likes of most people. Therefore, in order to improve the "quality" of sound and sight in auditoria, the two essential steps are: 1) to study the common subjective preference of a certain number of people through subjective testing, in other words, know what most people like; and 2) to find the quantitative connection between subjective preference and objective parameters that can be measured, so that certain objective parameters can be used as indicators in simulations and calculations in the design stage to achieve better subjective preference, in other words, predict what people like.

The entire subject of auditorium acoustics is based on improving the auditory condition, or sound quality perception, in performing spaces. The connection between subjective auditory preference and acoustic parameters was relatively well-studied. Certain parameters are found to influence subjective preference, and well-established standards such as ISO 3382-1: 2009 have harmonized measurement methods for each parameter, along with the recommended value ranges. Even before an auditorium is built, acoustic simulation software such as Odeon or CATT can predict the parameters based on computer models, giving designers and acousticians the opportunity to review and refine the design before construction.

However, the preferences for visual condition in auditoria is relatively under-studied. Standards and suggestions on visual condition in auditoria are undeveloped and outdated, so are methods for predicting and improving visual condition in the design stage.

To understand the auditory and visual perception in auditoria it is also important to take into account that while these are perceived through different senses, they cannot be considered completely separately. That is because, auditory and visual perception have cross-modal influence on each other.

1.2 Auditory preference in auditoria

The ultimate goal of auditorium acoustics research and design is to achieve “good acoustics”. To do that, there are two steps (Figure 1-1).

First, it is necessary to know what “good acoustics” is. Although personal preference is a very subjective thing that differs with every individual, there might be some common characteristics that most people like, which is usually investigated through subjective preference studies that investigate the preference of a group of people. The studies of auditory preference usually fall in one of the two categories: 1) trying to use objective acoustic parameters that can be measured or calculated to predict auditory preference (e.g., Hidaka & Beranek, 2000; Schroeder et al., 1974), and 2) trying to use subjective description words to refine the meaning of auditory preference (e.g., Soulodre & Bradley, 1995; Hawkes & Douglas, 1971; Lokki et al., 2012). With the second method, it is possible that subjective descriptions can predict auditory preference quite well, but subjective descriptions cannot be quantified or manipulated by design, unless the connections between them and certain objective parameters are found. Therefore, other studies are needed that focus on finding the best objective indicator for certain subjective descriptions, without any preference studies involved (e.g. Bradley & Soulodre, 1995b; de Keet, 1968).

Second, when it is clear how “good acoustics” translate to objective parameters, some measures need to be taken to try to achieve the desired values, which usually involve the manipulation of architectural geometries and materials (e.g., Beranek, 1992, 2012). Before an auditorium is even built, simulations and calculations can be adapted to predict the objective parameters with relatively good precision from the geometry and material of the design (e.g., using ray-tracing software such as Odeon, CATT-Acoustic). If the results are not ideal, certain changes can be made to improve it. But apart from acoustics, the design of an auditorium may also be affected by many other factors and limitations (e.g., budget, site condition, cultural background, aesthetics). As a result, every design is different from the other ones. Therefore, even though some rules have been proposed to be followed under any circumstances, in most situations, experiences from the past are needed to be able to make the best design decisions.

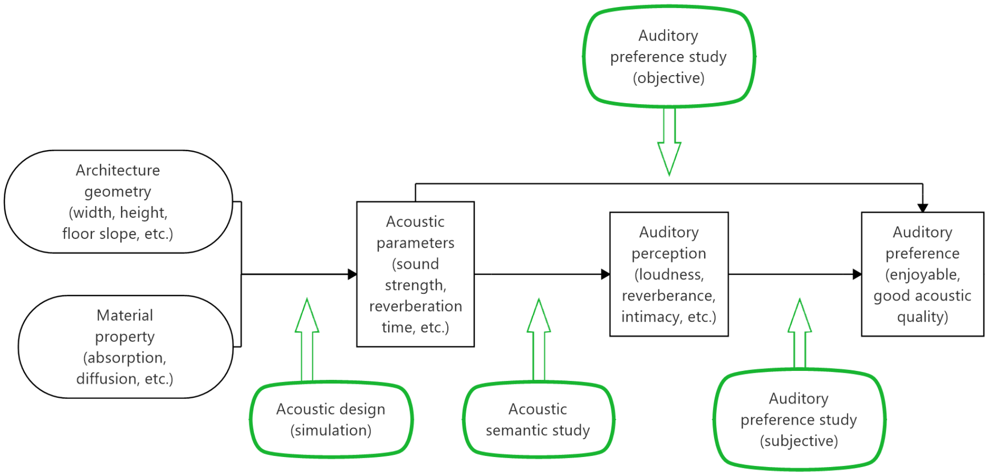


Figure 1-1 The process of studying and improving auditory preference in auditoria

As this section is about auditory preference in auditoria, only the first step stated above will be discussed. Some of the most relevant studies are summarized in Table 1-1. Various subjective attributes and their related objective parameters have been found to affect people's auditory preference, such as subjective loudness and sound strength (G), subjective reverberance and reverberation time (RT) or early decay time (EDT), subjective clarity and C_{80}, subjective apparent source width (ASW) and early lateral energy fraction (J_{LF} or J_{LFC}), subjective listener envelopment (LEV) and late lateral sound level (L_J), etc. (Barron, 1988; Beranek, 2012; Hawkes & Douglas, 1971; Lokki, 2013, 2014; Schroeder et al., 1974). Acoustic defects such as background noise or echoes also affect the overall quality and should be avoided (Barron, 2009). The question of "what is good" has been tested in numerous subjective studies in which the participants link the "overall sound quality" to various subjective descriptions, which were then linked to objective parameters that can be calculated from measured impulse responses. The understanding in these terms has developed and been refined through time since Sabine brought forward the concept of reverberation time (Sabine, 1900). Nowadays, design guidelines and standards have given specific recommendations for each acoustic parameter for each type and size of performing art spaces, which can be followed as part of the design process and tested after the completion of the project (Barron, 2009; ISO 3382-1: 2009). However, because of the complexity of subjective preference, the answer is still not definite, and disputes remain. Nevertheless, the influence of some factors has more supportive evidence than others, and are therefore widely believed to be important for auditory preference.

Table 1-1 Existing studies on auditorium auditory preference

Article title	Author	Year	Auditorium	Source	Equipment	Results (/ or \ for positive or negative trend; n or u for quadratic trend; x for no relationship found)	Method	No. of subjects	No. of tested halls
Subjective acoustic experience in concert auditoria	Hawkes & Douglas	1971	Concert halls	In situ		Definition, reverberance, balance and blend, proximity (/)	Questionnaire (continuous scale) + factor analysis	92	1 × 23 positions
						Reverberance, evenness, intimacy, definition, enjoyment, brilliance (/)		16	4 × 4 positions
Comparative study of European concert halls: correlation of subjective preference with geometric and acoustic parameters	Schroeder et al.	1974	Concert halls	BIR * symphony	2 speakers	EDT(/), D50(\), width of hall(\), IACC(\)	Paired-comparison + factor analysis	12	22
Effects of early multiple reflections on subjective preference judgments of music sound fields	Ando & Gottlob	1979	Synthetic	Simulated * chamber music	Speaker array	IACC(\)-early reflections	Paired-comparison	13	1 × 2 systems × 2 decay curves
Subjective study of British symphony concert halls	Barron	1988	Concert halls	In situ		RT(/) (Note: all of them have short RTs) Group1: reverberance(/) Group2: intimacy(/)~loudness(/)	Questionnaire (linear scale) + correlation	27 (acoustic-ian)	11 (40 positions)
Concert hall acoustic evaluations by ordinary concert-goers: I, Multi-dimensional description of evaluations	Sotiropoulou et al.	1995	Concert halls	In situ		Body(loudness), clarity, tonal quality, proximity(envelopment) (/)	Questionnaire (continuous scale) + factor analysis	NA	NA
Subjective evaluation of new room acoustic measures	Soulodre & Bradley	1995	Concert halls	BIR * symphony	Near-field speakers	Clarity(/), treble(/), loudness(x), reverberance(x), bass(x), ASW(x), LEV(x)	Paired-comparison + linear regression	10 (acoustic-ian)	7
Objective and subjective evaluations of twenty-three opera houses in Europe, Japan, and the Americas	Hidaka & Beranek	2000	Opera houses	Questionnaire for subjective evaluation BIR for objective measurements		RT(1.4-1.6s), C80,3(1-3dB), 1-IACCE3>0.6, ITDG<20ms, GM(1-4dB on stage), bass ratio>1.05, early reflection(15)	Questionnaire (5-point scale) + optimal range	22 (conduct -or)	23
Acoustic quality of theatres: correlations between experimental measures and subjective evaluations	Farina	2001	Opera houses	Questionnaire for subjective evaluation BIR for objective measurements		Ts(/), C80(\), SPL(/), LAeq(/), RASTI(\), C50(\), Rev/Dir(/), T30(x), EDT(x), ITDG(x), IACC(x)	Questionnaire (6-point scale) + multiple linear regression	47 (music -ian)	8
Relating auditory attributes of multichannel sound to preference and to physical parameters	Choisel & Wickelmaier	2007	\	Pop/classic	Speaker array	ASW(/), LEV(/), spaciousness(/), brightness(/), elevation(/), clarity(/)	Paired-comparison + factor analysis/ linear regression	39	1 × 8 settings
Subjective and objective evaluations of a scattered sound field in a scale model opera house	Ryu & Jeon	2008	Opera house	BIR * solo violin	2 speakers	Loudness(/), reverberance(/), clarity(x), LEV(x), ASW(x), SPL(/x), EDT(/), IACCL(\x)	Questionnaire/ paired-comparison + linear regression	31/20	1 (1:10 scale) × 2 settings × 15/6 positions
Disentangling preference ratings of concert hall acoustics using subjective sensory profiles	Lokki et al.	2012	Concert halls	SRIR * symphony	Speaker array	Proximity(/) Group1: reverberance(/), loudness(/), envelopment(/) Group2: intimacy(/), clarity(/)	Individual vocabulary profiling + correlation matrix	17	9
Relationships Between Perceived Room Acoustic Quality and Perceived Reverberance, Listener Envelopment, and Tonal Quality	Kocher & Vigeant	2015	Multipurpose hall	BIR * cello/ symphony	Electrostatic headphones	Reverberance(/), listener envelopment(/), tonal quality(/), vary by motif	5-point scale + correlation/linear regression	32	1 × 2 settings × 3 positions
Investigating listeners' preferences in Detmold Concert Hall by comparing sensory evaluation and objective measurements	Sahin et al.	2017	Concert hall	BIR * symphony	Headphones	SPL(/), LJ(/), IACC(/)	Paired-comparison + correlation	16	1 × 10 positions

1.2.1 Overall strength (loudness)

The loudness of music that the audience hears at a certain location in an auditorium is one of the most important factors that affect auditory preference in auditoria. The first and most basic acoustic purpose of an auditorium for unamplified music is to make the music sufficiently loud for a sizeable audience, by minimizing background noise and trapping the sound that would otherwise escape. Therefore, loudness is arguably the most basic characteristic of auditorium sound, describing how much sound there is. Most studies find that people like it louder in auditoria. Different studies used different indictors or predictors for this factor, mostly as sound pressure level, sound strength, or loudness. However, even though the indictor may differ depending on individual studies, the indicated factor is the same and the results are very similar. For convenience, the term “loudness” is used here as the indicated factor of all three indicators, because it describes an audience member’s experience of the phenomenon. It is one of the most obvious and clear attributes for listeners regardless of their backgrounds.

Sound pressure level (L_p, or *SPL*) is sound pressure, the pressure deviation from atmospheric average caused by sound wave, expressed in decibels (dB). It can be calculated using the following equation (ISO 16032:2004):

$$L_p = 10\log\frac{p^2(t)}{{p_0}^2}\,\text{dB}$$

Equation 1-1

In which $p(t)$ is the sound pressure, and p_0 is the reference sound pressure 20 µPa.

Sound pressure level describes how much sound there is at a certain location (e.g., the listener’s ear, microphone), and can be directly measured using equipment specified in IEC 61672-1:2003. Sound pressure level is related to both the sound source and the transmission process, and has multiple variations that emphasize different aspects of the sound (e.g., different time weighting, different frequency weighting). One of the most commonly used in this situation is equivalent A-weighted sound level ($L_{A,eq}$), which uses a filter that takes into account the auditory spectral sensitivity of humans (A-weighting), and averages pressure squared across an entire period of time-varying sound. In auditorium acoustics, the disadvantage of sound pressure level is that it confounds the sound source characteristics with the auditorium characteristics.

Sound strength (*G*) is the sound energy difference between the impulse response at a certain location within an auditorium and the reference value (10 m from the sound source in a free field). It can be calculated using the following equation (ISO 3382-1:2009):

$$G = 10\log\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10}^2(t)dt}\,\text{dB}$$

Equation 1-2

In which $p(t)$ is the instantaneous sound pressure of the impulse response from an omnidirectional sound source measured at the measurement point, and $p_{10}(t)$ is the instantaneous sound pressure of the impulse response measured at a distance of 10 m in a free field.

G is an expression of the sound pressure gain at a certain location of an auditorium, and can be calculated from an impulse response, which can be measured using a known sound source. *G* is a description of how loud the auditorium is. Hence, G describes the auditorium's characteristics independently from any sound sources. It is not related to the characteristics of the sound source, and varies with location (usually a negative correlation with distance due to the decrease of direct and early-reflected energy, e.g., Barron & Lee, 1988).

Loudness is the subjective impression of how loud the sound is. The loudness of a perceived sound is primarily indicated by SPL at the listener's ear. ISO 3382-1:2009 named *G* to be the primary indicator for loudness of auditorium, while some people argue that A-weighted *G* values are a better indicator (Soulodre & Bradley, 1995). However, loudness as a subjective attribute is also related to many other factors, including perceptual factors like frequency, temporal, and spatial characteristics of the sound, and cognitive factors like cultural context and individual experience (Florentine, 2011). Psychoacoustic models expressed in sones have been developed to predict the subjective loudness perception taking into account the perceptual factors (Chalupper & Fastl, 2002; Glasberg & Moore, 2002; ISO 532-1:2017; ISO 532-2:2017; Zwicker & Scharf, 1965).

In auditoria studies, these three attributes are closely related to each other. When the sound source is a controlled factor that is held constant in an experiment, which is the common case in most relevant studies, sound pressure level, sound strength, and loudness are generally positively correlated. In many studies, the loudness evaluated by the subjects in the same experiment that the auditory preference is studied is used as a predictor.

Most studies that studied the relationship between loudness and auditory preference found a positive correlation (Farina, 2001 (8 halls, listening level range 65.2-76.1dB); Jeon et al., 2005, 2008 (9 locations in hall, 62.7-68.5dB); Sato et al., 2012 (10 locations in one hall, 68.9-75.1dB)), it is also one of the acoustic qualities mentioned by Beranek (1992). Kuusinen & Lokki (2015) found a negative correlation between auditory preference and auditory perceived distance, which is usually also negatively correlated with loudness.

However, the studies of Barron (1988) and Lokki et al. (2012) both divided their participants into two groups according to their preferences, only one of which prefers greater loudness. Ando (1983) found a non-linear correlation between auditory preference and listening level, with an optimal level around 79 dB(A). Soulodre & Bradley (1995) found no significant correlation between loudness and auditory preference (10 halls, 74-82dB).

1.2.2 Temporal characteristics (reverberance and clarity)

The sense of reverberance or resonance is another important factor for auditory preference in auditoria, but the results are more controversial. It is to do with how sound changes over time in an auditorium, more specifically, how sounds gradually decay and vanish, and how the "tail" from an earlier sound affects a later sound. Several objective parameters are related to the sense of reverberance, including reverberation time, early decay time, etc.. The sense of clarity or clearness is another important factor, which is usually indicated by clarity, definition, or centre time. It is closely related to reverberance, but not perfectly correlated. In most cases, higher reverberance will result in lower clarity.

Reverberation time (T, RT, T_{30}, or T_{20}) stands for the time it takes in seconds for a sound to decrease by 60 dB after the source stops (ISO 3382-1:2009). It is usually calculated from a decay range of 30 dB (T_{30}) or 20 dB (T_{20}). The use of reverberation time as an indicator for how a room sustain the sound was first brought forward by Sabine (1900), and reverberation time has remained one of the most important room acoustics parameters ever since. It the most commonly used parameter to characterize a room due to its usually small spatial variations within a room.

Early decay time (EDT) is a variation from RT that describes the initial 10 dB of decay right after the source stops (ISO 3382-1:2009). It was found to be a better indicator for how people perceive the sense of reverberance compared to RT (Atal et al.,, 1966; Haas, 1972; Jordan, 1970; Soulodre & Bradley, 1995). EDT is usually highly positively correlated with RT, but varies more between different locations within a room, and tends to increase with source-receiver distance (Bradley, 1991; Ryu & Jeon, 2008).

Reverberance is the subjective impression of how sound-sustaining, or reverberant the room is. In ISO 3382-1:2009 it is characterized by EDT. There are also other psychoacoustic models that aim to fit better with the perceived reverberance (Osses Vecchi et al., 2017; Zarouchas & Mourjopoulos, 2009), including EDT_N and T_N (Lee et al., 2009, 2012, 2017) which take loudness into account (louder sounds being more reverberant).

Clarity (C_{80}, or C_{50}) is both the name of the subjective term for the clearness of sound (usually used for music and speech), and the name of the objective parameter for early-to-late index that can be calculated using the following equation (ISO 3382-1:2009):

$$C_{t_e} = 10\log\frac{\int_0^{t_e} p^2(t)dt}{\int_{t_e}^{\infty} p^2(t)dt}\,\mathrm{dB}$$

Equation 1-3

In which t_e is the time separator between early and late, which is usually 80 ms or 50 ms, the former of which more commonly used for music while the latter for speech, and $p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point.

While C_{80} proposed by Reichardt et al. (1975) is the regulated and most commonly used indicator for clarity (ISO 3382-1:2009), Soulodre and Bradley (1995) found that clarity is also strongly related to $G(A)$, and proposed a level adjusted C_{80}.

Other parameters such as definition (D_{50}, ratio between early energy of the impulse response before 50 ms and the total energy, interchangeable with C_{50}) and centre time (T_s, the gravitational centre of the graph of squared impulse response in milliseconds) are also given in ISO 3382-1:2009, but less frequently used compared to C_{80}, or C_{50}. While 80 ms (for music) and 50 ms (for speech) are the most commonly used time separators, other times have been used in different situations (e.g., 95 ms used by Lochner & Burger, 1958, 1964, based on their research on speech intelligibility; or 35 ms in some studies of classrooms and concert auditoria, Bradley, 1994; Whitlock & Dodd, 2008). When investigating the clarity of speech, other related parameters such as speech transmission index (STI, specified in IEC 60268-16:2020) are also used, but as the focus of this thesis is music auditoria, they will not be further discussed.

Clarity, definition, and centre time are all indicators for the clarity of sound. They are different but closely related. In usual cases, clarity and definition have positive correlations, while both of them have a negative correlation with centre time.

Reverberance and clarity are also related in most cases. When the shape of the decay curves and levels are similar, reverberance and clarity usually have a negative correlation. Halls that are too reverberant might suffer from low clarity and sound "muddy", while halls with very high clarity might suffer from less reverberance and sound "dead". When comparing between seats within one hall, while reverberance and EDT usually increase with distance, clarity and C_{80} decrease with distance (Bradley, 1991; Ryu & Jeon, 2008), partly due to the decrease of direct and early-reflected sound energy (modelled by Barron & Lee, 1988). Some early studies suggest that there should be an optimal RT for a given auditorium volume (Bagenal & Wood, 1931; Knudsen, 1932). Ando (1983) also suggests an optimal RT as a function of energy ratio between direct sound and total reflection. Beranek (2012) listed both "liveness", which is another term similar to reverberance, and "clarity" in the acoustic qualities, stressing the importance of both. Some subjective studies found that auditory preference positively correlates with reverberance or negatively correlates with clarity (Farina, 2001; Kocher & Vigeant, 2015; Schroeder et al., 1974), while some studies found the opposite (Sotiropoulou et al., 1995; Soulodre & Bradley, 1995; Sato et al., 2013). However, in Soulodre & Bradley (1995) and Farina (2001)'s studies, only relationships were found between preference and clarity (one positive, one negative), while no significant correlation was found for preference and reverberance.

Similar to loudness, only one of the two groups like higher reverberance in both studies of Barron (1988) and Lokki et al. (2012). However, in Barron's categorization, the group preferring reverberance is not the group preferring loudness, and both groups like longer RT, while in Lokki's categorization the same group preferred both loudness and reverberance.

1.2.3 Spatial characteristics (ASW, LEV, and intimacy)

How sound distributes across space is another important factor, and also one of the most complex aspects of auditorium acoustics. The most commonly accepted concepts relate to spatial balance are apparent source width, and listener envelopment. Intimacy is another important subjective concept in auditoria and also closely related to spatial balance. These attributes are more complex for subjective evaluation, and the connection to objective parameters are also more complicated.

Spaciousness, or **spatial impression,** is the subjective impression of how the sound comes from all directions in a three-dimensional space, and is generally considered to consist of two main aspects: apparent source width and listener envelopment (Bradley & Soulodre, 1995a, b; Griesinger, 1997, 1999; Morimoto, 1989, Morimoto et al., 2001).

Apparent source width (ASW), also referred to as auditory source width (e.g., Morimoto et al., 1993), is the subjective perceived auditory width of the sound source, which is strongly related to early reflections. It is generally considered, as regulated in ISO 3382-1:2009, to be indicated by **early lateral energy fraction (J_{LF} or J_{LFC})**, which is calculated from the energy arriving from lateral directions in the first 80 ms (Barron, 1971; Barron & Marshall, 1981; Marshall, 1967; de Keet, 1968).

Listener envelopment (LEV) is the subjective impression of being enveloped by the sound field, which is strongly related to late reverberation. It is generally considered, as regulated in ISO 3382-1:2009, to be indicated by **late lateral sound level (L_J)**, which is calculated from the energy arriving from lateral directions after the first 80 ms, and expressed in decibels (Bradley & Soulodre, 1995a, b; Morimoto, 1989).

Interaural cross-correlation coefficient (*IACC*) is an objective parameter calculated from a binaural impulse response recorded using a dummy head with pinna and ear canals or a real head (ISO 3382-1:2009). It has several variations including using different time limits and different frequency filters ($IACC_E$, $IACC_L$, $IACC_3$, $IACC_4$), which are used as alternative or supplementary measures for predicting ASW and LEV because of the negative correlations between $IACC_E$ and ASW, or $IACC_L$ and LEV (Hidaka et al., 1992, 1995; Okano et al., 1998).

Acoustic intimacy is the subjective impression of being close and intimately connected with the performers, and possibly other audiences. It is an even more complicated and undefined subjective attribute in auditoria, but considered to be as important as any other attributes for auditory preference, if not more important (Beranek, 2012; Hyde, 2002). It was first mentioned as a spatial attribute, but was later considered as a multifactorial attribute. Beranek (1992) proposed **initial time delay gap (*ITDG*)**, the time gap between the first reflected sound and direct sound arriving at the listener, as an indicator for intimacy, but later renounced the connection (Beranek, 2004), expressing the importance of both but admitting the lack of correlation between the two. Barron (1986, 1988) found that mid-frequency early sound level best correlates with intimacy. Hyde (2002, 2004, 2018) discussed the complexity and multisensory characteristics of acoustic intimacy and stressed importance of visual input.

Other factors, such as spectral characteristics, directional distribution of reflections, and overall sound strength, have also been found to be related to the subjective impression of spaciousness, ASW and LEV (Beranek, 2012; Blauert & Lindemann, 1986; Evjen et al., 2001; Hidaka et al., 1995; Jeon & You, 2010; Morimoto et al., 1995, 2001, 2007; Okano et al., 1998; Wakuda, 2003). There are also other parameters that researchers proposed as indicators for spatial impression, such as spatially balanced centre time (SBT_s), diffuse-field transfer function (DFT), and average interaural time delay (AITD) (Griesinger, 1999; Hanyu & Kimura, 2001), but are not accepted as widely as the parameters stated above and seldom used.

Some subjective auditory preference studies found positive correlations between the subjective evaluation of spaciousness, ASW, or LEV and auditory preference (Choisel & Wickelmaier, 2007; Kocher & Vigeant, 2015; Sotiropoulou et al., 1995), and some found negative correlations between IACC and auditory preference, which support the subjective findings (Ando, 1983; Ando & Gottlob, 1979; Schroeder et al. 1974).

However, some studies found no significant correlations between LEV, ASW, or IACC and auditory preference (Farina, 2001; Ryu & Jeon, 2008; Soulodre & Bradley, 1995).

Intimacy is also found to be positive correlated to preference (Hawkes & Douglas, 1971; Sotiropoulou et al., 1995), apart from the findings of Barron (1988) and Lokki et al. (2012) that connected intimacy with only the preference of one of the two groups.

Notably, the subjective auditory spatial impression is not completely auditory. All evaluations related to spatial impression are found to be influenced by visual input, or even possibly more influenced by visual input than auditory input. The interaction between auditory and visual perception will be discussed in detail in Section 1.5.

1.2.4 Spectral characteristics

Another factor that influences the perception or preference of sound in auditoria is how sound is distributed across different frequencies. Spectral characteristics are attributes of the sound source: the music, and the instruments. But auditoria can also react differently to different frequencies, enhancing certain frequencies while suppressing others, including effect on strength, reverberation, or spatial distribution. Compared to spatial characteristics, spectral characteristics are more straightforward and less affected by other factors. However, the importance of spectral characteristics for auditory preference is less emphasized.

Perceived treble is a commonly used subjective description for the enhancement of high frequencies, which could be best predicted by the energy ratio of high to mid-frequency (Soulodre & Bradley, 1995), while **brilliance** or **brightness** are usually associated with longer RT or EDT at high frequencies (Beranek, 1992, 2004, 2012; Hawkes & Douglas, 1971). Similarly, **perceived bass** or **bassiness** is considered to be related to the ratio of low to mid-frequency (Barron, 1988; Beranek, 2012) or early bass level (Soulodre & Bradley, 1995), while **warmth** is related to longer RT or EDT at low frequencies (Beranek, 1992, 2004, 2012; Griesinger, 1992).

Some studies found connections between treble or brilliance with auditory preference (Choisel & Wickelmaier, 2007; Hawkes & Douglas, 1971; Soulodre & Bradley, 1995), while others stressed the importance of bass or warmth (Beranek, 1992; Hidaka & Beranek, 2000), but Beranek (1992) stressed that it should only be so for large halls over 2000 seats.

Some studies used the term “tonal quality” to describe spectral balance, and find a positive correlation with preference (Kocher & Vigeant, 2015; Sotiropoulou et al., 1995), but did not give any objective definitions.

1.2.5 Other factors

Apart from the main contributing factors stated above, other factors may also affect subjective auditory preference, but the connections are more complicated and therefore no assertive conclusion has been made yet.

The most commonly mentioned factor in this category is the background and experience of participants. It is a general belief that musicians, acousticians, and frequent concert-goers might have different preferences than people with no expertise or experience, but no quantitative result has been found. Gender, age, and other inter-subjective factors may also have influence on personal preference.

The type of performance may also influence auditory preference. People might prefer different auditory conditions for symphony orchestras, classical operas, small ensembles, or instrument solos. Kawase (2013) found that posterior seats are preferred for large bands or orchestra, and anterior seats for small ensembles or solos, possibly due to the change in sound level of the source. But the study was based on a questionnaire survey instead of controlled experiment.

Also, visual perception, especially visual preference, is found to influence auditory preference, which will be elaborated in Section 1.3.

1.2.6 Experiment methods

Most auditory preference studies were either done using questionnaire surveys or done in labs with controlled stimuli.

Of the studies done with questionnaire surveys, some were distributed among concert goers for specific concerts at a number of selected concert halls (Barron, 1988; Hawkes & Douglas, 1971; Sotiropoulou, 1995), in which each participant only experiences one stimulus, so the inter-subjective evaluation difference might influence the results; some were based on the participants' personal experiences without specific stimuli (Farina, 2001; Hidaka & Beranek, 2000), in which the evaluations of some subtle attributes might not be meaningful. In most questionnaire surveys, the participants evaluated the auditory conditions on several semantic differential scales (Osgood et al., 1957). This is a useful method to find connections between preference and other subjective evaluations. Because of the simplicity of the method, it is possible to collect answers from a large number of participants, and thus have a relatively high statistical accuracy. The disadvantage of that is that each of the subjects only experience one stimulus or no specific stimuli, so the inter-subjective differences have a big influence on the results. Also, many other factors that are not considered in the study can affect the questionnaire results.

Many other auditory preference studies were done in labs with digital audio playback. The most common stimuli used in the lab experiments are anechoic recordings convolved with measured or simulated impulse responses, played back to the participants using headphones or loudspeakers in anechoic rooms (Ando & Gottlob, 1979; Kocher & Vigeant, 2015; Lokki et al., 2012; Ryu & Jeon, 2008; Schroeder et al., 1974; Soulodre & Bradley, 1995). With the technology for digital audio playback improving over the years, the quality of the audio playback gets ever higher and more realistic, even enabling the recreation of a 3D sound field (Lokki et al., 2012). Most of the lab experiments used paired-comparison for subjective evaluation (Ando & Gottlob, 1978; Ryu & Jeon, 2008; Schroeder et al., 1974; Soulodre & Bradley, 1995), while others used subjective scales (Kocher & Vigeant, 2015; Lokki et al., 2012). Compared to questionnaire surveys, lab experiments can control various factors of the stimuli, so that the relationships between different variables can be studied individually, and more reliable results can be found on how each objective parameter influence each subjective evaluation. However, because of the complexity of lab experiments and the longer experiment time, usually fewer participants are involved in the study, so the results are more inclined to be influenced by outliers.

1.3 Visual preference in auditoria

Compared to auditory preference, visual preference is relatively under-studied. Even though the visual experience of the audience is as important as, if not more important than, the auditory experience in performance spectating in auditoria, few studies have investigated the relationships between subjective visual preference and objective parameters. No ISO standards give any regulation or recommendation in terms of the sight in auditoria. Building codes in certain countries and some design guides give recommendations on auditorium rake, horizontal and vertical angle limits, and distance limits, some of which are listed in Table 1-1 (Burris-Meyer & Cole, 1964; JGJ57-2016). Due to the very limited literature in auditorium visual condition, some recommendations or regulations of sport stadiums are included (BS EN 13200-1:2019; John et al., 2007; Sheard, 2013). Regulations or recommendations of auditorium and stadium include some similarities, such as using C-value (the vertical distance from a spectator's eyes to sightline of the spectator directly behind) to define the rake, limiting maximum distance, etc. However, because the main purposes and focuses for watching performances and sport games are different, auditorium recommendations often include limits on angles, and usually have lower distance limits.

Table 1-2 Existing design guides and standards for auditorium and stadium visual condition

Source	Author or authority	Year	Type	Regulation or recommendation
Treatise on Sightlines	Russel	1838	Unknown	Bringing up sightlines and C-value
Theaters and Auditoriums	Burris-Meyer & Cole	1949 - 1975	Auditorium	Max horizontal view angle: 40° Max horizontal angle: 60° (30° for projection screen) Max horizontal angle from proscenium:100° Desirability rank: front centre, middle centre, middle side, front side, rear centre, rear side Max vertical angle: 30° Max distance: 23m (75') for legitimate drama, vaudeville and burlesque etc.; 38m (125') for grand opera, musical comedy, dance etc, C-value:12.7cm (5")
Stadia: A design and development guide	John, Sheard, & Vickery	1994 - 2007	Stadium	Max distance: 150m (extreme 190m) for rugby or football; 30m (extreme 41m) for tennis C-value: 15cm – excellent; 12cm – very good; 9cm – reasonable; 6cm - minimum
Sports Architecture	Sheard	2001 - 2013	Stadium	Max distance: 190m (optimum 150m) C-value: 15cm – with hats; 12cm – excellent; 9cm – good, head tilted backwards; 6cm – acceptable, between heads No obstructions (columns, beams, barriers, fences)
Code for Design of Theater Building (JGJ57-2016)	Ministry of Housing and Urban-Rural Development of the People's Republic of China	2016	Auditorium	Whole performance area visible to all audience (minimum visibility 80% for worst seats) Stage height: 0.6~1.1m for proscenium; 0.3~0.6m for thrust stage; 0~0.3m for arena stage Max vertical angle: 20° for the back; 35° for the side; 30° for thrust or arena Max distance: 33m for opera, dance; 28m for drama, Chinese opera; 20m for thrust or arena C-value: 12cm
Spectator facilities -Part 1: General characteristics for spectator viewing area (BS	British Standards Institution	2019	Stadium	Unobstructed view Max distance (outdoor): 230 m (rec 190m) for large; 190m (rec 150m) for medium; 100m (rec 70m) for small Max distance (indoor): 130m (rec 110m) for large; 110m (rec 85m) for medium; 80m (rec 60m) for small

EN 13200-1:2019)				

1.3.1 Distance

Objects further away from the eyes seem smaller, and the human eyes have limited resolution. The average minimum angular resolution is about 1 arcminute or 0.02° if the object has very high contrast (Yanoff & Duker, 2004). But anything smaller than 0.4° is difficult to be perceived clearly, especially if the object is moving (John et al., 2007). Therefore, the maximum distance is limited for auditoria so that even the person sitting at the furthest point of an auditorium would be able to see the main activities on the stage. Depending on the importance of different scales of movements in the performance (e.g., individual locations, body movements, gestures, facial expressions), different maximum distances are recommended for different types of performances. However, being inside the maximum limit does not necessarily mean good visual condition, because there are still less details visible at a further distance.

The recommended maximum distance is between 20 m to 40 m for theatres, and between 30m to 190m for sport stadiums (Table 1-1). No distance recommendations for concert halls are given based on the visual condition, but distance also affects acoustic parameters, especially sound strength, which might be the determining factor for the maximum distances in concert halls.

The minimum distance, on the other hand, is determined by the size of the performance area (e.g., proscenium, stage, or the range in which actors move around). If the angle of the performance area from the eye is too large, a person would need to turn his/her eyes and head often during the performance, which would result in discomfort and annoyance.

Many studies agree that there should be an optimum viewing distance for a certain performance. Veneklasen (1975) proposed the optimum distance of 9 m – 15 m (30' – 50'), and Vaupel (1998) discovered that the most favourable distance by the audiences is approximately the width of the auditorium. But these conclusions were based on the overall condition (including visual, auditory, and other aspects) instead of just the visual condition. Jeon et al. (2008) found a positive relationship between stage ratio (the ratio of stage on the projected image) and visual preference, and stage ratio is negatively related to distance.

1.3.2 Angle

Different from most sport games which are not affected much by the horizontal viewing angle, most theatre performances face a particular direction (with a few exceptions, e.g., immersive drama), and audiences sitting at other locations may miss some important content of the performances (e.g., the relationships of stage sceneries, actors' gestures and facial expressions, objects blocked by the prosceniums).

Vertical angle also affects the visual condition. If the vertical angle is too small and audiences are too close to the floor, they are more likely to be blocked by other audience members. And even if that is not an issue, there might still be problems of performers blocking each other. But if the vertical angle is too large and audiences are too far away from the floor, the shapes of objects and the gestures and facial expressions of performers on stage would seem different from usual eye-level perspective, and might cause discomfort.

Burris-Meyer and Cole (1975) proposed the maximum horizontal angle of 60° from the centre line and the maximum vertical angle of 30°, and stated that audiences sitting outside this range may fail to perceive the standard shapes or the intended relationships of objects on stage. The Chinese design code (JGJ57-2016) gave only limits for the vertical angle as 20° for the back of the hall; and 35° for the side balconies.

Most studies agree that the horizontal angle from the centre line is negatively related to preference, in other words, people prefer to be as close to the centre line as possible (Jeon et al., 2008; Kawase, 2013; Vaupel, 1998; Veneklasen, 1975). But conflicting results were found for the relationship between vertical angle and preference (Sato et al., 2012; Veneklasen, 1975). However, the difference in the results is likely mainly due to the very different methods used in the two studies, and the different ranges of angles included in the studies.

1.3.3 Rake and C-value

Obstructions are without doubt an important factor that might degrade visual condition in auditoria. In order for each audience member to be able to see the performance without visual obstructions from other audience members, auditoria usually apply a raked seating area, i.e., each row is higher than the one in front of it. If the riser height is too low, visual obstruction will likely to occur between the rows; but if all riser heights are very high, there would be fewer rows in an auditorium to make sure all seats are within the maximum vertical angle, and there might also be discomfort or safety issues when the rake is too steep. In the British Standard for stadiums (BS EN 13200-1:2019), the given maximum limit for the inclination angle is 35°, while the maximum limit for one step riser height is 510 mm for benches, 450mm for seating steps, and 225mm for standing. The Chinese design code for theatres (JGJ57-2016) required handrails over 1.05m for when one step riser height is over 500mm.

The concept of C-value was proposed by Russel (1838) to calculate the minimum required riser height for each row of seats, so that there can be as many seats in an auditorium as possible while all seats have acceptable viewing conditions. The calculation is done in sections, and the riser height of a particular row can be calculated with the following equation:

$$N = \frac{(R + C) \times (D + T) - R}{D}$$

Equation 1-4

In which *N* is the riser height behind a spectator; *R* is the vertical height from the point of focus to the eyes of the spectator; *D* is the horizonal distance from the point of focus to the eyes of the spectator; *T* is the seating row depth; and *C* is the C-value, the vertical distance from a spectator's eyes to sightline of the spectator directly behind (Figure 1-2).

In an auditorium, usually the location of the point of focus, and the values of T (row depth) and C are held constant for each row (except for rows adjacent to corridors which might have larger

T value), while R (vertical height from focus) and D (horizontal distance from focus) change per row, and thus the calculated riser height N will also be different for each row.

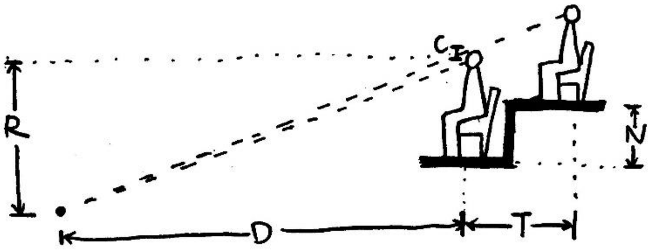


Figure 1-2 Seating riser height and C-value

Most standards and guides recommended C-values of around 12cm (Table 1-1), as it is approximately the average height from the eyes to the top of the head and allows the audiences to see the point of focus just slightly above the head of the audience directly in front. But some standards and guides allowed for smaller C-values down to 6cm with restricted views, for which audiences can only see between the heads of audiences in front.

The selection for the point of focus is also dependent on the type of performances. Each standard or guide gave specific recommendations for the location of chosen point of focus for different type of performances or sport games, and the most common location is the middle point of the stage outer edge at stage floor level for theatres, and the closest point to the target audiences on the game area floor for sport stadiums.

However, the C-value method usually only considers one section in theatre and concert hall designs. Therefore, it has very limited ability in non-traditional auditoria, e.g., vineyard concert halls or parametric designs. Also, it does not reflect issues on other areas of the stage.

1.3.4 Other factors

As Hyde (2002) discussed, static input such as the factors discussed above, and the room's dimensions, interior design, lighting, as well as dynamic input such as the performers' expressions and movements, may all contribute to the visual perception in an auditorium. Studies confirmed that body movements are important in conveying emotion in dance and music performances (Dahl & Friberg, 2007; Dittrich et al., 1996). Many studies investigated the cross-modal interaction between visual and auditory room dimensions (details in Section 1.5), but how these factors affect visual preference remain unstudied, as well as the effect of interior design and lighting.

1.4 Preference at each seat in auditoria

The previous two sections focus on the conditions of whole auditoria. Usually, one average value of a few representative seats is used to determine the auditory condition. For visual condition, a single C-value is used for a whole auditorium, and the distance or angle limits only focus on the worst conditions. However, the auditory and visual conditions at different seat locations in one auditorium can vary drastically, especially visual conditions. The best seat in the worst auditorium might be even better than the worst seat in the best auditorium. Therefore, on the basis of working out suitable parameters for the whole auditorium, it is also necessary that the condition of each seat be considered separately. The differences in visual and auditory conditions between seats is the most important factor in determining the ticket price for each seat. Also, having more seats with good visual and auditory condition and less bad should be a goal for all auditorium design.

The studies on seat preference in concert halls and opera theatres are listed in Table 1-3 (Ando, 1983; Dorado et al., 2017; Jeon et al., 2008; Kawase, 2013; Kuusinen & Lokki, 2015; Sato et al., 2012, 2013). Some similar studies to the ones in the table were neglected. The methods and results of all the studies and the gaps in the studies are summarized in Table 1-4.

Like acoustic conditions of whole auditoria, the auditory preferences at different seats have been relatively well-studied. In the same auditorium, most acoustic parameters do not vary as much to make a significant difference in people's perception. Sound pressure level (*SPL*), or sound strength (*G*), is the most obvious difference between seats in the same auditorium, mainly because the *SPL* of direct sound arriving at the listener follows the inverse square law, in other words, the further, the quieter. In most studies on seat preference in the one auditorium, it was found that auditory preference is positively correlated with *SPL* (Jeon et al., 2008; Sato et al., 2012, 2013) or distance from the stage (Kuusinen & Lokki, 2015). Other factors might affect auditory preference as well, but the results are less consistent, and therefore might be affected more by individuals.

Again, visual preferences are less studied. Only very limited results revealed that objective factors in visual condition such as distance to the stage, and vertical angle, can affect subjective preference (Jeon et al., 2008; Sato et al., 2012). However, no systematic study was found that characterizes the contribution of each factor and their relationships.

Visual preference and auditory preference are also found to have positive correlation and enhance each other (Jeon et al., 2005, 2008; Sato et al., 2012, 2013). Only a few studies investigated the contribution of auditory and visual preferences in overall preferences (as shown in Table 1-3), so the results might need verification. But the current results show that auditory preference has a large influence on overall preference in opera houses (Jeon et al., 2008; Sato et al., 2012), while visual preference has large influence in concert houses (Kawase, 2013; Sato et al., 2013)

Table 1-3 Existing studies on auditorium seat preference

Article title	Author	Year	Seat preference studied			Auditorium	Stimuli				Results (/ or \ for positive or negative trend; n or u for quadratic trend)			Method	No. of subjects	No. of locations
			Auditory	Visual	Combined		Auditory source	Auditory equipment	Visual source	Visual equipment	Auditory	Visual	Combined			
Design considerations from the viewpoint of the professional consultant	Veneklasen	1975									Distance(n), horizontal angle(\), under-balcony angle(\), c-value(/), vertical angle(/)					
Calculation of subjective preference at each seat in a concert hall	Ando	1983	Y			Concert hall	Simulated sound field * music	Speakers			SPL(n), ITDG(n), RT(n), IACC(\)			Paired-comparison	13\16\8	16\12\16
The best remaining seat: evaluating auditorium plans for desirability	Vaupel	1998	Choosing order without price difference			Concert halls(2) (shoe box)	In situ choosing before performance (can be considered as visual only)				Horizontal angle(\), distance(n) (Edges of seat blocks are popular - considered as noise, Optimal distance = width of orchestra platform)			Observation	NA	All seats
The effect of visual and auditory cues on seat preference in an opera theater	Jeon et al.	2008	Y	Y	Y	Opera theatre	BIR * solo tenor	Open type headset	Static photo	Projector	SPL(/)	Projected distance(/), stage ratio(/)	85% auditory +10% visual	Paired-comparison	50	9
Effects of acoustic and visual stimuli on subjective preferences for different seating positions in an Italian style theater	Sato et al.	2012	Y	Y	Y	Opera theatre	BIR * soprano +keyboard	Headphones /speakers	Static model render image	Projector/ LCD screen	SPLtotal(/), SPLbalance(/)	Vertical angle(\)	More stable, auditory>visual	Paired-comparison	21+61	10
Effect of acoustic and visual stimuli on preference for different seating positions in a concert hall and an opera theater	Sato et al.	2013	Y	Y	Y	Concert hall	BIR * solo violin (+fixed SPL)	Headphones	Static model render image	Projector/ LCD screen	SPL(/), C80(SPL fixed,/)		More stable, visual>auditory	Paired-comparison	21	5
Factors influencing audience seat selection in a concert hall A comparison between music majors and nonmusic majors	Kawase	2013	Music/non-music major			Concert hall	Concert hall plan with 6 different types of concerts				Closer for small ensembles /close to centre line apart from piano solo, visibility>sound quality			Questionnaire Choose favorite	60+65	All seats
Investigation of auditory distance perception and preferences in concert	Kuusinen & Lokki	2015	Y			Concert halls(4)	SRIR * symphony/ brass	Speakers			Perceived distance(\)			Paired-comparison	8	2

halls by using virtual acoustics																
Comparing VR environmnent for seat selection in an opera theater	Dorado et al.	2017		Y		Opera theatre			VR model	GearVR/ CAVE		Different VR equipment - no effect		Choose favorite	14	14

Table 1-4 Summary and limitations of existing studies on auditorium seat preference

	Stimuli			Results			Method
	Auditory	Visual	Used seats	Auditory	Visual	Combined	
Summary	**Binaural audio** with **solo music** is used in most studies. **Spatial audio** with **symphony** is used in Kuusinen 2015, but it only studied the influence of distance.	**Static picture** on **projector** without performers or other audiences is used in most studies. **Virtual reality** is used in Dorado 2017, but it only compared different VR equipment in decision making.	All the studies used **existing concert halls** or **opera theatres**, where seat locations are limited by the existing layout of the halls.	**SPL**: most studies found that it is positively correlated to preference and the main influencing factor. Other factors like **ITDG, RT, IACC, C80** can also affect preference, but has a smaller influence compared to SPL.	People generally prefer **closer to the symmetry axis**, **closer to stage** especially for small ensembles. Vaupel 1998 gives the optimal distance of orchestra platform width.	Auditory preference dominants in theaters, visual preference dominants in concert halls.	**Observation** is used in Vaupel 1998, but the subjects make no comparison. **Paired-comparison** is a frequently used method, among which **balanced incomplete block design** is used in Kuusinen 2015. **Questionnaire** is used in Kawase 2013, but the subjects only see a plan of the hall.
Limitations	Solo music is generally uncommon in real concerts. Binaural audio does not work if participants turn their heads.	Static visual stimuli cannot convey the spatial information well (e.g., distance).	Different factors could not be studied individually. The sight of the halls might influence the results in an uncontrollable way.		Relatively under-studied, few results.	Relatively under-studied, few results.	Paired comparison eliminates order effect, but limits the number of experiment conditions tested. BIBD can partly increase the number of tested locations but the problem persists.

1.5 Auditory-visual cross-sensory interaction

1.5.1 Auditory-visual interaction in psychology

Human beings perceive the world through multiple senses, and integrate all the sensory inputs to get the most accurate and correct information of their environment (Stein & Meredith, 1993). Therefore, the interactions between multiple senses has been a field of interest in for many years, of which the interaction between auditory and visual senses are the most studied due to their importance in human perception of the world.

On the one hand, the combination of synchronized visual and auditory stimuli may improve the general performance of perception and information collection, one common case being the great enhancement of speech intelligibility when the listener can see the speaker's lips, especially in noisy environments (Binnie et al., 1974; Sams et al., 1991; Sumby & Pollack, 1954). The physiological explanation for this has been found in multiple experiments (Meredith & Stein, 1986; Stein & Meredith, 1993) that when given simultaneous visual and auditory stimuli, the evoked potential of brain cells were much higher than when given the same stimuli separately, and the reaction time is much shorter. Which means, the interaction does not happen after the ears and the eyes receive information separately (stage of analysing the signal), but within the very beginning of the perceptions themselves (stage of receiving the signal).

On the other hand, visual and auditory stimuli with different or contradicting information may interfere with both senses and make people perceive the wrong information. An example also relevant to speech is the famous "McGurk effect" (MacDonald & McGurk, 1978; McGurk & MacDonald, 1976; Moore, 2012), which describes the phenomenon that when a sound is given with the image of the lips forming another sound, the brain does not hear the sound as it is anymore. And the most interesting thing about it is that even when the listeners are fully aware that the sound is the same, they still hear another sound when seeing the different lips (Rosenblum, 2011). Another example named as "Illusory Audiovisual Rabbit" is that when different numbers of flashes and beeps are presented at the same time, the perceived number of flashes are constantly incorrectly perceived as the number of beeps (Shams et al., 2000; Stiles et al., 2018). The reason for this can also be found in the activities of brain. Functional magnetic resonance imaging (fMRI) studies (Calvert et al., 1997; Sams et al., 1991) show that even only seeing the movement of lips evoke activities in the auditory cortex, which means that for connected visual and auditory stimuli like the image and sound of speech, people actually "hear" the visual stimuli in their brains.

However, this cross-modal influence may be biased across different senses. It is widely believed that when stimuli from multiple senses are given at the same time, the dominant modality is the one that gives the most realistic and accurate information (Welch et al., 1986), which in most cases is visual modality unless the intensities of stimuli differ greatly (Stein & Meredith, 1993). One of the most representative and most studied examples of this bias, is the influence of visual cues on auditory spatial localization and source-receiver distance estimation (Bertelson & Aschersleben, 1998; Bertelson & Radeau, 1981; Da Silva, 1985; Gardner, 1968; Hairston et al., 2003; Jackson, 1953; Loomis et al., 1998; Paquier et al., 2016). In other words, normally people judge distance and location more accurately with visual cues than auditory ones, so the general localization and distance perception is more influenced by visual factors. Another famous example is the “ventriloquism effect” (Howard & Templeton, 1966), which describes the phenomenon that in ventriloquism performances, people experience the voice from the dummy instead of the ventriloquist because of the visible movements of the dummy. However, this bias towards visual cues may not always be the case. The intensity of this influence is dependent on the acoustic environment (stronger in rooms with higher reverberation times where sound localization is more difficult than in anechoic rooms (Maempel & Jentsch, 2013)), the difference between individuals(Postma & Katz, 2017), previous practice on the judgement (Zahorik, 2001), etc..

Different from spatial localization, in terms of temporal rate perception, auditory modality dominates (Welch et al., 1986). This is in line with the “Illusory Audiovisual Rabbit” experiment mentioned in previous paragraphs. A possible explanation of this is that it is related to the minimum time difference for distinguishing two successive stimuli in visual and auditory perception respectively, and may have something to do with the persistence of vision.

Some of the cross-modal influences happen because of “perceptual constancy”, a sensory psychological phenomenon which means that people tend to use existing knowledge from past experience to perceive things as non-changing constant objects instead of directly perceive the ever-changing sensory input (Walsh & Kulikowski, 1998). This phenomenon is very obvious in vision, as when an object is of different distance from a viewer, or when the orientation of the object is different relative the viewer, or when different light is cast on the object, the visual input on the retina is of different size, different shape, or different colour and brightness respectively, but the viewer still perceive the object as the same object. On the other hand, if two objects are of the same size on the retina, the object that looks further looks bigger (size constancy).

Similar but less obvious effect exists in hearing. The auditory analogue of size constancy is loudness constancy, which might be the most obvious aspect of auditory constancy. It could be observed that when the sound level at the listener’s ears is the same, the sound source that is more distant from the listener is perceived to be louder (Chomyszyn, 1994; Chowning, 1990; Zahorik & Wightman, 2001). Since the perceived distance to the source mainly rely on visual cues (as discussed in the previous section), when given the same auditory stimuli, people will think that whichever source looks further is louder.

1.5.2 Auditory-visual interaction in architecture and landscape environment

The interaction between multiple senses characterizes the world we know. In the field of architecture and landscape, the visual-auditory interaction is widely studied in the aspect of environmental comfort in indoor and outdoor spaces, especially in soundscape (Carles et al., 1992, 1999; Kang, 2006; Jeon et al., 2011). Studies have found that the combination of visual and auditory stimuli of “tranquil spaces” has better restoring effect than separate single stimuli (Carles et al., 1999; D’Alessandro et al., 2018; Pheasant et al., 2010; Ren & Kang, 2015; Zhao et al., 2018), and different kinds of visual stimuli may have different effect (Viollon et al., 2002).

1.5.3 Auditory-visual interaction in auditoria and rooms

Apart from the auditory-visual interaction in preference studies that are stated in Section 1.3.2, most of other auditory-visual interaction studies mainly focus on spatial perception attributes, including perceived distance, perceived room size, ASW, and LEV.

Table 1-5 Existing studies on visual-auditory interaction in auditoria and rooms

Article title	Author	Year	Auditorium/ room	Stimuli			Variables		Results of visual-auditory influence	Method	No. of subjects
				Auditory	Visual	Combined	Independent (AV condition excluded)	Dependent			
Ecological acoustics and the multi-modal perception of rooms: real and unreal experiences of auditory-visual virtual environments	Larsson et al.	2001	Theatre/ concert hall/ practice room	Simulated RIR * solo female singing + headphones	None/ photo/ VR/ In situ (speakers)	A + AV(4 conditions)		ASW, PD, perceived room size	ASW: high in situ PD: low in situ Perceived room size: low in situ	Linear scale	80
Estimating Sound Source Distance with and without Vision	Zahorik	2001	Semi-reverberant room (RT0.3s)	Female speech + 5 loudpseakers in a line (visually blocked)		A + AV	5 distances (only distance varies)	PD	PD: precision AV>A	Physical scale	34
Auditory versus visual spatial impression: A study of two auditoria	Cabrera et al.	2004	Concert hall	Measured BIR * symphony + headphones	Grey scale projected photo (chair)	A + V	2 halls/ 15+9 locations	V: Spaciousness, envelopment, stage dominance, intimacy, PD; A: ASW, LEV, intimacy, PD	PD: precision V>A Spaciousness: V~distance(/), ASW(x) Envelopment: V(x), LEV~distance(\) Intimacy: A~V~distance(\)	10-point scale + physical scale (PD)	13
Subjective scaling of spatial room acoustic parameters influenced by visual environmental cues	Valente & Braasch	2010	Multipurpose room	Measured BIR * 5 solo music/speech + Headphone	Video (empty room/ speaker/ performer/ performer + speaker	AV(4 conditions)	4 locations/ 5 music clips	A: ASW, LEV, adjusted direct & reverb level	ASW: combined>none>performer>speaker LEV: combined>none>performer>speaker D/R ratio: small difference	Real-time adjustment (levels) + linear scale	12
Influence of visual information on sound evaluation in auditorium	Tokunaga et al.	2013	Multipurpose small hall	Measured RIR * solo flute	Photo (empty room)/ video (performer)	V(photo) + A + AV(video)	6 locations (only distance varies)	A: Loudness, reverberance	Reverberance: AV>A at further distance, AV more stable Loudness: AV>A	6-point scale	10
Auditory and visual contribution to egocentric distance and room size perception	Maempel & Jentsch	2013	Control/ seminar room/lecture/ concert Hall	Measured BIR * Female speech /Cello solo + headphones	Stereoscopic Photo (speaker)	A + V + AV(paired and non-paired)	4 rooms	PD, perceived room size	PD: A>V, average for AV, absorption~ precision, low absorption-A overestimate Perceived room size: best accuracy when optical size is 6 m greater than acoustical size	Physical scale	35
Impact of architectural variables on acoustic perception in concert halls	Galiana et al.	2016	Concert hall	In situ		AV	17 halls	53 attributes (27 acoustics + 26 architecture)	Auditory preference~functional organization(/), innovative design(/), intimacy(/)	Questionnaire (5-point scale)	310
The influence of visual distance on the room-acoustic experience of auralizations	Postma & Katz	2017	Theatre	Simulated SRIR * 2 actor play + Headphone	VR + point-cloud video (performer)	AV(paired and non-paired)	3 locations (mismatch)	PD, Loudness, ASW, LEV, plausibility	Group1: visual distance~acoustic distance Group2: visual distance~loudness Group 3: visual distance no effect ASW(x), LEV(x)	7-point scale	23

1.6 Using virtual reality for auditory-visual study in auditoria

When investigating the visual-auditory cross-modal influence in auditoria, the types of visual and auditory stimuli are quite important and may have certain influence on the results.

Using real auditoria and performances to conduct the experiment, or asking audiences to fill out the questionnaire after a real performance, can no doubt characterizes the experience most authentically (Barron, 1988; Galiana et al., 2016). However, the drawbacks are that it is hard (and almost impossible) to control variables in real auditoria and performances, so that some influential factors may not be taken into account and it is hard to identify the influence of each single factor. It is hard to separate the visual factors and the auditory factors as well, and excluding psychological factors including the building's aesthetics and reputation. The difficulty of organizing experiments in operating auditoria and other logistics problems may also add to the limitations. Also, if the subjects fill in the questionnaires after the whole performance, general feelings towards the entire experience could influence the results, and the fact that it is based on memories could also affect the accuracy.

That is why more studies chose to do the experiments in lab conditions, mostly in anechoic rooms, with simulated visual and auditory stimuli.

The auditory stimuli commonly used in the experiments are anechoic recordings convolved with room impulse responses: 1) measured room impulse response (Tokunaga et al., 2013); 2) measured binaural room impulse responses (Cabrera et al., 2004; Jeon et al., 2008; Maempel & Jentsch, 2013; Valente & Braasch, 2010); 3) measured spatial room impulse responses; or 4) simulated room impulse response (Larsson et al., 2001; Postma & Katz, 2017). Measured room impulse responses, especially binaural room impulse responses, are more accurate in terms of simulating the real situation, but simulated room impulse response is more controllable. The acquired auditory stimuli would be played to the subjects using headphones or stereo speakers. Some of the experiments use head-tracking techniques for headphones to increase the sense of reality and space (Postma & Katz, 2017), but it could only be applied when the room impulse responses are measured spatial room impulse responses or simulated room impulse responses with spatial information.

Some common types of visual stimuli include: 1) photos (Cabrera et al., 2004; Jeon et al., 2008; Larsson et al., 2001; Tokunaga et al., 2013; Valente & Braasch, 2010), with stereoscopic photo as a special case (Maempel & Jentsch, 2013); 2) videos (Tokunaga et al., 2013; Valente & Braasch, 2010); 3) virtual reality models (Larsson et al., 2001; Postma & Katz, 2017). Photos are relatively easy to acquire, but information contained is limited and the fidelity is relatively low. Subjects cannot see the whole space through photos or see the dynamic movements of performances. Compared to photos, videos add more realism through the dynamic movements and their interaction with audios. Subjects get more sense of involvement. VR models simulate the space best and are more convincing. They can also capture the sense of depth and space better through binocular rendering and headtracking. But VR models require larger computation and is limited by the equipment available. Larsson et al. (2002) emphasized the importance of virtual simulation fidelity in auditory-visual interaction experiments using virtual environments, and Postma & Katz (2017) found that the methods of visual rendering would have influence on the experiment results.

Chapter 2 Designing subjective testing in virtual reality

As this thesis was the first to trial the method of remote audio-visual virtual-reality experiments in concert hall perception studies, this chapter summarizes the detailed methods used for the experiments for future reference, including generation and validation of the auditory and visual stimuli, and user-interaction design and data recording methods with special considerations for the remote experiment conditions. Part of this chapter has been published as:

Chen, Y., & Cabrera, D. (2022). Using lab-based and non-lab-based audio-visual virtual reality experiments for auditorium seat preference studies. *Proceedings of Acoustics 2021*, p14.

All experiments used virtual reality and digital playback to present experiment stimuli for subjective testing. Some parts of the experiments were conducted in the laboratory of University of Sydney, with the researcher instructing and assisting the volunteers to complete the experiment. Due to the influence of COVID-19 social-distancing rules, some parts of the experiments could not be conducted in the laboratory. To adapt to the situation, the experiment was re-designed so that volunteers could participate without physical contact with the researchers or travelling to the laboratory. The experiment was coded into single standalone executable files and distributed to the volunteers through the internet with necessary instructions. The volunteers could follow the instructions and complete the experiment with their own equipment in their own time, while the researcher answered any question they had through online communication. Due to the different experiment conditions, the testing methods were different with certain similarities.

2.1 Base auditorium

To ensure the realism of virtual reality models, some of the visual and auditory models used in the experiments were built based on an existing auditorium. The Verbrugghen Hall (Figure 2-1) is the largest performance space at the Sydney Conservatorium of Music in Macquarie Street, Sydney, New South Wales, Australia. It was used as the base reference for all virtual auditorium models used in the experiments, including the visual model for experiments 1, 3, and 4, and the acoustic model for experiments 1 and 3.

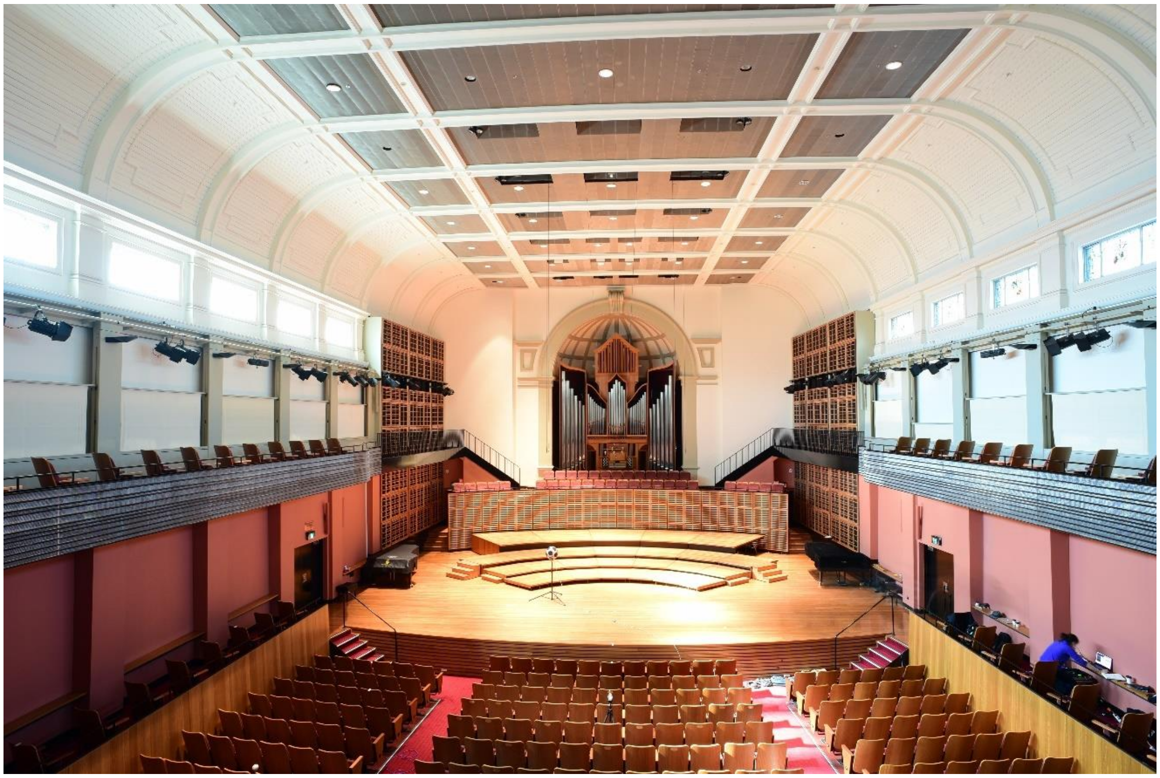


Figure 2-1 Measurement photo in Verbrugghen Hall

An acoustic measurement at 18 seat locations was conducted and used as reference audio in the first and third experiment. Full details of the measurements are given in Appendix A, while the full measurement results are given in Appendix B. All the measured locations are shown in Figure 2-2.

Location M12 was used in the first experiment, with the measured impulse response at the location and modified impulse responses manipulated from the measured one. For the third experiment, all 18 measured locations were used. The impulse responses used in the third experiment were simulated from a model calibrated using the measured impulse responses. More details of the auditory stimuli used in the individual experiments are given in Sections 2.3 and Chapters 3 to 5.

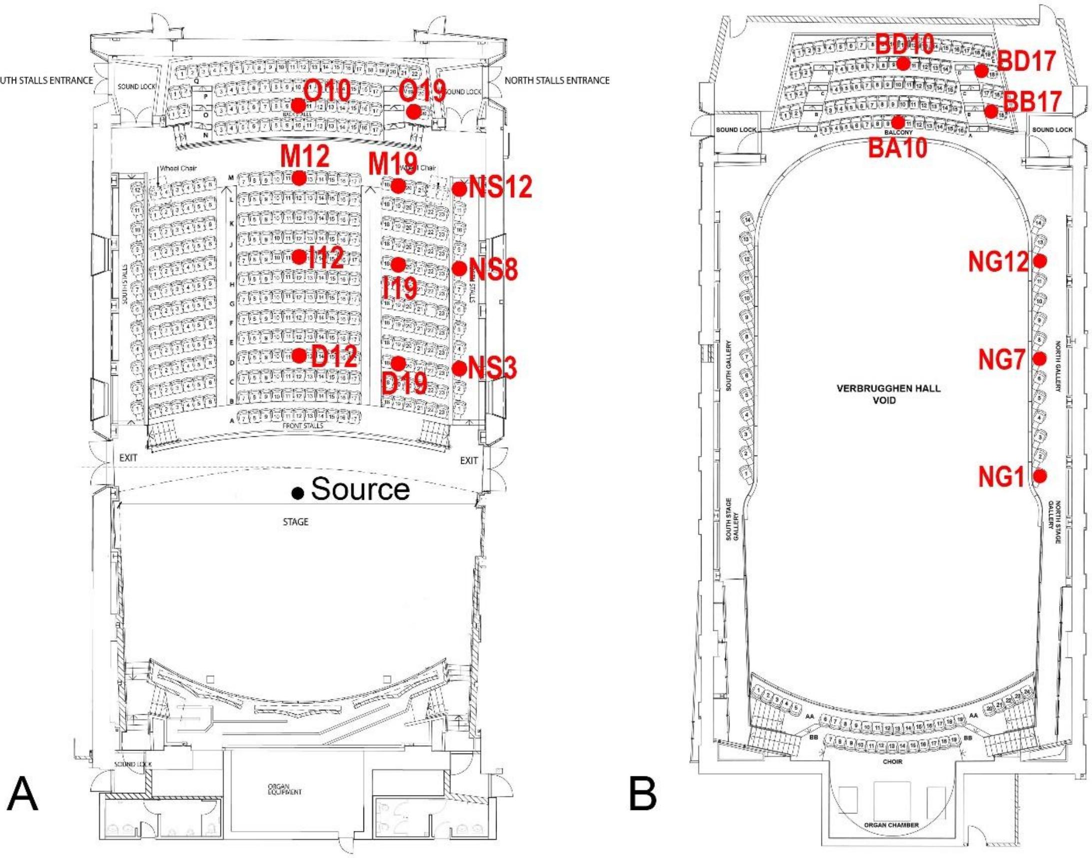


Figure 2-2 Measurement locations in Verbrugghen Hall, The Sydney Conservatorium of Music. A: Stalls and lower side balcony. B: Back balcony and upper side balcony.

2.2 Visual stimuli

The visual models for the experiment were built in Rhinoceros (3D computer graphics and design software developed by Robert McNeel & Associates), including the models of the concert halls in the first and third experiment, and the models of the musicians with instruments in all experiments for visual cues.

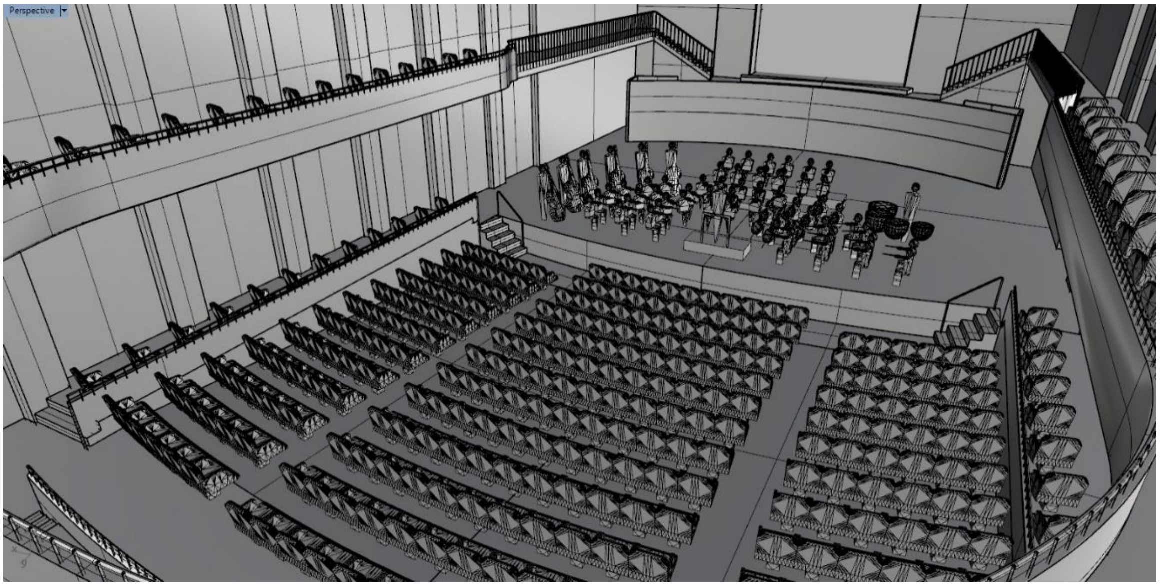
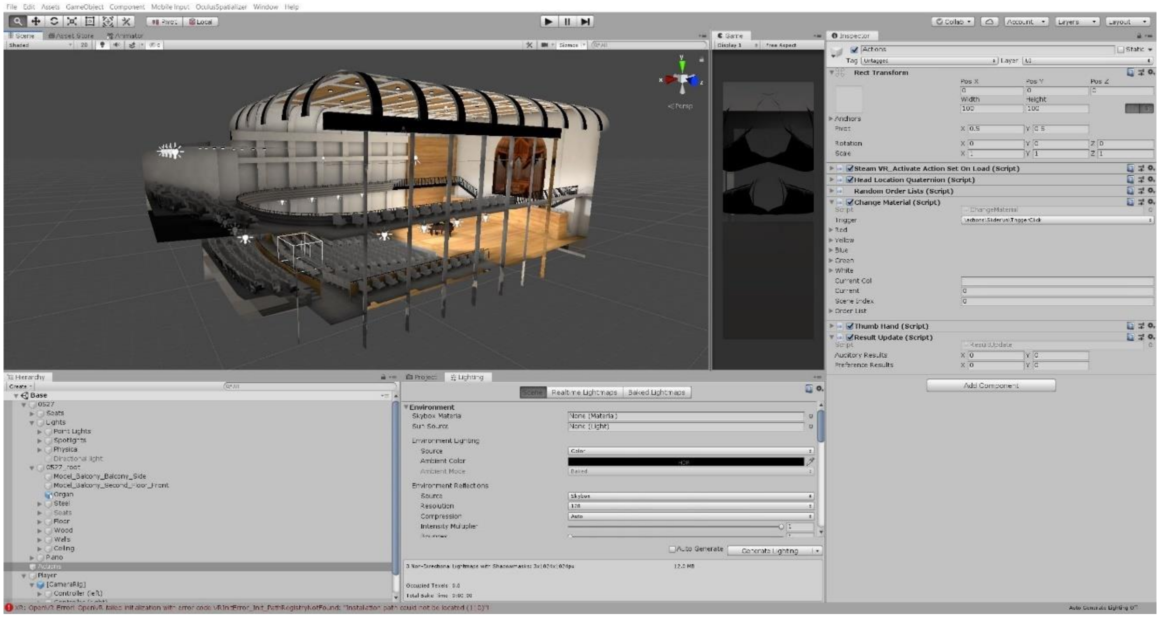


Figure 2-3 Example of model in Rhinoceros

The models were converted into meshes and exported as Wavefront OBJ file, which were then imported to Unity (a cross-platform real-time engine developed by Unity Technologies, Figure 2-4). Suitable materials were assigned to different surfaces of the models, and suitable lighting was added in the models: spotlights for the stage lighting, and point lights for ambient lighting in the auditoria. High-resolution pre-baked lightmaps were calculated for the models except for user-interactable objects to reduce real-time calculation during the experiments.

Virtual reality experiences with headtracking were enabled with scripts from SteamVR plugin (Valve Corporation) for Unity, and additional scripts in C# were written to create user interactive actions for test subjects, including subjective evaluation for the experiments and other assisting actions.



Actions
Tag: Untagged; Layer: UI
Rect Transform: Pos X 0, Pos Y 0, Pos Z 0; Width 100, Height 100
Pivot: X 0.5, Y 0.5
Rotation: X 0, Y 0, Z 0
Scale: X 1, Y 1, Z 1
☑ Steam VR_Activate Action Set On Load (Script)
☑ Head Location Quaternion (Script)
Random Order Lists (Script)
☑ Change Material (Script)
Script: ChangeMaterial
Trigger: \actions\Slider\in\TriggerClick
Red
Yellow
Blue
Green
White
Current Col
Current: 0
Scene Index: 0
Order List
☑ Thumb Hand (Script)
☑ Result Update (Script)
Script: ResultUpdate
Auditory Results: X 0, Y 0
Preference Results: X 0, Y 0

Environment
Skybox Material: None (Material)
Sun Source: None (Light)
Environment Lighting
Source: Color
Ambient Color: HDR
Ambient Mode: Baked
Environment Reflections
Source: Skybox
Resolution: 128
Compression: Auto
Intensity Multiplier: 1
☐ Auto Generate
3 Non-Directional Lightmaps with Shadowmasks: 3x1024x1024px 12.0 MB
Occupied Texels: 0.0
Total Bake Time: 0:00:00

XR: OpenVR Error! OpenVR failed initialization with error code VRInitError_Init_PathRegistryNotFound: "Installation path could not be located (110)"!

Figure 2-4 Example view of Unity Editor

The visual stimuli were presented to the test subjects through head-mounted virtual reality display (VR headsets). An HTC Vive VR headset was used in the first experiment, and various VR headsets by HTC and Oculus were used in the second and third experiment. The differences in different VR headsets were considered to be sources of random error. The VR headsets provide head location and movement tracking, which was decoded by SteamVR plugin to update the display in the VR headsets, enabling virtual reality experiences, so that the test subjects could turn their heads and view the whole surrounding environment in any direction.

2.3 Auditory stimuli

2.3.1 First experiment

As the first experiment was conducted in laboratory, a large variety of audio-playback methods were available to be chosen from. The selected method was: 1) pre-calculating all audio files by convolving measured and manipulated second-order-Ambisonic room impulse responses with anechoic recordings for each source-receiver combination, and mix to one audio file for each receiver location; 2) using an HRTF binaural decoder in SPAT~ Plugin (Ircam Forum) for Max/MSP/Jitter (a visual programming language for music and multimedia developed by Cycling '74) to decode the convolved second-order-Ambisonic audio files into a pair of Sennheiser HD 800 Headphones. The binaural decoder was tested for its validity, and the headphones used in the experiment were calibrated to match the approximate absolute sound pressure level in the scene. Details of the complete validation are included in Appendix C. The head-tracking data was sent real-time from Unity to Max/MSP/Jitter through Open Sound Control (OSC). A summary diagram of the production procedure for the experiment stimuli in the first experiment is shown in Figure 2-5.

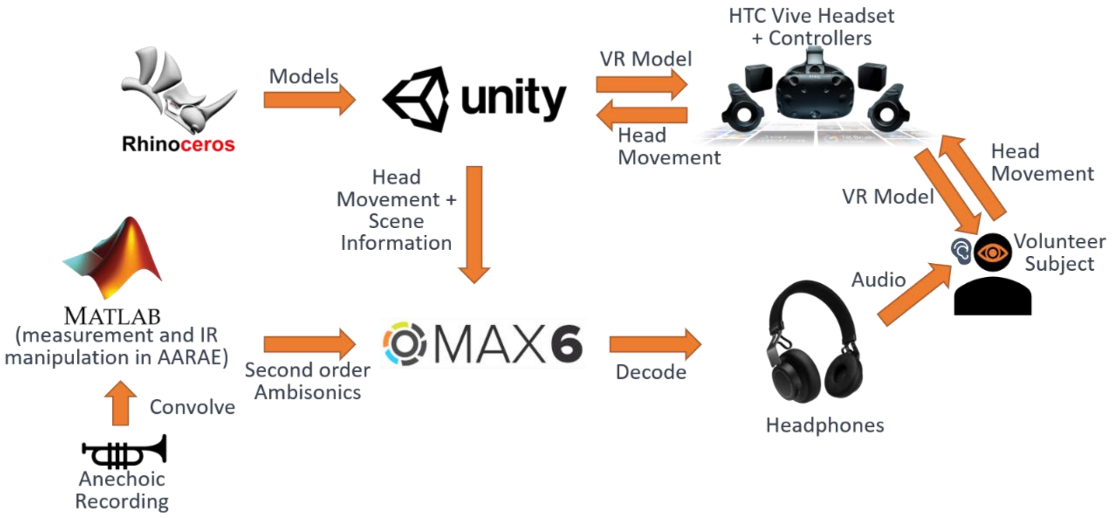


Figure 2-5 Stimuli production procedure in the first experiment

2.3.2 Other experiments

To allow easier online distribution, both visual and auditory stimuli were included in Unity, and the use of Max/MSP/Jitter was removed from the experiment. Compared to the first experiment, the binaural decoders in Unity were less controllable, and the absolute level of headphones could not be calibrated, but the auditory stimuli were still relatively accurate and realistic. The differences in different headphones used by the volunteers were considered as random error.

For the second experiment, as it mainly focused on visual factors, the auditory stimuli were relatively simple: using non-anechoic recordings with no added reverberation or room acoustics information, decoded binaurally by Steam Audio plugin (Valve Corporation) for Unity. The only variable in the auditory stimuli was gain level, and the only spatial information included was the orientation of the sound source relative to the listener.

For the third experiment, first-order-Ambisonic room impulse responses for each source-receiver combination were simulated by ODEON (modelling software for simulating room acoustics developed by Odeon A/S), with materials calibrated using the measured impulse responses at the same locations, and instrument directivity information for each source. The impulse responses were convolved with anechoic recordings and mixed to one audio file for each receiver location. The convolved Ambisonic audio files were decoded binaurally by Resonance Audio plugin (Google) for Unity.

The fourth experiment did not include any auditory stimuli.

More details of the auditory stimuli used in each experiment are included in Chapter 4-6.

2.3.3 Headphones calibration for in-lab experiments

For the in-lab experiments (first experiment and part of third experiment), the audio was played to the participants using Sennheiser HD 800 Headphones. To ensure that the absolute playback level at the listener’s ears was approximately the same level as the situation that was being simulated (listening to the selected performance in the selected concert hall at the selected seat location), a calibration process was conducted.

2.3.3.1 Measurement equipment and setup

The absolute sound pressure level of headphones playback was calibrated and measured with Neumann KU 100 Dummy Head system (Figure 2-6).

The headphones were positioned on the calibrated dummy head, with the centre of the inner speakers in line with the ear canals. The received audio signals were recorded from inside the microphones at the entrances of the blocked ear canals.

For the first experiment which used a string quartet recording - a 3’20” music excerpt from Movement III (Presto) of Concerto No. 2 in G minor, Op. 8, RV 315, “Summer” (L'estate) in Antonio Vivaldi’s Four Seasons (Thery & Katz, 2019), the whole excerpt at the selected seat (M12) was played through the headphones and recorded by the dummy head, when the reverberation time was set as original, and gain is set as times one (0 dB).

For the third experiment which used a symphony orchestra recording – Movement I, II, and IV of Symphony No. 8 in F Major, Op. 93, by Ludwig van Beethoven, the first 3 minutes of the first movement at seat D12 (no. 1), M12 (no. 3), BD10 (no. 6) and BSide1 (no. 16) in both auditoria were played through the headphones and recorded by the dummy head.

Figure 2-6 Neumann KU 100 Dummy Head system used for headphones calibration

2.3.3.2 Measurement results and analysis – first experiment

The sound pressure level data (calibrated absolute level) of the whole excerpt measured by the dummy head is shown in Table 2-1.

Table 2-1 Absolute sound pressure level of whole music excerpt measured by the dummy head

	L_{eq}	L_{max}	L_1	L_5	L_{10}	L_{50}	L_{90}
16	41.9	59.2	51.0	47.7	45.9	37.9	23.2
31.5	41.9	59.2	51.0	47.7	45.9	37.9	23.2
63	50.3	70.1	63.4	57.7	52.2	34.9	19.6
125	67.6	85.0	78.6	74.8	72.0	58.5	32.7
250	67.3	87.8	77.4	73.7	71.6	60.9	40.6
500	58.9	78.5	69.2	65.5	63.2	52.3	34.3
1000	44.0	63.3	54.3	50.4	48.1	38.3	22.7
2000	40.4	59.8	50.3	46.8	44.6	35.0	19.6
4000	29.8	48.1	38.8	35.8	34.0	25.8	11.2
8000	29.9	52.1	38.1	35.7	34.2	26.5	11.9
16000	34.5	56.4	42.7	40.3	38.8	31.0	16.4

The sound pressure level (relative level) of the original anechoic recording is shown in Table 2-2.

Table 2-2 Relative sound pressure level of original anechoic recording

	L_{eq}	L_{max}	L_1	L_5	L_{10}	L_{50}	L_{90}
16	-98.9	-72.6	-87.0	-95.5	-99.5	-111.0	-127.1
31.5	-84.3	-56.2	-71.3	-81.1	-85.4	-97.0	-112.5
63	-42.7	-22.9	-29.5	-35.2	-40.8	-62.6	-83.8
125	-26.6	-9.4	-15.6	-19.4	-22.3	-35.5	-62.9
250	-25.9	-4.5	-15.9	-19.5	-21.6	-32.3	-53.0
500	-33.7	-14.7	-23.1	-27.1	-29.5	-40.4	-58.4
1000	-48.0	-28.2	-38.1	-41.8	-43.9	-53.2	-69.1
2000	-48.7	-29.7	-38.6	-42.3	-44.5	-54.2	-70.5
4000	-50.4	-29.7	-40.1	-43.9	-46.2	-56.2	-72.5
8000	-79.0	-52.2	-67.2	-72.9	-76.2	-88.2	-105.6
16000	-123.5	-82.8	-111.9	-117.4	-120.4	-132.9	-150.6

To verify the frequency response, the sound pressure level of the original anechoic recording was added with the sound strength value measured at the selected seat, and compared to the measured sound pressure level of recorded by the dummy head (Table 2-3). The original anechoic recording is uncalibrated, so the absolute value is meaningless. However, the relative level in each frequency band should correspond to that of dummy head recording. L50 (median) level was used to reduce the influence of random events during the measurement and background noise.

Table 2-3 Absolute sound pressure level calibration process

Centre Frequency (Hz)	Anechoic L_{50} Level (dB)	*G* at M12 (dB)	Anechoic + *G* (dB)	Anechoic + *G* + 79.2 (dB)	Headphones L_{50} Level (dB)
125	-35.5	14.7	-20.8	58.5	58.5
250	-32.3	11.7	-20.6	58.6	60.9
500	-40.4	10.1	-30.4	48.9	52.3
1000	-53.2	7.1	-46.1	33.2	38.3
2000	-54.2	4.0	-50.1	29.1	35.0
4000	-56.2	7.9	-48.3	30.9	25.8
8000	-88.2	-1.0	-89.3	-10.0	26.5

In Table 2-3, “Anechoic L50 Level” is the relative L50 level of the original anechoic recording. “*G* at M12” is the measured sound strength at the selected seat. “Anechoic + *G*” is the sum of the first two columns. The sum of anechoic L50 level and G is added by 79.2 dB to align the level at 125 Hz to the L50 level of the headphone measurement for easier comparison. The frequency spectra are approximately the same apart from the 8000 Hz octave band, where the headphone playback has a much higher value than the calculated level. This discrepancy may be due to the high frequency background noise in the measured room.

Additionally, in order to verify the absolute value of the sound pressure level, the recording was compared to the estimated sound pressure level of the same type of music at the selected seat location.

ISO 23591:2021 provides an estimation method of sound pressure level of a given instrumental group in auditoria (Annex A, A.2).

The sound pressure level at a certain location in an auditorium when the instruments are playing at *forte* can be estimated using the given equation with the measured Sound Strength (*G*):

$$L_p(f) = G + 59 + 10\log\sum_i n_i P_i \ (dB)$$

Equation 2-1

In which n_i is the number of instruments of type *i*, and P_i is the sound power for an instrument type *i*, listed in Table A.1 of ISO 23591:2021.

For a string quartet, the sound power *P* for each instrument is listed and the total sound power is calculated (Table 2-4).

Table 2-4 Sound power calculation of a string quartet

Instrument	Number, *n*	Sound power, *P*
Violin	2	0.8
Viola	1	0.5

Cello	1	1.0
Total		3.1

Therefore, the approximate sound pressure level at the selected seat when the music is played at *forte* can be calculated from G:

$$L_p(f) = G + 59 + 10\log 3.1 = G + 63.9\ (dB)$$

Equation 2-2

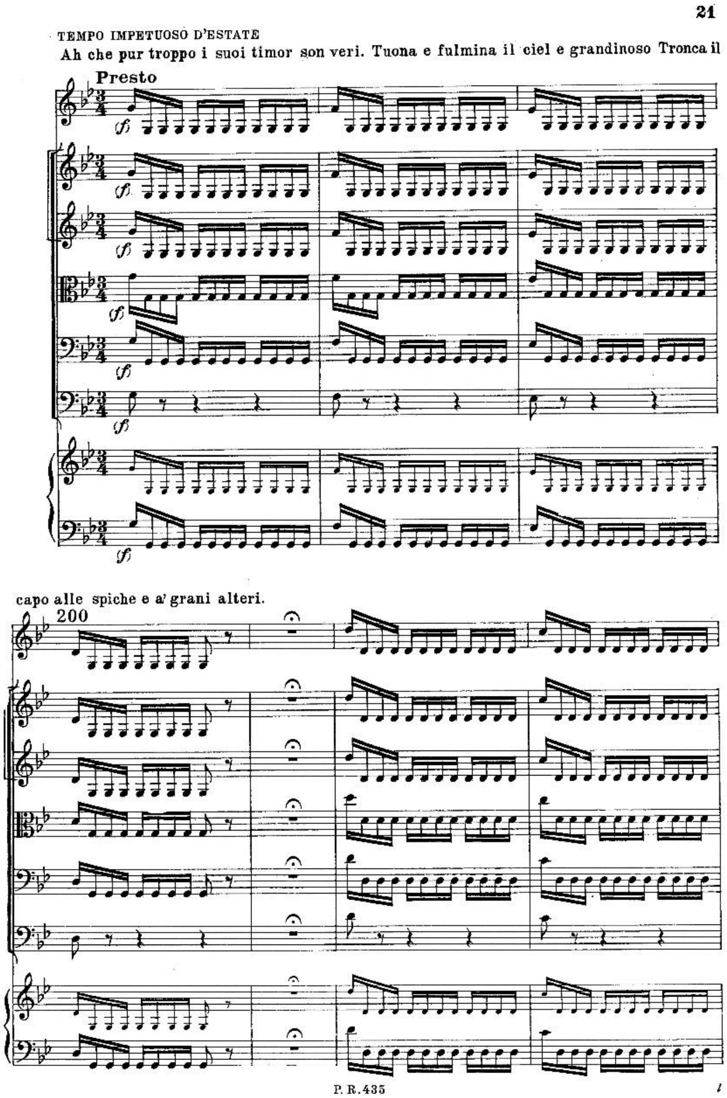



Figure 2-7 First page of music score of the music excerpt used in the experiment ("Summer" (L'estate) in Antonio Vivaldi's Four Seasons)

Only the first phrase of the piece where all the instruments are played in unison at *forte* is used (Figure 2-7).

Because the sound level estimation does not consider the frequency spectrum of the instrument, only a single value at 500 Hz is calculated (Table 2-5).

Table 2-5 Absolute sound level calibration at 500 Hz octave band

	Leq	**Lmax**	**L1**	**L5**	**L10**	**G+63.9**
500 Hz	63.5	78.7	73.1	69.1	67.4	74.0

In Table 2-5, L5 was used as a representation of the sound level when played at forte to eliminate the influence of gaps, fade-ins and fade-outs, and the difference between the measured sound level and the target sound level was added as a 4.9 dB gain.

2.3.3.3 Measurement results and analysis – third experiment

As the frequency response was already verified in the first experiment, only the absolute sound level was calibrated.

The sound power level of each instrument was attained from Weinzierl et al. (2018). The midpoint sound power level between minimum sound power level and maximum sound power level of each instrument is obtained. Then the sum sound power level of all 61 instruments, including 2 flutes, 2 oboes, 2 clarinets, 2 bassoons, 2 French horns, 2 trumpets, 25 violins, 11 violas, 6 cellos, 6 basses, and timpani, was calculated as the sound power level of the orchestra, L_w, which was 102.7 dB. The sound pressure level at each seat is calculated using the following equation:

$$L_p(f) = L_w + 10 \times \log(\frac{1}{400 \times \pi}) + G = G + 71.7\ (dB)$$

Equation 2-3

The expected sound pressure level at the measured seats are:

Table 2-6 Expected sound pressure level at 4 seats in 2 sizes of auditoria

	D12	M12	BD10	BSide1
Original hall	81.1 dB	79.3 dB	77.0 dB	81.4 dB
Large hall	80.2 dB	78.1 dB	76.4 dB	79.9 dB

As the calculated sound pressure level represents all instruments playing at the same time but at a moderate dynamic, L10 of the measured sound pressure level was used to match the calculated sound pressure level. The average difference between the calculated and measured sound pressure level at all the measured seats was used to set the headphones' gain of the experiment.

The final sound pressure level at the listener's ears are:

Table 2-7 Final measured sound pressure level at the listener's ears at 4 seats in 2 sizes of auditoria

	D12	M12	BD10	BSide1
Original hall	80.7 dB	79.9 dB	77.7 dB	80.1 dB

Large hall	79.6 dB	78.8 dB	77.4 dB	79.2 dB

2.4 User-interaction and data recording

2.4.1 First experiment

The diagram in Figure 2-8 shows the detailed data flow during the experiment and all operations. Volunteers completed the experiment in laboratory with the instruction and assistance of the researcher. All operations by the test subjects were done with VR controllers, including subjective evaluation for each scene (“Move Slider”) and changing to the next scene (“Trigger Down”, “Trigger Up”). The researcher input the participant ID for each subject (“Input Participant ID”), the start of the experiment (“Start”), and changing to the last scene if the subject made a mistake (““B” Key Down”, ““B” Key Up”). All operations done in Unity and head rotation information were sent real-time to Max/MSP/Jitter through OSC (“Open Sound Control Data Transmission”), and data was recorded in both software for data insurance (“Store Data From Unity”, “Store Data From Max”).

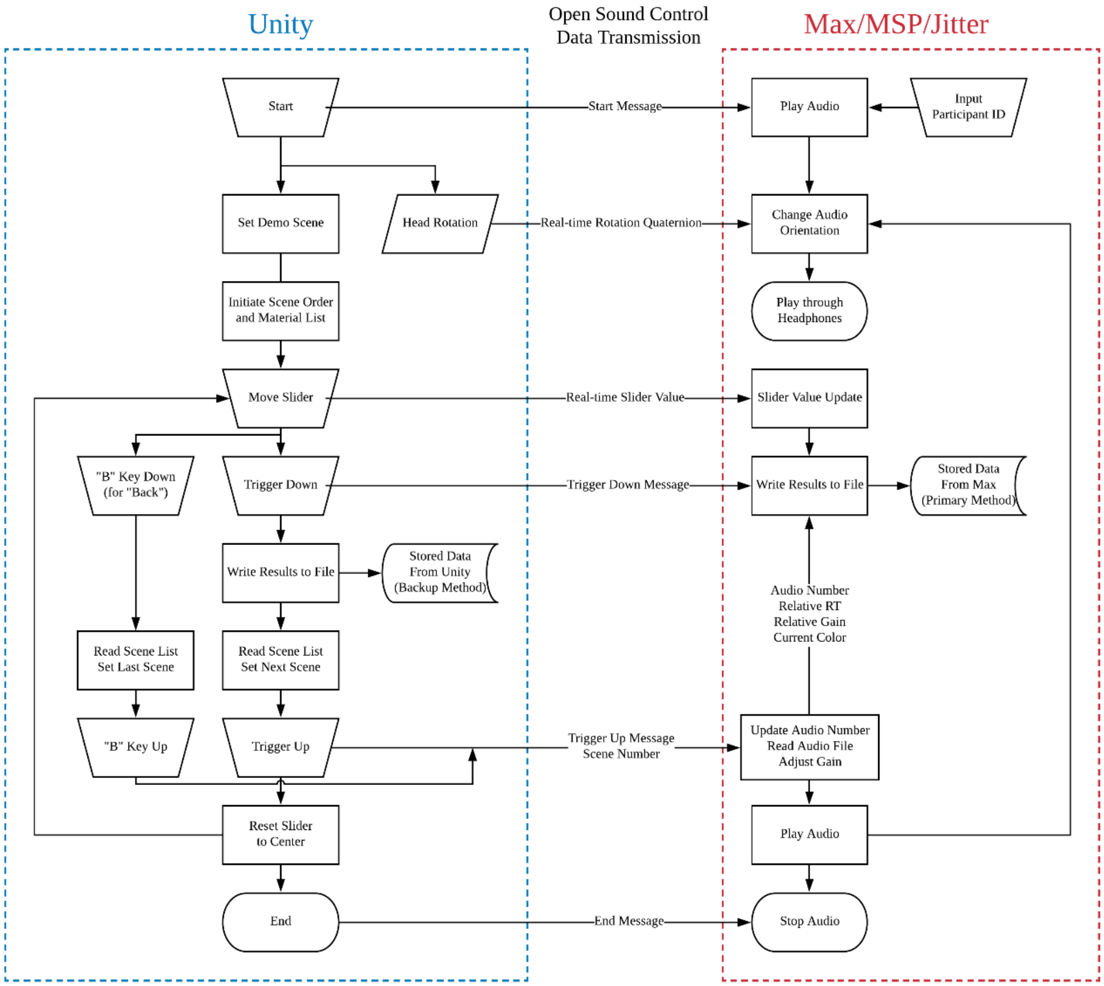


Figure 2-8 Operation and data flow in the first experiment

Because the first experiment examined 4 different subjective parameters, two 2D sliders were used for subjective evaluation (Figure 2-10). The subjects used the VR controllers (Figure 2-9) to move the knobs of the sliders by moving the controllers towards the location of the sliders, pressing down the grip buttons on the side of the controllers, and moving their hands in 3D space until the locations of the knobs on the sliders matched their subjective evaluation. When they were satisfied with their evaluation for each scene, they pressed a trigger on the controllers to move to the next scene. The order of the scenes was pre-defined, with 4 different randomly generated orders.

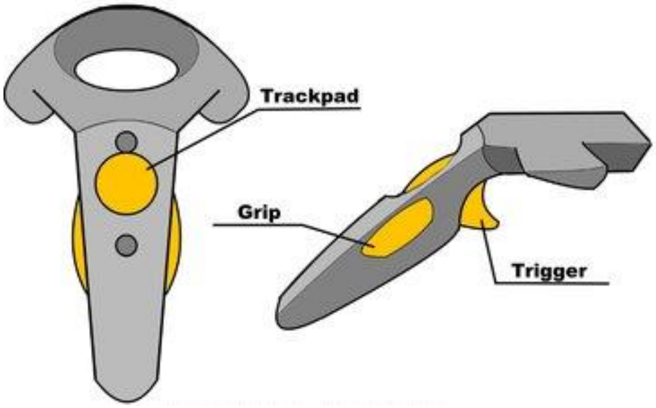


Figure 2-9 HTC Vive VR controller diagram with marked buttons (source: Coomer et al., 2018)

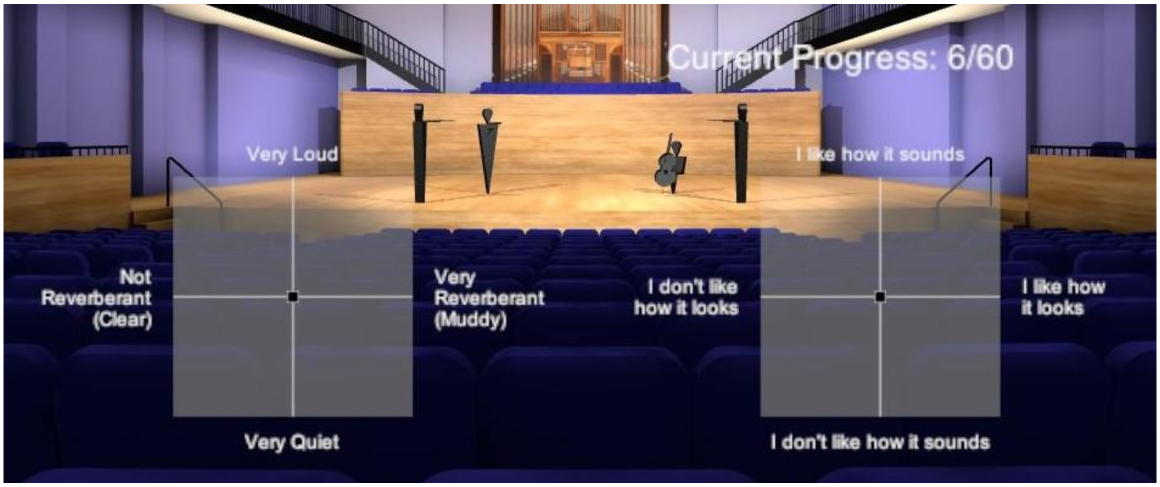


Figure 2-10 Subjective evaluation interface with 2D sliders in the first experiment

2.4.2 Other experiments

For the other experiments, the complete experiment stimuli were compiled into standalone executable files.

For non-lab-based participants, the files were sent to them through Dropbox Transfer, which they could run on their own computer with their own VR equipment and headphones. All instructions were written in a PDF document which was sent to the participants at the same time. They could do the experiment in their own time, and could also save the progress and complete the experiment in multiple sessions. When they were satisfied with their evaluation, they could export the results into a text file which recorded their subjective evaluation for each location, the total time they spent on each location, and the stimulus settings for each location. The file extension was removed to prevent the subjects from changing the results after exporting.

For lab-based participants, the same executable file was run on the laboratory computer, and the participants conducted the operations with the researcher’s aid.

The diagram in Figure 2-11 shows the detailed data flow during the experiment and all operations in the second experiment. The black double-lined arrows in Figure 2-11 represent the normal completion procedure, while the red single-lined arrows represent quitting and continuing the experiment before completion. There were two parts in the experiment (“Level 1”, “Level 2”). The subjects needed to export and send through email the result file for “Level 1” in order to attain the password to unlock “Level 2”. In “Level 2”, the gain levels of the auditory stimuli were different at each seat, and the design was balanced between every four subjects. The used auditory stimuli were determined by the Participant ID (“Player ID”) input by the subjects.

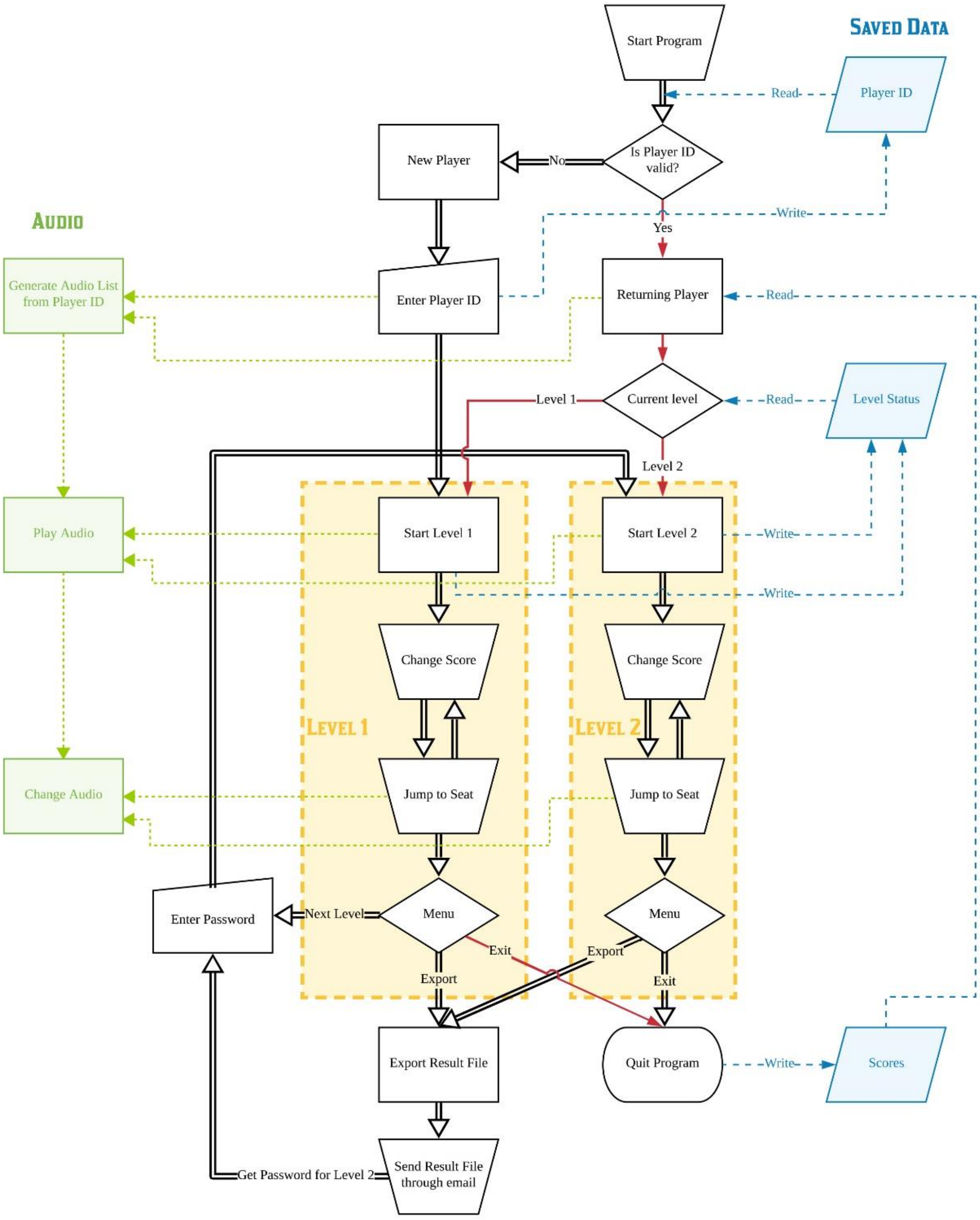


Figure 2-11 Operation and data flow in the second experiment

The third experiment (Figure 2-12) was slightly different from the second experiment. Instead of two “Levels” that the subjects needed to complete in order and export separately, there were four parallel “Auditoria” which the subjects were free to switch between. Only one result file was exported after the subjects completed evaluating all four “Auditoria”. Another difference was that all subjects experienced the same stimuli. The fourth experiment was similar to the third experiment, only with no auditory stimuli.

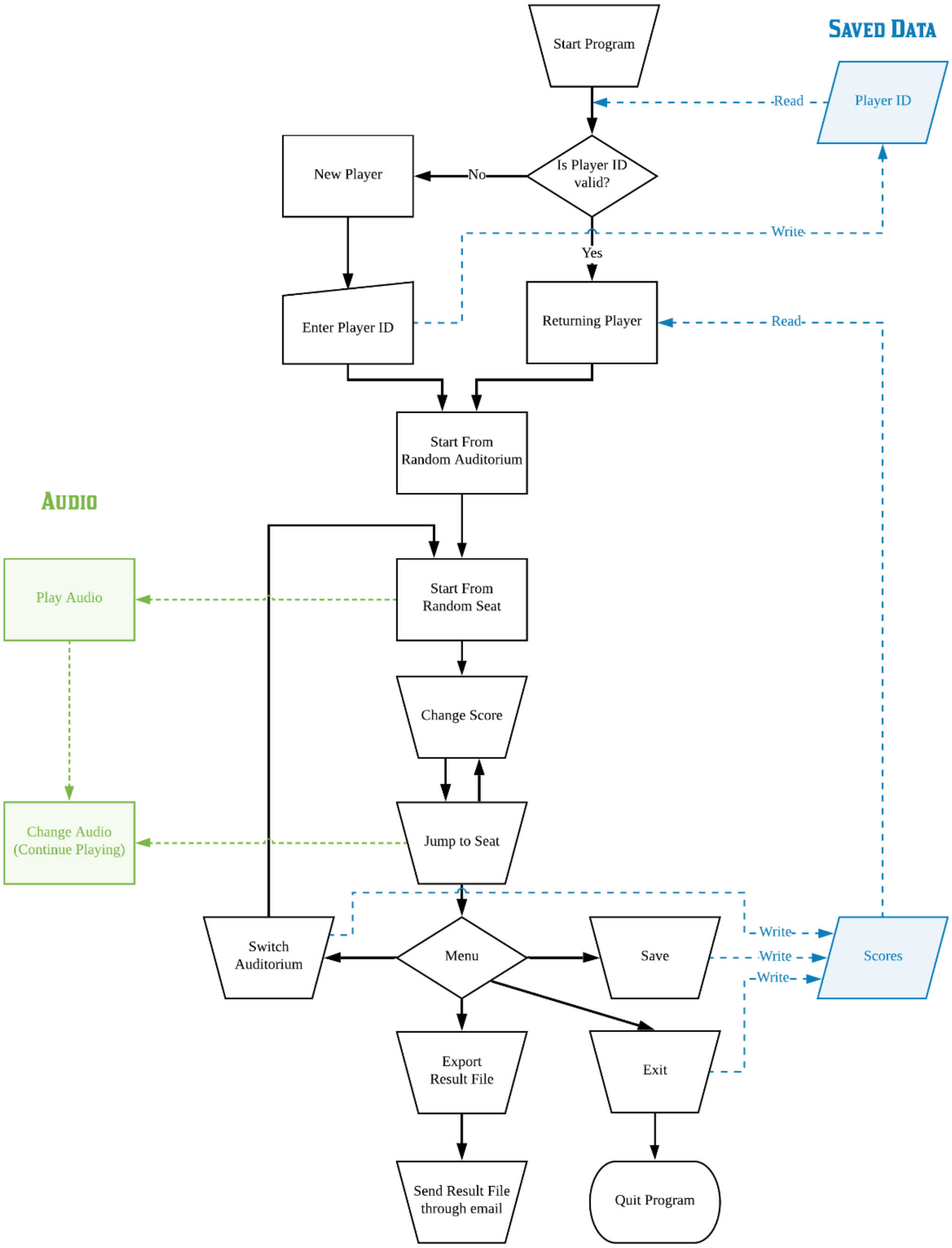


Figure 2-12 Operation and data flow in the third experiment

Only one subjective parameter, the overall preference, was evaluated in the second and third experiment. The overall preference was given by choosing a score from 0 to 100 for each location. The subjects could view the current score of the current location by touching the thumbstick or touchpad on the VR controllers, and change the score up or down by moving their finger clockwise or anti-clockwise (Figure 2-9). All locations started with a score of 0 and they could change the scores of all locations for as long as they wished. The fourth experiment had an added subjective evaluation, which was the overall preference for each auditorium not specific to any seat.

The subjects could choose their own order to experience each stimulus by viewing and selecting from all available locations. They could view all available locations by pressing down the trigger on the VR controllers (Figure 2-9). In the second experiment, all available locations would appear as spheres with an underlying frame for spatial localizing (Figure 2-13). In the third and fourth experiment, all available locations would appear as models of seated people with the corresponding scores for the locations (Figure 2-14). A laser beam would appear from the VR controller model in the scene, if they pointed it at any location that they wish to move to and release the trigger, the visual and auditory stimuli would switch to the ones for the selected location.

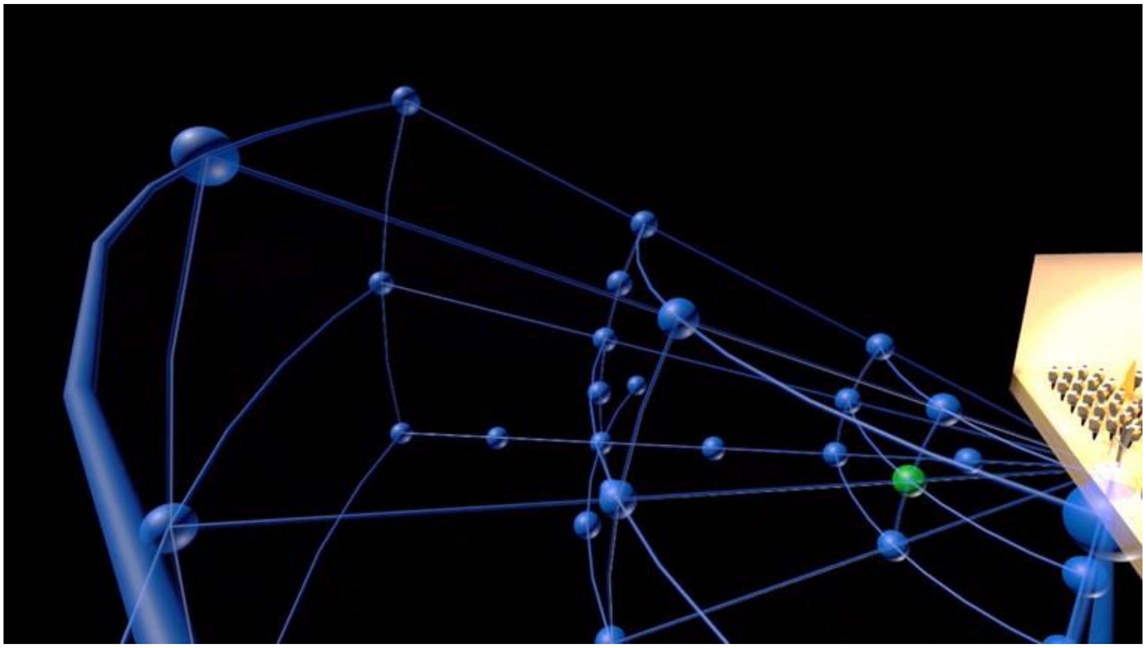


Figure 2-13 Seat selection interface in the second experiment

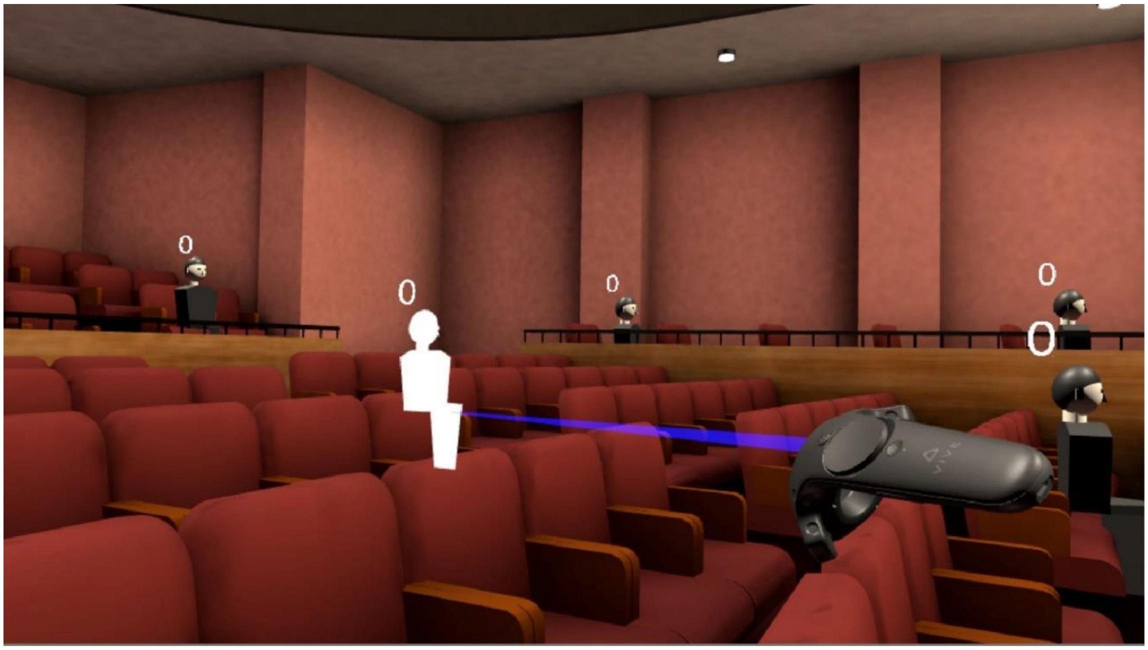


Figure 2-14 Seat selection interface in the third and fourth experiment

For other auxiliary operations, a menu was designed that included all available functions. The subjects could access the menu by pressing the menu button, then choose their intended operation using the same way as seat selection. Figure 2-15 shows the menu in the third experiment, while in the second experiment the operations for music playback (the three small buttons on the top) and the "Switch auditorium" button were not available, but there was an extra button for "Next level", which activated the interface to input password for the next "Level". Clicking the "Export result file" or "Switch auditorium" button would activate sub-menus, in which the subjects could choose a location to export the result file, or choose an "Auditorium" to switch to. For the operations that changes saved data (the three small buttons on the bottom), a safety lock was added to prevent accidental data deletion, and the subjects would need to click twice in order to carry out the operation.

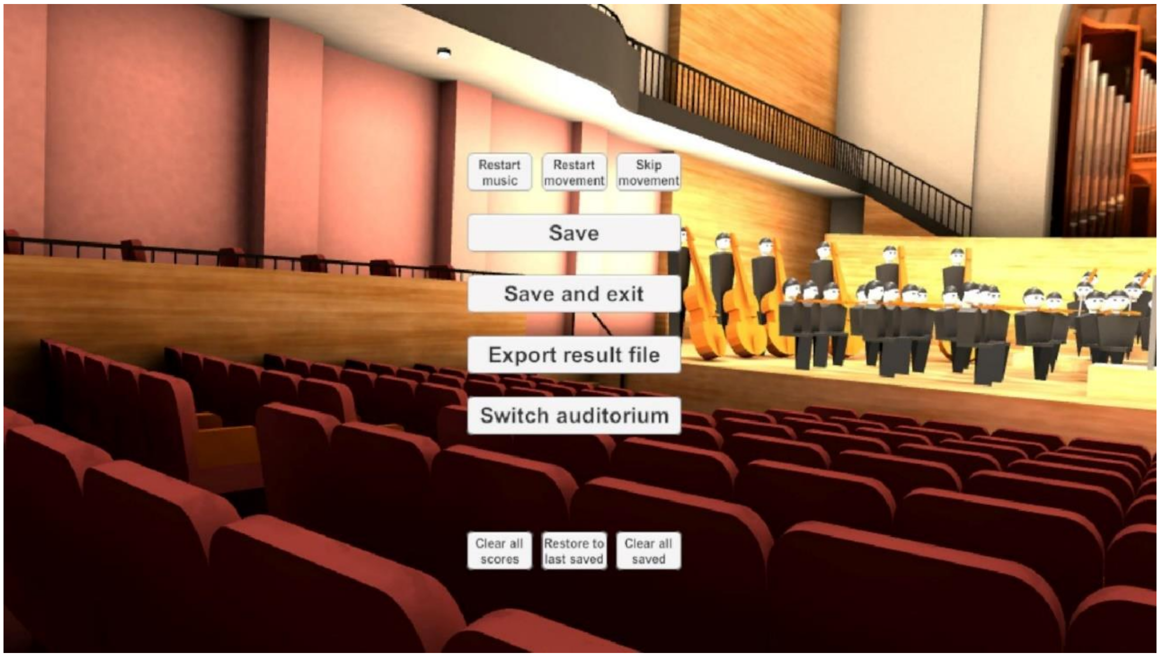


Figure 2-15 Menu interface in the third experiment

In the fourth experiment, because there were twelve different auditoria for the participants to choose from and evaluate, in the auditorium selection interface, each available auditorium was presented as a thumbnail picture with the overall auditorium score that the participant had given (Figure 2-16), so the participants could easily select the auditorium to which they wished to go.

Figure 2-16 Auditorium selection interface in the fourth experiment

Apart from the abovementioned operations that were explained in the instructions sent to the volunteers with the experiment program, there were also operations only known to the researcher, and the subjects would only be informed in special circumstances. For example, there was a key combination to delete all saved data (including “Player ID”), and would only be told to the subjects in the case that multiple subjects were doing the experiment using the same computer.

Due to the uncommonness of conducting this type of experiment online, a reward scene was designed in order to encourage participation and completion for the experiment. In the reward scene, the subjects could walk or “Teleport” to anywhere on the stage (and in the auditorium for the third experiment). They could interact with the musicians by “grabbing” each individual model. When a model was attached to their hands, a short audio clip of timbre demonstration for the corresponding instrument would be played. The demonstration audio clips were extracted from the “Instrument Timbre Comparison (Scale)” playlist on YouTube recorded by Utah Symphony & Utah Opera (2017), or computer generated. They could rearrange the musicians and instruments as they wish. There was also a “Teleport Point” in the scene, and when they “Teleport” to the location, the whole model would scale to 1/10 of the original size. The reward scene was coded into the same executable file, and the method to activate it would be given to the subjects when they had completed the experiment and sent back the result files.

Chapter 3 The effect of concert hall colour on preference and auditory perception

This chapter examines the effect of concert hall interior design colour on auditory and visual preference, together with two auditory perception attributes, through the first virtual reality experiment. Part of this chapter has been published as:

Chen, Y., & Cabrera, D. (2021). The effect of concert hall colour on preference and auditory perception. *Applied Acoustics*, *171*, 107544. https://doi.org/10.1016/j.apacoust.2020.107544

Chen, Y., & Cabrera, D. (2020). Does virtual concert hall colour affect loudness?. *Proceedings of e-Forum Acusticum 2020*, 2837–2840. https://hal.archives-ouvertes.fr/FA2020/hal-03242468

The visual design of a concert hall contributes to the visual experience of seeing a concert, and colour is one of the most obvious elements of the visual design. While some studies have reported that colour affects vehicle loudness, the influence of concert hall colour on the auditory experience of seeing a concert has been little-studied. In this experiment 30 volunteers evaluated loudness, reverberance, and their visual and auditory preference for multiple virtual reality scenes of a concert hall with various colours and with a music excerpt of various levels of gain and reverberation time. Results show that colour has little or no effect on loudness and reverberance compared to changing gain or reverberation time. However, colour does affect visual and auditory preference, and these are positively correlated and mutually influential. Of the five colours tested, red is the most-liked colour for the selected concert hall, followed by neutral, blue, and yellow, while green is the least liked colour. The colour preference is related to the commonly used colour styles of existing halls.

3.1 Introduction

What audiences see in a concert is an important part of the concert-going experience, which includes both the performance on the stage and the appearance of the concert hall itself. While various kinds of interaction have been found between auditory and visual perception, how the interior design of a concert hall can influence the visual and auditory perception of a performance remains unknown. Does the look of an auditorium affect the experience of seeing and listening to a concert? This chapter approaches this question experimentally, by investigating the influence of different interior colours of a virtual concert hall on the subjective perception of loudness, reverberance, visual preference, and auditory preference.

3.1.1 Visual-auditory interaction in auditoria

As reviewed in Section 1.5, human beings perceive the world through multiple senses, and integrate all sensory inputs to understand their environment. On the one hand, the combination of synchronized visual and auditory stimuli may improve the general performance of perception and information collection; on the other hand, visual and auditory stimuli with different or contradicting information may interfere with both senses, leading to perception that diverges from the stimulus' physical properties. When stimuli from multiple senses are given at the same time, the dominant modality is the one that gives the most realistic and accurate information, which in most cases is the visual modality unless the intensities of stimuli differ greatly. Hence, vision influencing auditory perception is a common phenomenon.

Most of the existing studies of visual influence on auditory perception in rooms (including auditoria) focus on perceived spatial attributes. Among the published experiments regarding visual-auditory cross-modal influence on perception in auditoria or other music-related rooms, the most-studied auditory perceptual attributes are: 1) perceived distance; 2) apparent source width (ASW); and 3) listener envelopment (LEV) (Barron, 1988; Cabrera et al., 2004; Calcagno et al., 2012; Galiana et al., 2016; Jeon et al., 2008; Larsson et al., 2001; Maempel & Jentsch, 2013; Postma & Katz, 2017; Tokunaga et al., 2013; Valente & Braasch, 2010; Zahorik, 2001).

Visually perceived distance influences auditorily perceived distance in most cases, both by improving the accuracy of auditory distance perception when using corresponding stimuli, and misleading auditory distance perception when using non-corresponding stimuli (Cabrera et al., 2004; Calcagno et al., 2012; Larsson et al., 2001; Maempel & Jentsch, 2013; Postma & Katz, 2017; Tokunaga et al., 2013; Zahorik, 2001). This may be due to the accuracy of visual distance perception being relatively greater than auditory distance perception (Anderson & Zahorik, 2014; Kolarik et al., 2016).

However, results on ASW and LEV are more scattered or insignificant. Some studies found no significant difference in ASW related to the change of visual stimuli (Cabrera et al., 2004; Postma & Katz, 2017), while Larsson et al. (2001) found an increase in ASW with VR or *in situ* visual stimuli than without any visual stimuli, and Valente and Braasch (2010) found differences in different types of visual stimuli. Similar trends were found on LEV by Valente and Braasch (2010), while no significant difference was found in other studies (Cabrera et al., 2004; Postma & Katz, 2017). The contrast in the results may be due to the difference in the experiment settings including the type of stimuli and the type of comparison.

3.1.2 Visual influence on loudness and reverberance

Loudness and reverberance are two of the most important subjective attributes in auditoria (Barron, 1988, 2009; Beranek, 1992; Sabine, 1900; Sabine & Egan, 1994).

Loudness is a subjective attribute that describes the volume or force of sound perceived by the listener (Beranek, 2012) and is one of the most fundamental and obvious attributes of sound for general listeners. The loudness of a sound is primarily indicated by sound pressure level (*SPL*) at the listener's ears, and the loudness of an auditorium is primarily indicated by sound strength (*G*) (ISO 3382-1: 2009), which is an expression of the auditorium's acoustic gain, and varies with location. More elaborate psychoacoustic models of loudness of sounds are also available, taking auditory processes into account, such as the ears' transfer function, auditory filter bank and temporal integration (Chalupper & Fastl, 2002; Glasberg & Moore, 2002; Zwicker & Scharf, 1965).

Reverberance is a subjective attribute that describes the ability of the hall to sustain a sound after the sound source stops emitting sound (Beranek, 2012). Some studies distinguish running reverberance (during continuous music) from terminal reverberance (reverberance when the sound emission stops) (Morimoto & Asaoka, 2004). It is primarily indicated by early decay time (*EDT*) (Atal et al., 1966; Haas, 1972; ISO 3382-1: 2009; Jordan, 1970; Soulodre & Bradley, 1995), which is closely related to reverberation time (*RT*), one of the most important and most characteristic attributes used in room acoustics. More elaborate psychoacoustic models of reverberance have been proposed (Lee et al., 2017; Osses Vecchi et al., 2017; Zarouchas & Mourjopoulos, 2009), but are less mature than loudness models.

Existing studies have found that loudness judgments are influenced by visual distance due to perceptual constancy (Barron, 1996; Walsh & Kulikowski, 1998; Zahorik & Wightman, 2001). Colour of vehicles and trains has also been found to influence loudness of the noise perceived in some studies (Fastl, 2004; Menzel et al., 2008, 2010; Patsouras et al., 2002; Rader et al., 2004), but conflicting results exist (Parizet & Koehl, 2011). Visual influence on reverberance has been little-studied, but Schutte et al. (2019) found that visual room impression did not affect reverberance.

3.1.3 Visual and auditory preference in auditoria

Auditory preference in auditoria has been extensively studied. It has been found that auditory preference is related to some subjective attributes and their corresponding objective indicators, such as loudness and *G*, reverberance and *EDT*, ASW and early lateral energy fraction (J_{LF} or J_{LFC}, or traditionally, J_F or J_{FC}), LEV and late lateral sound level (L_J), etc. (Barron, 1988; Beranek, 2012; Bradley & Soulodre, 1995a; Hawkes & Douglas, 1971; Lokki, 2013, 2014; Schroeder et al., 1974). In most studies on auditory preference in auditoria, objective sound level or subjective loudness is found to be positively correlated to preference. In other words, usually people prefer louder sound in auditoria. Reverberance, on the other hand, is liked by some people but not all (Lokki, 2014). Preferable visual input has also been found to have a positive effect on auditory preference (Jeon et al., 2005).

Visual preference in auditoria is relatively under-studied compared to auditory preference. Some researchers have found that visual preference is related to stage size and projected distance to the stage (Jeon et al., 2008), and the vertical angle from the stage (Sato et al., 2012). However, those results are all from different seat locations in one auditorium, and there are no known studies on how interior design can affect visual preference.

3.1.4 Colour preference and arousal theory

Preference for different colours is a very well-studied yet controversial area. While a universal preference for the colour blue is found in some studies (McManus et al., 1981; Ou et al., 2004), personal colour preference is found to be affected by age (Adams, 1987), gender (Hurlbert & Ling, 2007), related objects (Palmer & Schloss, 2010), related emotions (Ou et al., 2004), and cultural contexts (Ou et al., 2004). It is also argued by some researchers that colour preference of an individual at different times is related to the person’s mood and the colours’ psychological arousal levels (Walters et al., 1982), which is related to the psychological “reversal theory” (Smith & Apter, 1975). Higher arousal level is related to longer wavelength, greater brightness, and greater saturation (Gerard, 1958; Küller et al., 2009; Pressey, 1921; Walters et al., 1982; Wilms, 2018; Wright & Rainwater, 1962).

Arousal theory also applies to sound, for which higher arousal level is related to greater sound level (or sound intensity, loudness), faster tempo (or higher modulation rate), and stronger accentuation (Dean et al., 2011; Droit-Volet et al., 2013; Gomez & Danuser, 2007; Mikutta et al., 2013). It is also related to the genre, emotion, and context of the music (Blumstein et al., 2012; Dillman Carpentier & Potter, 2007; Rickard, 2004).

The combination of visual (colour) and auditory stimuli on arousal level is relatively under-studied, but the red/loud combination was found to associate with excitement in a computer game (Wolfson & Case, 2000). The effect of colour on vehicle loudness (Fastl, 2004; Menzel et al., 2008, 2010; Patsouras et al., 2002; Rader et al., 2004) may also indicate similar interactions.

3.2 Method

3.2.1 Visual and auditory stimuli

The experiment used a head-mounted virtual reality display for visual stimuli, with headphones for auditory stimuli.

The concert hall studied is the Verbrugghen Hall at Sydney Conservatorium of Music. Measurements were done in the hall with four sound source positions on the stage that correspond to the standing position (1.5 m from stage floor) of four musicians of a small ensemble, based on Panton et al. (2019): S1 (-1.5 m, -3 m), S2 (-4 m, -2 m), S3 (-4 m, 2 m), and S4 (-1.5 m, 3 m) in Figure 3-1. More details of the measurement are presented in 0. Second-order-Ambisonic room impulse responses were measured at seat M12 (middle of the last row of front stalls, approximately 13.5 m from the edge of the stage, Figure 3-1), 1.2 m from the floor, with a 32-channel spherical microphone (mh acoustics EM32 Eigenmike® microphone array). The measured reverberation time at seat M12 is presented in Figure 3-2 (solid line).

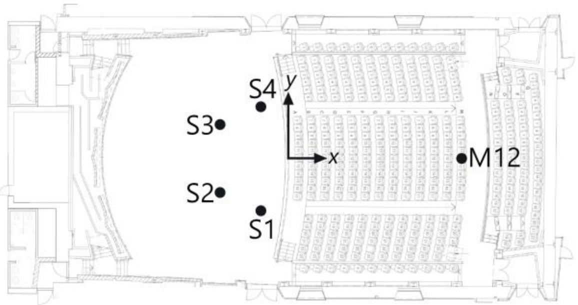


Figure 3-1 Floor plan of the selected hall with source (S1-S4) and receiver (M12) positions

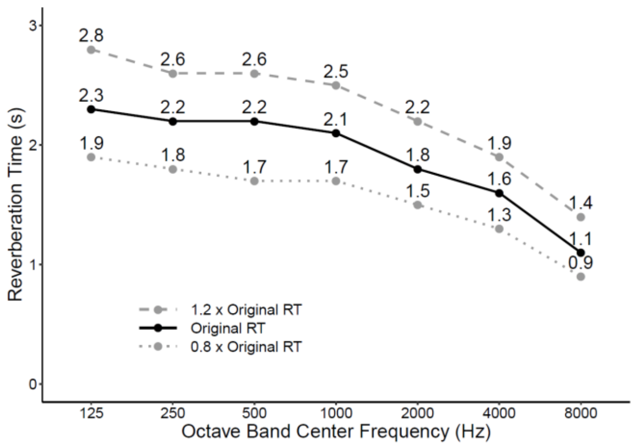


Figure 3-2 Original and modified octave band reverberation time at seat M12 (average of four source positions)

The measured spatial room impulse responses (SRIRs) were modified with the reverberation time changing function in AARAE (Cabrera et al., 2014) (acoustic analysis environment based on MATLAB (MathWorks)). Three reverberation time (RT) conditions were chosen: the original RT, 0.8 × the original RT, and 1.2 × the original RT (Figure 3-2). The adjustments were made in octave bands with centre frequencies spanning 125 Hz – 8 kHz. The SRIRs were convolved with an anechoic recording of a string quartet (Thery & Katz, 2019), with the SRIR for each of the four source positions individually convolved with the recording of the corresponding instrument (S1 to S4: 1st violin, viola, cello, and 2nd violin). The selected music excerpt was a 3’20” recording of the third movement (*Presto*) of *Concerto No. 2 in G minor*, Op. 8, RV 315, "Summer" (L'estate) in Antonio Vivaldi’s *Four Seasons*.

The convolved audio files were played to the participants through Sennheiser HD 800 Headphones using Max/MSP/Jitter (Cycling '74) software. Four levels of gain were applied to the audio playback. The reference level is the approximate sound pressure level expected from a string quartet in the real situation (calculated with the measured *G* of the used seat location, and the estimation method given in ISO 23591:2021). Further gain adjustments of 0.6, 0.8, and 1.2 times the reference waveform were also used for the experiment stimuli (i.e., -2.2 dB, -0.9 dB, +0.8 dB in gain respectively). Therefore, a total number of 12 distinct auditory stimuli were used (3 levels of RT × 4 levels of gain). The A-weighted equivalent sound pressure level of the whole excerpt for each auditory stimulus is presented in Table 3-1.

Table 3-1 A-weighted equivalent sound pressure level ($L_{A,eq}$) of each auditory stimulus for the three RT levels and four gain levels

$L_{A,eq}$ (dB)		**Gain (dB)**			
		- 2.2	**- 0.9**	**± 0.0**	**+ 0.8**
RT (s)	**1.7**	62.7	64.0	64.9	65.7
	2.1	63.8	65.1	66.0	66.8
	2.6	64.7	66.0	66.9	67.7

A 3D model of the concert hall was built in Rhinoceros (Robert McNeel & Associates), then exported to and rendered in Unity (Unity Technology). The model in Unity was presented to the participants via an HTC Vive VR headset with SteamVR plugin (Valve Corporation) for head-tracking, and the participants entered their evaluation with handheld Vive Controllers. Five colours were assigned to the model under the same neutral lighting and rendering condition. To ensure that the scenes remained realistic, only selected architectural elements were changed between the scenes. The HSV (Hue-Saturation-Value) system was used for controlling variables. For each selected element, the saturation and brightness values of the colours and the texture of the materials were constant between scenes, while only hue was changed (apart from the neutral scene, for which saturation was set to 0%). Table 3-2shows the settings of each element in each scene, and screenshots of the 5 visual scenes are presented in Figure 3-3.

Table 3-2 Colour settings for each scene in HSV colour system (S: saturation; V: value)

Colour	**Hue**	Carpet	Seats	Walls	Ceiling
Red	0°	S: 50% V: 60%	S: 70% V: 70%	S: 40% V: 90%	S: 20% V: 100%
Yellow	60°				
Green	120°				
Blue	240°				
Neutral	NA (S: 0%)				

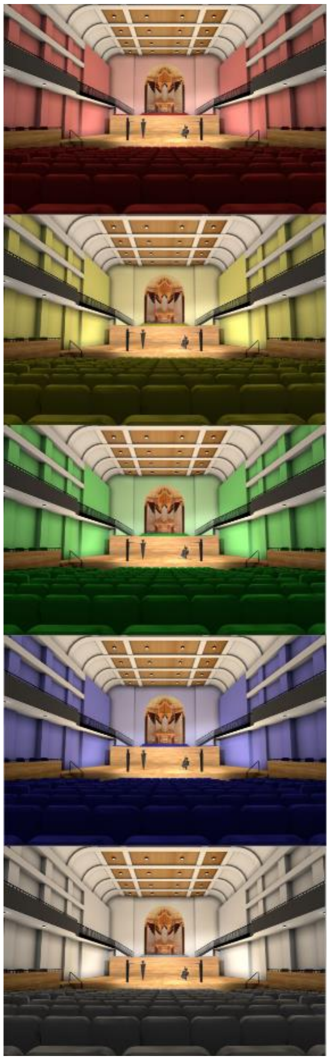


Figure 3-3 Visual stimuli of the 5 colour settings of the selected auditorium (top to bottom: red, yellow, green, blue, and neutral).

Head movement was tracked by the VR Headset and sent real-time from Unity to Max/MSP/jitter through Open Sound Control (OSC). The second-order-Ambisonic audio files were decoded real-time to the two channels of the headphones using the Spat (IRCAM) binaural decoder with head-related transfer functions (HRTF) of a KEMAR dummy-head microphone.

While a virtual model and digital playback have some limitations from reduction of details and realism compared to an actual concert experience, the use of virtual reality provides a more realistic environment than static photographs, which were used in many previous studies, and the head-tracking binaural audio playback provides a surrounding sound field that adds to realism.

3.2.2 Experiment set-up

Thirty volunteers aged from 18 to 47 years participated in the experiment. Before the experiment, each participant went through a colour vision test and a hearing test to screen for normal colour vision and hearing. The colour vision test was done with the HRR Pseudoisochromatic Test (Hardy et al., 1954) (24 Plates, 4th ed., by Richmond Products), with the result interpretation method provided in the product, which has been evaluated by clinical trials (Bailey et al., 2004; Cole et al., 2006). The hearing test was done with a Next audiometer (Benson Medical Instruments), which meets the requirements of Type 4 Audiometer in the American National Standard (ANSI S3.6–1989), and the results were compared to the Occupational Safety and Health Administration standard for hearing loss (OSHA 3074). All volunteers met the standard for normal colour vision and normal hearing given by the test equipment.

The participants wore the VR headset and headphones to receive the visual and auditory stimuli at the same time. Two 2D sliders were presented in each scene, each with two subjective evaluation scales (Figure 3-4): one for auditory evaluation (loudness and reverberance), the other one for preference evaluation (auditory and visual preference). The use of 2D sliders was chosen to present the evaluation scales orthogonally and reduce possible influence between the scales. The participants could use the handheld controllers to move the slider knobs anywhere on the 2D scale so that the *x* and *y* value matched their evaluation. They could move to the next scene when they were satisfied with their evaluation. A number between 0 and 100 (precision: 0.1) was returned for each attribute from the locations at which the participant placed the slider knobs for each scene.

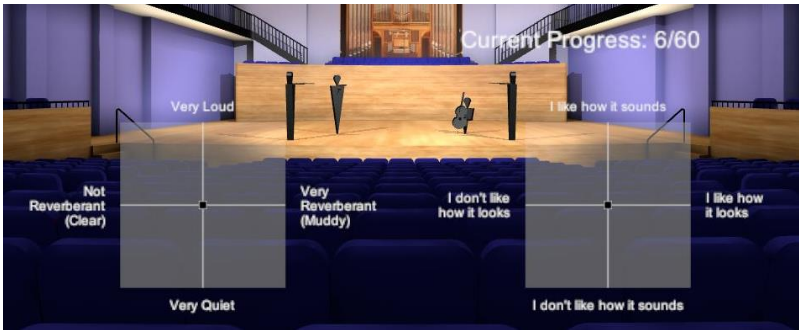


Figure 3-4 Subjective evaluation interface (left: 2D scale for loudness and reverberance evaluation, right: 2D scale for auditory and visual preference evaluation)

Each participant was led through a short induction to experience the loudest, quietest, most, and least reverberant sound that they would hear, and to see all the five colours of the visual stimuli. Then each participant evaluated all the 60 stimuli (12 auditory stimuli × 5 visual stimuli) in one of four randomly generated orders, with a 10-15-minute break in the middle to prevent cybersickness and fatigue.

The experiment was conducted in a sound studio with a very low background noise level. The computer (with its noise-making cooling fan) was in a different room to the participant.

3.3 Results and Discussion

Statistical analysis was performed with the software RStudio (RStudio Inc.) with packages “plyr” (Wickham, 2020), “tidyverse” (Wickham, 2019), and “sjstats” (Lüdecke, 2020). To eliminate the effect of each individual subject, all subjective entries are standardized to *z*-scores based on the mean and standard deviation of each participant.

3.3.1 Overall results

Results of three-way repeated measures analysis of variance (ANOVA) for each dependent variable's relationships with the three independent variables are shown in Table 3-3. Assumptions of the test were checked using diagnostic plots of the residuals.

*Table 3-3 ANOVA results of all the dependent variables (***p<0.001, **p<0.01, *p<0.05)*

Dependent Variable	**Independent Variable**	**Df**	**F value**	***p*-value**	**Eta squared**
Loudness	**Gain**	3	627.7	< 0.001 ***	0.487
	RT	2	89.7	< 0.001 ***	0.046
	Colour	4	3.2	0.013 *	0.003
Reverberance	**Gain**	3	30.3	< 0.001 ***	0.045
	RT	2	77.5	< 0.001 ***	0.076
	Colour	4	1.6	0.166	0.003
Auditory Preference	**Gain**	3	64.7	< 0.001 ***	0.096
	RT	2	3.7	0.026 *	0.004
	Colour	4	10.4	< 0.001 ***	0.021
Visual Preference	**Gain**	3	0.2	0.927	0.000
	RT	2	0.3	0.739	0.000
	Colour	4	152.6	< 0.001 ***	0.254

It can be concluded that loudness and reverberance are both significantly affected by gain and RT. Although loudness is significantly affected by colour, the effect size is much smaller than the effect of gain or RT. Reverberance is not significantly affected by colour. Visual preference, on the other hand, is only significantly affected by colour. Auditory preference is mostly affected by gain, but also significantly affected by colour, and weakly affected by RT.

The average values of each subjective scale are presented in Figure 3-5. Only the factors that significantly influence each of the variables (with *p*-values smaller than 0.01) are presented. It can be seen that both loudness and reverberance have positive linear trends when gain or RT increases. Auditory preference also has a positive linear trend when gain increases. Colour influences auditory and visual preference similarly.

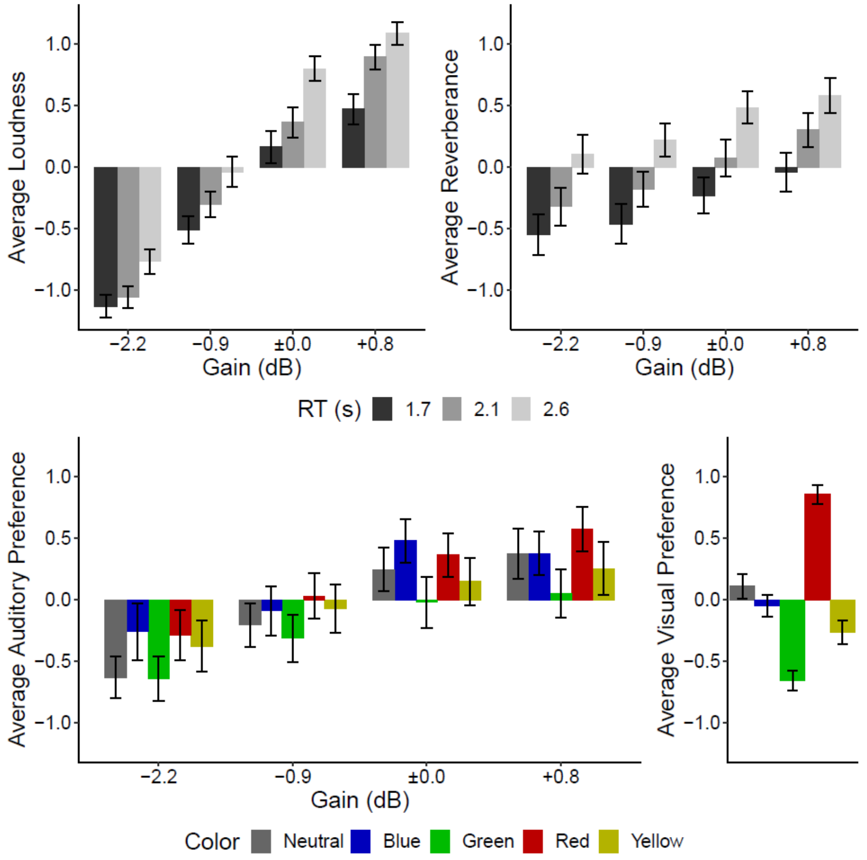


Figure 3-5 Average values and 95% confidence intervals of the subjective judgements (only independent variables with significant influences are included)

To further understand and quantify the effect of each factor on the tested attributes, stepwise linear regression was used to find the best prediction equation that describes each attribute, and correlation coefficients (Pearson's product moment correlation coefficient *r*) between the predictor variables and result variables were calculated.

3.3.2 Loudness results

3.3.2.1 Correlation and regression analysis

Loudness is found to be positively correlated with gain ($r = 0.695$, $p < 0.001$) and RT ($r = 0.215$, $p < 0.001$). Of the five colours, only blue is found to have a significant effect on loudness compared to neutral ($p < 0.001$), but the difference (slope = 0.17) is much smaller than changing 1 dB in gain (slope = 0.62), which is the just noticeable difference for subjetive level of sound (ISO 3382-1: 2009). Therefore, even though it is significant, the influence of colour on loudness is negligible. The results of subjective loudness can be predicted using the following equation:

$$Loudness \approx 0.62(Gain) + 0.58(RT) + C_1$$

In which $Loudness$ is the standardized subjective loudness; $Gain$ is the controlled gain change (in dB); RT is the controlled reverberation time (in s); C_1 = -0.88; R^2 = 0.53 (r = 0.73); $p < 0.001$.

To visually demonstrate the equation, the observed values and predicted values are shown in Figure 3-6. The regression lines of each colour are approximately coincident, illustrating that colour does not clearly affect loudness.

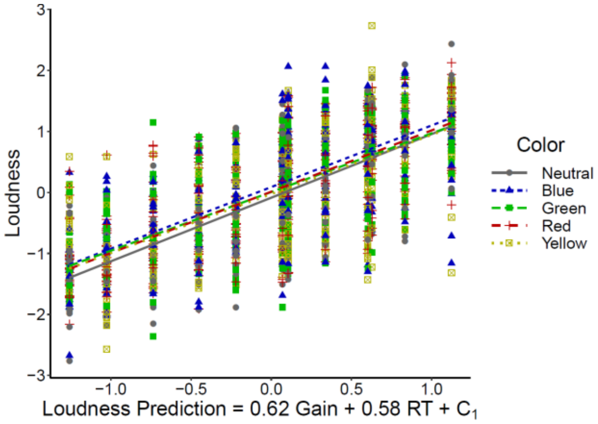


Figure 3-6 Loudness judgements plotted against objective prediction according to Eq.1 (with linear regression line for each colour)

3.3.2.2 Comparison to modelled loudness

The results of subjective loudness in this experiment are compared with the calculated loudness of the stimuli (in sones) using the time-varying loudness model proposed by Glasberg & Moore (2002; Moore & Glasberg, 2007). The 95th percentile values of the long-term loudness calculated from the model are listed in Table 3-4.

Table 3-4 Calculated loudness of each auditory stimulus using the time-varying loudness model

Loudness (sones)		**Gain (dB)**			
		- 2.2	**- 0.9**	**± 0.0**	**+ 0.8**
RT (s)	**1.7**	16.5	17.9	18.8	19.8
	2.1	17.5	18.9	19.9	20.9
	2.6	18.4	19.8	20.9	21.9

The correlation coefficient between the experiment result of loudness and modelled loudness is 0.700 ($p < 0.001$). Figure 3-7 shows that the loudness model aligns with the experiment results well, but RT has a smaller effect on evaluated loudness than on modelled loudness.

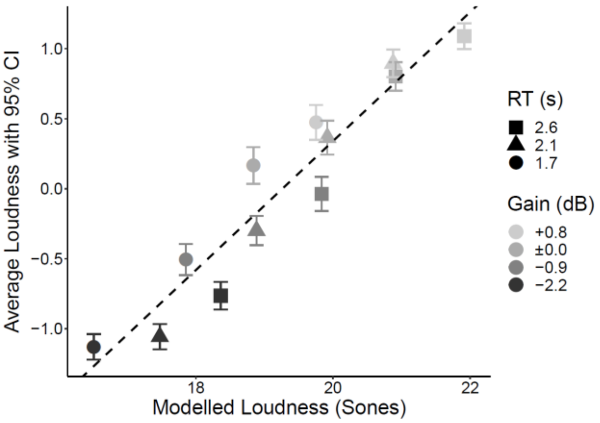


Figure 3-7 Loudness judgements (mean and 95% confidence interval) plotted against objective prediction according to the Glasberg & Moore loudness model

3.3.3 Reverberance results

3.3.3.1 Correlation and regression analysis

The results of reverberance are much more scattered than loudness results, indicating that subjects found it more difficult to evaluate and differentiate reverberance with the given stimuli. Reverberance was only found to be weakly correlated with gain ($r = 0.205$, $p < 0.001$) and RT ($r = 0.275$, $p < 0.001$), and can be predicted using the following equation:

$$Reverberance \approx 0.18(Gain) + 0.74(RT) + C_2$$

In which $Reverberance$ is the standardized subjective reverberance; $Gain$ is the controlled gain change (in dB); RT is the controlled reverberation time (in s); $C_2 = -1.48$; $R^2 = 0.12$ ($r = 0.35$); $p < 0.001$. The observed values and predicted values are shown in Figure 3-8. Like loudness, the regression lines of different colours coincide, but the observation points are scattered across a much larger range than for loudness.

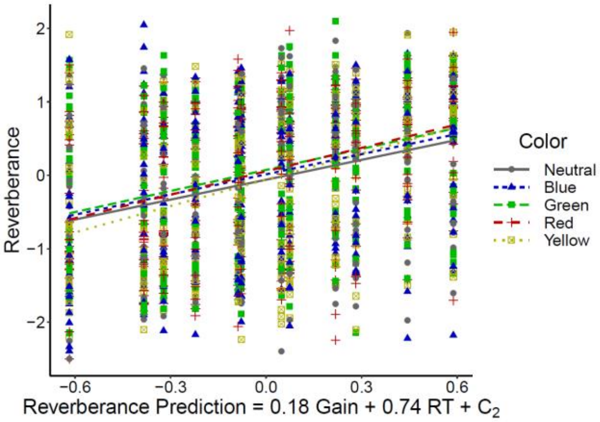


Figure 3-8 Reverberance judgements plotted against objective prediction according to Eq.2 (with linear regression line for each colour)

3.3.3.2 Comparing with EDT_N

As studies about reverberance have been refined over time, the objective attribute most accurately predicting subjective reverberance developed from reverberation time (*RT*) (Sabine & Egan, 1994) to early decay time (*EDT*) (Atal et al., 1966; Barron, 1988; Jordan, 1970; Soulodre & Bradley, 1995), and then to more recent loudness-based early decay time (EDT_N) (Lee et al., 2012; Lee & Cabrera, 2009) and other approaches. One advantage of EDT_N is that it accounts for experimental evidence that increased gain is associated with increased reverberance, which is also found in this experiment. The results of subjective reverberance in this experiment are compared with the results of EDT_N calculated using the method given in (Lee & Cabrera, 2009) with the three impulse responses and $L_{A,eq}$ of the audio playback for each of the 12 auditory stimuli (Table 3-5).

Table 3-5 EDT_N (loudness-based early decay time) of each auditory stimulus

EDT_N (s)		**Gain (dB)**			
		- 2.2	**- 0.9**	**± 0.0**	**+ 0.8**
RT (s)	**1.7**	1.80	1.81	1.82	1.83
	2.1	2.29	2.31	2.32	2.33
	2.6	2.65	2.67	2.68	2.69

However, the correlation between reverberance and EDT_N is still weak ($r = 0.279$, $p < 0.001$). The relationship between EDT_N and the experimentally evaluated reverberance (mean and standard deviation) is shown in Figure 3-9. It can be seen that EDT_N does not sufficiently account for the effect of gain on reverberance.

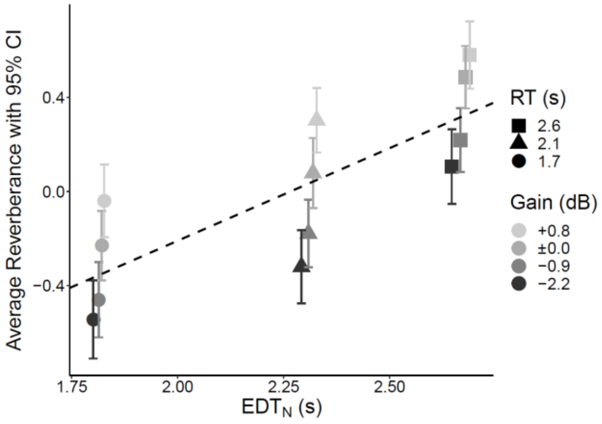


Figure 3-9 Reverberance judgements (mean and 95% confidence interval) plotted against objective prediction according to EDT_N model

3.3.4 Auditory preference results

3.3.4.1 Correlation and regression analysis

Auditory preference is positively correlated with gain ($r = 0.304$, $p < 0.001$) and visual preference ($r = 0.162$, $p < 0.001$), and very weakly correlated with RT ($r = 0.048$, $p = 0.04$), which is therefore neglected in the prediction equation.

Auditory preference can be predicted using the following equation:

$$AuditoryPreference \approx 0.27(Gain) + 0.16(VisualPreference) + C_3$$

In which $AuditoryPreference$ is the standardized auditory preference; $Gain$ is the controlled gain change (in dB); $VisualPreference$ is the standardized visual preference; $C_3 = 0.16$; $R^2 = 0.12$ ($r = 0.35$); $p < 0.001$.

Because auditory preference and visual preference are both dependent variables, to further explore the direction of effect between the two, partial correlation was calculated with the R package "ppcor" (Kim, 2015). When controlling the effect of gain, the partial correlation coefficient between auditory and visual preference is 0.169 ($p < 0.001$), which means that visual preference influences auditory preference. The separate effect of gain and visual preference on auditory preference is plotted in Figure 3-10 (top). The intercept of each line represents the influence of gain, while the slopes show the influence of visual preference. All the slopes are significantly larger than zero, which points to a positive influence of visual preference on auditory preference.

Even though the effect of RT on auditory preference is relatively weak compared to the effect of gain or visual preference, it may still be of interest to some readers, and is therefore plotted in Figure 3-10 (bottom). As the figure suggests, the effect of RT on auditory preference is indeed very weak, but the level of RT1.7s (0.8 × the original RT) has slightly lower auditory preference ratings than the other two levels, especially at low visual preference ratings.

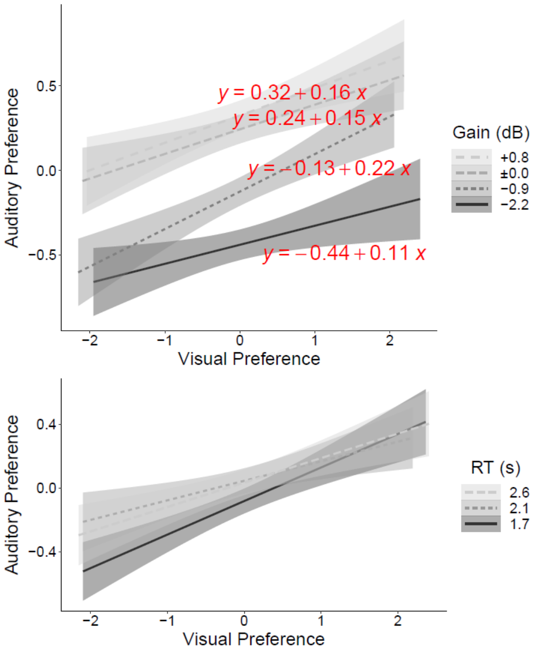


Figure 3-10 Auditory preference judgements (linear regression and 95% confidence interval) plotted against visual preference judgements (top: at each level of gain; bottom: at each level of RT)

3.3.4.2 Comparison with other studies

The positive correlation found between auditory preference and gain agrees with the results of previous studies that found positive correlations between auditory preference and SPL (Jeon et al., 2005, 2008; Kuusinen & Lokki, 2015; Sato et al., 2012). The correlation found in this experiment ($r = 0.304$, $p < 0.001$) is not as strong as the results found by Jeon et al. (2008) ($r = 0.98$, $p < 0.05$) or Sato et al. (2012) ($r = 0.86$, $p = 0.06$), which might be due to the evaluations in this experiment being made on a linear scale for each stimulus without repeat, while paired comparisons were used in the other studies. Another difference is that the independent variable in this experiment, gain, does not account for the effect of RT on SPL.

3.3.5 Visual preference results

3.3.5.1 Correlation and regression analysis

Visual preference is positively correlated with auditory preference, and is significantly affected by colour. When controlling for the effect of colour, the partial correlation coefficient between auditory preference and visual preference is 0.162 ($p < 0.001$), which means that auditory preference influences visual preference, but less so than the influence of visual preference on auditory preference. Visual preference can be predicted using the following equation:

$$\begin{aligned} VisualPreference \\ &\approx 0.11(AuditoryPreference) + 0.72(Red) + 0.12(Neutral) - 0.18(Blue) \\ &- 0.39(Yellow) - 0.76(Green) \end{aligned}$$

Equation 3-1

In which $VisualPreference$ is the standardized visual preference; $AuditoryPreference$ is the standardized auditory preference; the coefficients before Red, $Neutral$, $Blue$, $Yellow$, and $Green$ stands for the mean visual preference difference of the corresponding colour compared to the average of all colours; $R^2 = 0.27$ ($r = 0.52$); $p < 0.001$.

The relationship between visual and auditory preference for each colour is presented in Figure 3-11. The intercept of each regression line indicates the effect of the corresponding colour on visual preference. The red scene is the most liked, followed by the neutral scene, while the green scene is the least liked. It should be noted that because all results are standardized, the values can only be compared and indicate the difference between the five colours used in the experiment. The positive slopes indicate that auditory preference had a consistently positive effect on visual preference for all colours.

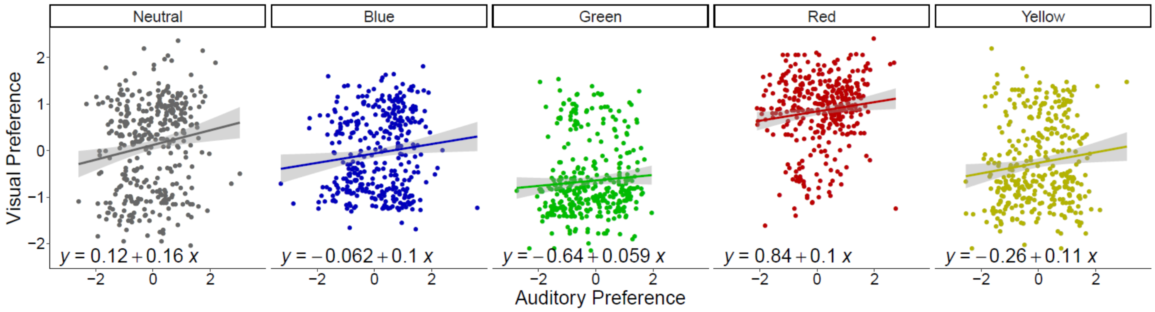


Figure 3-11 Visual preference judgements plotted against auditory preference judgements for each colour (with linear regression and 95% confidence interval)

3.3.5.2 Visual preference and personal preference

Compared to auditory preference, visual preference varies more between individuals. Therefore, to further understand the different visual preference of each individual, the average visual preference of each participant for each colour is calculated and divided into two groups: if the average value is larger than zero, the individual is considered to “like” the colour; if it is smaller than zero, the individual is considered to “dislike” the colour. The distributions of visual preference of the two groups are plotted separately in Figure 3-12, together with the number of participants in each group.

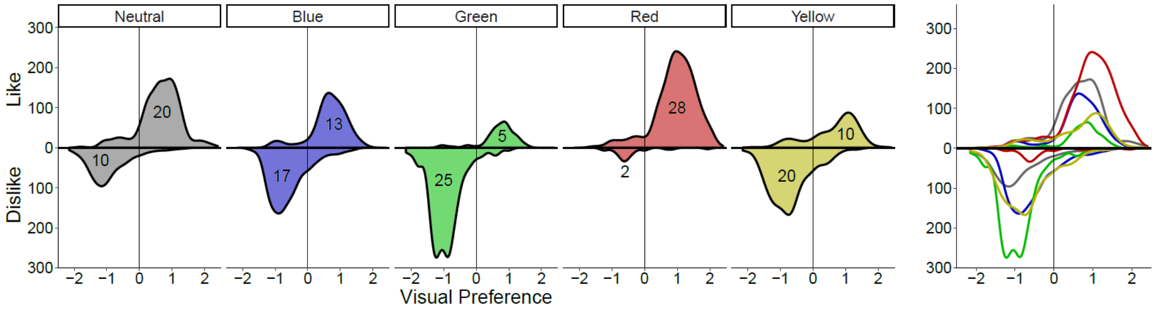


Figure 3-12 Visual preference judgements density plot (separated by participants that "like" or "dislike" each colour)

It can be seen that the number of participants who “like” each colour corresponds to the average visual preference of all participants: red being liked by the largest number of people, followed by neutral, blue, and yellow, while green is liked by the smallest number of people. In the last plot, the plots of all the colours are stacked together, and the *x* location of the peaks can be compared. It can be seen that the negative peak of green is not only the biggest but also the furthest towards the left, which means that not only do more people “dislike” the colour green, but the extent to which people “dislike” it is also larger than other colours. Similar trends are found for other colours, but with two exceptions: even though less people “like” yellow compared to neutral or blue, the average extent of “like” is larger; less people “dislike” neutral compared to green, yellow, or blue, but the average extent of “dislike” is larger.

3.3.5.3 Visual preference and colours of existing concert halls

The result of the visual preference of each colour appears to be related to the usual colour styles of existing performing art spaces. To examine this hypothesis, the colours of the 100 concert halls and opera houses listed in Beranek’s book (Beranek, 2012) have been analysed using photographs of the auditoria. As it can sometimes be difficult to definitively categorize auditoria by colour, three distinct methods were used to provide a more robust and objective result.

The first method involves visually categorizing the 100 halls according to their colour styles, on the basis that there exist some popular interior design styles of auditoria. A colour is considered a main colour of an auditorium if the colour takes up more than 30% of the visible interior surfaces in a representative photograph, so usually the colours of seats, walls, balconies, and ceilings are considered. Although the categories are relatively subjective and there might exist some ambiguous cases, this method is the most holistic and might best indicate the overall impression of auditoria. The categorization results of the color styles or the 100 auditoria along with descriptions and examples for each category are presented in Table 3-6. The photos used for each auditorium is given in Figure 3-13. The names of the halls are ordered alphabetically and referenced by number 1 to 100 (Appendix D) and the colours of the hall numbers correspond to the colours the halls are categorized in (black for “Neutral”, pink for “Other Colours”).

Table 3-6 Colour styles of 100 concert halls and opera houses

Colour	Style	Count	Example	Description
Red	Red+gold/white (classical)	29	Milan Teatro alla Scala	The most common style in classical opera houses: usually red seats, carpets, and walls, white balcony front with golden carvings
	Red+wood/white (modern)	31	Christchurch Town Hall	A modern variation of classical red: usually red seats and carpet, with white or wooden walls and ceilings
	Total	60		
Neutral	Wood+white/dark (modern)	22	Berlin Philharmonie	The most common style in modern concert halls: usually white balcony front, wooden or dark seats and floor, white or wooden walls and reflectors
Blue	Blue+wood/white (modern)	11	Buffalo Kleinhans Music Hall	Neutral hall with blue seats and/or curtains, sometimes also with small proportion of red as decoration (e.g. Berlin Konzerthaus)
Yellow	Other styles	2	Paris, Opera Bastille	Neutral hall with yellow (including orange-yellow) used on seats or walls
Green		1	Hong Kong Culture Centre Concert Hall	Neutral hall with other colors (including multiple colors) used on seats
Other Colours		4	Rotterdam De Doelen Concertgebouw	

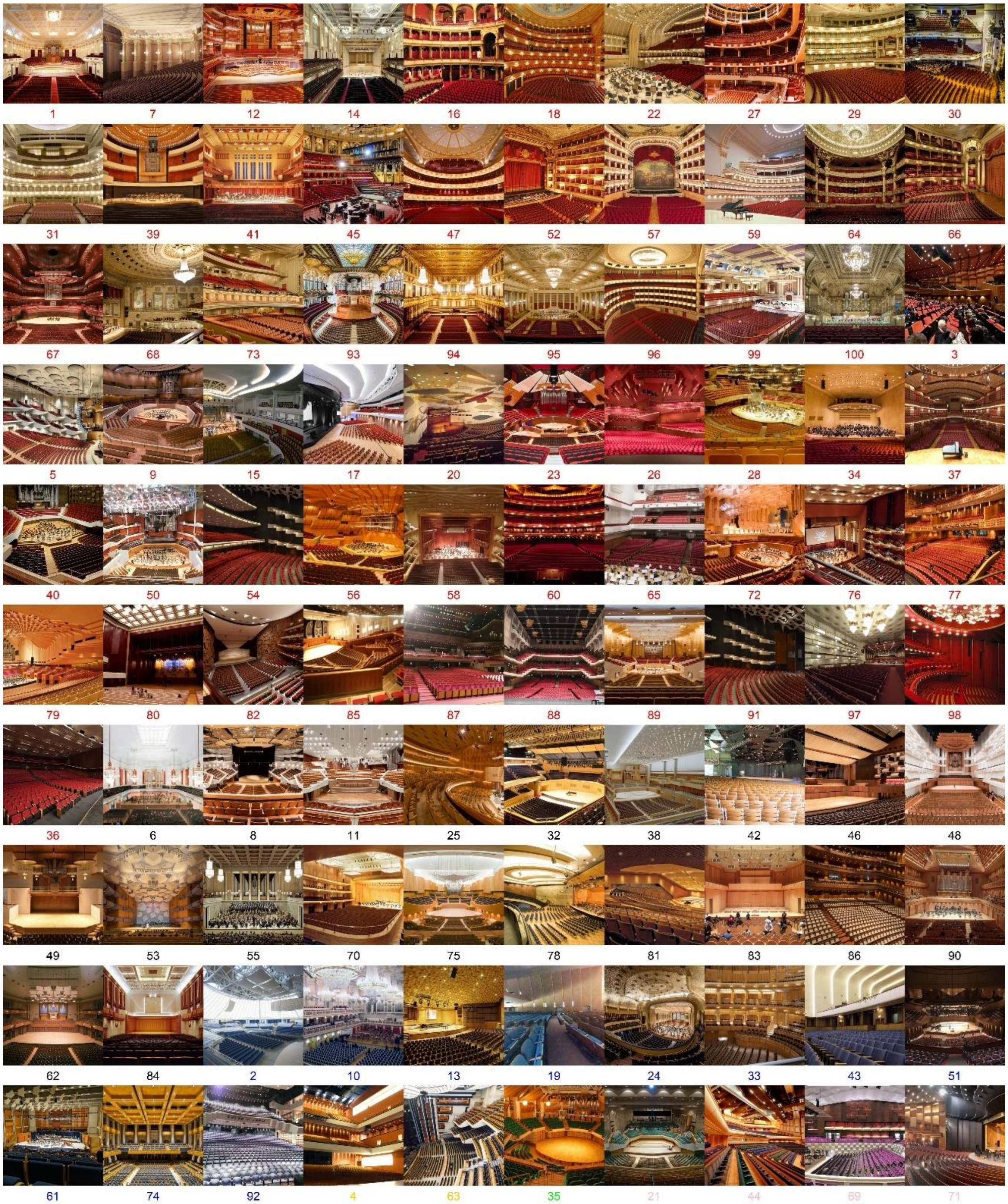


Figure 3-13 Auditorium photos used for colour analysis (hall names and image sources listed in Appendix D). Colour of photo number represent the categorized colour group in Table 3-6 (black for Neutral, pink for Other Colours).

The second method involves visually categorizing seat colour, on the basis that seats usually take up a large visual part of the auditorium, and often have high saturation, and so are usually unambiguously categorized.

The third method involves using automatic analysis with RStudio, to pick out the pixels of each photograph that have saturation and value larger than or equal to the third quartile, then among those selected pixels, pick out the hue of highest density for each photograph. The photographs chosen for the analysis contain no or very few people, with large visible areas of the main surfaces (seats, walls, ceiling). Colour temperature bias resulting from photography or lighting conditions was diminished by white-balance adjustment. The availability and quality of photographs vary between auditoria, but this method is purely objective and therefore not affected by subjective bias.

The 100 halls listed by Beranek do not include major auditoria built after 2012, the year in which the book was published. Each of the three methods has its advantages and disadvantages. However, the similar tendencies in the results of different methods and large differences between the colours are demonstrative enough: Figure 3-14 shows the visual preference results of the present experiment (mean and 95% confidence interval), the number of halls out of 100 that use each colour for main colour or seat colour, and the density plot of the main hues of the photographs.

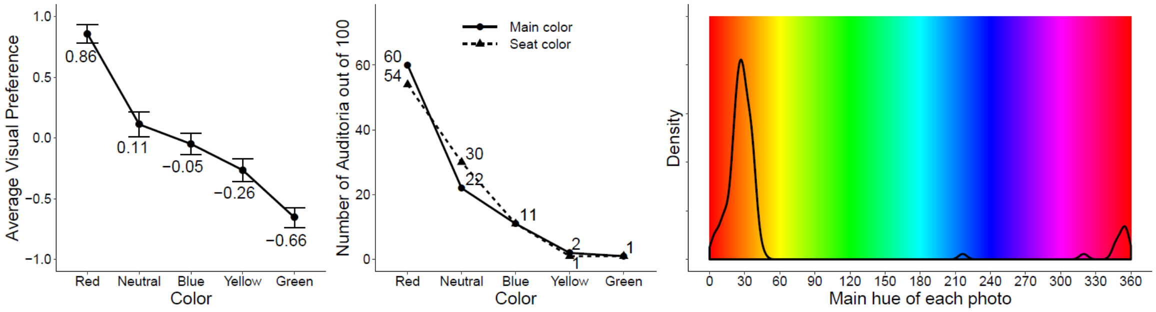


Figure 3-14 Left: visual preference for each colour (mean and 95% confidence interval). Middle: number of auditoria categorized as each colour. Right: density plot of the main highly saturated hue from 100 representative auditorium photographs.

It can be seen that, both the number of auditoria using the corresponding colour for main colour, and the number using it for seat colour, have the same trend as visual preference. From the density plot of the main hue of each photograph, it can be seen that among the photographs with colours of a relatively high saturation or value, most of the photographs have a main hue around 0° to 45° (peak: 27°), with the colour red or orange. Only one photograph has the main hue of blue (216°), and a few fall between 300° to 360°, with the colour between red and magenta.

3.3.5.4 Visual preference and colour arousal

According to the colour arousal theory, the arousal level of the five colours used in the experiment rank from high to low approximately in the order of red, yellow, green, blue, neutral. The colours with highest preference, red and neutral, relate to the highest and lowest arousal levels, and all of the 20 people that “like” neutral also “like” red, suggesting that the preference for red and neutral is inclusive in individuals. Because the experiment was done in a relatively short period of time (30-60 minutes per participant), and the colour stimulus order was randomized, the results do not relate to the reversal theory. Therefore, the differences in visual preference are unlikely to be the result of different participant arousal levels.

3.4 Conclusion

This chapter used virtual reality and headphone playback for subjective testing, and investigated the effect of concert hall colours on perceived loudness, reverberance, auditory preference, and visual preference. Results show that loudness and reverberance in the virtual concert hall are both positively affected by gain and RT, but are not appreciably affected by the colour of the concert hall. This indicates that the findings of some previous studies relating the colour of vehicles to loudness may not translate to the auditorium context. The results of reverberance are much more scattered than loudness. The loudness results can fit reasonably well with the loudness model proposed by (Glasberg & Moore, 2002), but EDT_N proposed by (Lee et al., 2012) does not sufficiently account for the effect of gain on the reverberance results.

Auditory preference is positively affected by gain and visual preference, but is only marginally affected by RT for the range of stimuli tested. The positive correlation between gain and auditory preference agrees with previous studies. Visual preference is affected by colour and auditory preference. Among the five colours tested, the visual preference ranks from high to low in the order of red, neutral, blue, yellow, and green. The preference for each colour is related to the commonness of the colour used in existing halls. Positive influence is found in both directions between auditory preference and visual preference. In other words, preferable sound and preferable view enhance each other.

Chapter 4 The effect of distance, lateral angle, vertical angle, and audio gain on concert preference

This chapter examines the effect of visual location and audio gain on the overall audiovisual preference and constructs a prediction model through the second experiment.

In a concert auditorium, conditions at different seats vary greatly, and are mostly affected by the view of the stage and the received sound of the performance, the former of which much less studied. With a focus on visual seat location, this chapter systematically investigates the effects of three visual factors: distance, lateral angle, and vertical angle, on the subjective seat preference of a symphony music performance, with one additional reference auditory factor: loudness (audio gain). Experimental investigation used virtual reality presentations of a 3D static orchestra on a stage with simplified binaural orchestral audio, so that each factor could be changed independently. Results show that all factors significantly affect preference: smaller distances, smaller lateral angles, vertical angles around 18°, and greater audio gains are preferred. The effect of audio gain is relatively small compared to the visual factors within the range and method used for this experiment, thus requires further investigation. A prediction model based on the results is shown to be largely compatible with previous general observations and case-studies of particular auditoria.

4.1 Introduction

A concert hall is usually judged by its acoustics and architectural appearance. However, the variation in auditory and visual conditions at different seat locations within one concert hall may be even larger than the variation between equivalent seats of different concert halls. Each audience member only experiences a given concert at a single seat location. Therefore, it should be an important goal for auditorium design to have as many seats with good visual and auditory conditions as possible, avoiding seat locations with unacceptably poor visual and auditory conditions. This introduces the need for evidence-based prediction methods for the quality of seat locations.

Compared to auditory preference, visual preference in auditoria has been much less studied, but is nevertheless important for the overall enjoyment of a concert. This study aims to fill this gap, by experimentally investigating the relationship between subjective preference and three of the most apparent stage-view factors that differ between different seats in an auditorium: distance to stage, vertical angle from stage level, and horizontal angle from the mid-plane of symmetry. While the main focus of this study is on the visual factors, one auditory factor that was already known to influence preference, listening level, is included for reference, to enable quantitative connection between visual and auditory effects. The use of virtual reality made it possible for each factor to change independently and orthogonally without the limitation of real concert hall seating plans, and thus the individual effect of each single factor could be studied.

4.1.1 Preference at different seats in an auditorium

While preference at different seats in an auditorium is relatively less studied compared with between auditoria, there have been some studies that investigated factors affecting seat preference within the same auditoria. The studies are summarized and reviewed in Section 1.4.

Most studies found a positive relationship between auditory preference and sound pressure level, so long as it did not exceed the optimal listening level of 79 dB(A) proposed by Ando (1983). Kuusinen & Lokki (2015) found a negative correlation between auditory preference and auditory perceived distance, which is usually also negatively correlated with sound level. Both Jeon et al. (2008) and Sato et al. (2012, 2013) found that for various seats in one auditorium, among all the common acoustic parameters, sound pressure level was the main factor affecting auditory preference, which may mask the effect of other non-orthogonal factors. Most studies agree that visual preference is negatively affected by the lateral angle from the centre plane of the auditorium (Burris-Meyer & Cole, 1964; Chen & Wu, 2013; Jeon et al., 2008; Kawase, 2013; Vaupel, 1998; Veneklasen, 1975), and many agree that there exists an optimal distance (Chen & Wu, 2013; Kawase, 2013; Vaupel, 1998; Veneklasen, 1975). However, the effect of vertical angle from the stage plane is more controversial (Jeon et al., 2008; Sato et al., 2012; Veneklasen, 1975), which may be due to the fact that vertical angle often varies with distance in real auditoria. Studies agree that the overall preference is affected by both auditory and visual preferences (Jeon et al., 2008; Sato et al., 2012, 2013).

Generally speaking, because of the traditional emphasis on acoustics in auditoria, seat preference studies in auditoria have developed much further for auditory preference than visual preference. Limited studies have used visual stimuli in the experiment, but their visual stimuli and analysis of visual preference was much more simplified than the auditory part. Furthermore, most of the existing seat preference studies were based on real auditoria, where seat locations were limited to the layout of particular halls, and the different predictors were not mutually independent. This may limit the generalizability of those studies' prediction models.

4.1.2 Preference in different auditoria

Compared to preference at different seats in the one auditorium, preference between different auditoria has been studied much more extensively, especially in terms of acoustics. Some established results are summarized in Sections 1.2 and 1.3.

Many factors have been defined and found to affect auditory preference, or perceived acoustic quality, between auditoria, such as sound strength or loudness of the auditorium, reverberation and clarity, spatial parameters, spectral attributes, and inter-subjective differences. Generally, loudness is found to positively affect auditory preference, so long as it does not exceed the optimal listening level of around 79 dB(A) (proposed by Ando, 2010, 2014), while the effect of other parameters are more complex and many studies and standards have proposed optimal values to each parameter.

Visual preference, on the other hand, has not been studied as thoroughly as auditory preference. It is commonly believed that visual obstruction affects visual preference negatively, and the visual obstruction between audience members is largely dependent on the rake of the seats, which is determined by the *c*-value (line-of-sight clearance height) (John et al., 2007; Russel, 1838; Sheard, 2013). Auditorium interior colour was found to influence visual preference (Chapter 3), and the effect was related to the commonness of the colour in existing auditoria.

4.1.3 Other factors affecting preference in auditoria

Auditory and visual preferences in auditoria are not mutually independent: humans perceive the world through multiple senses, and integrate all the sensory inputs to get the most accurate and correct information of their environment (summarized in Section 1.5). Auditory preference and visual preference of architecture have been found to have a mutual positive effect (Chapter 3; Galiana et al., 2016), and as described in Section 4.1.1, they both contribute to the overall preference. Studies in auditoria have found that various types of auditory perception, especially intimacy, listener envelopment, apparent source width, and distance perception, are all affected by visual input (Cabrera et al., 2004; Hyde, 2002, 2004; Maempel & Jentsch, 2013; Postma & Katz, 2017; Tokunaga et al., 2013; Valente & Braasch, 2010; Zahorik, 2001), and auditory perception in turn affects auditory preference. Visual inputs including colour and lighting also directly or indirectly affect auditory preference (Ando, 1998; Chapter 3).

All the above summarized preference studies were based on the auditory, visual, or audio-visual conditions in auditoria. In practical situations, there are other factors not related to vision and hearing that might influence people's seat preference or seat selection, including but not limited to economical, ergonomic, and cultural factors, such as the comfort of the seat and the environment (Giannis et al., 2016; Kavgic et al., 2008), ease of access to the seat (Vaupel, 1998), social status of the audience members (Williamson, 2009), or professional background of the audience members (Galiana, et al., 2016). As these factors cannot be captured in laboratory experiments, they are usually considered part of random errors in the experiments.

4.1.4 Preference in other viewing spaces

Seat preference has also been studied in other viewing spaces, especially spaces that emphasize view much more than sound, such as movie cinemas or sports stadia. While the context and conditions are very different, some results are similar.

In cinemas, people like sitting around the centre (close to centreline, middle row), because seats towards the side would experience shear distortion of the flat screen, seats too close to the screen would involve excessive head movement and/or head raising and neck strain, and seats further back will result in less clear images (Italie, 2015; New York Times, 1941; Yan et al., 2019). However, the shear distortion and neck straining problems are specific to cinemas due to the use of a vertical screen higher than eye level, and does not apply to auditoria where audiences are usually looking down or slightly up at a horizontally spread 3D target. Compared to auditoria, movie cinemas are usually much smaller with fewer seats and steeper rake, as unobstructed view and distance are more critical.

Sport stadia are closer to music auditoria than cinemas in terms of the visual target, but they are usually much larger with steeper seating rakes. The two most important factors for stadium seating are the maximum distance (which is usually 100 m to 200 m depending on the sport) and seating rake, because the main goal is for all spectators to be able to see the action (John et al., 2007; Sheard, 2013). However, because most sport games do not have a specific orientation like music or drama performances, lateral or vertical angle is less of a concern.

While there are some similarities between music auditoria and these other viewing spaces, it is important to understand the differences, and thus understand that the experiment results or recommendations may not transfer between types of space.

4.2 Materials and methods

4.2.1 Materials

The experiment used head-mounted virtual reality display for visual stimuli, with headphones for auditory stimuli.

A model of a 98-piece symphony orchestra with a stage space 15 m wide × 11 m deep × 6 m high was built in Rhinoceros (Robert McNeel & Associates, 2019) 3D modelling software, then exported to and rendered in Unity (Unity Technologies, 2019) virtual reality software (Figure 4-1). The stage size with an area of 165 m^2 was chosen to represent a classical symphony concert hall stage, being close to the stage size of Wiener Musikverein (163 m^2), Amsterdam Royal Concertgebouw (160 m^2), and Boston Symphony Hall (152 m^2) (Beranek, 2012). In order to exclude the influence of other visual factors and the limitation of a seating plan, no auditorium model was used. Apart from the stage, the rest of the camera view was rendered black.

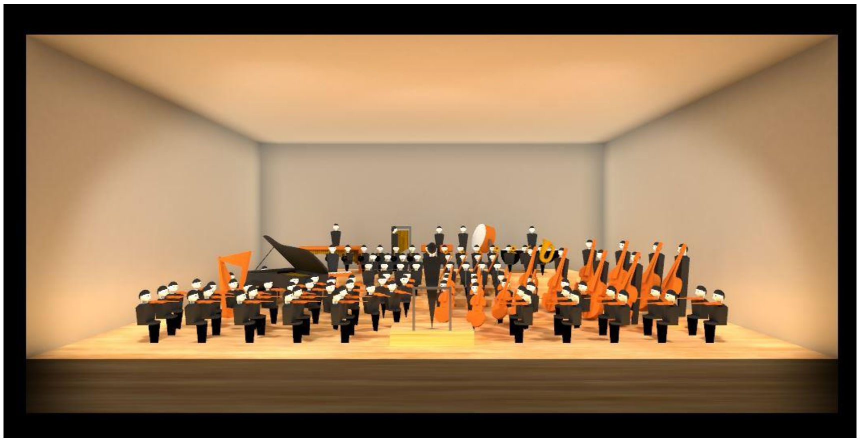


Figure 4-1 Model of orchestra with stage in 2D

Thirty-six locations were chosen for the experiment (Table 4-1). The point of focus was set to be the location of the conductor, at the height of seated eye level above stage. In order to examine the individual effect of each factor, an orthogonal 27-point grid of 3 levels of distance (10 m, 20 m, and 30 m) × 3 levels of lateral angle from the centre symmetric plane (0°, 30°, and 60°) × 3 levels of vertical angle from the horizontal plane (0°, 15°, and 30°) were chosen (points 1-27 in Table 4-1). On top of the main grid, 9 additional points were added to increase precision and range (points 28-36 in Table 4-1).

Table 4-1 Location settings for the experiment

No.	Distance (m)	Lateral angle (°)	Vertical angle (°)
1	10	0	0
2	10	0	15
3	10	0	30
4	10	30	0
5	10	30	15
6	10	30	30
7	10	60	0
8	10	60	15
9	10	60	30
10	20	0	0
11	20	0	15
12	20	0	30
13	20	30	0
14	20	30	15
15	20	30	30
16	20	60	0
17	20	60	15
18	20	60	30
19	30	0	0
20	30	0	15
21	30	0	30
22	30	30	0
23	30	30	15
24	30	30	30
25	30	60	0
26	30	60	15
27	30	60	30
28	5	0	0
29	15	0	0
30	25	0	0
31	20	-15	0
32	20	15	0
33	20	45	0
34	20	0	-7.5
35	20	0	7.5
36	20	0	22.5

Example views at 12 of the 36 locations are given in Figure 4-2 (with the location numbers from Table 4-1). These are only the 2D screenshots with a 60° angle-of-view, but the participants saw the scenes in 3D in virtual reality.

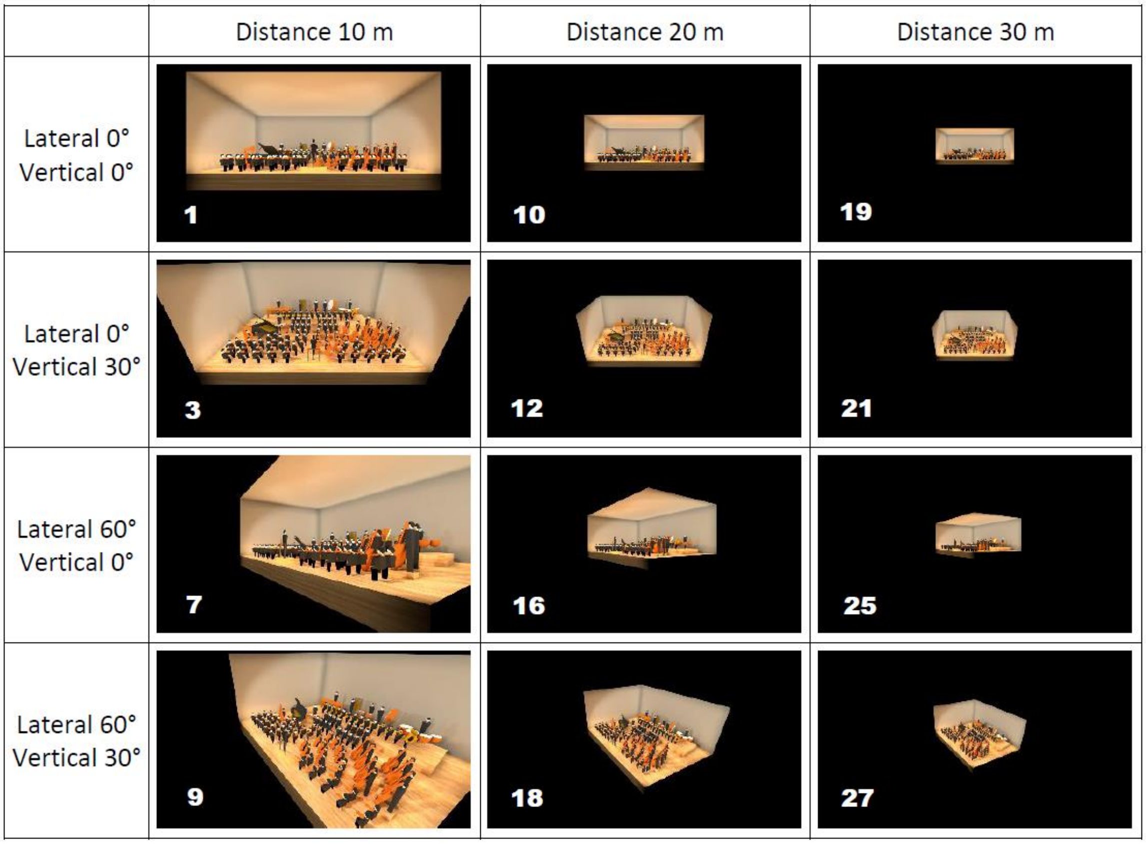


Figure 4-2 Example views at 12 locations in 2D

With lateral angle, even though lateral bias towards the right side has been observed for many human behaviours, including seat selection in cinemas (Karev, 2000; Harms et al., 2014), no obvious lateral bias was found in the seat selection studies mentioned above apart from piano solo performance (Kawase, 2013; Vaupel, 1998), and therefore it can be assumed that the effect of lateral bias is relatively small compared to the effect of differences in auditory and visual stimuli, and the left and right side of centre line can be considered symmetric. Hence, to limit the total experiment time of each participant, only locations on the right side of the centre line facing stage were used, apart location 31 which is the symmetric location of location 32 (Table 4-1).

The music used for the experiment are recordings from the 2018 Weiner Philharmoniker New Year's Concert conducted by Muti (Vienna Philharmonic & Muti, R., 2018), with 4 pieces excluded because of their popularity (No. 6, 18, 19 and 20). Viennese classical music was chosen because of the relatively constant style, dynamics, and tempo. The 2-channel stereophonic recordings were mixed down to a single channel, preserving the original reverberation time.

The music was played back in Unity, with binaural panning using Steam Audio (Valve Corporation, 2017). The audio played through the headphones included 70% of fixed stereo playback (exactly same audio in both ears independent of location and head rotation), and 30% of 3D source localization to match the visual position of the orchestra relative to the listener. The centre of the source was set to the relative direction of the conductor to the listener (the same location that was used to calculate the visual factors), with a spread angle of 10°. The audio was designed to be as simple and non-varying as possible to avoid introducing any new variables (e.g., direct-to-reverberant ratio, early decay time, or parameters associated with lateral reflections), but not too unrealistic such that the participants might be distracted (e.g., if the audio was completely fixed stereo playback). Because of the emphasis of the present study on visual factors, and the exclusion of any auditorium model, there was no attempt to simulate the acoustics of a particular auditorium (beyond that already in the recordings), nor to simulate the acoustic effect of particular positions in an auditorium.

4.2.2 Procedure

In consideration of COVID-19 social distancing regulations, the volunteer recruitment process was done online. Thirty-three volunteers aged over 18 with access to VR equipment and headphones participated in the experiment.

The experiment stimuli were distributed as an executable file and sent to the participants through email with necessary instructions. The participants ran the program in their own time with VR headsets and headphones. Each participant entered their given Participant ID at the start, and the experiment loaded accordingly. They were instructed to adjust the computer volume to their comfort level at the beginning, and not to alter the volume settings once the experiment began. For each location, they returned a score in the range 0-100 using VR controllers based on how much they liked the sound and the view. They started at a randomly assigned location, then they were able to use VR controllers to choose and jump to any of the 36 available locations. They could also view the scores they had already given to other locations, and return to a scored location if they wish to use it for reference or change previously assigned scores.

Participants could spend as much time as they wished, and it was also possible for them to save their progress and complete the experiment in separate time slots. They could make any changes before submitting the results. When they were satisfied with all of their scores, they exported the results into a file and sent it back to the researchers through email. The files record their Participant ID, the scores given for each location, and the total time spent at each location. Participants also filled in an information questionnaire with their age, gender, the brand and model of the VR equipment and headphones they used, and any feedback if they wished.

There were two parts in the experiment, with the same locations and visual stimuli. The difference was that the audio was kept constant in the first part, while the second part involved different gains applied to the audio. In both parts, the 16 short music pieces were played consecutively in randomly generated orders, and the music continued between location changes. In the first part, the only change in audio between different locations was the 3D orientation corresponding to the relative visual orientation of the stage to the listener. In the second part, 4 levels of audio gain (0 dB (same as in the first part), -3 dB, -6 dB, and -9 dB) were randomly applied to the 36 locations (9 locations for each level).

The gain adjustment in the experiment was designed as an additional reference for the visual factors, to construct a quantitative connection between the effect of visual factors and auditory factors on subjective preference, because the effects of various acoustic parameters, including sound pressure level, have already been studied extensively in previous auditorium acoustics studies.

4.2.3 Participants

Thirty-three participants aged 19 to 48 took part in the experiment, with an average age of 32. The participants comprised 25 males and 8 females. Of the VR headsets the participants used, 26 were HTC (including Vive and Vive Pro) and 7 were Oculus (including Rift S, Rift CV1, and Quest). Of the headphones used, 10 were built-in with the VR headsets (including both HTC and Oculus), and 23 were standalone headphones (including Sennheiser, Bose, Beats, and AKG). All of the headphones were over-ear types.

As listed in **Error! Reference source not found.**, the sample sizes of similar in-lab experiments range from 8 to 60, with an average of 25. Therefore, a sample size of 32 for each part of the experiment was used (explained in Section 4.2.4), and was justified by the power analysis for the regression model in Section 4.3.3.

The average time spent on parts 1 and 2 was 23 minutes (SD = 10.5) and 14 minutes (SD = 4.8) respectively. Even though the number of locations was the same for the two parts, usually participants needed more time at the beginning of the first part for familiarization. The recorded time only includes the actual time the participants spent on the scenes, and does not include the time they spent reading the instructions, communicating with the researchers, or resting halfway through the experiment.

4.2.4 Statistical considerations and analysis

The three visual factors included in the experiment were designed to be independent and orthogonal, with the same degrees of freedom. For the second part of the experiment, while the four levels of audio gain were randomly applied to the locations, in order to prevent the influence of the arrangements on the results, every four participants were counterbalanced, so that each location was paired with all of the four gain levels in each group of four participants. One participant completed the first part only, another participant completed the second part only, and the rest of the participants completed both parts. Therefore, there are 32 results for each part, forming 8 balanced groups in the second part. As a result, audio gain could also be considered orthogonal to all of the visual factors.

The experiment had a hierarchical (two parts) and repeated-measures (each participant providing multiple scores for locations) design, which are sources of random variability. This was explicitly modelled as crossed random effects in mixed-effects models, with an independently varying intercept for each participant for each part of the experiment. Further, robust mixed-effects models were used to reduce the influence of any outliers (Koller, 2016). Modelling independently varying slopes (i.e., random slopes) for each participant was also attempted. However, since the residuals of such models did not meet parametric assumptions, they are not reported here, i.e., only random intercept models are reported in the following.

The modelling included starting with an intercept-only linear model without random effects, and developing mixed effects models in a stepwise manner, with the model at each step increasing in complexity in terms of the fixed effects (independent variables) and random effects. The statistical significance of each fixed and random effect was determined using goodness-of-fit comparisons between models without and with the effect. For the goodness-of-fit comparisons, the chi-square log-likelihood test and the Akaike information criteria (AIC) were used, where the ΔAIC value with and without an effect of ≤2 was used as the criterion to determine whether including the effect improves the overall model fit (Burnham & Anderson, 2004). Instead of explicit modelling steps, only the final models are presented and discussed. For the fixed effects in these models, bootstrapped confidence intervals were calculated, which are robust against distributional assumptions of parametric statistics (Efron & Tibshirani, 1998). The effect size of fixed effects is presented as the f^2 value (Aiken et al., 1991), which compares the conditional R^2_{mm} value (suitable for mixed-effects models) (Nakagawa et al., 2017) between models without and with an effect, with the effect size considered small, medium, and large at f^2 values of 0.02, 0.15, and 0.35, respectively (Cohen, 1992). For the overall model performance, the conditional R^2_{mm} value is used.

Besides the mixed-effects modelling as described above that uses subjective responses in their original scale (0-100), linear models with *z*-scored data were also created. This was done to allow comparisons with some previous studies that provided models with *z*-scored data (or using similar scaling) and insufficient information to revert back to the original scales. For the *z*-scored model in the current study, only the model coefficients for the final model are provided, which had the same fixed effects as the final mixed effects model but did not have any random effects (not required after *z*-scoring). Note that the focus of this paper is on using the mixed-effects models for prediction (since it handles variances more explicitly), except for using linear models with *z*-scored data for comparisons, where indicated.

Statistical analysis was performed with the software RStudio (RStudio Inc.) with packages “plyr” (Wickham, 2020), “tidyverse” (Wickham, 2019), “lme4” (Bates et al., 2015), “robustlmm” (Koller, 2016), “effects” (Fox & Weisberg), and “sjstats” (Lüdecke, 2020).

4.3 Results

4.3.1 Test-retest reliability

Since each participant (except for two; section 4.2.4) scored certain locations in both parts of the experiment (i.e., those with audio gain of 0 dB; section 4.2.2), it is possible to assess the test-retest reliability of the experimental task based on the interclass correlation coefficient (ICC; ranging from 0–1) for these repeated locations. A high ICC value represents small measurement errors in comparison to the true underlying variability between repeated measurements by participants. In other words, with a high ICC value, the inherent, error-free variability in the repeated measurements can be relatively well distinguished. For low ICC values, the variability between repeated measurements could be due to the relatively large underlying measurement errors compared to the actual variability between observed values across repeated measurements.

To determine the ICC, a mixed-effects model was fitted to compare the participants’ scores (dependent variable) across the two parts (fixed effect). The random effects due to the same participant scoring in both parts for a selection of locations were explicitly modelled as independently varying (random) intercepts. The ICC of the resulting model was 0.49, which can be considered ‘fair to good/moderate’ based on common criteria across research disciplines, mostly involving clinical trials (Fleiss, 2011; Koo & Li, 2016). The moderate test-retest reliability is considered adequate due to the various sources of variability in the current design (e.g., headset types, etc.).

4.3.2 Relationships between objective factors and preference

In order to show the effect of each individual factor on preference, the *z*-score mean and 95% confidence interval for each level of each factor are plotted in Figure 4-3 (black points and lines). For the three visual factors (Figure 4-3(A-C)), the round dots represent the levels in the 27-point main grid, for which all the combinations are experienced by all participants (each point = 9 locations × 32 participants); while the crosses represent the levels of the additional 9 points, for which only one location is experienced by each participant (each point = 1 location × 32 participants). For audio gain, the dot represents 0 dB gain level, which was used for all the points in the first part of the experiment and 1/4 of points in the second part of the experiment (36 locations × 32 participants + 9 locations × 4 participants × 8 groups); while the crosses represent the additional levels in the second part of the experiment (each point = 9 locations × 4 participants × 8 groups). The separate results of each part and both parts together are presented in different colours, and it is evident that the results for the visual factors are very similar in the two parts.

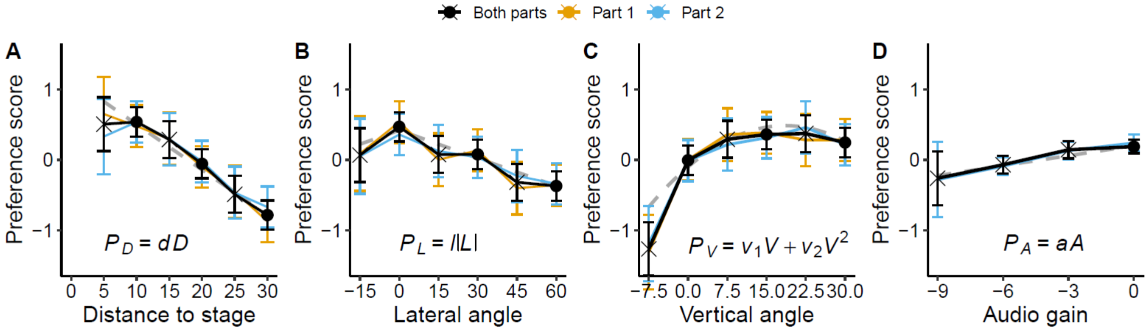


Figure 4-3 Subjective preference scores (z-score mean and 95% confidence interval) and prediction equations plotted against each level of each factor (A: preference score vs. distance to stage; B: preference score vs. lateral angle; C: preference score vs. vertical angle; D: preference score vs. audio gain)

It can be seen that the effects of distance on preference follow a linear trend within the tested range, with the exception of the smallest distance (5 m) which has approximately the same mean as 10 m. The effects of lateral angle and vertical angle follow quadratic trends, and the effect of audio gain follow a linear trend.

For lateral angle, it can be seen that -15° and 15° have very similar scores, verifying the assumption that the effect of lateral angle is approximately symmetric, and thus the absolute values of the lateral angle can be used. When using the absolute values, the effect of lateral angle follows a linear trend. For vertical angle, it can be seen that the maximum is reached approximately between 15° and 22.5°.

4.3.3 Prediction model

Table 4-2 summarizes the coefficients for the mixed-effects prediction model and standardized *z*-score prediction model for measured subjective seat preference.

Table 4-2 Mixed-effects model coefficients to predict subjective preference in relation to the independent variables (fixed effects) and random effects (see section 4.2.4). For the fixed effects, intercept and slope estimates (effect size as described in section 4.2.4) are provided along with the bootstrapped 95% confidence intervals. All fixed effects are significant at $p<10^{-2}$. For the random effects, the standard deviation along with the bootstrapped 95% confidence intervals are provided. The final column provides model estimate for a linear model with z-scored data (see section 4.2.4) which is used for comparisons with some previous studies.

Fixed effects	**Estimate [95% CI]**	**Effect size (f^2)**	**Estimate (*z*-scored data) [95% CI]**
Intercept (c)	90.17 [85.74,94.61]		1.4232 [1.3269,1.5194]
Distance (d)	-1.30 [-1.39,-1.21]	0.31	-0.0626 [-0.0668,-0.0585]
|*Lateral*| (l)	-0.28 [-0.31,-0.25]	0.12	-0.0127 [-0.0140,-0.0114]
Vertical (v_1)	1.20 [1.02,1.38]	0.05	0.0613 [0.0530,0.0696]
(*Vertical*^{2}) (v_2)	-0.03 [-0.04,-0.03]	0.05	-0.0017 [-0.0020,-0.0014]
Audio (a)	0.96 [0.69,1.23]	0.03	0.0512 [0.0417,0.0608]
Random effects	**Parameter**	**Std. Dev.**	
ε_1	Intercept	9.64 [7.08,11.88]	
ε_2	Intercept	1.39 [0.00,3.26]	
ε_r		15.97 [15.72,16.70]	

$$P = (c + \varepsilon_1 + \varepsilon_2) + d(Distance) + l(|Lateral|) + v_1(Vertical) + v_2(Vertical^2) + a(Audio) + \varepsilon_r$$

Equation 4-1

The equation above shows the mixed-effects regression model (R^2_{mm}= 0.51; see model coefficients in Table 4-2) to predict the combined subjective preference scores (*P*) for a seat location as a function of the fixed effects, while incorporating the crossed random effects of the intercorrelation between each participant's scores (ε_1) across the two parts of the experiment (ε_2) as independently varying intercepts, along with the error residual (ε_r). In the equation, *d* is effect of *Distance* (from the point of focus in meters); *l* is effect of *Lateral angle* (from the center symmetric plane in degrees); v_1 and v_2 are the linear and quadratic effects of the *Vertical angle* (from the horizontal plane in degrees); *a* is the effect of *Audio* (relative audio gain in decibels). This equation represents the final model that was built in a stepwise manner in terms of significance of fixed effects and random effects as described in section 4.2.4, further informed by the trend analysis in Section 4.3.2 for the fixed effects. The model includes linear coefficients (i.e., slopes) for the fixed effect of distance, audio gain, and the absolute value of lateral angle, and a quadratic coefficient for vertical angle. Even though the fixed effects of distance and audio gain also showed slight quadratic trends in Figure 4-3, the quadratic coefficients did not attain significance. Assumptions of the test were checked using diagnostic plots of the residuals. Of the tested ranges, distance has a large effect (largest overall), with the other independent variables having small effects on the overall prediction (Table 4-2). Interactions between the independent variables were not significant.

From the prediction equation, it can be seen that *Distance* and *Lateral angle* negatively affect preference, while *Audio* has a positive effect. The effect of a 1 m reduction in distance, is similar to a 4.6° reduction in lateral angle, or a 1.3 dB increase in audio gain (within the tested ranges). There is a maximum at around *Vertical angle* = 20°.

4.3.4 Visualization of results

In order to view the effect of different visual factors more intuitively, the effect of the audio gain is subtracted from the results and presented at each location in Figure 4-4(A). The average scores are presented through the rendering colour of spheres (colour scale: red-yellow-green for 0-50-100) and number notations. Figure 4-4(B) shows the prediction results using the equations calculated in Section 4.3.3. From the comparison of the two figures, it can be seen that the prediction equation captured the observed results well.

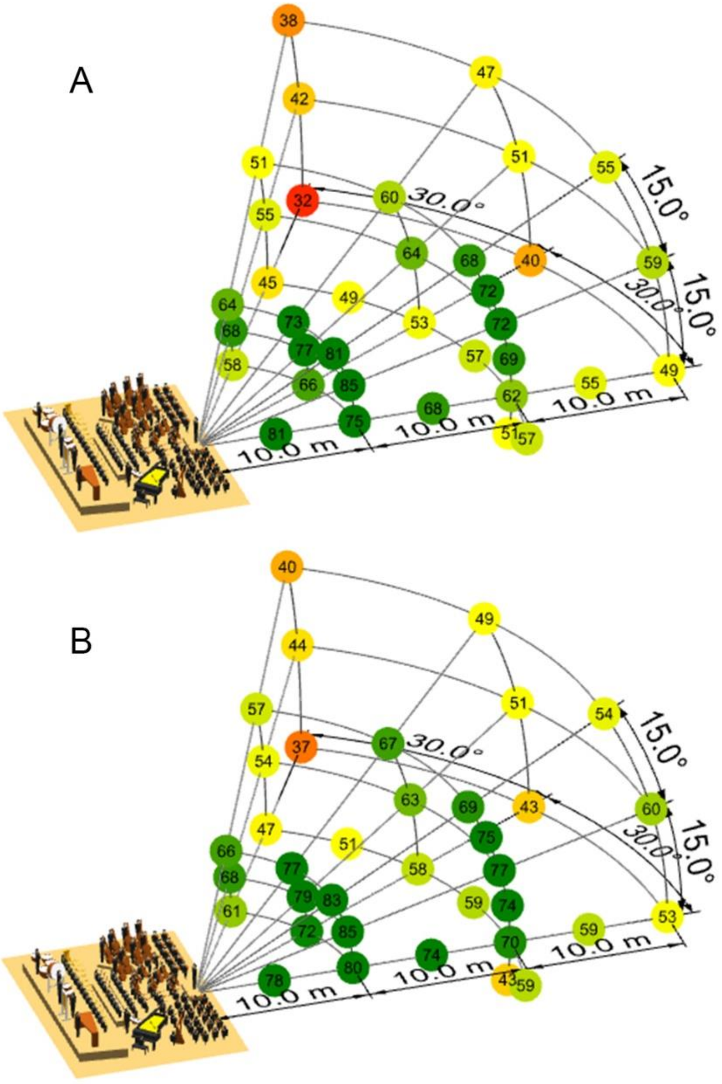


Figure 4-4 Visualization of the preference score at each tested location (without the effect of audio gain) (A: average of observed subjective evaluation; B: predicted value)

4.4 Discussion

4.4.1 Comparison with online survey

To validate the model with a larger sample size, a relevant question was included in an online survey about people's preferences in concert attending (Chapter 7). Pictures representing the stage view of 8 locations from the current experiment were evaluated by 142 respondents using the same 0 to 100 scale based on their preference. The selected locations are all combinations 2 distances (20 m and 30 m), 2 lateral angles (0° and 60°), and 2 vertical angles (0° and 30°). The pictures shown to the respondents are the same as in Figure 4-2 (locations 10, 12, 16, 18, 19, 21, 25, 27). No audio was presented in the online survey. Therefore, for comparison, only the visual part of the current experiment results and model was used, with the effect of audio removed.

Results showed high correlation with the mean results of the current experiment (Figure 4-5(A)), and even higher with the prediction model (Figure 4-5(B)). The compatibility of results from different testing methods and sample sizes supports the reliability of the experiment and prediction model for visual assessment.

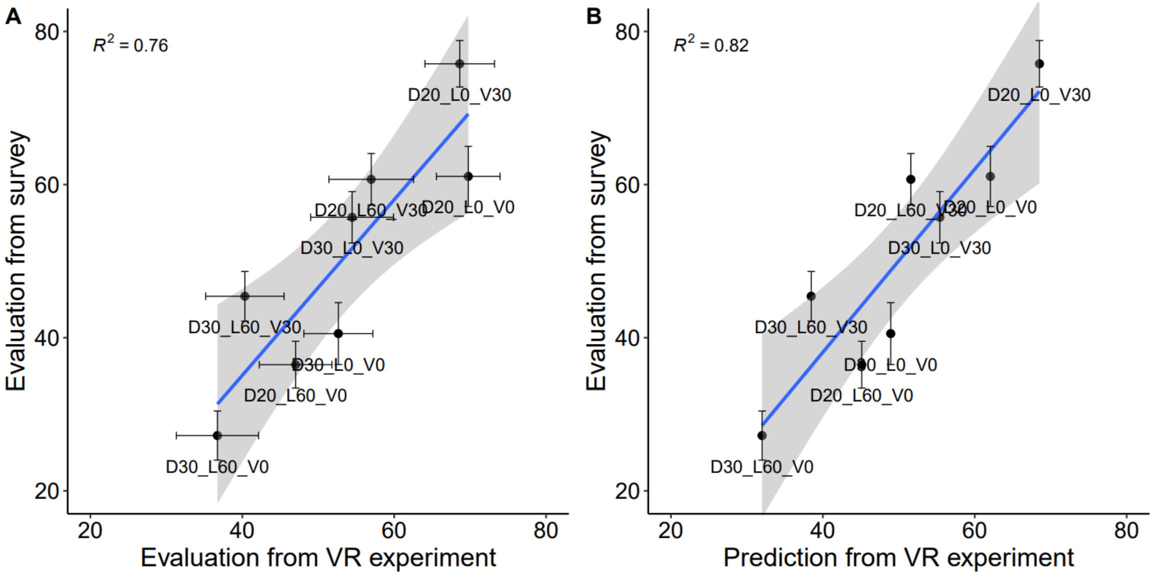


Figure 4-5 Mean and 95% confidence interval of preference scores from online survey plotted against experiment results and prediction (A: survey results vs experiment visual results; B: survey results vs predicted visual results)

4.4.2 Comparison with pre-existing case studies

In order to test its validity and robustness, the prediction equation derived in this study is compared with the results from two case studies (Jeon et al., 2008; Sato et al., 2012) that tested the preference scores for a set of seat locations in particular auditoria. Note that for both these comparisons, it was not possible to use the mixed-effects model predictions due to inconsistent scales in the previous studies (Jeon et al., 2008; Sato et al., 2012), and the current. Hence model coefficients from *z*-scored subjective scores (section 4.2.4 and Figure 4-3) for the current study are used to compare with these previous studies with similarly scaled subjective scores. Using *z*-scored data is not ideal since data in its original scale (and resulting mixed-effects model) allows more explicit handling of variability (section 4.2.4). Hence, the comparisons in this section should be considered mostly for illustrative purposes due to the inherent limitations of the scaling issues.

Further, compared to the current experiment with factorial design, case studies cannot separate the effect of individual factors due to the covariance of variables in realistic conditions, but they can provide more realistic stimuli (e.g., using visual or auditory stimuli recorded in real auditoria). These two methods have complementary strengths and limitations, and validation from case studies can indicate the applicability of the prediction model derived from the current factorial experiment to more realistic contexts. Predicted preference values are calculated using the prediction equation of this study using the objective location information provided in the reference studies (distance, lateral angle, vertical angle, and SPL). The predicted values are compared with the subjective evaluated values from those studies.

4.4.2.1 Jeon et al. (2008)

The predicted preference values of the nine locations in an opera theatre tested in the study of Jeon et al. (2008) are calculated from the given information. Visual and auditory preference scores are calculated separately. Visual preference predictions include the effects of distance, lateral angle, vertical angle, and the auditory preference predictions include the effect of audio gain. Visual preference, auditory preference, and overall preference are compared individually in Figure 4-6(A-C). Judging from the images of visual stimuli provided in “Figure 2” of the paper (Jeon et al., 2008), location F, G, and I all have visual obstructions interfering with the view of the stage. Because visual obstruction was found to negatively affect visual preference (Jeon et al., 2008), but the current model does not include the effect of visual obstruction, those three locations were separated from the other locations in the visual preference analysis.

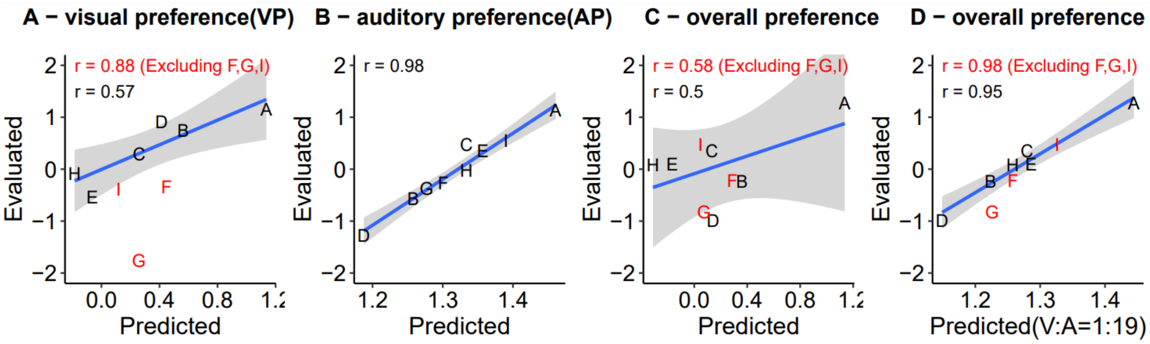


Figure 4-6 Preference prediction and comparison with experiment results of Jeon et al. 2008 (A: evaluated visual preference vs. predicted visual preference; B: evaluated auditory preference vs. predicted auditory preference; C: evaluated overall preference vs. predicted overall preference (visual preference + auditory preference); D: evaluated overall preference vs. predicted overall preference with changed weighting (5% visual preference + 95% auditory preference))

From Figure 4-6(A), it can be seen that predictions match the evaluated values of visual preference quite well when locations F, G, and I are excluded. As expected, the visual preference of these three locations are all relatively lower than the predicted values, and the extent of the obstruction also matches the size of the difference. On the other hand, Figure 4-6(B) suggests that the auditory preference predictions based on audio gain fit the evaluated value well for all locations, which also agrees with the findings of Jeon et al. (2008) that the auditory preference was mainly affected by sound level.

The overall preference predictions, however, only roughly fit the evaluated values in Figure 4-6(C). It can be seen that the locations with lower evaluated values than predicted (D, G, F, B) are the locations with the lowest auditory preferences. In other words, the current model underestimates the weight of auditory preference in overall preference for Jeon’s results. A weighting of 5% visual preference and 95% auditory preference applied to the calculation of overall preference prediction (rather than the original weighting of 50% and 50%) fits the evaluated overall preference much better (Figure 4-6(D)). The greater importance of visual preference in the current study compared to the reference study might be due to the use of different types of visual and auditory stimuli, different tested ranges for each factor, the limited audio changes (gain only) in the present study (versus more realistic auditory stimuli in the reference study), or the difference in participant sampling.

To conclude, the prediction equation given in this study can predict the visual and auditory preference in the reference study (Jeon et al., 2008) relatively well, disregarding the influence of visual obstruction. However, the overall preference in the reference study is more affected by auditory preference than predicted. Extensive analyses of variability in Jeon et al (2008) and this study using mixed-effects modelling is not possible due to differing scales and assumptions.

4.4.2.2 Sato et al. (2012)

The same method was used to predict the visual, auditory, and overall preference values for ten locations in an opera theatre studied by Sato et al. (2012) and compare with the evaluated results. Because the measurement method used in the reference study for distance, lateral angle, and vertical angle are quite different from the current study, the values are re-measured for each location based on plan and section of the auditorium (Table 4-3).

Table 4-3 Measured distance, lateral angle, and vertical angle for each location used in Sato et al. 2012

Location number	1	2	3	4	5	6	7	8	9	10
Distance (m)	7.1	10.9	14.1	8	14.4	10.9	17.2	15.8	19.6	17.5
Lateral angle (°)	0	0	0	25	13	45	17	45	16	27
Vertical angle (°)	-9	-5	-3	-7	-3	7	6	40	21	30

Judging from the visual stimuli provided in "Figure 3" of the paper (Sato et al., 2012), the displayed photographs have very wide angle of view, even though the screen for display was also very wide and curved (Figure 4 (top) in the paper), which may compensate for the photograph distortion to an extent, especially at the edges of the photos. The wide-angle photographs may have led to greater perceived distance (Kraft & Green, 1989), and the high aspect ratio may emphasize the lateral angle more than the vertical angle. To compensate for this effect, the measured distances were multiplied by 2 to calculate the predicted preference values. The calculated prediction results are compared with the evaluated in Figure 7.

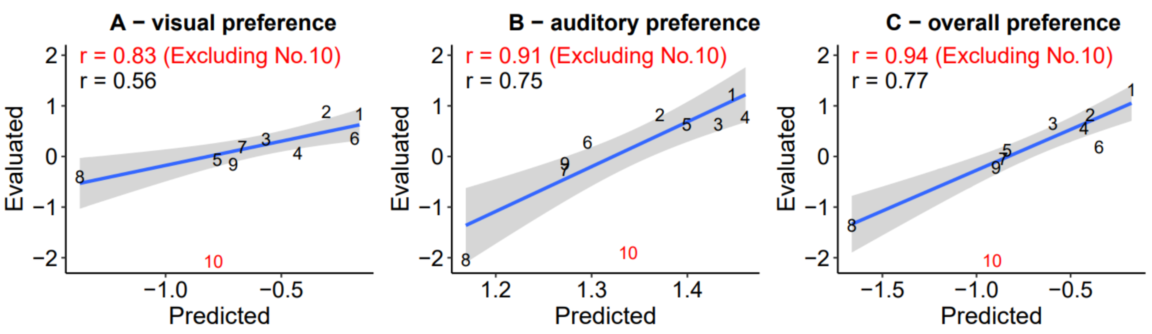


Figure 4-7 Preference prediction vs. experiment results of Sato et al. 2012 (A: visual preference; B: auditory preference; C: overall. Numbers (1-10) represent seat location numbers used by Sato et al. 2012. The linear regression and confidence interval is calculated with location 10 omitted.

As Figure 7(A) suggests, the visual predictions fit relatively well to the evaluated values, though not as well as the fit for data in Jeon et al. (2008). The most noticeable exception is location number 10, for which the evaluated value is much lower than predicted. This location is located on the uppermost gallery, which is above the upper edge of the proscenium and very close to the ceiling ("Figure 3" in Sato et al., 2012). The low preference value might be affected by the mental discomfort at such high elevation, and the fact that a large part of the stage scenery is obscured by the proscenium. The smaller differences in other seats may be due to the distortion of wide-angle photograph in the reference study that has not been fully compensated for by the added weighting in distance; and the effect of the view of the auditorium included in the reference study. The difference in the effect of vertical angle between the current and reference studies may also be related to the difference in visual contents, as the current study used a full orchestra in which a sufficient vertical angle would reduce obstruction between musicians, while the reference study used a solo opera singer in which lower vertical angle would provide better view of the singer's face.

A similar trend can be seen for the auditory preference in Figure 7(B), the prediction also failed to capture the low auditory preference for location 10. As the paper (Sato et al., 2012) indicates, the balance between sound level of the soprano and the keyboard has large influence on auditory preference, and the sound at location 10 has relatively low soprano sound level compared to other locations. However, the prediction equation in the current study only accounts for the total sound level.

The overall preference predictions fit well with the results apart from 10, which is much lower than predicted value as expected, due to the influence of both auditory and visual preference.

4.4.3 Comparison with other prediction models

The *z*-score prediction model from current experiment was also compared with two other prediction models proposed by Vaupel (1998) and Veneklasen (1975). Vaupel's model includes lateral angle and distance, and was related to the width of the orchestra platform (15 m in the current experiment); and Veneklasen's model includes distance, lateral angle, and vertical angle, and two other factors that are related to the design of the auditorium, thus not applicable in the current experiment. Vaupel's model was derived from the order of audience seat selection in two flat rectangular auditoria (with no raked seating), and Veneklasen's model was derived from personal experience instead of experiments. Due to the very different nature and context of the models, the values are not expected to be comparable, but the general trends may still be compared.

Since no interaction effect was observed between different individual factors in the current study or any of the reference studies, the prediction models for each separate factor are plotted and compared separately in Figure 4-8. Because no equation was given for Veneklasen's model, the curves are extracted from the corresponding plots in the paper (Veneklasen, 1975) using data point matching. The curves from reference studies are translated and scaled for best comparison with the current study due to the different scales used, but the relative relationships between factors were kept constant.

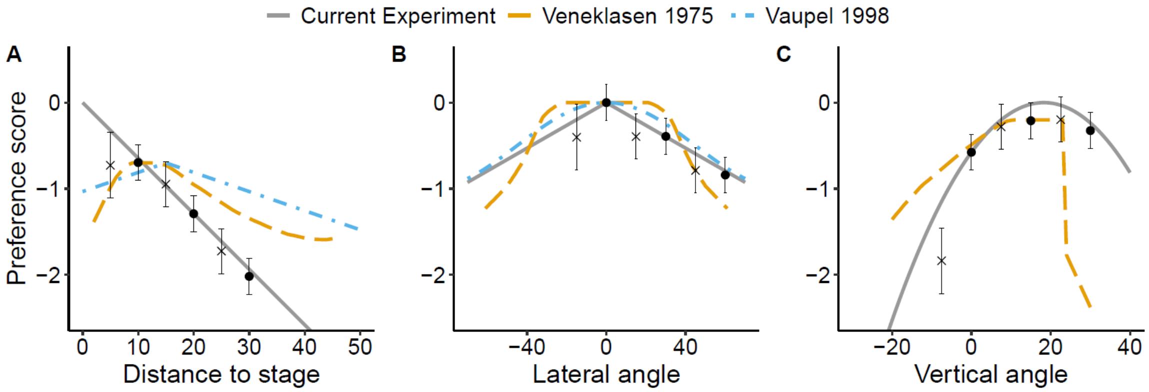


Figure 4-8 Preference prediction model comparison between current experiment, Vaupel (1998), and Veneklasen (1975)

Because Veneklasen's model was not quantitatively verified, only the general trend is compared. The trends and optimal values for the effect of lateral angle and vertical angle fit relatively well with the current experiment, while the trend for the effect of distance emphasizes more the decrease when the distance is smaller than the optimal distance.

On the other hand, Vaupel's model matches well with the current experiment for the effect of lateral angle, but the effect of distance on preference is smaller than the current experiment, and the proposed optimal value was not found statistically in the current experiment.

The difference in the current model for the effect of distance may be affected by the following: the reference study did not consider the effect of vertical angle separately (Vaupel, 1998), so the effect may be included in the distance analysis; the current study used virtual reality while the reference study used *in situ* seat selection, and distance perception may be different; the current study did not include any view of the interior architecture, which might affect subjective preference.

4.4.4 Prediction example

An example of a typical-sized shoe-box concert hall was analysed using the prediction model as an example, based on visual factors (distance, lateral angle, and vertical angle).

The dimension of the concert hall used was 50 m length × 25 m width × 18 m height (Wiener Musikverein: 49 m × 19 m × 18 m; Amsterdam Royal Concertgebouw: 44 m × 28 m × 17 m; Boston Symphony Hall: 38 m × 23 m × 19 m), with an audience area of 35 m × 20 m.

The audience area was meshed into approximately 1 m × 1 m squares, and the preference prediction of each vertex was calculated using the visual part of the prediction model (*Distance*, *Lateral angle*, and *Vertical angle*). The average value, maximum value, and minimum value of the whole audience area were calculated. A colour map is also generated for the whole area for better presentation of the preference distribution (colour scale: red-yellow-green for 0-50-100), together with a histogram using the same colour scale.

Four scenarios of the same auditorium are analysed for comparison: horizontal audience area with same level as the stage floor (Figure 4-8(A)), horizontal audience area 1 m below the stage level (Figure 4-8(B)), audience area inclined by 5° (Figure 4-8(C)), and audience area inclined by 10° (Figure 4-8(D)). While the current prediction model does not include the effect of visual obstruction from other audience members, this is likely to be a problem with scenario A. Commonly used methods to solve that problem include raising the stage or using raked seating, which are demonstrated by scenario B and scenario C-D. It can be seen that while having a raised stage may potentially ease the problem of audience self-obstruction, it is at the cost of visual preference (Figure 4-8(B)), especially for the seats close to the stage where audience members will not be able to see most of the orchestra because of the low vertical angle. On the other hand, having raked seating could improve the overall seat preference (Figure 4-8(C-D)), and the steeper the rake the better.

Therefore, it can be seen that compared to raising the stage level (to ameliorate audience obstruction), having a raked audience area may be a better solution because it provides better stage views.

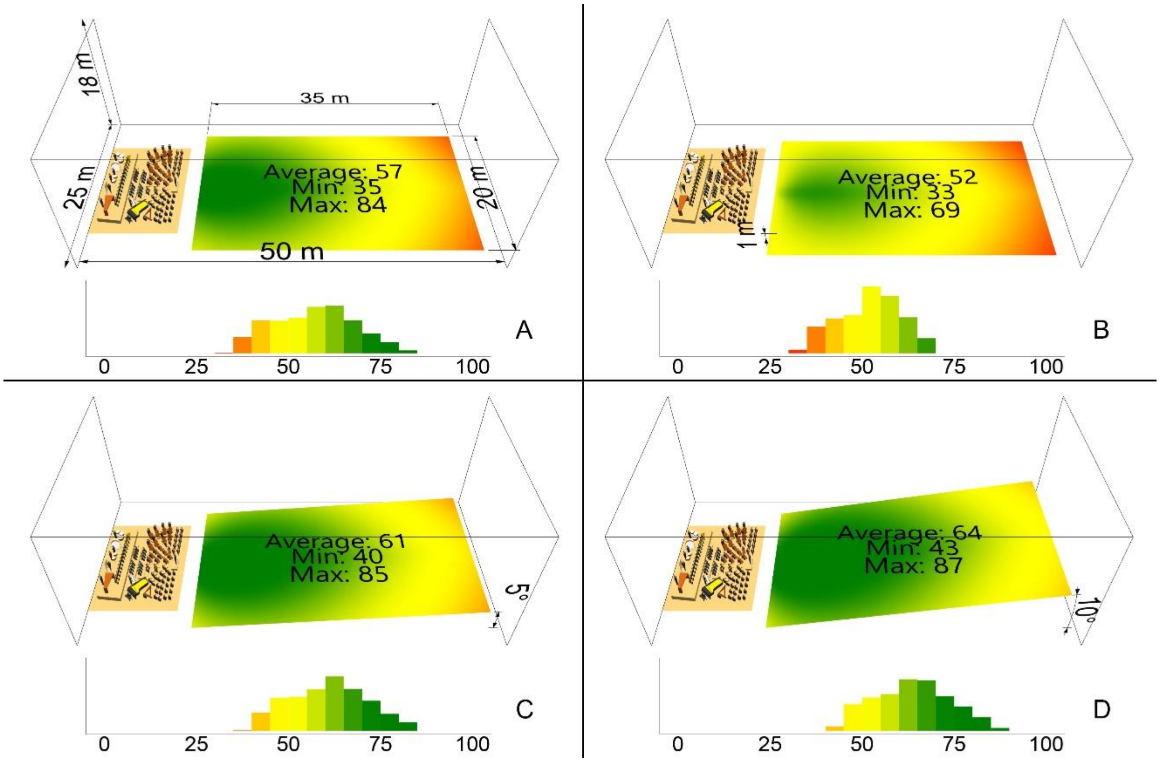


Figure 4-9 Example analysis using the view-based preference prediction model in different scenarios in a shoe-box concert hall (colour maps and histograms)

4.4.5 Further options and limitations

While the current prediction model does not account for the effect of visual obstruction on preference, it is possible to combine it with a sightline analysis tool that investigates visual obstruction (Chen & Fearnside, 2019; Marshall Day Acoustics, 2020). Analysis of visual obstruction considers details such as seat staggering that are beyond the parameters considered in this paper. However, it should be noted that while visual obstruction is known to degrade visual preference in auditoria (Jeon et al., 2008), it has yet to be systematically studied and quantified using subjective methods.

The given example in Section 4.4.4 only includes the effect of the visual factors in the prediction model because it was not a real auditorium. For a given auditorium it would be possible to combine this with acoustic simulation results (e.g., using a geometric acoustics computer program), so that the effect of sound level is also included.

With the effect of distance on preference, the outlier of the closest distance (5 m) suggested the possibility that an optimal distance may exist within the range of 0 m to 10 m, which in broad terms would be consistent with the theories of Veneklasen (1975) and Vaupel (1998). However, because there was only one location in the experiment that had the distance of 5 m, and the confidence intervals (error bars) were relatively large, there was insufficient statistical support for an optimal distance, and hence a linear model was used. Therefore, the model is likely to be most reliable for distances in the 10-30 m range.

While the current study uses orthogonal factorial design and completely separates the effect from each investigated factor, some of the factors commonly covary in reality, especially distance and audio gain. In a semi-diffuse field (like most auditoria), sound pressure level decreases when distance increases from the decrease in direct sound partly due to the inverse square law (Barron, 1996), and people perceive a sound to be louder when distance increases without changing the sound level (Barron, 1988; Zahorik & Wightman, 2001). In addition, because the audio in the current study was largely simplified in order to control variables, even though the direction of the sound source was changed with the visual stimuli to add a certain degree of realism, the lack of other changes in audio (e.g., direct-to-reverberant ratio, early decay time, or parameters associated with lateral reflections) may also create incongruences from the participants' expectations when the visual locations change. Therefore, apart from the effect of each factor on preference, there may exist an additional effect from the audio-visual incongruences. Mismatching auditory and visual stimuli has been found to decrease plausibility or pleasantness for audio-visual contents (Postma & Katz, 2017; Viollon et al., 2002), although the incongruence in the current study may be less obvious than the incongruences in the reference studies (source location or content).

The current experiment used a full-sized symphony orchestra on a proscenium-style stage with a straight stage front, so the prediction model may need further verifications and adjustments if applied to other types of performances (e.g., recitals, operas, or plays), or to seats to the side or back of the stage. The used stage dimensions were chosen to represent a classical symphony concert hall stage, while opera houses and some modern concert halls may have larger stages, while recital halls may have smaller stages (Beranek, 2012). In addition, no room information was added in the experiment for full control of the variables. In real situations, different stage sizes, interior design, and seating layouts may also result in deviations from the prediction model. The use of virtual reality could provide more accurate visual information compared to using photographs, but the visual distance and angle perception may still be slightly different from real situations. Also, the use of static model of the orchestra could not represent the dynamic changes and full details of real visual scenes.

The effect size of audio gain is relatively small compared to the visual parameters. The larger effect of vision is in line with the finding of Kawase (2013) that expected good visibility precedes expected good sound as the primary reason for choosing their most or least favourite seats, and the finding of Maempel and Horn (2022) that geometric estimations of auditoria depend 90% on vision and only 10% on audio. However, the results of Jeon et al. (2008) with a more similar experiment found that the audiovisual preference of their subjects is more affected by auditory preference (85%) and less by visual (10%). The opposite results between the current and Jeon et al.'s study may be related to the stimuli used in the experiments. The study of Jeon et al. (2008) used projected grey-scale photographs and anechoic recordings convolved with measured binaural impulse responses, while the current study used head-tracked virtual-reality renders with simplified audio that had no spatial information apart from the orientation of the direct sound, without absolute level calibration. The 2D grey-scale photographs in the study of Jeon et al. (2008) may result in lower visual realism and immersiveness, while the relatively simple auditory stimuli in the current study may result in lower auditory realism, so the participants may have been more dependent on sensory input that was more realistic with more details. Due to the current limitations and the mixed results in literature, the effect size of audio compared with visual factors will need to be verified in future experiments.

The participants were only asked to evaluate the overall preference of the combined audiovisual scene, while most of other similar studies either presented auditory and visual stimuli separately or asked the participants to judge auditory and visual preference separately. The consideration is to investigate the audiovisual experience as a whole which is the case in reality, instead of guiding the participants to think about the two sensory input separately which may affect how they judge the integrated experience. However, the limitation is that the auditory and visual preference cannot be really separated. While the experiment controlled the changes in view and sound separately and orthogonally, the subjective judgements may still be affected by audiovisual interaction. This may be another reason for the different results between the current and Jeon et al.'s study.

4.5 Conclusion

The effect of distance, lateral angle, vertical angle, and audio gain on overall subjective preference for a virtual symphony concert was studied using subjective testing with virtual reality and headphone playback. Results show that all four factors significantly affect preference, of which distance has the largest effect. No interactions are found between the factors.

Within the tested range of 5 m to 30 m, the visual distance to stage has a negatively sloped linear effect on preference. Within the tested range of 0° to 60°, the lateral angle from the centre plane has a negatively sloped linear effect on preference, and the effect is symmetric on either side of the centre plane. Within the tested range of 0° to 30°, the vertical angle from the horizontal plane has a quadratic effect on preference, with a maximum at around 18°. Within the tested range of -9 dB to 0 dB relative to the participants' chosen listening level for the experiment, audio gain has a positive linear effect on preference. The effect of audio is relatively small compared to the visual factors, possibly due to the ranges used in the current experiment and the simplified audio presentation. Further testing with more realistic auditory stimuli and absolute level calibration would be required to confirm the size of this effect. The combined effect of the four factors can be calculated from the sum of the effect of each individual factor. A prediction model is derived from the results, which accounts for the effects of the four studied factors.

The *z*-score model is compared with the experiment results from two related studies (Jeon et al., 2008; Sato et al., 2012) and the proposed models from two other studies (Vaupel, 1998; Veneklasen, 1975). It is proven to be mostly robust, and the differences are analysed and discussed. An analysis example using a simple shoebox concert hall demonstrates the potential use of the model.

Chapter 5 The effect of auditory and visual locations on concert preference

This chapter verifies and modifies the prediction model proposed in the last chapter in realistic audiovisual simulations of auditoria, and examines the separate effect of auditory and visual room size on preference, through the third experiment. Part of this chapter has been published as:

Chen, Y., Cabrera, D., & Alais, D. (2022). Separate effects of auditory and visual room size on auditorium seat preference: a virtual reality study. *Perception*, *51*(12), 889–903. https://doi.org/10.1177/03010066221125864

Thirty-three participants evaluated their overall subjective preference at eighteen seats in four virtual auditoria, which comprised congruent and incongruent auditory and visual renders of two auditoria that differ only in size. Results show no significant difference between participants who completed the experiment in a fully calibrated and standardized laboratory environment and participants who completed remotely using various VR equipment in various environments. Both visual and auditory auditorium size have significant main effects, but no interaction. The larger hall is preferred for both conditions. Audiovisual congruency does not significantly affect preference. The prediction model proposed in the orthogonally controlled Chapter 4 experiment in Chapter 4 was verified and refined. The final model that explains 93% of variance includes negative effects of distance to stage, lateral angle from centreline, and obstruction of stage view, a positive effect of early sound strength (G_{early}), and a polynomial effect of vertical angle from stage plane. Other acoustic parameters do not further significantly contribute to seat preference. Findings highlight the potentially strong influence of stage-view on the audiovisual quality of concert auditoria.

5.1 Introduction

Concert auditoria are a context where visual and auditory sensory input combine through architecture and performance. While most studies of auditorium quality focus on sound alone, this is a context where multisensory studies could provide useful insights.

5.1.1 Audiovisual interaction

The last two decades has seen a boom in multisensory research which has revealed the extent to which sensory experience is inherently multisensory at both neural and perceptual levels (Alais et al., 2010). Sensory signals for sight, sound and touch are integrated very early in a subcortical structure called the superior colliculus, before they arrive in the brain at their respective primary sensory cortices (Stein & Meredith, 1993). Once in the cortex, the primary sensory regions once thought to be unisensory are now known to interact through anatomical links before converging on a host of multisensory cortical areas at higher-levels (Ghazanfar & Schroeder, 2006; Murray & Wallace, 2012). The perceptual consequences of this rich multisensory interaction are considerable. For example, perception of vision and sound is improved in sensitivity and precision when the signals are synchronised and from a common origin (Frassinetti et al., 2002; Alais & Burr, 2004). Importantly, studies of multisensory cortex show that audiovisual integration requires more than just blindly applying a spatial and temporal coincidence rule: stimuli must be congruent to trigger audiovisual integration. That is, video of an action must be paired with the appropriate sound of the action (Barraclough, et al., 2005). For example, video of a violinist bowing the strings would not trigger integration if paired with sound of a drum roll on the tympani.

Recent theories of perception view the brain as a Bayesian predictive process that uses prior probability distributions to model the world and generate expectations and predictions (Knill & Pouget, 2004; Clark, 2013). These predictions originate from high-level, multisensory brain regions and thus perception is shaped at all times by top-down, multisensory input. For example, upon entering a large auditorium, vision of its vast expanse leads to a strong expectation that sounds will be highly reverberant – a prediction built upon years of experience and stored knowledge about the relationship between visual space and reverberation. Expectations are surprisingly powerful in shaping a host of perceptual experiences in all sensory modalities and there is an increasing awareness that audiovisual interactions play a role in how we experience an environment. A number of recent studies have shown audiovisual interactions in how soundscapes and landscapes are rated, with visual factors significantly influencing preferences for the sound environment (Jeon & Jo, 2020; Li & Lau, 2020).

Research into audiovisual interactions in room acoustics have mostly focused on spatial auditory perception. For example, studies have shown that perceived distance of an auditory source is more accurate and less variable with visual cues present (Zahorik, 2001; Calcagno et al., 2012), and when auditory and visual stimuli are incongruent, the combined perceived distance is affected by both (Maempel & Jentsch, 2013). Other spatial room acoustic perception attributes like perceived room size, apparent source width (ASW, also called auditory source width) or listener envelopment (LEV) have also been found to be affected by visual input (Cabrera et al., 2004; Larsson et al., 2001; Maempel & Jentch, 2013; Valente & Braasch, 2010). A recent paper (Neidhardt et al., 2022) summarized studies relating to audiovisual perceptual matching in augmented reality. On the other hand, fewer studies have addressed audiovisual factors in auditorium preferences. In two early studies on the effect of auditory and visual factors on seat preference in opera theatres using static photographs and binaural auditory renders (Jeon et al., 2008; Sato et al., 2012), significant visual effects were found. The Chapter 3 study using virtual auditoria found that while concert hall interior colour affects visual preference and sound level affects auditory preference, these two preferences enhanced each other.

5.1.2 Audiovisual seat preference

As summarized in Chapter 1, some influential studies of concert hall quality have focused on how subjective preference varies between auditoria and such studies are mostly concerned with acoustics (Barron, 1988, 2009; Beranek, 2012; Galiana et al., 2016; Giménez et al., 2011; Lokki et al., 2012, 2019). Relatively fewer studies have focused on how the quality of the concert experience varies within a given auditorium and these studies concentrate on acoustic attributes that vary across seat locations (summarized in Section 1.4). Because such studies typically use an existing auditorium as the basis for their investigations, stimulus parameters are generally not individually controlled and may covary across seat locations, limiting the scope of the findings. Nevertheless, from various studies certain correlations have been found between subjective preference and several objective parameters and recommended standards and values have been proposed for each parameter (e.g., Barron, 2009; Hidaka & Beranek, 2000; ISO 3382-1:2009).

The acoustical characteristics of auditoria are usually characterized following ISO 3382-1 (2009), which defines several parameters that affect quality. Reverberation time (RT or T_{30}), which is the most discussed parameter in room acoustics, is a characteristic of the room as a whole, and has been an important parameter in inter-auditorium studies. Optimal RT values have been proposed (e.g., Ando, 1983; Bagenal & Wood, 1931; Barron, 2009; Beranek, 2012; Knudsen, 1932). Other parameters tend to vary systematically within an auditorium – e.g., with distance from the stage, or exposure to reflections from large surfaces, in addition to varying between auditoria. These include early decay time (EDT), sound strength (G), clarity index (C_{80}), early lateral energy fraction (J_{LF}), late lateral sound level (L_J), and inter-aural cross-correlation coefficient (IACC). Most intra-auditorium subjective studies find positive correlations between preference and G (Farina, 2001; Jeon et al., 2008; Sato et al., 2012; Sotiropoulou et al., 1995), and negative correlations between preference and IACC (Ando, 1983; Ando & Gottlob, 1979; Schroeder et al. 1974). Correlation analyses between other parameters and acoustic quality have exhibited mixed or non-linear results.

In addition to acoustic characteristics, visual factors are also a relevant consideration in seat preference studies. Vision exerts a strong influence on auditory perception, especially in spatial localisation and distance perception (Gardner, 1968; Zahorik, 2001; Alais & Burr, 2004), and visual preference in music concerts also contributes to the overall preference (Jeon et al., 2008; Sato et al., 2012). Various parameters in an auditorium can affect visual perceptual input and these are mainly defined by geometric relationships: distance, lateral angle, and vertical angle. Distance is found to be negatively correlated with preference (Chapter 4) or non-linearly with an optimal distance (Vaupel, 1998). Similarly, for vertical angle, some studies have found a negative correlation (Jeon et al., 2008; Sato et al., 2012) while others discovered an optimal angle (Chapter 4). Lateral angle has been found to be negatively correlated with preference by most studies (Chapter 4; Jeon et al., 2008; Vaupel, 1998). In addition to the geometric location, visual obstruction is also believed to have a negative effect on preference, though it has not been quantitatively studied.

Compared to acoustic quality, visual quality is much less studied. In addition, because the existing results are all based on case-studies, the effect of each individual factor is not separated and systematically manipulated, and the results from different studies are not mutually compatible. That led to the Chapter 4 experiment, which was the first orthogonally controlled factorial study on visual quality in auditoria.

The Chapter 4 experiment orthogonally examined how seat preference was affected by visual distance to the stage (5 to 30 m), lateral angle from the symmetric plane (0° to 60°), vertical angle from the stage plane (-7.5° to 30°), and audio gain level (9 dB range). To be able to control each factor independently, and eliminate the effect of the view and acoustics of the auditorium, the study used a virtual reality render of a stage with a static 3D orchestra model against a black background, with simple panned binaural audio that only included orientation information without other spatial information and variation. The Chapter 4 experiment proposed a prediction equation based on the found effects that distance and lateral angle negatively affect preference, while audio gain level positively affects preference, and vertical angle has a polynomial effect with an optimal angle of around 18°. While the Chapter 4 experiment also proposed a prediction equation based on a mixed-effects model, the prediction equation from the standardized model has better compatibility and comparability between experiments with different designs. Therefore, only the standardized model is used to compare with the results of the current study (more details in Section 4.2).

While a controlled study can identify the separate effects of normally inter-dependent factors, the lack of environmental information (e.g., view of the auditorium, spatial acoustics) may affect perceived distance and audio gain level, as studies found that both visual and auditory environmental contexts affect perceived distance (Cabrera et al., 2005; Kuusinen & Lokki, 2015; Lappin et al., 2006; Maempel & Jentsch, 2013; Vergara et al., 2016; Witt et al., 2007; Zahorik, 2001), and perceived distance affects perceived loudness (Barron, 1988; Chomyszyn, 1994; Zahorik & Wightman, 2001). The absence of environment also reduces the realism of the stimuli, which may affect preference evaluation. Therefore, to verify and possibly refine the prediction equation from the Chapter 4 experiment in a more realistic setting, the current experiment used realistic visual and auditory stimuli of an auditorium to test the preference of various seat locations.

Already used in a number of studies, virtual-reality (VR) is still a relatively new experimental method for audiovisual research. One of its great advantages is the possibility to construct environments that would be impossible in reality, such as spaces with conflicting vision and sound. This makes VR a perfect method for manipulating auditory and visual factors in experiments. Moreover, with VR technology becoming more and more accessible at the consumer level, and the ease of online data transfer, the possibility of recruiting VR participants for remote participation in audiovisual experiments has great potential for increasing sample size and diversity. We first trialled this approach under the pressure of the COVID-19 pandemic, but the compatibility of experiments using highly controlled laboratory setups versus remote participants with differing equipment needs to be investigated for various VR experiment scenarios.

5.1.3 Objectives

This chapter aims to: 1) examine the separate auditory and visual effect of two auditorium sizes on subjective seat preference; 2) compare the results of laboratory-based participants using standard, calibrated equipment with those of remote participants using their own individual setups; 3) verify and refine the prediction equation for seat preference proposed in the orthogonally controlled Chapter 4 experiment in realistic audio-visual auditorium environments; and 4) identify any additional effects of acoustic parameters other than audio gain level (sound strength) on seat preference.

5.2 Method

Testing was done in virtual reality with 33 volunteer participants, of which 18 participated remotely with their own VR headsets and headphones using an executable application distributed over the internet, and 15 participated in a laboratory using calibrated equipment. The participants experienced four distinct audiovisual auditorium simulations: two auditory room sizes crossed with two visual room sizes. They evaluated 18 seat locations in each auditorium simulation, of which 12 had the same relative positions to the stage. As the focus of this paper is on room size perception, only the 12 locations with the same positions are analysed. The participants listened to orchestral music at each location and, taking into account the audiovisual environment, they rated their overall preference for each location.

5.2.1 Visual stimuli

The visual environment used for the experiment were two auditorium models that were different in size but had the same materials and decorations. The smaller hall was approximately 35 m × 18 m × 12 m (length, width, height), while the larger hall was approximately 35 m × 28 m × 14 m (Figure 5-1). The dimensions and material layouts of smaller hall model was based on an existing auditorium, the Verbrugghen Hall at the Sydney Conservatorium of Music, a space regularly used for concerts and rehearsals of solo, ensemble, and orchestral music. A 3D static 61-piece orchestra model was also presented on the stage (Figure 5-1).

The simulations were presented in head-mounted virtual reality displays (VR headsets) using the 3D engine of Unity (Unity Technologies, 2019) with SteamVR plugin (Valve Corporation, 2019) for virtual-reality calculation. The lab-based participants used an HTC Vive VR headset with calibrated height and position. The remote participants used their own VR headsets, but they were told to ensure that the seating position was correctly centred at the start of the experiment, and use a non-moving chair if possible. Of the VR headsets used by the remote participants, 10 were HTC VR headsets, 7 were Oculus VR headsets, and 1 was Varjo VR headset.

Figure 5-1 Example views of the visual simulations used in the experiment. Left: the smaller auditorium based on Verbrugghen Hall (35 m × 18 m × 12 m). Right: the larger auditorium (35 m × 28 m × 14 m).

5.2.2 Auditory stimuli

The acoustic environment were simulated in ODEON (Odeon A/S, 2020), room acoustics simulation software that can accurately calculate and recreate acoustic environments of complex 3D spaces. The acoustic simulations used the same space dimensions, surface materials, sound sources, and listening positions as the visual simulations. The absorption coefficients of the surface materials were initially chosen based on the materials used in Verbrugghen Hall (e.g., plaster walls, wooden boards on ceiling and stage, carpet auditorium floors and fabric seats), then calibrated by matching the simulated results of the smaller hall to measured results conducted at the same locations in the Verbrugghen Hall, so that the reverberation times (T_{15}, T_{20}, and T_{30}) and early decay times (EDT) at all seat locations were as close as possible between the measurements and simulations (4.0% mean relative difference for all octave bands between 250 Hz and 4000 Hz). The average octave band reverberation time (T_{30}) and its ranges in the two simulated room sizes together with the reference measurements in the Verbrugghen Hall are plotted in Figure 5-2. The mid-frequency reverberation time of the larger hall (2.6 s) is 0.5 s longer than that of the smaller hall (2.1 s, same as measured in the Verbrugghen Hall).

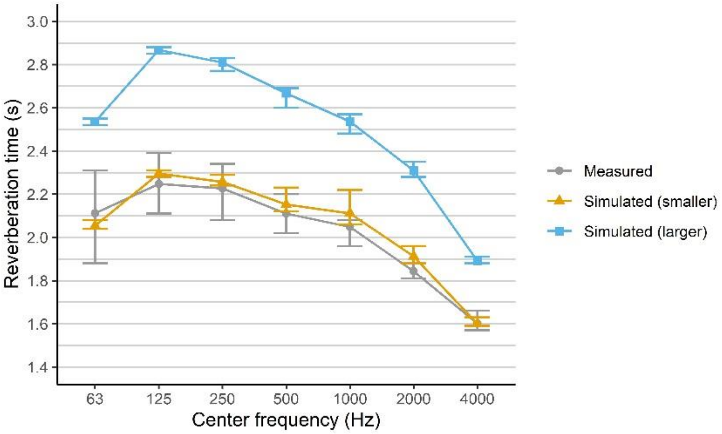


Figure 5-2 Octave band reverberation time (T_{30}, mean in seconds) at all seats in the physical and the two simulated concert halls. Error bars are minima and maxima.

The propagation of sound in the space was simulated using combined image-source and ray-tracing methods, and the calculation was done from each sound source on stage (61 distinct locations, one for each musician in the orchestra: see Figure 5-1) to each simulated location in the audience. The locations and instruments of each musician were matched in audio and vision.

The music used was Beethoven Symphony No. 8 in F Major (Op. 93) (movements 1, 2, and 4). Each instrument was recorded individually in an anechoic chamber (a room with almost no sound reflections) by TU Berlin (Böhm et al., 2018), so that the only room effect in the auditory stimuli was from the simulated auditoria. The relative gain of each source used in the auralization was set based on the aural judgement of the experimenter (who is an experienced musician) and kept constant across the two halls, to ensure the final auralization results sounded as natural as possible. Individual directivity for each instrument measured by Otondo and Rindel (2004) was used, apart from the timpani for which an omnidirectional source was used.

First-order Ambisonic impulse responses were simulated for all 61 × 18 × 2 = 2196 combinations of the source-receiver locations in the two simulations, convolved with the corresponding anechoic recording channels, then mixed down to one first-order Ambisonic music signal for each receiver location. The Ambisonic audio format contains both the musical information (pitch, dynamic, timbre, etc.) and the spatial information (directions from which the sounds came). Both the convolution and mixing processes were done in ODEON. The Ambisonic audio was decoded binaurally in real time into the headphones according to the head orientation tracked by the VR headsets so that the auralization was updated for dynamic head movements. The decoding was done using the Ambisonics decoder in the Resonance Audio plugin for Unity

(Google, 2018) with KU 100 head-related transfer functions (HRTFs). Due to the need for online distribution of the experiment program, all the real-time calculations needed to be done within the experiment program without the need to install any software, and among the Ambisonic-to-binaural decoder plugins available for Unity, we chose the Resonance Audio plugin due to its more up-to-standard procedures and thorough documentations.

The lab-based participants completed the experiment in a room with very low background noise, while the computer and researcher remained in a different room to eliminate the effect of the computer cooling fan noise on the experiment. The headphones used by the lab-based participants were Sennheiser HD 800 open-back headphones. The sound pressure level was calibrated using a Neumann KU 100 Dummy Head system to match the realistic sound pressure level in the auditoria, calculated using sound strength and the estimated sound power level of each instrument given by Weinzierl et al. (2018).

The remote participants completed the experiment in their own chosen environment with their own headphones, and they were told to adjust to a comfortable listening level at the beginning and to keep the same audio gain throughout the experiment. Of the headphones used by the remote participants, 11 were closed-back over-ear headphones (including 2 built-in with the VR headset), 6 were open-back over-ear headphones, and 1 was in-ear headphones.

5.2.3 Experiment procedure

The two visual room size simulations and the two auditory room size simulations were cross-paired to form four pairs, two that were congruent and two that were incongruent. There were: 1) matched simulation of smaller auditory room size + smaller visual room size; 2) unmatched simulation of smaller auditory room size + larger visual room size; 3) unmatched simulation of larger auditory room size + smaller visual room size; 4) matched simulation of larger auditory room size + larger visual room size.

The 18 seat locations were used in each hall (Figure 5-3). The 12 red locations (number 1-12, of which 8 were on the first floor in the stalls, 4 were on the second floor in the rear balcony) have the same relative position to the stage between the two room sizes, thus are included in the analyses of this paper. The 6 grey locations (numbers 13-18) were located on the side galleries (3 on the first floor, 3 on the second floor) and their relationships with the side walls stayed relatively constant between the two room sizes, meaning that their positions relative to the stage changed (they were further away from the centreline of the auditorium and had larger source-receiver distances in the larger hall due to its larger width). As this paper’s focus is on the effect of room sizes and the change of source-receiver position introduces extra variables, seats 13-18 were excluded from the analyses. The distances of each location to the conductor location on stage ranged from 4.7 m (location 1) to 22.1 m (location 12).

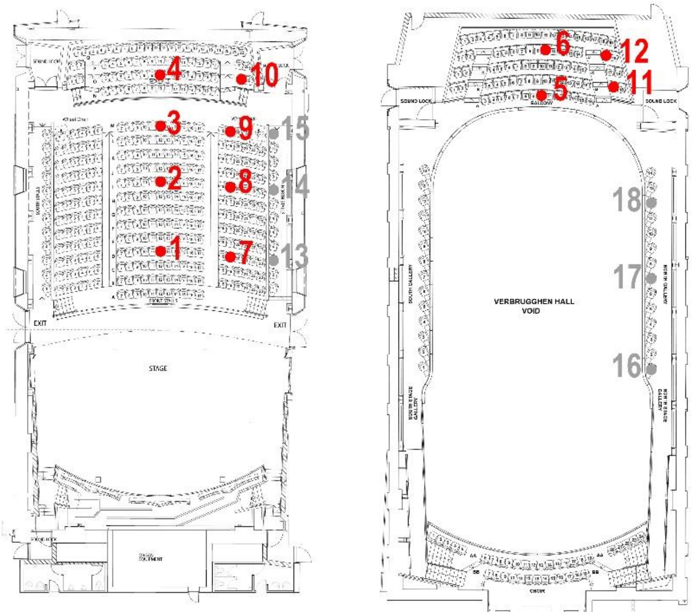


Figure 5-3 Floor plans of Verbrugghen Hall (on which the smaller hall was based) with the 18 marked seat locations used in the experiment. Left: first floor (orchestra level); right: second floor. Red locations (1-12) are included in the analyses of this paper.

Every participant experienced 18 seat locations in all four combined auditory and visual simulations, spending a total of 36.6 minutes on average (*SD* = 14.9 min). The participants were instructed to give each seat location in each auditorium a rating out of 100 based on how much they liked the overall experience of the seat location given the sound and view from the seat. No separate evaluations of the auditory and visual preference were asked, to control the total experiment time and avoid fatigue of participants. They started at a random seat position in a random auditorium simulation, and subsequently chose their own order to visit and evaluate all of the seats. They could visit the same location and auditorium multiple times, and modify their ratings. Results were recorded when they were satisfied with all of their ratings.

The participants used VR hand controllers to conduct all operations including giving their preference scores, changing seats, and exporting results. While they were touching the thumbpad or thumbstick on the VR controller, the score for the current location would appear inside the VR display as floating texts (Figure 5-4(A)). All seats started with a score of 0, then they could move their thumb clockwise to increase the score or anti-clockwise to reduce the score. Every 60 degrees of rotation would trigger an increment or decrement of 1, and the controller would give a short feedback vibration. They could not change the score to higher than 100 or lower than 0. When they pulled the trigger at the back of the VR controller, all available locations would appear as seated person models with the score previously given for each location (Figure 5-4(B)), and a laser-like beam would be visible from the location of the controller. If they pointed the beam at any location, and while the person was highlighted, released the trigger, the audiovisual scene would be switched to the selected location.

Participants were familiarized with the controls through the experimenter (live demonstration for the lab-based participants, and video demonstration for the remote participants) and an instruction document with detailed pictures before they put on the VR headset and headphones. Once they were inside the VR environment, the experiment began directly with no training session. However, they were encouraged to visit a few different seats before starting their evaluation process. There was also a menu button on the controller that turned a menu on/off. The menu included options for saving the process (if the participants wanted to pause the experiment and return at a later time), switching between the four “auditoria”, or exporting the results if they were completely satisfied with the scores that they have given to all the seats in all the auditoria. When the participants switched between seat locations within one auditorium, the music continued in time, while the auditory renders changed according to the locations; when they switched between auditoria, the music restarted from the beginning of the first movement. There were also options in the menu to restart music from first movement, restart the current movement, or skip the current movement. The participants had full control of how long they spent at each seat location, how many times they visited each location, and in what order they completed the evaluations.

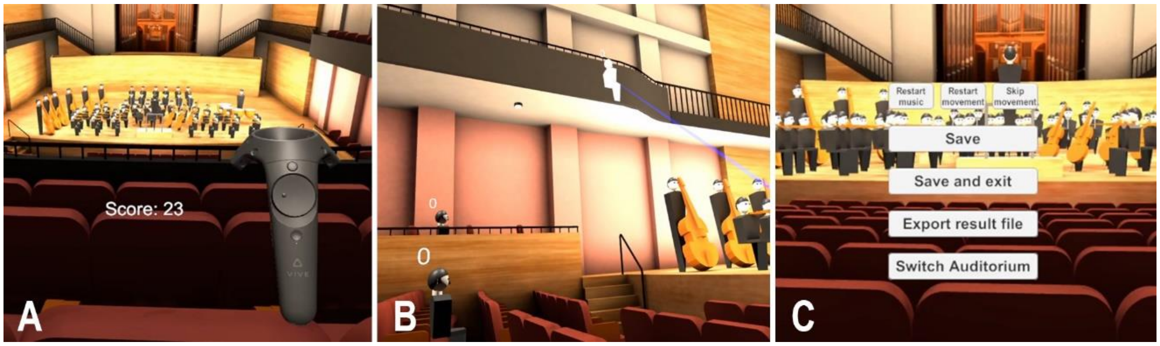


Figure 5-4 User interface examples (A: scoring interface example (enabled when thumbpad/thumbstick was being touched); B: seat selection interface example (enabled when with trigger was being pulled); C: menu interface example (turned on/off when menu button was pressed).

5.2.4 Seat parameters

In contrast to the Chapter 4 experiment where the effects of distance to stage, lateral angle, vertical angle, and audio gain were tested independently, the current study was based on realistic auditorium models with simulated spatial audio, and the auditory and visual locations covaried. Therefore, the three visual parameters manipulated in the Chapter 4 experiment (distance, lateral angle, vertical angle) affected both visual and auditory input in the current study, and thus were categorized as geometric parameters. They were calculated with the same method as in the Chapter 4 experiment, which used the stage level at the conductor’s location as the reference point.

To investigate more detailed effects of sound on seat preference, all acoustic parameters defined in ISO 3382-1 (2009) were calculated in ODEON and included in the analysis, including early decay time (EDT), reverberation time (T_{30}), sound strength (G), clarity index (C_{80}), early lateral energy fraction (J_{LF}), late lateral sound level (L_J), and inter-aural cross correlation coefficient (IACC). The single number value for each parameter calculated from the average of 5 on-stage measurement source positions is calculated according to ISO 3382-1 and shown in Table 5-1.

Table 5-1 Coordinates and parameters (geometric and acoustic) of each location (D: Distance to stage; L: Lateral angle from symmetric axis; V: Vertical angle from stage level; VO: Visual obstruction, proportion of orchestra area invisible *from the location; G: Sound strength; EDT: Early decay time; T_{30}: reverberation time; C_{80}: Clarity index; J_{LF}: Early lateral energy fraction; L_J: Late lateral sound level; IACC: Inter-aural cross correlation)*

		D	L	V	VO	EDT	T_{30}	G	G_{early}	C_{80}	J_{LF}	L_J	IACC
Room size	No.	m	°	°	/	s	s	dB	dB	dB	/	dB	/
Original	1	4.7	0.0	-9.8	0.00	2.0	2.1	9.3	6.7	0.96	0.21	2.09	0.30
	2	9.6	0.0	-1.8	0.00	2.1	2.1	7.6	4.1	-0.92	0.26	1.35	0.29
	3	13.7	0.0	0.0	0.00	2.0	2.1	7.6	3.9	-1.28	0.27	1.23	0.28
	4	17.0	0.0	2.0	0.00	2.0	2.1	6.3	2.6	-1.24	0.25	0.13	0.27
	5	18.7	0.0	13.3	0.00	2.1	2.1	5.7	2.0	-1.26	0.24	-0.15	0.29
	6	21.9	0.0	13.8	0.02	2.0	2.1	5.3	2.0	-0.62	0.26	-1.18	0.30
	7	6.4	47.5	-7.2	0.00	2.0	2.1	9.3	6.6	0.79	0.26	1.89	0.32
	8	10.4	27.1	-1.7	0.00	2.1	2.1	7.9	4.7	-0.44	0.26	1.41	0.31
	9	14.0	19.7	0.0	0.00	2.0	2.1	7.7	4.0	-1.24	0.24	1.23	0.27
	10	17.4	18.9	2.0	0.00	2.0	2.1	6.6	3.1	-0.88	0.22	0.37	0.28
	11	20.1	15.0	13.2	0.22	2.1	2.1	5.5	1.5	-1.83	0.27	-0.41	0.27
	12	22.1	12.3	13.6	0.08	2.0	2.2	5.2	1.7	-0.81	0.21	-1.31	0.31
	13	8.8	63.1	2.0	0.03	2.1	2.1	9.3	6.1	-0.34	0.30	2.31	0.36
	14	11.8	41.2	1.5	0.02	2.1	2.1	8.0	3.9	-1.79	0.22	1.64	0.28
	15	14.8	31.4	1.2	0.03	2.1	2.1	7.6	3.5	-1.85	0.23	1.54	0.29
	16	9.5	90.0	27.0	0.55	2.1	2.1	9.7	6.4	-0.64	0.17	2.56	0.29
	17	11.1	53.0	22.8	0.58	2.1	2.2	8.8	5.1	-1.30	0.21	1.99	0.31
	18	14.3	35.7	17.5	0.59	2.2	2.2	8.1	4.0	-1.86	0.22	1.52	0.29
Large	1	4.7	0.0	-9.8	0.00	2.3	2.6	8.5	5.9	1.18	0.15	1.25	0.33
	2	9.6	0.0	-1.8	0.00	2.5	2.6	6.6	3	-1.01	0.23	0.62	0.31
	3	13.7	0.0	0.0	0.00	2.5	2.6	6.3	2.3	-1.90	0.26	0.45	0.30
	4	17.0	0.0	2.0	0.00	2.6	2.6	5.3	1.4	-1.57	0.23	-0.54	0.28
	5	18.7	0.0	13.3	0.00	2.6	2.6	4.7	0.1	-2.77	0.15	-0.47	0.30
	6	21.9	0.0	13.8	0.02	2.7	2.7	4.6	-0.2	-3.14	0.21	-0.39	0.31
	7	6.6	45.6	-7.0	0.00	2.5	2.6	7.8	4.7	-0.07	0.20	1.22	0.33
	8	10.6	26.3	-1.6	0.00	2.5	2.6	6.7	3.2	-0.87	0.22	0.64	0.32
	9	14.3	19.2	0.0	0.00	2.6	2.6	6.2	2	-2.15	0.21	0.45	0.27
	10	17.8	18.1	1.9	0.00	2.5	2.6	5.2	1.6	-1.12	0.25	-0.76	0.28
	11	20.4	14.5	13.1	0.07	2.6	2.6	4.7	0.2	-2.63	0.18	-0.5	0.30
	12	22.3	11.9	13.5	0.04	2.6	2.6	4.5	-0.4	-3.14	0.23	-0.71	0.29
	13	13.4	72.9	1.3	0.00	2.6	2.7	7.0	3.1	-1.60	0.34	1.07	0.41
	14	15.5	55.3	1.1	0.00	2.6	2.6	6.0	1.6	-2.44	0.28	0.54	0.35
	15	18.0	45.2	1.0	0.00	2.6	2.6	5.6	1.2	-2.42	0.28	0.26	0.32
	16	12.5	90.0	20.2	0.31	2.6	2.6	8.2	4	-2.08	0.16	1.83	0.29
	17	13.8	62.6	18.2	0.24	2.6	2.6	7.6	3	-2.76	0.15	1.44	0.28
	18	16.4	46.3	15.2	0.24	2.6	2.6	7.0	2.3	-2.92	0.18	0.87	0.27

As the current study used realistic auditorium models, some of the tested locations may include visual obstructions caused by architectural elements (e.g., balcony railings). To quantify the extent of visual obstruction, several different calculation methods were tested, and the method that best fit preference prediction was chosen. In this method, a 3D boundary was drawn around the orchestra, to include all musicians and instruments expanded by an approximately 0.6 m margin (Figure 5-5 (left)), intended to define the main visual focus area of a concert. Then 1000 points were randomly populated within the boundary's enclosed volume (Figure 5-5 (right)). For each seat location, a line-of-sight was connected between the approximate eye location of the participants in the VR experiment and each of the random populated points, and tested for any interruption using the corresponding architecture model. The proportion of interrupted lines-of-sight out of 1000 was calculated, and used as the objective representation of visual obstruction (Table 5-1). This calculation method only accounts for visual obstructions caused by the architectural elements; mutual obstructions within the orchestra are not included, because obstructions between musicians are expected to be completely explained by the changes in lateral angle and vertical angle. The viewing location may slightly differ between participants because it is affected by their seated eye height, their head and torso movements during the experiment, and the calibration of the VR headsets. Nonetheless, the calculated obstruction provides a straightforward and simple estimation of the typical condition that can be easily used for the analysis.

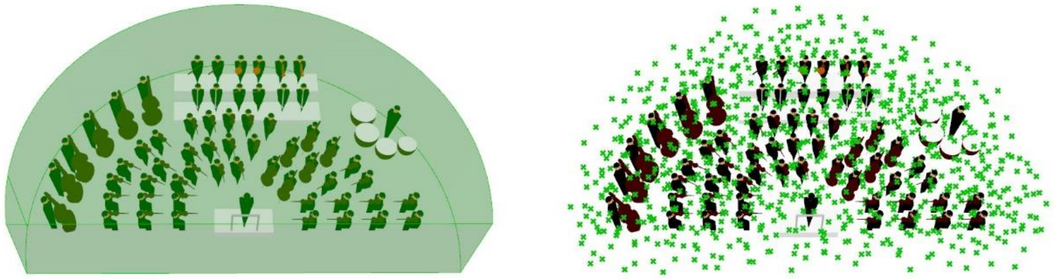


Figure 5-5 Demonstration of deriving visual focus area used for view obstruction calculation (as detailed in section 5.2.4). Left: 3D boundary shape around the orchestra with 0.6 m margin. Right: 1000 randomly populated points within the 3D boundary shape to be used as visual focus points in the obstruction calculation.

5.2.5 Statistical analysis

Statistical analyses were performed with the software RStudio (Rstudio Inc.) with packages "plyr" (Wickham, 2020), "tidyverse" (Wickham, 2019), and "sjstats" (Lüdecke, 2020). To eliminate the effect of differences between individual subjects, all rating scores were standardized to *z*-scores based on the mean and standard deviation of each participant.

5.3 Result analysis

The results of the preference ratings were analysed in three sections that examine: 1) the effect of experiment environment on the group averages; 2) the separate effects of auditory and visual room size and the effect of auditory and visual room size congruency; 3) the effect of various factors on seat preference.

5.3.1 Remote vs. lab-based experiment

Figure 5-6 contrasts the ratings for the remote versus the lab-based participants. To test whether the two groups differed significantly in their results, a two-way mixed-effects ANOVA was conducted for the rating scores, with the experiment environment (remote vs. lab-based) as the between-subject independent variable, and each unique audiovisual stimulus (12 seats × 2 auditory room sizes × 2 visual room sizes = 48 stimuli) as the within-subject independent variable. While the main effect of unique stimulus was significant as expected (F(47,1457)=15.52, *p*<.001), the experiment environment showed neither a significant main effect (F(1,31)=0.04, *p*=.837) nor a significant interaction with unique stimuli (F(47,1457)=0.63, *p*=.976). This indicates that in terms of group average, the ratings given by the group who completed the standardised experiment in the laboratory with calibrated VR headset and headphones and the other group who completed the experiment remotely in their own selected environment with their own VR headset and headphones do not significantly differ from each other. This supports for the validity of the method of conducting VR experiments remotely in the context of this experiment for the analysis of average preference, and shows that the results of all participants can be analysed together.

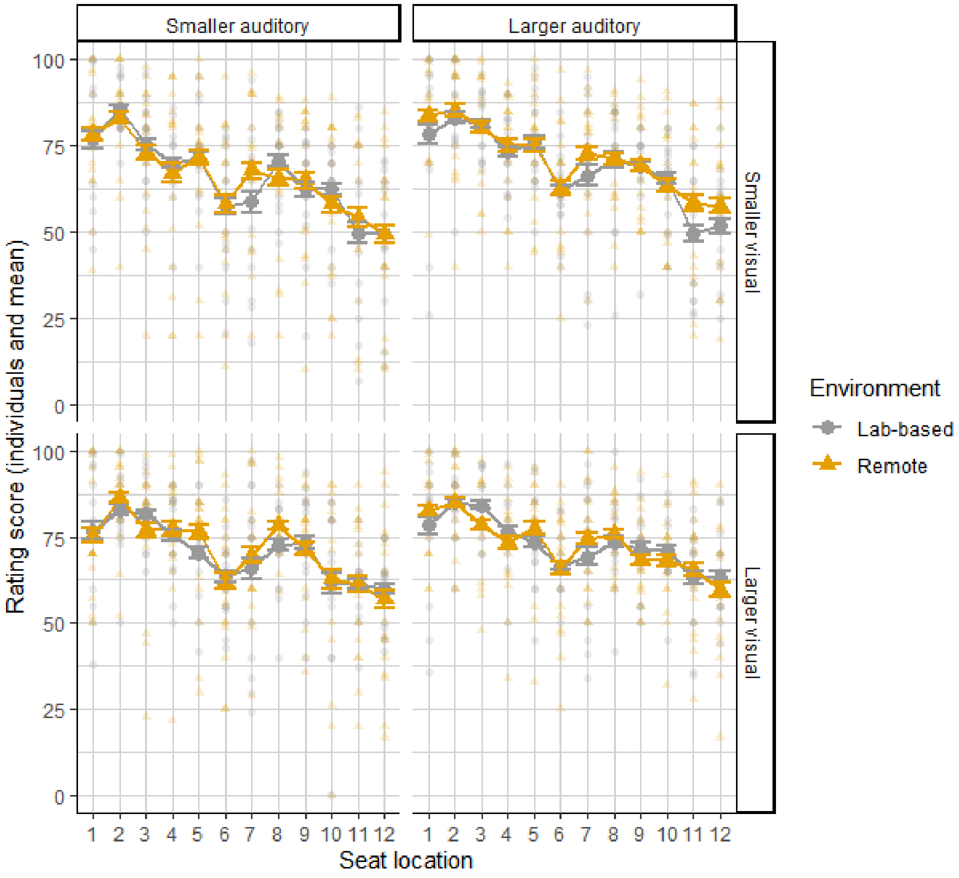


Figure 5-6 Mean (with 95% confidence intervals) and individual rating scores for each unique audiovisual stimulus, with the experimental environment separated by colour and point shape.

5.3.2 Between auditoria

5.3.2.1 Auditory room size vs. visual room size

Figure 5-7 plots the preference ratings for each audiovisual auditorium on both experimental groups combined. A tendency of higher ratings can be seen for both larger visual room size and larger auditory room size at most seat locations.

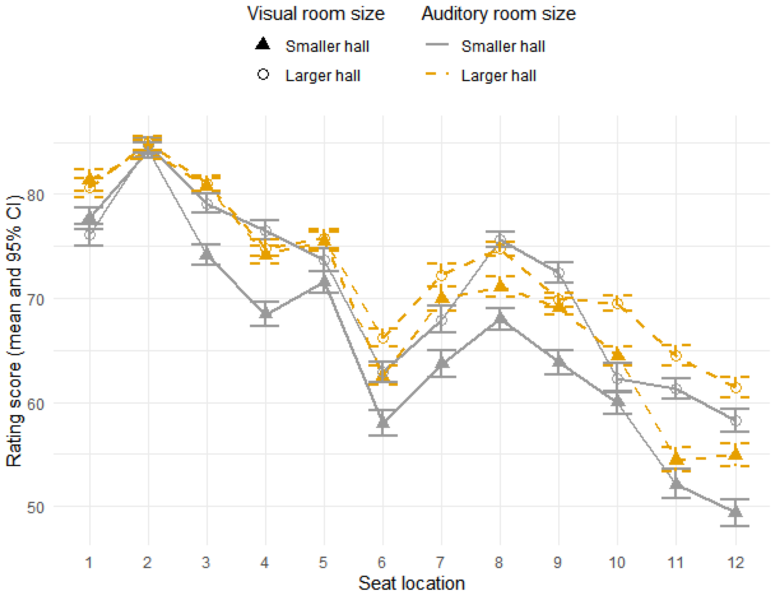


Figure 5-7 Means and 95% confidence intervals of rating scores in each combined auditory and visual auditorium renders at seat locations 1 to 12.

To examine the effect of different auditory room size and different visual room size, a three-way random-effects ANOVA was conducted for auditory room size, visual room size, and seat positions. Both auditory room size and visual room size have significant main effects (auditory room size: F(1,1504)=23.30, *p*<.001; visual room size: F(1,1504)=34.74, *p*<.001), but no significant interaction (F(1,1504)=2.98, *p*=.084). All other interactions between auditory room size, visual room size, and seat location are not significant.

To further examine the effect, paired-sample t-tests were conducted between different auditory room size, and between different visual room size. The seat ratings are significantly different between the two auditory room sizes (*t*(791) = -6.33, *p* < .001), with the larger auditory room size preferred by a mean difference of 3.17. The seat ratings are also significantly different between the two visual room sizes (*t*(791) = -7.81, *p* < .001), with the larger visual room size preferred by a mean difference of 3.86. Together, this shows that on average across all seats, people prefer both the acoustics and the appearance of the larger auditorium.

As preference is a subjectively defined attribute, the preference of each individual participant is also examined in terms of the preference difference between the two room sizes (auditory and visual). Figure 5-8 shows each participant's mean preference difference between the larger and smaller auditory or visual room size as a correlation between visual and auditory preference differences. The values for each participant were calculated for all seats and both halls (for example, the visual preference difference for a participant is the mean difference between all the 12 × 2 seat ratings they gave in the two halls with larger visual room size, and the 12 × 2 seat ratings they gave in the two halls with smaller visual room size). A value of preference difference larger than 0 indicates that the larger hall is preferred by the participant. The number of people preferring the larger hall acoustically (24/33) and the number of people preferring the larger hall visually (25/33) are similar. However, the 8/33 who preferred the smaller visual hall to the larger one rated the two sizes of visual halls similarly, with a maximum difference of 1.96, which may possibly have been random error, as the differences between seats are generally much larger. This means that the people who rated the smaller visual hall higher did not have a strong preference for the smaller hall. In other words, all people who have strong visual preferences prefer the larger hall. On the other hand, the few participants (9/33) who preferred the smaller auditory hall showed relatively large rating differences, with a maximum difference of 9.42, meaning that although relatively few in number, there are some people who relatively strongly prefer the smaller auditory hall. It also shows that there is a moderate and highly significant positive correlation between auditory preference difference (i.e., large minus small) and visual preference difference (*r*=.587, *p*<.001). This indicates that people's preference for the different auditorium sizes are relatively consistent between auditory and visual perception, as those who rated the larger auditory room size higher also tended to rate the larger visual room size higher.

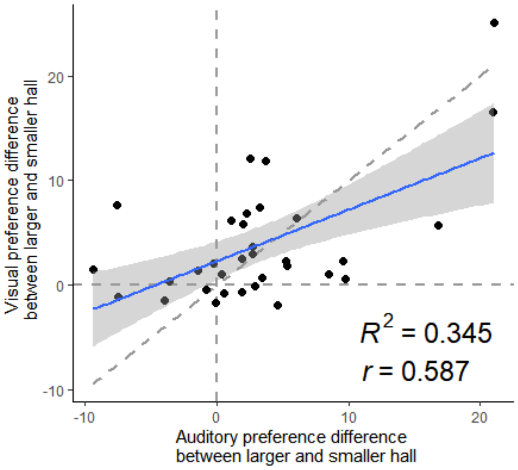


Figure 5-8 Mean difference of seat rating between larger and smaller auditory or visual room size for each participant: scatter plot and correlation of visual preference difference vs. auditory preference difference.

5.3.2.2 Congruent vs. incongruent auditory and visual room sizes

As previous research has found that congruent and collocated audio and vision triggers better audiovisual integration, the seat ratings were also compared between congruent auditory and visual room sizes (auditory and visual renders both of the larger hall, or both of the smaller hall) and incongruent auditory and visual room sizes (mismatched for size, with one of the visual and auditory render being the larger hall and the other the smaller). A two-way random-effects ANOVA was conducted with congruency and seat locations factors. While seat location still had a significant main effect (F(11,1528)=56.78, *p*<.001), whether the audiovisual room sizes were congruent or not only has a small non-significant effect (F(1,1528)=2.87, *p*=.090), with no interaction (F(11,1528)=0.51, *p*=.901). The independent t-tests between congruent and incongruent audiovisual room sizes also shows that there is no significant difference between them ($t(1581.7) = -1.19$, $p = .231$).

5.3.3 Between seats

5.3.3.1 Variance between halls and seats

The distributions of each parameter in the two concert hall simulations with matching audiovisual room sizes (Figure 5-9) showed that all geometric and visual parameters (distance, lateral angle, vertical angle, and obstruction) varied mostly between seats with no significant difference between halls. The acoustic parameter distributions included results from all 5 individual sources used for parameter calculation. Among the acoustic parameters, only reverberation parameters varied mainly between halls, with a mean difference of approximately 0.5 s for both EDT ($t(30.8) = 20.3$, $p < .001$) and T_{30} ($t(33.1) = 41.8$, $p < .001$), while the differences between seat locations were less than the just noticeable difference (JND) given in ISO 3382-1:2009. G and C_{80} varied both between seats and halls, but more between seats. All the other parameters varied mostly between seats, with no significant difference between halls. IACC did not vary much between any stimuli, and most of the differences were less than the JND. Therefore, it was excluded from the analysis.

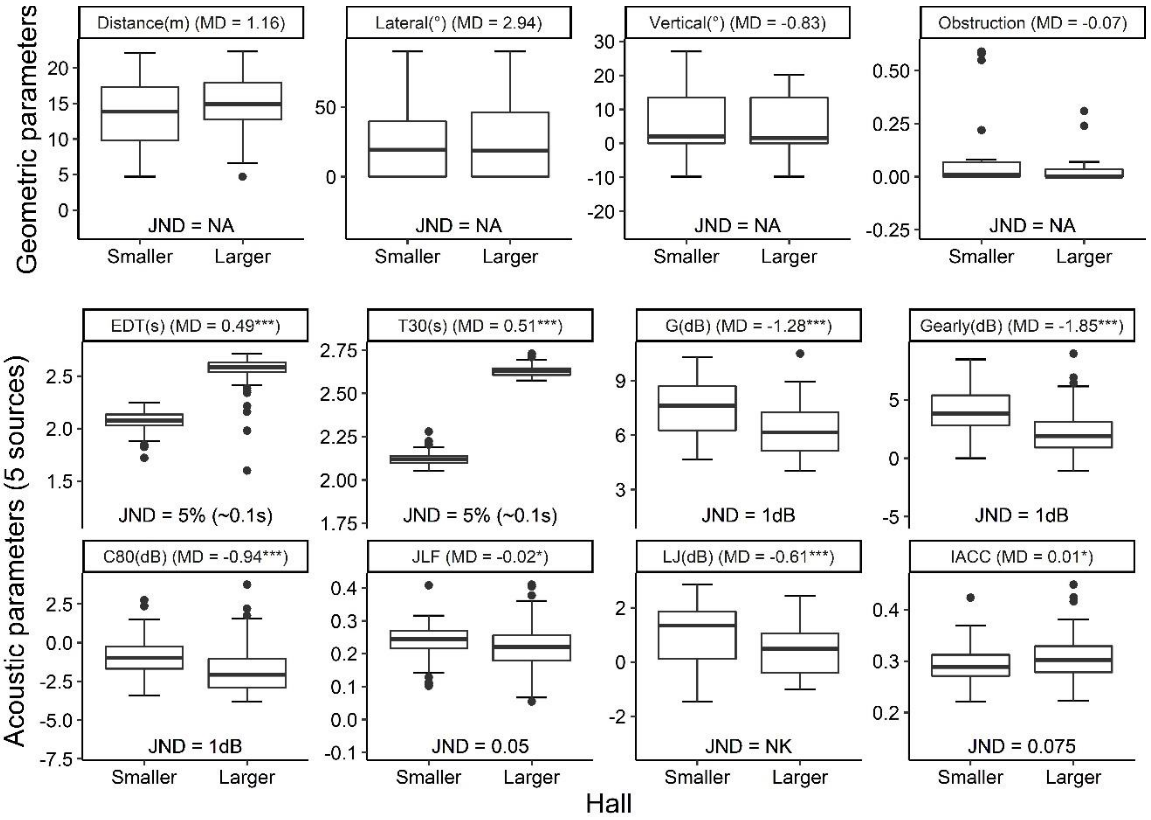
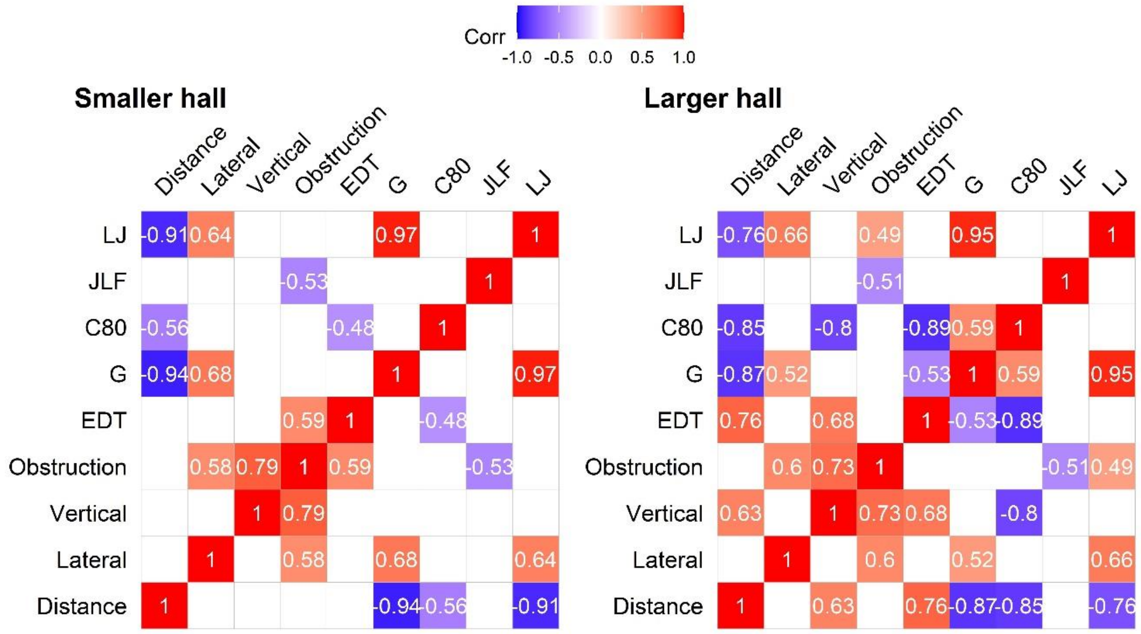


*Figure 5-9 Distribution boxplots of all seat parameters in each hall (see details in section 5.2.4 and Table 5-1) to compare variances between seats and between halls. The label of each plot shows the main difference (MD) between two halls, and results of independent t-tests between two halls (*p < .05; ** p < .01; *** p < .001).*

5.3.3.2 Relationship between parameters

Correlation tests were conducted for all parameters in each concert hall simulation with matching audiovisual room sizes excluding T_{30}, because its variation at different seats within each hall was less than the JND (Figure 5-10). Figure 5-10 shows the significant correlations ($p < .05$). In both halls, there were high positive correlations between the sound energy parameters (G and L_J), both of which were negatively correlated with distance, and moderately positively correlated with lateral angle, probably due to stronger reflection from the side walls. Visual obstruction showed a positive correlation with vertical and lateral angle, indicating that visual obstructions tended to occur at relatively high locations or locations closer to the side. C_{80} was negatively correlated with distance and EDT. J_{LF} was moderately negatively correlated with obstruction.



Smaller hall

	Distance	Lateral	Vertical	Obstruction	EDT	G	C80	JLF	LJ
LJ	-0.91	0.64				0.97			1
JLF				-0.53				1	
C80	-0.56				-0.48		1		
G	-0.94	0.68				1			0.97
EDT				0.59	1		-0.48		
Obstruction		0.58	0.79	1	0.59			-0.53	
Vertical			1	0.79					
Lateral		1		0.58		0.68			0.64
Distance	1					-0.94	-0.56		-0.91

Larger hall

	Distance	Lateral	Vertical	Obstruction	EDT	G	C80	JLF	LJ
LJ	-0.76	0.66		0.49		0.95			1
JLF				-0.51				1	
C80	-0.85		-0.8		-0.89	0.59	1		
G	-0.87	0.52			-0.53	1	0.59		0.95
EDT	0.76		0.68		1	-0.53	-0.89		
Obstruction		0.6	0.73	1				-0.51	0.49
Vertical	0.63		1	0.73	0.68		-0.8		
Lateral		1		0.6		0.52			0.66
Distance	1		0.63		0.76	-0.87	-0.85		-0.76

Figure 5-10 Correlation coefficient matrix between all seat parameters (including 4 geometric/visual parameters, and 5 acoustic parameters) within each concert hall simulation (with matched audiovisual room size). Only significant coefficients (p<.05) are shown. Red cells are positive correlations and blue cells are negative correlations, with the saturation of the colours representing the size of the correlation.

5.3.3.3 Effect of all parameters

A stepwise multiple linear regression of the effect of all parameters on the average evaluated preference score was calculated. The auditory and visual room sizes were also added as potential predictors. The final selected model included 6 predictors, $R^2 = 0.92$, $p < .001$. The coefficient, explained variance, and p-values of each predictor were given in Table 5-2, in the order of contribution. Lateral angle, distance, and obstruction all had negative coefficients, which agrees with previous studies including the Chapter 4 experiment (Jeon et al., 2008; Sato et al., 2012; Vaupel, 1998; Veneklasen, 1975). Vertical angle had a small positive coefficient, while previous studies found mixed results on the effect of vertical angle, including a positive effect mentioned by Veneklasen (1975), and negative effects found by Jeon et al. (2008) and Sato et al. (2012). This may be explained by the polynomial effect identified in the Chapter 4 experiment and the different ranges of stimuli in different studies. C_{80} had a negative coefficient, meaning that seats with lower direct-to-reverberant ratio are preferred. The visual room size of the larger hall had higher preference than the smaller hall, but audio room size did not have a significant effect. EDT, T_{30}, G, J_{LF}, and L_J did not have significant effects unique from the selected predictors. In general, geometric and visual parameters explained most of the variance in seat ratings.

Table 5-2 Final best-fit model of 6 predictors (all p<.001) selected from 11 parameters using stepwise regression. The 11 parameters include all 9 seat parameters (4 geometric/visual parameters and 5 acoustic parameters), auditory room size, and visual room size. Final model includes only 4 geometric/visual parameters, C_{80}, and visual room size.

Order	Predictor	Regression coefficient [95% CI]	Explained variance
	(Intercept)	2.220 [2.091, 2.350]	
1	Lateral angle	-0.018 [-0.019, -0.017]	39.1%
2	Distance	-0.141 [-0.150, -0.131]	32.4%
3	Obstruction	-3.032 [-3.339, -2.725]	11.0%
4	Vertical angle	0.039 [0.032, 0.045]	4.9%
5	C_{80}	-0.139 [-0.169, -0.110]	2.4%
6	Visual room size (large)	0.201 [0.153, 0.248]	2.2%
Residuals			8.0%

A stepwise regression using only the acoustic parameters and auditory and visual room sizes was also conducted. The best performance model consisted of C_{80} (coefficient 0.823), G (-1.456) and L_J (1.662), but the explained variance (R^2) was only 0.50, which was much lower compared to the stepwise regression result using all parameters. Also, G had a negative coefficient, which is contrary to most other findings (Chapter 4; Farina, 2001; Jeon et al., 2008; Sato et al., 2012; Sotiropoulou et al., 1995). This probably reflects the higher preference for the larger auditorium size, as the average G in the larger hall was lower, rather than the actual effect of G. Therefore, the results are not further detailed.

5.3.3.4 Comparison with predicted results

The predicted results for each seat were calculated using the prediction equation:

$$P = d(Distance) + l(|Lateral|) + v_1(Vertical) + v_2(Vertical^2) + a(Audio)$$

Equation 5-1

In which P is the seat preference prediction based on the effect of distance, lateral angle, vertical angle, and audio gain, d is effect of *Distance* (from the point of focus in meters); l is effect of *Lateral angle* (from the centre symmetric plane in degrees); v_1 and v_2 are the linear and quadratic effects of *Vertical angle* (from the horizontal plane in degrees); a is the effect of *Audio* (relative audio gain in decibels). $d = -0.0626$; $l = -0.0127$; $v_1 = 0.0613$; $v_2 = -0.0017$; $a = 0.0512$. The intercept from the original prediction model is left out because the subjective scales used in both experiments are arbitrary, and standardized results are used in the analysis. G_{early} (early sound strength in decibels) was used to represent the audio gain level because it is the acoustic parameter most related to the perceived direct sound level, and provides the best fitting with the results.

The average result of each location was plotted against the predicted result, and separated by hall number for clearer presentation (Figure 5-11). As visual obstructions were not included in the prediction calculation, the locations with obstruction were distinguished from the other locations with different colours, and excluded from the linear regression. The linear regression for all halls was added to each subplot for referencing between the subplots (black dashed line). The correlation coefficient between the predicted values and average results was 0.40 ($p < .001$), or 0.86 ($p < .001$) if the locations with visual obstructions are excluded.

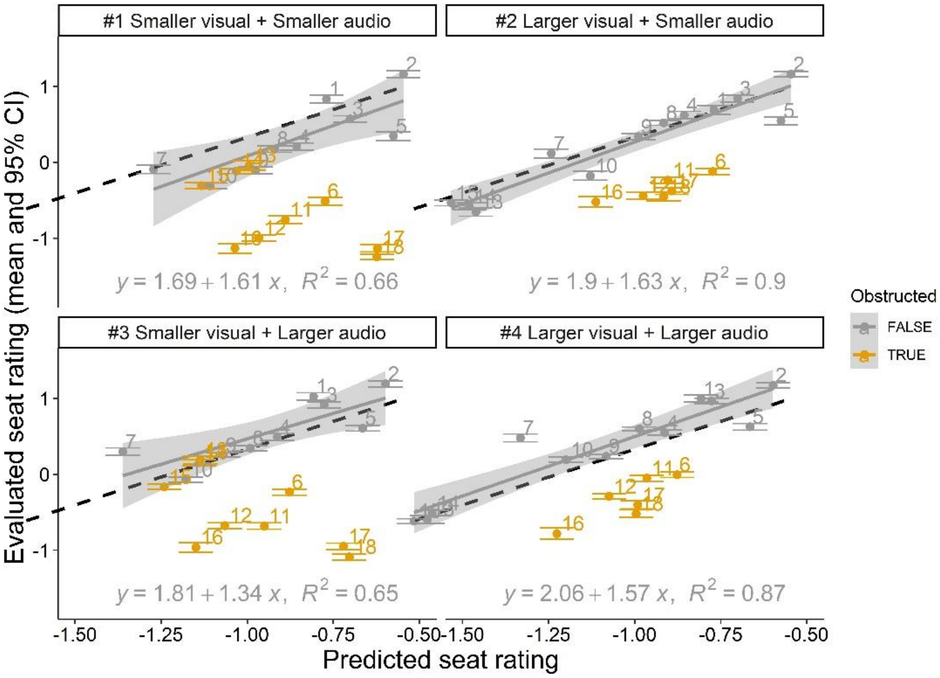


Figure 5-11 Evaluated seat ratings (mean and 95% confidence interval) plotted against predicted ratings based on Equation 1, separated by each virtual reality auditorium simulation. Black dashed reference lines (same in each subplot) are the linear regression line for all halls, shown for better comparison between halls.

With visual obstruction excluded, the predicted results roughly matched the evaluated results. All locations with visual obstruction had lower results than predicted, with larger differences for locations having more severe visual obstructions (e.g., locations 17 and 18 in the smaller hall). While the linear regression line for each hall was approximately parallel to the linear regression line for all halls, the intercept was different, and the preference for the larger hall was greater in terms of both auditory and visual room sizes. This means that there were differences in preference between the auditorium room sizes that were not related to seat location but to the overall impression of the auditorium.

Within each auditorium, the prediction results tended to overestimate for locations 5 and 10, and underestimate for locations 1, 2, and 7. The overestimated locations were the ones with the largest distances to the stage, while the underestimated locations were the ones with the smallest. In other words, the effect of distance was greater than predicted.

From the above observations, a modified prediction equation was calculated based on the original prediction equation, to include the effect of visual obstruction and to adjust for the underestimation of the effect of distance:

$$P_{adj} = d_{adj}(Distance) + l(|Lateral|) + v_1(Vertical) + v_2(Vertical^2) + a(Audio) + o(Visual\ obstruction)$$

Equation 5-2

In which P_{adj} is the modified seat preference prediction; d_{adj} is the adjusted effect of *Distance*; d_{adj} = -0.101; o is the effect of *Visual obstruction* (the proportion of stage obstructed by obstacles at the point of view); o = -2.01.

In addition, to include the effect of preference difference between the auditorium room sizes, different intercepts were used for different auditory and visual room sizes: 0 for smaller auditory room size, 0.190 for larger auditory room size; 0 for smaller visual room size, 0.129 for larger visual room size.

The correlation coefficients of the adjusted prediction values and the average results were 0.97 ($p < .001$) when using all locations. Figure 5-12 compares the predictions from the modified model (C) with the original model (B), together with the final model of the stepwise regression using all parameters given in Section 5.3.3.3(A). It shows that the modified prediction equation improved the accuracy of prediction to a large extent, and fits well for all locations both with and without visual obstruction. Compared to the stepwise regression using individual parameters, the modified equation derived from the pilot experiment with orthogonally controlled factors had a slightly better fit, but because of the method used, it is more likely to be compatible with other contexts.

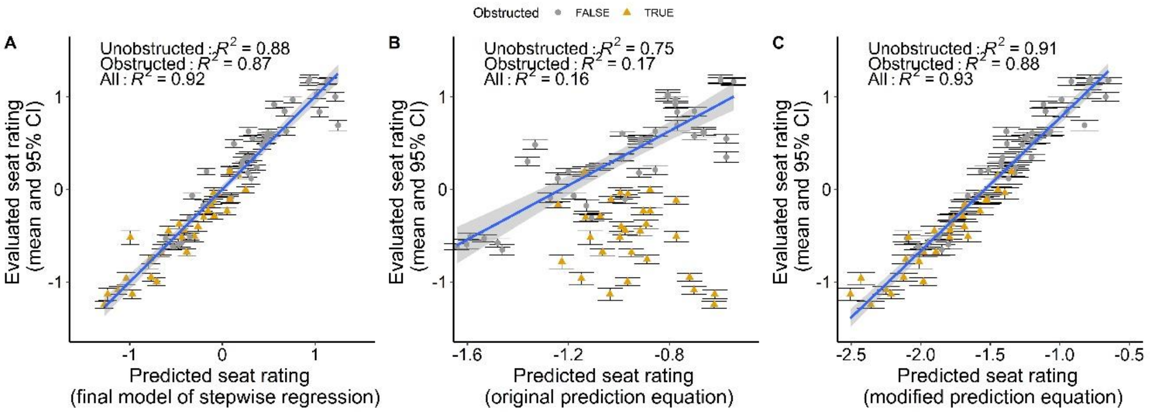


Figure 5-12 Evaluated seat ratings plotted against predicted ratings based on (A) final model of stepwise regression using all parameters, (B) original prediction model derived from the Chapter 4 experiment, and (C) modified prediction model with effect of obstruction, extra effect of distance, and effect of hall size.

To examine whether there were any additional effects from the rest of the acoustic parameters, EDT, C_{80}, J_{LF}, and L_J were added one-by-one to the prediction equation to test for statistical significance. T_{30} was not included because its variance within each auditory room size was less than the JND. None of the parameters yielded a significant effect or increased the explained variance by more than 0.1%.

Even though C_{80} was included in the final predictors of the stepwise regression, explaining 2.7% of variance, it did not have an additional effect that was not explained by the prediction equation. A possible explanation is that the stepwise regression considered linear effects only, while the prediction equation included polynomial effects of the vertical angle found in the orthogonally controlled Chapter 4 experiment. Therefore, C_{80} may have explained the additional variance that was missed by the first-degree model of vertical angle. To test that hypothesis, C_{80} was modelled as a second-degree polynomial in vertical angle to examine the significance of each degree, and both first-degree and second-degree coefficients were significantly different from 0 ($p < .001$). This provides evidence that the coefficient of C_{80} found in the stepwise regression was mainly caused by the polynomial effect of vertical angle, but not the acoustic parameter itself.

5.4 Discussion and conclusion

This chapter examined the subjective ratings of eighteen seat locations in four audiovisual concert hall simulations produced by combining two levels of visually defined auditorium size with two levels of auditorily defined auditorium size. The virtual auditoria were experienced using head-mounted virtual reality displays with headphone audio playback, and the study compared lab-based and remotely participating subjects. The main findings are discussed below.

In terms of average preference, there was no significant difference between the ratings of participants who did the experiment in the laboratory using calibrated VR headsets and headphones and those who did the experiment in their own environments using various VR headsets and headphones without calibration. This is a promising finding that opens up future research possibilities by showing the viability of remote virtual reality audiovisual experiments as a feasible alternative to traditional lab-based experiments in the context of this study. While our results only validated this method for the specific context of this experiment – for studying mean preference of people in two sizes of concert halls – it may encourage future studies to test this method on other similar audiovisual studies. It might be especially useful when an experiment requires a large sample size, when a target population is remote from a laboratory testing location, or when it is simply impractical to conduct lab-based experiments. Nonetheless, this is a very new method and more experimental studies will be needed to validate the method of remote audiovisual VR experiments in other experimental contexts and to establish the limitations. As the testing environment was an inter-participant factor in the current experiment, meaning that each participant only experienced one of the two environments, further tests may be needed to compare between the results of the same participants in different environments. In addition, only preference was studied in the current experiment, other attributes of room perception were not examined in the current study and will need to be examined in future experiments, especially the more subtle attributes that may have higher requirements on the listening environment (e.g., auditory source width). One practical limitation of this method is that the quality of the audio may be constrained because of online data transfer limits, so this may not suit experiments that use very large file size (e.g., very long audio files, a large number of audio files, or very high-quality audio files). Remote virtual reality audiovisual experiments would also not suit experiments where the absolute sound level is strictly controlled or is manipulated as part of the experimental design or where specific equipment is required.

Significant main effects were found for both seat location and the size of the auditorium (both auditory size and visual size) on the participants' ratings but no interaction between these factors. This means that the size of the auditorium environment does affect people's preference

– with larger halls being preferred both auditorily and visually – and that preference also depends on seat location within each auditorium, independently of the auditorium. These findings are consistent with a number of previous studies that have separately investigated seat preference (Chapter 4; Jeon et al., 2008; Sato et al., 2012) and auditorium preference (Barron, 1988; Beranek, 2012; Lokki, 2014), although fewer results have been established of the relationship between seat preference and auditorium preference (Lokki et al., 2016), and the current study is the first to examine this with both visual and auditory stimuli. It was also found that the variation in ratings between seat locations was generally larger than between auditoria. However, the effect sizes are related to the range of stimuli, as the seat locations were spread out across the whole auditoria, while the two auditoria were very similar and only differed in size. Using more drastically different auditoria could reveal a greater dependency of preference by auditorium than we report here (e.g., Lokki et al., 2016), especially given that seating layouts in most auditoria tend to be similar and so should produce relatively constant seating preferences. We also used VR to produce a more immersive 3D experience than was possible with the photographs or stereoscopic images used in most previous studies. The ease of manipulating the visual environment in VR will facilitate further exploration of preference variation due to seat location and auditorium.

Both auditory and visual auditorium sizes have significant main effects on the seat ratings, and people preferred both the audio and visual simulations of the larger hall over the smaller hall, but no interaction is observed. In other words, both the changes in visual environment and auditory environment have significant and separate effect on preference, but the larger hall was always preferred. The visual room size has a slightly larger effect than the auditory room size. All participants rated the two visual room sizes similarly or the larger hall higher and most participants rated the two auditory room sizes similarly or the larger hall higher, while a few participants rated the smaller auditory room size higher. A consideration here is that the smaller hall model (35 m × 18 m × 12 m) is relatively small in size compared to most other symphony concert halls (e.g., Wiener Musikverein: 49 m × 19 m × 18 m; Amsterdam Royal Concertgebouw: 44 m × 28 m × 17 m), due to the fact that the base auditorium is part of a conservatorium of music instead of a commercial auditorium. While the larger hall model (35 m × 28 m × 14 m) is still relatively small, it is closer to people's expectations for orchestral performance. This may be part of the reason why the larger hall is preferred for both visual and auditory room size. Further investigation of other auditorium sizes or interviews may be needed to confirm the explanations for the preference difference in different halls.

Both simulations that had mismatched auditory and visual dimensions (i.e., one large, one small) were preferred over the auditorium that was small in both sensory modalities. While this clearly underlines the preference for the larger of the two auditoria, it raises the interesting question of whether the participants were aware of the size mismatch. The same question is raised from the insignificant or small effect of audiovisual incongruency (section 5.3.2.2). If the participants did perceive the incongruency, then the preference for a larger auditorium is a powerful one that trumps the perceived mismatch in size. On the other hand, they may not have been aware of the size mismatch between the visual and auditory modalities, suggesting considerable malleability in the merging of auditory and visual representations of auditorium size. Our data cannot answer which was the case, however, it would be very interesting in future studies to investigate the relationship between the preference for larger auditoria and the perceptual threshold for noticing crossmodally mismatched sizes.

Data relating to congruent versus incongruent audiovisual stimuli in an auditorium context is scarce, with one study finding that incongruent audiovisual stimuli from different seat locations sometimes but not always results in lower plausibility (Postma & Katz, 2017), one finding that congruent or incongruent audiovisual stimuli from different rooms did not significantly affect distance or room size perception (Maempel & Jentsch, 2013), while another has shown that perception of reverberation in a variety of rooms is not affected when the visual dimensions are altered to make the visual room incongruent with the auditory one (Schutte et al., 2019). In the study of Jeon et al. (2008), when crossmatching 3 auditory and visual stimuli with different subjective preferences, a significant interaction was observed, although the effect size was very small compared to the main effects. All the above findings point to the hypothesis that audiovisual incongruency has little to no effect on perception in the context of auditoria. If the threshold for noticing an auditorium size difference between sensory modalities is large, then it would lend further weight to using virtual reality in audiovisual studies of auditoria as small errors or inconsistencies in size would not be a critical limitation.

One possible explanation for the insignificant or small effect of audiovisual congruency in the listed auditorium studies is the relatively small distinctions between the auditory stimuli, and the difficulty in auditory-based spatial judgements. Compared to most psychology experiments investigating audiovisual interaction which usually have very clear and distinguishable sound sources (e.g., Battaglia et al., 2003; Frassinetti et al., 2002), the acoustic environments in auditoria are much more complex with numerous reflections and late reverberation, increasing the difficulty for auditory localization or environment recognition. Past studies have found that auditory-perceived room size of the same room dimensions is significantly different when varying reverberation time, source-receiver distance, or the type of sound source (Cabrera & Jeong, 2007; Cabrera et al., 2005; Kolarik et al., 2021), and auditory-perceived distance is also much less accurate compared to visual-perceived distance (Anderson & Zahorik, 2014; Maempel & Jentsch, 2013) and is significantly affected by sound pressure level (Cabrera et al., 2005; Kuusinen & Lokki, 2015) and visual input (Anderson & Zahorik, 2014; Calcagno et al., 2012). On the other hand, the combined audiovisual perception of distance and room size in simulated auditoria depends 90% on visual input and only 10% on auditory input (Maempel & Horn, 2022). Due to the large variance and general inaccuracy of auditory spatial perception, the audiovisual incongruency may not have been perceived as incongruent by the participants. This may prompt future studies to investigate the perception of incongruency along with preference to confirm the extent of incongruency perceived by the participants when using different stimuli, and the relationship between perceived incongruency and preference.

The most influential predictors for subjective preference are geometric parameters (distance, lateral angle, vertical angle, and visual obstruction), and the final prediction model that has an R2 of 0.93 with the subjective evaluations only consists of the abovementioned parameters, Gearly, and audiovisual simulations, with no other acoustic parameters. This indicates that when comparing between different seats within an auditorium, the less-studied visual preference in auditoria may have more effect on people’s overall enjoyment than usually believed, and calls for more research in this area. However, in the current experiment using realistic concert hall simulations where the audiovisual seat locations change correspondingly, seat location (defined by the geometric parameters) affects both visual and auditory input. Many of the parameters covary between seats, and some acoustic parameters (e.g., G, C80, LJ) are correlated with distance or lateral angle. Therefore, the effect of auditory perception on preference may have been already accounted for by the effect of geometric parameters. This can also be shown in the result that G was not included in the final model of stepwise regression. However, G was included in the prediction equation because its effect was found separately from distance in the Chapter 4 experiment with orthogonally controlled factors. While other parameters may also be investigated further by individual controls, it is difficult to do so due to the complexity of sound fields and correlations between acoustic parameters. Though some studies have tried to control some acoustic parameters individually and orthogonally (e.g., Ando, 1983; Chapter 4), it can only be done using signal processing methods and not realistic simulations, and only for limited parameters. Another potential influential factor is that visual perception of location and distance also affects auditory perception, especially on perceived location of source and loudness, which have both been found to affect preference (Kuusinen & Lokki, 2015; Chapter 4).

The finding that other acoustic parameters such as EDT, RT, C80 and IACC did not exhibit significant effects on between-seat ratings in addition to the effects of geometric parameters and sound strength aligns with other single-auditorium audiovisual experiment results from Jeon et al. (2008) and Sato et al. (2012). However, those parameters were found to affect preference when comparing between different concert halls (Ando, 1983, 2014; Barron, 1988; Beranek, 2012; Farina, 2001; Hidaka & Beranek, 2000; Schroeder et al., 1974), and in the current experiment the difference between the two auditory room sizes was larger than that between the two visual room sizes. This may suggest that acoustic parameters have more effect on inter-auditorium preference, but when comparing between different seats within one auditorium, the variance in the acoustic parameters is relatively small and more difficult to discern, so people tend to use visual input and loudness, which have more obvious differences, for preference judgements. This hypothesis is also supported by previous studies which found that geometric estimations, such as distance perception and room size perception, depend mainly on visual input as it provides much better accuracy (Maempel & Horn, 2022; Zahorik, 2001), and by a survey in which participants reported to be making seat selections mainly based on the view (Kawase, 2013).

The effect of distance in the current study is larger than in the Chapter 4 experiment. This may be related to the differences between stimuli used in the current experiment and the Chapter 4 experiment from which the prediction equation was derived. First, the current experiment visually rendered the complete architectural interior of the auditorium, while the Chapter 4 experiment only rendered the stage against a black background. It has been found that visual environmental cues and context are important for distance judgements (Lappin et al., 2006; Sinai et al., 1998; Tai & Inanici, 2009; Witt et al., 2007). When given a fixed limited angle of view (which is similar to the condition of stage-only against a black background), people tend to underestimate distances (Creem-Regehr, 2005). Greater illumination contrasts between the target and environment also result in shorter perceived distance (Tai, 2013; Tai & Inanici, 2010), and presenting a stage against a completely black background can also be considered an extreme case of high illumination contrast with the environment having no illumination.

Therefore, the distance to stage may have been underestimated in the Chapter 4 experiment, yielding a model that underestimated the effect of distance. This explanation also agrees with the finding in the Chapter 4 experiment that the prediction model derived from the Chapter 4 experiment matches well with the subjective ratings in an experiment by Jeon et al. (2008) while a multiplication factor of 1.5 was needed on the coefficient of distance for the prediction model to match the results of Sato et al. (2012), as the photos provided by Jeon et al. only consist of the stage while the photos provided Sato et al. contain environmental context of the auditorium. Second, the maximum distance in the experiment from which the prediction was derived was 30 m, while for the current experiment it was approximately 22 m. Another possible contributory factor is that people may scale their evaluation based on the available stimuli. Third, the auditory stimuli in the Chapter 4 experiment varied independently from visual distance, while in the current study, the auditory and visual stimuli always covaried between seats. While visual distance perception is much more accurate than auditory distance perception, it may still be slightly affected by auditory perception, which tends to underestimate in reverberant environments and when the source-receiver distance is large (Anderson & Zahorik, 2014; Zahorik, 2001).

While it is commonly known that visual obstruction negatively affects preference (Chen & Fearnside, 2019; Burris-Meyer & Cole, 1964; Jeon et al., 2008; Russell, 1838), the current study is the first to quantify this effect in relation to the effects of other factors. The quantification method with a linear negative effect can predict the effect of obstruction well in conjunction with the geometric parameters. As detailed in 2.2 and 4.2.2, the visual obstruction is calculated for the orchestra and a 0.6 m of extra margin around the orchestra. This means that it is not only when the view of the orchestra is obstructed that the preference is negatively affected. Even when the whole orchestra is visible, visual obstructions of stage areas adjacent to the orchestra would also degrade the viewing quality. This may be explained by people's expectations of audience obstruction, as the current experiment did not include any other audience members, and when architectural elements (e.g., balcony railings) are already blocking the view of parts of the stage, it would be expected that when the hall is occupied, audience members sitting in front of the viewer are likely to obstruct view of the orchestra. This hypothesis may be tested in future experiments with models of other audience members included.

Limitations of the current study are mainly related to the methods of using virtual reality audiovisual simulations. Even though the virtual environment was modelled to match the physical hall in terms of size, material, decoration, lighting, and acoustics, it was still different from the real environment due to computer rendering, head-mounted display, digitally generated audio, and headphones playback. The orchestra model used was a static 3D orchestra, while in real situations the orchestra would have visible movements and human expression matching the sound. In addition, the simulations do not contain other audience members, which is seldom the case in real concerts, and the presence of other audience members may affect the perception of the performance and preference. Whether the obstructions from other audience members have the same effect as the obstructions from architectural elements needs to be examined in future experiments. In terms of audio rendering, the audio format used was first-order Ambisonics. Even though it contains some spatial information, there is still some information loss which may potentially result in lower realism and affect spatial perception compared to higher-order Ambisonics or real situations (Neal & Vigeant, 2015). The binaural decoding was done using a generic HRTF, which may affect localization and spatial perception compared to individualized HRTFs or real situations (Begault & Wenzel, 2001). It is possible that larger effects of other acoustic parameters may be detected if using more advanced auralization techniques.

The main conclusions of this chapter are: 1) there was no significant difference between the results remote participants and lab-based participants, supporting the viability of conducting this type of audiovisual experiments remotely; 2) both visual and auditory auditorium sizes have significant main effect on seat preferences within an auditorium but not interaction, and no significant difference was found between congruent and incongruent audiovisual room sizes; 3) the prediction model derived from the orthogonally controlled Chapter 4 experiment with no environmental information matches relatively well with the results from realistic concert hall simulations, but modifications were needed to compensate for the underestimation of distance in a context-free environment.

Chapter 6 The effect of auditorium on visual preference of hall and seats

This chapter compares between the preference of seats and halls in various visual auditoria of different sizes, colours, and occupancies, and verifies the prediction model from Chapter 5 in various scenarios, through the fourth and last experiment.

6.1 Introduction

The last two chapters describe the process of deriving and modifying a prediction equation for seat preference in concert halls, through two virtual-reality experiments. The orthogonally controlled experiment in Chapter 4 examined the separate effects of three geometric parameters (distance, lateral angle, and vertical angle), and audio gain, and the realistic simulation experiment in Chapter 5 verified these effects in realistic auditorium environments, adjusted the effects of distance, and added the effects of obstruction. However, while the modified prediction equation in the Chapter 5 experiment fits the results well, there are still some unanswered questions, some of which are explored and verified in this experiment.

First, the effect of distance was larger in the third experiment with realistic auditorium renders compared to in the second experiment with only the stage in a black background. However, the range of distances of the locations used in the two experiment was also different (up to 30 m in the second experiment, up to 22.1 m in the third experiment), and may also have affected the results. Whether the difference was caused by the presence of visual environment, the range of stimuli, or the relationship between visual and auditory stimuli is uncertain.

The range of lateral angles tested in the last two experiments was up to 90°, while in some concert halls, especially vineyard style designs, there can be seats at the side and back of the stage. Whether the prediction equation is still valid for lateral angles larger than 90° needs to be verified.

Also, both experiments used visual renders of empty auditoria, whereas real concerts have occupied auditoria. In the Chapter 5 experiment, it was found that even when view of the whole orchestra is unobstructed, obstruction of stage area adjacent to the orchestra also negatively affected preference, and a hypothesis was proposed that people may be affected by expectations of other audience members. Whether obstructions caused by audience members have the same effect as obstructions caused by architectural elements needs to be examined.

In addition, the results of the Chapter 4 study using the same base auditorium showed that different auditorium colours affect visual preference, but whether it has effect on seat preference, and how the effect of auditorium colour compares with other factors, remain unknown.

In order to answer these questions, the current experiment was designed with a range of different auditoria, to test the effect of various visual factors on visual seat preference.

6.2 Method

In this experiment, 30 participants evaluated their personal preference for 6 seat locations each in 12 variations of an auditorium (a total of 72 distinct stimuli) and their overall preference for each auditorium, based on head-mounted virtual reality display of computer-rendered 3D models with no auditory stimuli.

6.2.1 Auditorium models

Parametric models were built based on the base auditorium used in the last chapter with individually controlled parameters. Twelve variations of the auditorium were chosen to test for different effects (Table 6-1). The “Original” model has approximately the same dimensions and designs as the base auditorium and the “Original” model in the Chapter 5 experiment. To limit the experiment time for each participant, only 6 seat locations were chosen in each auditorium, which location numbers 1 to 6 respectively corresponds to seat number 1, 3, 6, 8, 15, and 17 in the Chapter 5 experiment. The first 3 variations (halls 2-4) were scaled in width, length, and height, respectively, to test the effect of the range of stimuli (auditorium dimensions). The “Wide” model had similar width to the “Large” model in the Chapter 5 experiment. In all three models, the seat locations were scaled proportionally. Because the dimension of the stage was kept the same in the “Long” model for realism (15 m depth), the length of the audience area was scaled by 5/3 (from 15 m length to 25 m), and the seat locations were scaled proportionally to the audience area. The “High” model has a height of 6/5 times the “Original” height, with the seating rake scaled proportionally while keeping the same level at the bottom of the stalls. Halls 5 and 6 rendered the stage against a black background without auditorium like in the Chapter 4 experiment, while the seat locations were the same as “Original” and “Long” models, to test the effect of visual environment. Halls 7 and 8 had the same models as “Original” and “Wide”, with only the seat locations 1, 3, and 5 and three additional seats on the side and back of the stage, to test the validity of the prediction equation on surround locations. Halls 9 and 10 had the same models as “Original” and “High”, but with rendered audience models at each seat, to test the effect of audience obstruction. Halls 11 and 12 had the same model as “Original” but with different interior design colours, which are similar to the “Neutral” and “Green” auditorium in the previous study (Chapter 3), to test the effect of auditorium design on seat preference. The red colour theme of the “Original” model and the green colour theme of the “Green” model are the most and least favourite colours in the previous study, and so their inclusion was also to be able to quantitatively unite the results of both studies. The location and visual obstruction parameter of each seat location are given in Table 2.

Table 6-1 Parametric model settings for the current experiment

No.	Testing goal	Model	Change	Length	Width	Height
1	Reference	Original	\	30	18	12.5
2	Effect of dimensions	Wide	3/2 width	30	27	12.5
3	Effect of dimensions	Long	4/3 length (seat locations scaling by 5/3)	40	18	12.5
4	Effect of dimensions	High	6/5 height	30	18	15
5	Effect of visual environment	Original stage	Black background	\	\	\

6	Effect of visual environment	Long stage	Black background + seat locations scaling by 5/3	\	\	\
7	Preference for surround locations	Original surround	Including seats on choir	30	18	12.5
8	Preference for surround locations	Wide surround	Including seats on choir + 3/2 width	30	27	12.5
9	Effect of audience obstruction	Original audience	Including full audience	30	18	12.5
10	Effect of audience obstruction	High audience	Including full audience + 6/5 height	30	18	15
11	Effect of colour	Original green	Green auditorium	30	18	12.5
12	Effect of colour	Original neutral	Neutral coloured auditorium	30	18	12.5

The seat locations used in each auditorium, with the geometric information (distance, lateral angle, and vertical angle), together with the extent of visual obstruction and a short description of the location, are given in Table 6-2.

Table 6-2 Coordinates and parameters (geometric) of each location in the current experiment (D: Distance to stage; L: Lateral angle from symmetric axis; V: Vertical angle from stage level; VO: Visual obstruction, proportion of orchestra area invisible from the location). An indicative description of the location is provided.

Hall No.	Model	Seat No.	D (m)	L (°)	V (°)	VO	Location description
1	Original	1	4.9	0.0	-8.3	0.00	Stalls front
		2	13.8	0.0	0.0	0.00	Stalls back
		3	21.8	0.8	14.4	0.05	Back balcony
		4	10.6	26.3	-1.6	0.00	Stalls side
		5	14.9	31.2	1.5	0.02	First side gallery
		6	10.6	51.8	25.2	0.33	Second side gallery
2	Wide	1	4.9	0.0	-8.3	0.00	Stalls front
		2	13.8	0.0	0.0	0.00	Stalls back
		3	21.8	0.8	14.4	0.05	Back balcony
		4	11.7	35.6	-1.5	0.00	Stalls side
		5	17.0	41.7	1.3	0.00	First side gallery
		6	13.3	61.8	19.8	0.10	Second side gallery
3	Long	1	7.8	0.0	-5.1	0.00	Stalls front
		2	22.8	0.0	0.0	0.00	Stalls back
		3	32.5	0.5	10.1	0.00	Back balcony
		4	16.3	16.8	-1.4	0.00	Stalls side
		5	22.1	20.4	1.0	0.02	First side gallery
		6	13.2	37.1	19.9	0.33	Second side gallery
4	High	1	4.9	0.0	-8.3	0.00	Stalls front
		2	13.8	0.0	0.8	0.00	Stalls back
		3	22.3	0.8	17.8	0.04	Back balcony

		4	10.6	26.3	-1.1	0.00	Stalls side
		5	14.9	31.2	1.5	0.02	First side gallery
		6	11.1	51.8	30.4	0.41	Second side gallery
5	Original stage	1	4.9	0.0	-8.3	0.00	Stalls front
		2	13.8	0.0	0.0	0.00	Stalls back
		3	21.8	0.8	14.4	0.00	Back balcony
		4	10.6	26.3	-1.6	0.00	Stalls side
		5	14.9	31.2	1.5	0.00	First side gallery
		6	10.6	51.8	25.2	0.00	Second side gallery
6	Long stage	1	7.8	0.0	-5.1	0.00	Stalls front
		2	22.8	0.0	0.0	0.00	Stalls back
		3	32.5	0.5	10.1	0.00	Back balcony
		4	16.3	16.8	-1.4	0.00	Stalls side
		5	22.1	20.4	1.0	0.00	First side gallery
		6	13.2	37.1	19.9	0.00	Second side gallery
7	Original surround	1 (Original 1)	4.9	0.0	-8.3	0.00	Stalls front
		2 (Original 3)	21.8	0.8	14.4	0.05	Back balcony
		3 (Original 5)	14.9	31.2	1.5	0.02	First side gallery
		4	11.2	132.2	23.7	0.38	Balcony on side of stage
		5	13.0	179.6	11.1	0.00	Choir seating behind stage
		6	14.2	157.7	11.4	0.00	Choir seating behind stage
8	Wide surround	1 (Wide 1)	4.9	0.0	-8.3	0.00	Stalls front
		2 (Wide 3)	21.8	0.8	14.4	0.05	Back balcony
		3 (Wide 5)	17.0	41.7	1.3	0.00	First side gallery
		4	13.8	121.9	19.0	0.17	Balcony on side of stage
		5	13.0	179.6	11.1	0.00	Choir seating behind stage
		6	15.4	148.2	10.5	0.00	Choir seating behind stage
9	Original audience	1	4.9	0.0	-8.3	0.21	Stalls front
		2	13.8	0.0	0.0	0.46	Stalls back
		3	21.8	0.8	14.4	0.62	Back balcony
		4	10.6	26.3	-1.6	0.33	Stalls side
		5	14.9	31.2	1.5	0.13	First side gallery
		6	10.6	51.8	25.2	0.34	Second side gallery
10	High audience	1	4.9	0.0	-8.3	0.25	Stalls front
		2	13.8	0.0	0.8	0.43	Stalls back
		3	22.3	0.8	17.8	0.34	Back balcony
		4	10.6	26.3	-1.1	0.37	Stalls side
		5	14.9	31.2	1.5	0.13	First side gallery

		6	11.1	51.8	30.4	0.41	Second side gallery
11	Original green	1	4.9	0.0	-8.3	0.00	Stalls front
		2	13.8	0.0	0.0	0.00	Stalls back
		3	21.8	0.8	14.4	0.05	Back balcony
		4	10.6	26.3	-1.6	0.00	Stalls side
		5	14.9	31.2	1.5	0.02	First side gallery
		6	10.6	51.8	25.2	0.33	Second side gallery
12	Original neutral	1	4.9	0	-8.3	0	Stalls front
		2	13.8	0	0	0	Stalls back
		3	21.8	0.8	14.4	0.05	Back balcony
		4	10.6	26.3	-1.6	0	Stalls side
		5	14.9	31.2	1.5	0.02	First side gallery
		6	10.6	51.8	25.2	0.33	Second side gallery

6.2.2 Audience model

In order to simulate the effect of audience obstruction, models of seated people were built for each seat in the audience area. To make the audience models less distracting for the participants, the models are made up of simple geometries, but with randomly assigned clothes colours (60% black, 40% other HSV colours with randomized hue, saturation, and value), hair colour (40% black, 40% brown, and 20% grey), and hair shape (50% long and 50% short). When the participant is sitting at one of the seats in the auditorium, the corresponding audience member model is hidden. The height of the eyes of the audience models matches approximately the height of the eyes of the seated participants in the VR environment.

Figure 6-1 Screenshot of auditorium models with full audience (left: view of the auditorium; right: view from one of the tested seats)

6.2.3 Procedure

All participants completed the current experiment in the laboratory with an HTC Vive VR headset. No auditory stimulus was used, but the room was kept at a very low background noise level to prevent any noise from distracting the participants.

Each participant experienced all 12 concert halls × 6 locations = 72 visual stimuli. Similar to the Chapter 5 experiment , they started at a random location in a random scene, and used the VR controller to switch between the seat locations and the auditoria and give each seat a score out of 0 to 100 based on their preference. In addition, they were asked to give a "hall score" out of 0 to 100 for the overall preference of each scene.

Because there are many more scenes than the Chapter 5 experiment , to make it easier for the participants to know which scene they wish to switch to, the "switch auditorium" button in the menu would bring out a panel of thumbnail pictures of each auditorium, along with any "hall scores" that they have already given. The order of the halls in the panel display was randomized for each participant to limit ordering effect. Similar to the Chapter 5 experiment , they could visit a hall or seat multiple times and change the scores they gave, up to the point that they were satisfied with all the scores that they gave and exported the results. The result files contain the scores for each seat and each hall, and the total time spent on each seat.

Figure 6-2 Auditorium selection panel with given "hall scores"

6.2.4 Participants

30 participants took part in the experiment. The age of the participants ranges from 19 to 70 (*M* = 37.1, *SD* = 13.1). The average time each participant spent on the experiment was 31.6 minutes (*SD* = 16.5 min), and average time spent on each seat was 26 seconds. The average time spent for the current experiment is shorter than the Chapter 5 experiment because the current experiment did not include auditory stimuli.

6.3 Results and discussion

Cronbach's α (Cronbach, 1951) was calculated for all participants' seat preference and hall preference rating, and yielded 0.92 and 0.62, respectively. While the internal consistency for seat preference was excellent, it was only medium for hall preference. This means that compared to seat preference, people's preferences for auditoria are more divided. This indicates that preference for different auditoria is more subjective, while the perceived quality of view at different seats within one auditorium varies less between people. This supports the validity of the seat preference prediction models, as even though preference is a subjective matter, in terms of visual seat preference, it does not vary much between people.

6.3.1 Hall preference results

6.3.1.1 Overall results

The average "hall score" of each scene, along with the average seat preference score, are plotted in Figure 6-3.

With the geometry change, the "Original" is the most preferred, followed by "High", "Wide", and "Long". However, both "High" and "Wide" has higher average seat preference than "Original". The difference in average seat preference is likely to be caused by less visual obstruction, especially for the seats on the side balconies in the "Wide" hall due to the change of angle, and the seats on the back balconies in the "High" hall due to the change of rake. However, people still prefer the look of the "Original" hall most. This could be related to the proportions of the auditoria, or simply people's familiarity, as the "Original" is based on an existing auditorium in the same city where the experiment was conducted.

Both halls without visual environment ("Original stage" and "Long stage") have lower hall preference but higher average seat preference compared to those with visual render of the auditoria ("Original" and "Long"). The higher average seat preference may be related to the absence of visual obstruction, as the architecture elements that cause view obstruction in the auditoria (e.g., balcony railings) are not present. However, people still like the halls with the visual environment, as the auditorium itself was found to be an important part of the concert-going experience (Chapter 7).

Both halls with surround locations are rated lower than their counterparts in both hall preference and average seat preference. The same goes for the halls with audience. The "Neutral" model is less favourable than the "Original" (red), and the "Green" model is the least favourable of all auditoria, which matches the findings in Chapter 3, and puts the effect of colour in context in comparison with other factors. The same trend can be observed for average seat preference, but the difference between seat preference is much smaller than between halls, meaning that preference for auditorium interior design would affect preference for individual seats within the auditoria to a smaller extent.

While there are some different trends between the average seat preference and hall preference, the two are positively correlated. The correlation coefficient between the average seat preference of each hall and the hall preference is .58 (p<.001) for all participants, and .62

(*p*=.031) for the average values of all participants. This means that there is a small tendency that the average seat preference is higher for halls with higher preference. When comparing halls with same seat locations but only differ in colour ("Original", "Original green", and "Original neutral"), the same tendency is found (*r*=.52, *p*<.001 for all participants), indicating that preference for halls affects preference for seats. The same goes for halls that look almost identical but have different seat locations ("Original" and "Original surround": *r*=.45, *p*<.001; "Wide" and "Wide surround": *r*=.57, *p*<.001), indicating the preference for seats the participants experienced in each hall also affect preference for the hall. Even though the correlations are not very high, they are all statistically significant. This shows that seat preference and hall preference have mutual positive effect.

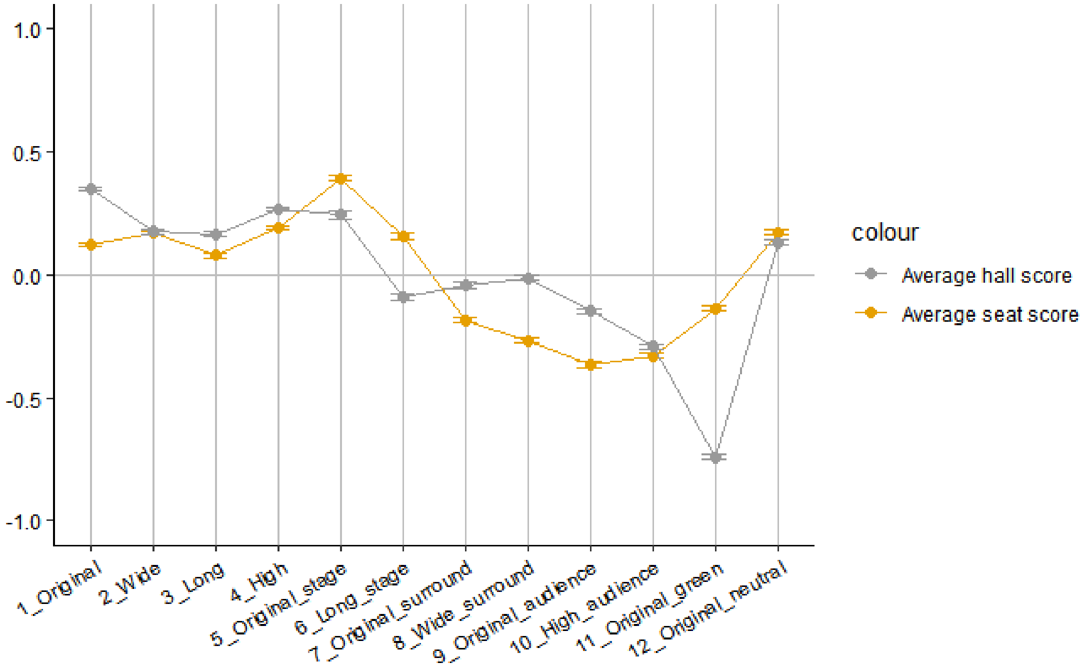


Figure 6-3 Average hall preference and seat preference in each scene (error bars are 95% confidence intervals)

6.3.1.2 Difference between individuals

As there are larger differences between individual preferences for different auditoria, the hall preferences of each participant are separated. Each participant's preference for each hall together with the average preference for each hall are plotted in Figure 6-4.

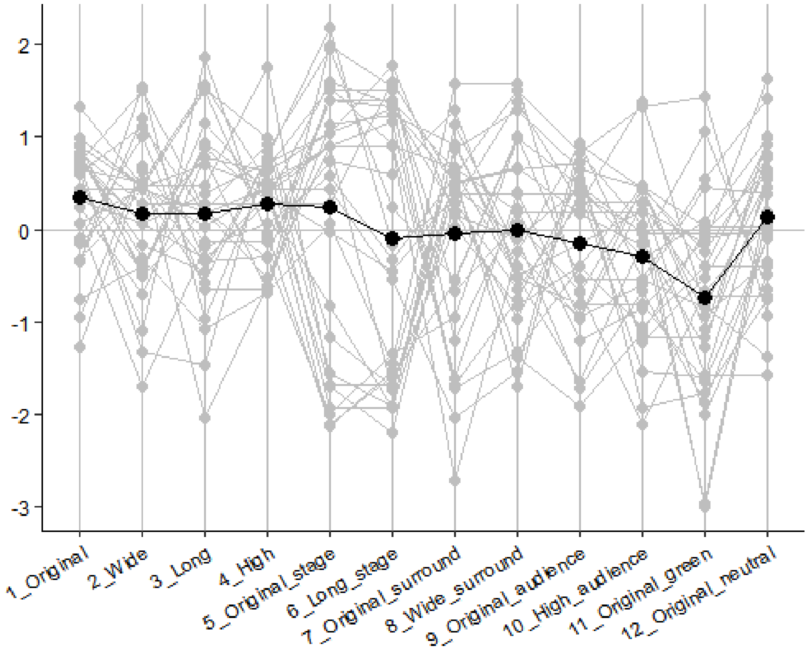


Figure 6-4 Individual hall preference of all participants (grey) and average preference (black)

While the results are generally scattered for all halls, opinions are the most divided for the two halls with stage only and no visual environment (halls 5 and 6). While their average preferences are both lower than "Original", some participants rated them as their favourite halls. Preferences for "Original surround" and both halls with different colours are also relatively scattered, but most people rated "Original green" lower, which matched the finding from the first experiment (Chapter 3). For all halls, there are people who liked them and people who disliked them. This confirms that visual preference for different halls is very subjective and differs between people.

6.3.2 Seat preference results

6.3.2.1 Overall results

The average result of each unique stimulus is plotted in Figure 6-5, separated by the testing goals. An additional plot is added for the comparison between the same locations in the Chapter 5 experiment.

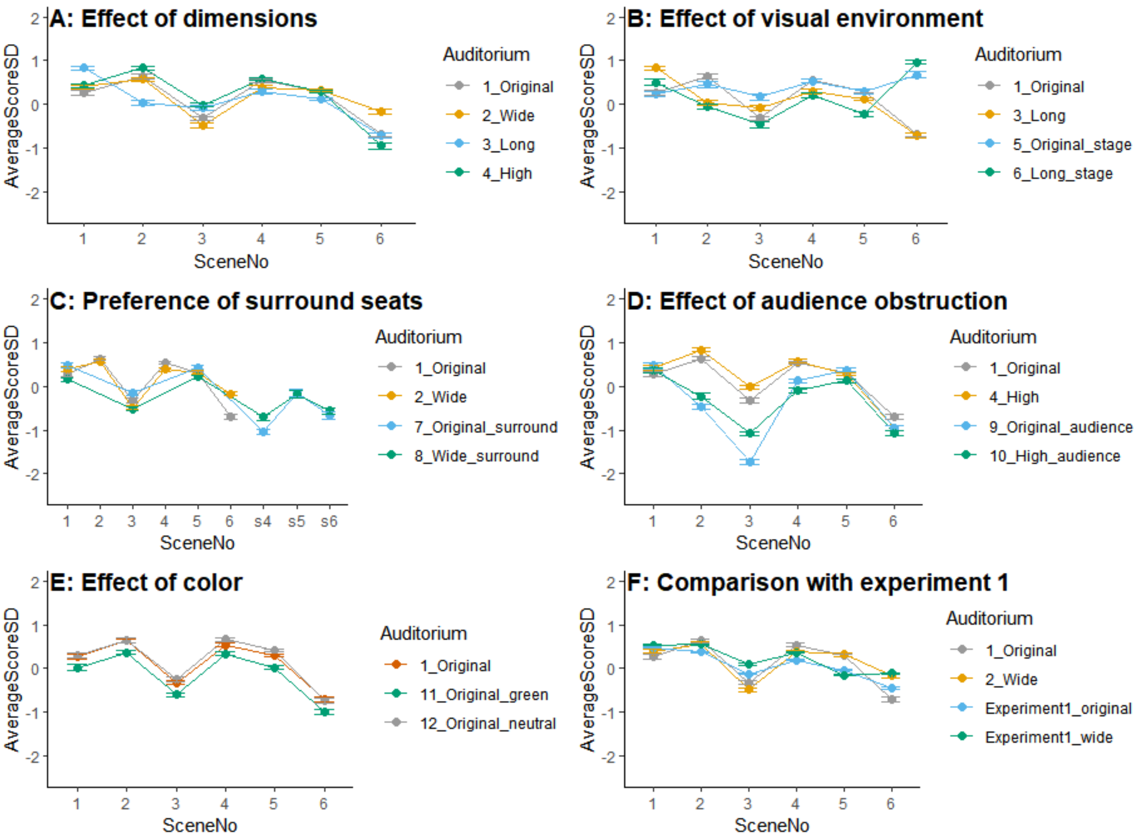


Figure 6-5 Average result of each stimulus separated by testing goals

Figure 6-5(A) shows that the seat preferences for the “Original”, “Wide”, and “High” halls were very similar. The “High” hall has slightly higher ratings than the “Original” at location 3 (back balcony, paired-sample t-test: $M_{dif} = 0.31$, $t(29) = 2.32$, $p = .027$), and slighter lower ratings at location 6 (second floor side balcony, $M_{dif} = 0.26$, $t(29) = 1.90$, $p = .068$). This matches expectation because the optimal vertical angle was found to be about 18° (Chapter 4; Chapter 5), so the increased vertical angle improves the condition for location 3 (from 14.4° to 17.8°), but degrades the conditions for location 6 (from 25.2° to 30.4°), and the other locations have similar vertical angles between the two models. The “Wide” hall only has a higher rating at location 6 than “Original” ($M_{dif} = 0.53$, $t(29) = 2.96$, $p = .006$), which is probably due to the decrease of visual obstruction. The “Long” hall has a higher rating at location 1 ($M_{dif} = 0.56$, $t(29) = 3.82$, $p < .001$) and lower rating at location 2 ($M_{dif} = 0.60$, $t(29) = 3.35$, $p = .002$). Location 1 is slightly further from the stage but still very close, and has a higher vertical angle which leads to higher preference. While the prediction equation for the effect of distance is linear, the results of the Chapter 4 experiment did show slight trend that the locations too close to the stage may receive lower ratings, which may have also contributed to this difference. Location 2 only differs in distance, with 13.8 m for the “Original” hall and 22.8 m for “Long”, which was likely the main cause for the higher preference in “Original”.

Figure 6-5(B) shows that the models with or without rendering of the auditorium are very similar for the “Original” hall, apart from locations 3 ($M_{dif} = 0.49$, $t(29) = 2.02$, $p = .053$) and 6 ($M_{dif} = 1.38$, $t(29) = 5.99$, $p < .001$) for which the stage-only model has much higher ratings, probably due to the absence of obstruction. The stage-only model for the “Long” hall is only higher at location 6 ($M_{dif} = 1.67$, $t(29) = 8.16$, $p < .001$), and slightly lower at locations 3 and 5, though mean differences are not statistically significant ($M_{dif} = 0.38$, $t(29) = 1.77$, $p = .088$; $M_{dif} = 0.34$, $t(29) = 1.90$, $p = .068$). These two locations have a relatively long distance to stage, so this may be evidence for the effect of visual environment on distance perception.

In Figure 6-5(C), the first three locations in “Original surround” and “Wide surround” are plotted with the matching locations in “Original” and “Wide” (1, 3, and 5), and the extra locations are plotted separately. As expected, there was no significant difference between the corresponding seats between “Original” and “Original surround”, “Wide” and “Wide surround” ($p > .05$). The surround locations only differ at location 4 ($M_{dif} = 0.33$, $t(29) = 1.53$, $p = .137$) , which is probably caused by the difference in obstruction, although it did not reach statistical significance.

Figure 6-5(D) shows that the addition of audience models has significantly degraded the visual preference at locations 2, 3, and 4 for both “Original” ($M_{dif} = 1.10$, $t(29) = 5.65$, $p < .001$; $M_{dif} = 1.42$, $t(29) = 7.636$, $p < .001$; $M_{dif} = 0.42$, $t(29) = 3.79$, $p < .001$) and “High” model ($M_{dif} = 1.06$, $t(29) = 5.17$, $p < .001$; $M_{dif} = 1.07$, $t(29) = 7.35$, $p < .001$; $M_{dif} = 0.68$, $t(29) = 3.78$, $p < .001$), but did not have significant effect at locations 1, 5, and 6 ($p > .05$), even though the calculated obstructions at 1 and 5 are also higher than the models without audience obstruction. This may be related to the location of the additional obstruction caused by audience models, as locations 2 to 4, especially 2 and 3, have obstructions that blocked some of the most important information, such as the conductor, while locations 1 and 5 only have obstructions at the edges of the view. However, it was noticed that when the obstructions were caused by architectural elements such as balcony railing, it degrades the preference even when obstructions were at the edge of the view. This means that people judge differently between obstructions from audience and architectural elements, possibly due to the fact that obstructions from audience are considered temporary while obstructions from architectural elements are permanent. Another explanation is that when people judge the auditoria without audience obstruction, they already add some expectations for audience obstruction, so only when the audience obstruction is more severe than they expected will the preference be degraded.

Figure 6-5(E) shows that interior colours do have effects on seat preference, but the effects are small compared to changes in geometry, and do not vary between seats. There is a small but constant difference between “Original” and “Original green” at all locations ($M_{dif} = 0.26$, $t(179) = 4.70$, $p < .001$), while no significant difference between “Original” and “Original neutral” ($M_{dif} = 0.06$, $t(179) = 1.03$, $p = .303$).

Finally, Figure 6-5(F) compares the results from the Chapter 5 experiment and 2 at the similar models and locations, with the results from the Chapter 5 experiment scaled to best match the results from the current experiment. As expected, the results are very similar, except that the Chapter 5 experiment has slightly higher preferences at locations 3 (location 6 in the Chapter 5 experiment), and lower preferences at locations 5 (location 15 in the Chapter 5 experiment). While the models and locations are similar, they are slightly different due to the different methods of model construction, and the differences in results match the differences in visual obstruction.

6.3.2.2 Comparison with predicted results

The predicted results for each seat were calculated using the prediction equation from the Chapter 5 experiment:

$$P = d(Distance) + l(|Lateral|) + v_1(Vertical) + v_2(Vertical^2) + o(Visual\ obstruction)$$

Equation 6-1

In which *P* is the seat preference prediction; *d* is the effect of *Distance* (from the point of focus in meters); *l* is effect of *Lateral angle* (from the centre symmetric plane in degrees); v_1 and v_2 are the linear and quadratic effects of *Vertical angle* (from the horizontal plane in degrees); *o* is the effect of *Visual obstruction*; *d* = -0.101; *l* = -0.0127; v_1 = 0.0613; v_2 = -0.0017; o = -2.01. There was also a component of audio gain level in the prediction model from the previous experiments, but as the present experiment does not include any auditory stimuli, the component is excluded.

The average results along with 95% confidence intervals are plotted against the predicted results at each location (Figure 6-6). Each point is labelled with the hall number (1 to 12) on the left and seat number (1 to 6) on the right. It can be seen that even though the prediction model includes some effect of obstruction, the locations with obstructions still have lower ratings than predicted, meaning that the effect of obstruction is larger than in the Chapter 5 experiment. Therefore, even though the model predicts the ratings of the locations without obstruction relatively well (r = .79, R^2 = .62), the fitting for all locations is not as good (r = .67, R^2 = .44).

The larger effect of visual obstruction may be due to the visual only stimuli as this is the main difference between the current experiment and the Chapter 5 experiment. That suggests that when sound is present, people are more tolerant of visual obstruction. This is easy to understand, as when both visual and auditory stimuli are present, the overall preference is affected by both. Sound usually is not affected much by minor obstructions in auditoria due to its relatively long wavelengths. Even though the propagation of sound may be affected by diffraction and reflection when transmitting through an audience area (named "seat-dip effect") (Schultz & Watters, 1964; Sessler & West, 1964), it was found that in most reverberant spaces it is perceptually negligible (Tahvanainen et al., 2017). On the other hand, other parameters in the prediction model (distance, lateral angle, vertical angle) are related to the geometric location and affect both view and sound. Therefore, the overall preference would be less affected by obstruction when using both auditory and visual stimuli compared to visual only.

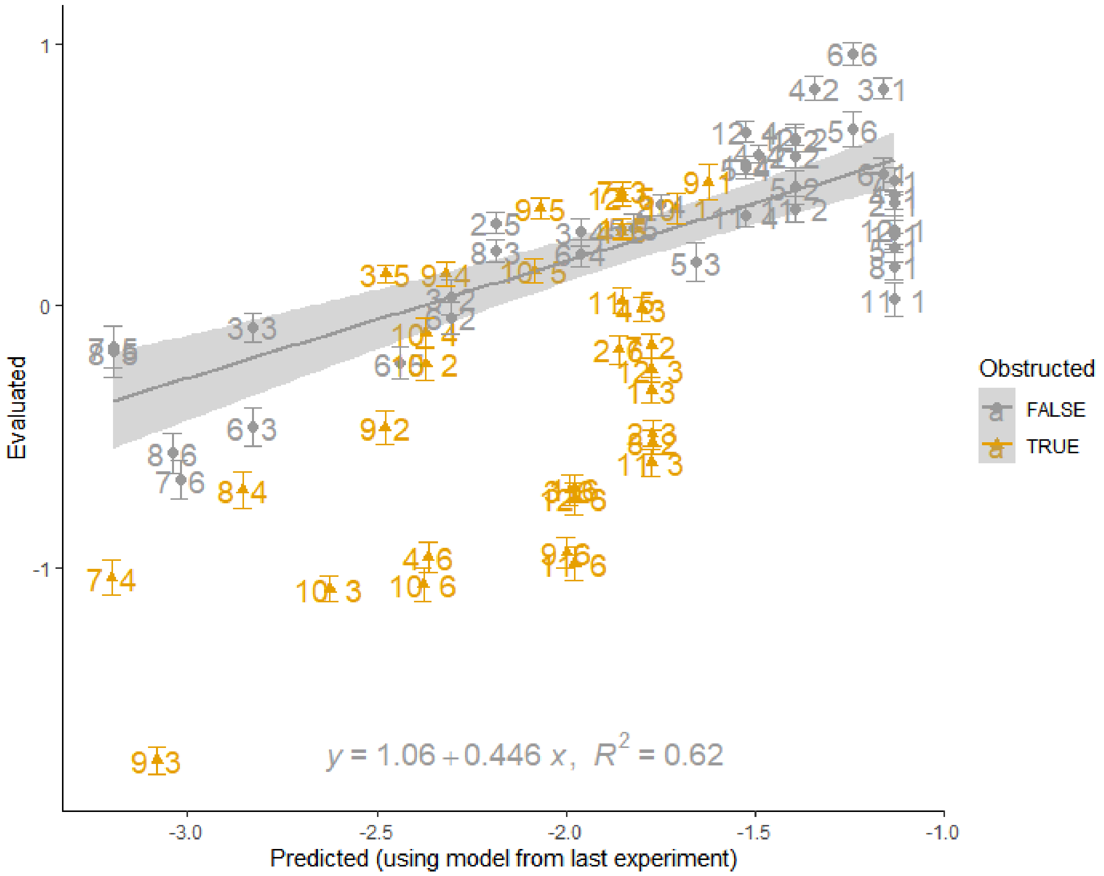


Figure 6-6 Average and 95% CI result plotted against prediction from Chapter 5 experiment. Each point is labelled with the hall number (1 to 12) on the left and seat number (1 to 6) on the right.

6.3.2.3 Additional effect of visual obstruction

To account for the extra effect of visual obstruction, a linear regression was conducted for the standardized experiment results using the predicted results from the above model and visual obstruction (Figure 6-7). The adjusted regression coefficient for *Visual obstruction* is -5.63, and the modified prediction model can provide a moderate fit for all locations (r = .81, R^2 = .65).

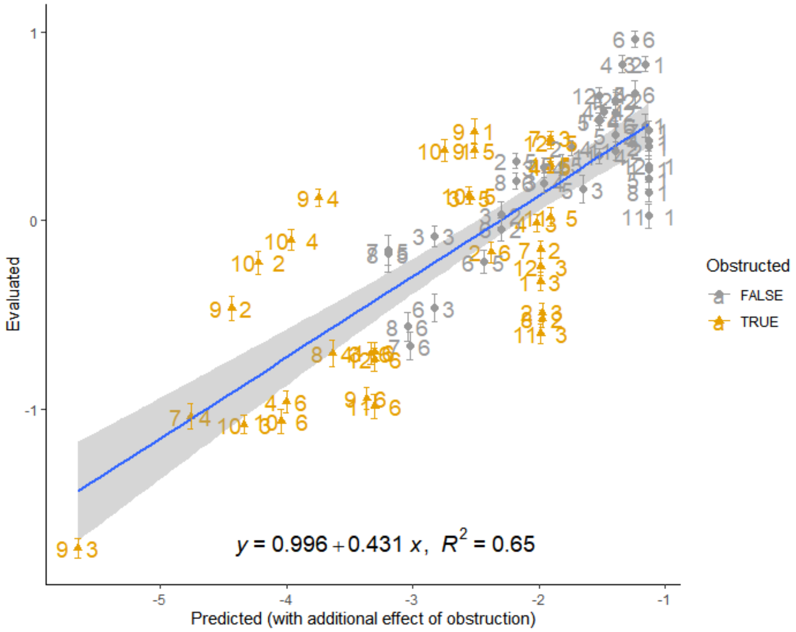


Figure 6-7 Average result plotted against modified prediction

However, the results for locations 1, 2, 4, and 5 in halls 9 and 10 are higher than the predictions. Halls 9 and 10 are the occupied halls, and locations 1, 2, 4, and 5 all have visual obstruction from other audience members. The result that those locations have higher ratings than prediction means that the negative effect of obstruction from audience members is not as large as obstruction from architecture elements. This supports the previously stated hypothesis that when the visual stimuli are of unoccupied auditoria, people make evaluations with some anticipation of the occupied situation. However, while location 3 in both halls also have obstruction from audience members, they are not rated better than the prediction as the other locations. From Figure 6-8 it can be seen that at location 3 in the occupied halls, the obstruction is very severe, especially in Hall 9 where the centre of the stage including the conductor is completely occluded. This may mean that while a higher proportion of obstruction corresponds to lower preference, the location of the obstruction is also important, as obstructions of the central area of the orchestra cause the loss of more important information compared to obstructions of the sides, and thus lead to lower ratings. However, this will need to be systematically investigated by controlling the location and proportion of obstructions separately.

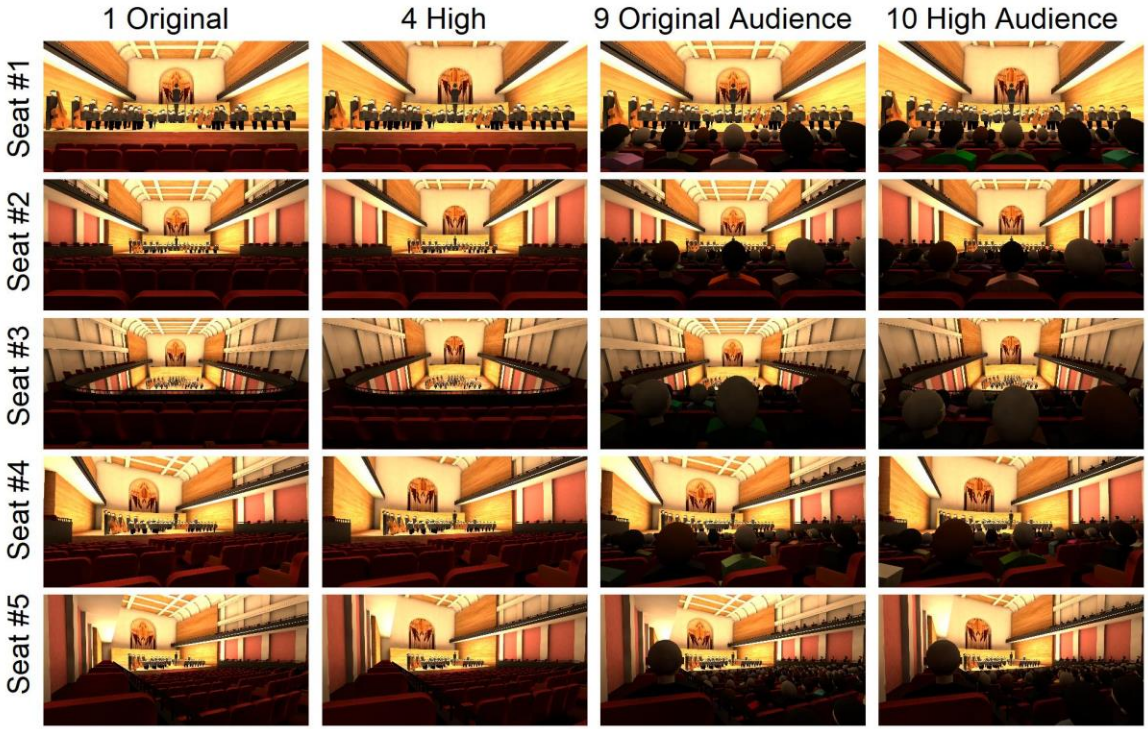


Figure 6-8 Typical views from Halls 1 (Original), 4 (High), 9 (Original audience), 10 (High audience) at locations 1-5 (location 6 does not have audience obstruction in any hall and is left out)

In addition, while the prediction results for locations 1, 3, and 6 for most halls are similar across different halls, the evaluated results are different. The last study found that for similar locations, people would rate differently in different auditoria, and this effect is not yet considered in the prediction.

6.3.2.4 Seat preference in different halls

To further examine the difference of seat preference between halls, Figure 9 shows the results of each hall separated, with the linear regression of all locations as reference (black dashed line). The prediction results in most halls fit well with the evaluation. The regression line in the halls with different sizes (halls 1-4), without visual render (halls 5-6), and with surround seats (7-8) mostly coincide with the regression line for all halls, showing that the prediction model was compatible with the geometry changes, absence of visual environment, and with seats on the side and back of the stage (lateral angle larger than 90°).

No noticeable difference is observed between the halls without visual render (halls 5-6) and the ones with same locations but inside visual auditoria (halls 1 and 3), meaning that the effect of visual environment on distance perception was not obvious. This means that the larger effect of distance of the third experiment compared to the second experiment may not be caused by the presence of visual distance, but more likely to be related to the combination of auditory and visual stimuli, as the second experiment used orthogonal control of distance and sound level. It was found that sound would be perceived louder by listeners when the arriving sound pressure level is the same, but the source is further away (named “loudness constancy”) (Barron, 1988; Zahorik, 2001). Therefore, when the sound level remained the same between different distances in the second experiment, the locations at further distances may have been perceived to be louder, which corresponds to higher preference. This in turn reduces the negative effect of distance. On the other hand, in the current experiment, when there is no sound presence, the effect of distance is consistent with the third experiment with corresponding audiovisual distance.

The ratings for halls with audience (halls 9-10) are generally higher than predicted, which was discussed in the earlier section. Seat preferences in hall 11 (green interior colour) are generally lower than predicted (given that the prediction model does not account for colour), which corresponds to previous observations that when the interior design colour changes, the seat preference changes in parallel, in the same direction as overall preference for the auditoria.

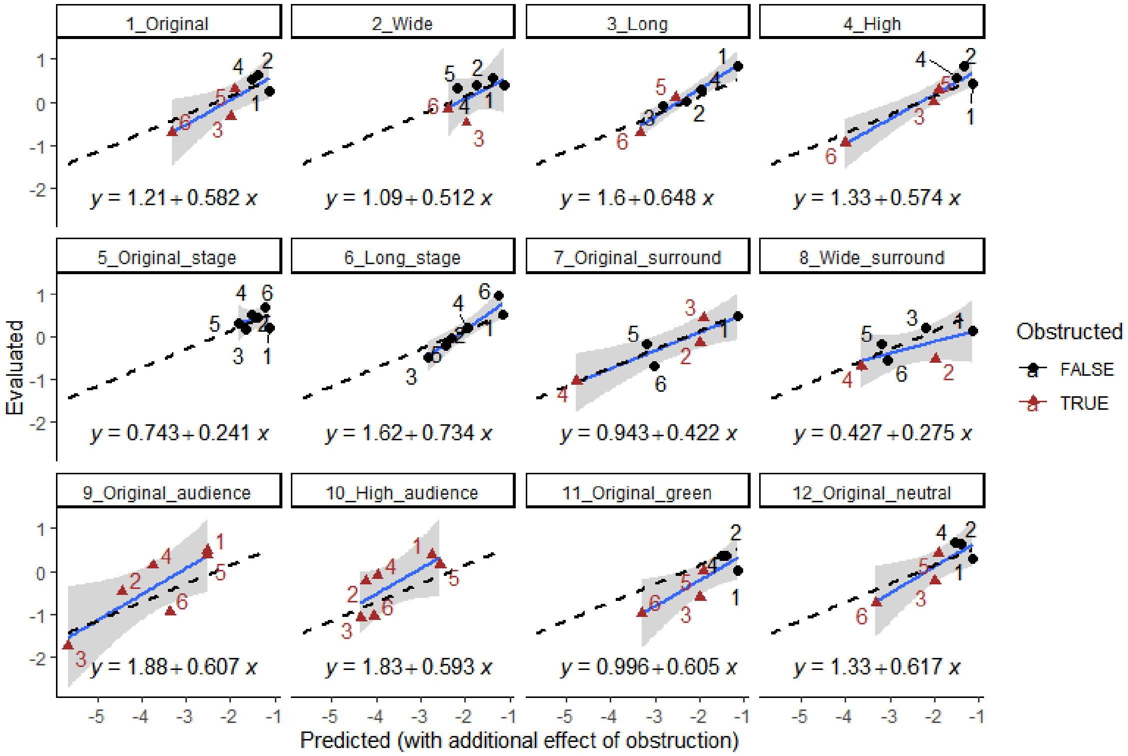


Figure 6-9 Average result in each hall plotted against modified prediction

6.4 Conclusion

Using subjective testing and virtual-reality simulations, this experiment examined the effect of various visual factors, including auditorium dimension, presence of visual environment, seats on side and back of stage, occupancy, and colour, on preference in auditoria. The main findings of this experiment are listed below.

Preferences for different auditoria are more diverse between people compared to preferences for different seats, but the two have mutual positive effects.

Obstruction has a larger negative effect on visual preference compared to combined audiovisual preference, likely due to its larger effect on light propagation (and vision) compared to sound (and hearing).

The prediction model proposed in the Chapter 5 experiment fits the results of the current experiment relatively well when taking into account the additional effect of visual obstruction, including for different hall dimensions, with and without visual environment, and for seats at the side and back of stage.

Although differing between people, on average of all participants, the presence of visual environment of auditorium increases hall preference but decreases preferences for some seats due to obstruction.

View obstructions caused by other audience members are more tolerated than obstructions caused by architectural elements. This could mean that people evaluate with anticipation of obstruction from audience members to a certain extent in unoccupied halls. However, obstruction of more important areas (e.g., centre of stage, conductor) have larger effect.

Auditorium colour has the largest effect on hall preference within the range of used stimuli, which in turn affects all seat preferences within the hall to a smaller extent, but does not affect how people rate different seats in relative terms.

Chapter 7 The effect of other environmental factors on concert preference and decision making

As a complementary method to the virtual-reality experiments, this chapter examines the effect of other environmental factors through an online survey. Part of this chapter has been published as:

Chen, Y., & Cabrera, D. (2022). Environmental factors affecting classical music concert experience. *Psychology of Music*. https://doi.org/10.1177/03057356221110631

Concert-going is a complicated, multi-faceted experience. Apart from acoustic and visual conditions, which have been investigated in detail in the previous chapters, many other factors can also affect the experience. To put the more focused results in a larger context, this chapter investigated the effect of various aspects of the concert going experience, including those related to performance, acoustic condition, visual condition, price, comfort, architectural design, and social aspects, on participants' selection of concert, seat, and their experience of attending classical concerts, based on an online survey. From 153 valid responses, it was found that the most important factors were related to performance, acoustics, and view; but price, comfort, and social factors were also moderately important. Performance and acoustic factors, comfort and view, social aspects and architectural design were closely linked in participants' judgements. More frequent concert-goers focused more on the music itself, including performance and acoustics, whereas less frequent concert-goers cared more for the experience of going to a concert, and were more concerned with price, social aspects, view, and architecture. People who were professional musicians, or had backgrounds in acoustics or architecture, attached more importance to visual factors and acoustics. Differences between groups of participants were generally smaller than differences between attributes.

7.1 Introduction

For most people, going to a classical music concert is a special event. High-fidelity audio reproduction does not replace the live music concert experience (Coutinho & Scherer, 2017). This is not just because of the additional visual information and auditorium acoustic rendering of the performance—going to a concert also has a social and broader psychological significance. As a complex and multifaceted experience, it is affected by diverse factors, including those related to aspects of the concert and environment, and those related to the concert-goers' background and personal experience. The present chapter utilised a questionnaire to investigate how such factors interrelate in contributing to the experience of concerts, helping contextualize the more focused research that is traditionally done in this area, such as auditorium acoustics.

7.1.1 Concert factors

The most important elements in a concert are the musicians and the music they play, and numerous studies have investigated how music and music performance affect people's emotions and behaviour (e.g., Cook, et al., 2019; Liljeström & Västfjäll, 2012; Schubert, 2007; Timmers & Juslin, 2010). The main difference between experiencing a concert at an auditorium and listening to music recordings at home is the environment, and many factors including acoustic, visual, physical comfort, social, and economic contribute to the physical and psychological environment encountered by the concert-goer. From planning to attend a concert to savouring the night after returning home, everything in between contributes to the experience. Given the extensive body of literature on musicians and music choices, this paper will focus on environmental factors contributing to the concert goers' experience.

Auditorium acoustics is the most-studied concert environmental factor. Various attributes have been extracted and defined that affect the audience's perception of a concert hall's acoustic quality, such as loudness, reverberance, clarity, spatial attributes like intimacy and envelopment, spectral attributes like brightness and warmth, and acoustic defects like background noise or echoes (e.g., Ando & Gottlob, 1979; Barron, 1988, 2009; Beranek, 2012; Choisel & Wickelmaier, 2007; Hawkes & Douglas, 1971; Kocher & Vigeant, 2015; Lokki, 2013, 2014; Lokki et al., 2012; Ryu & Jeon, 2008; Sotiropoulou et al., 1995; Soulodre & Bradley, 1995). Measurable or calculable objective parameters have been linked to particular subjective attributes through experiments, and recommendations have been developed for some parameters (e.g., Barron, 2009; Chalupper & Fastl, 2002; Farina, 2001; Hidaka & Beranek, 2000; Schroeder et al., 1974), but the question of what "good" acoustics is is not entirely settled. In the results of Thompson's survey about factors affecting people's concert enjoyment (2007), acoustics was listed along with "performance techniques" ", performance commitment," and "lack of distraction" as the most important factors.

Visual conditions also contribute to concert experience. Visual input, such as facial expression and body movement, have been found to affect performance perception both informationally and emotionally (Coutinho & Scherer, 2017; Davidson, 1993; Krahé et al., 2015; Mitchell & MacDonald, 2014; Thompson, et al., 2005; Vines et al., 2011). Studies indicate a preference for views from positions near the stage, near the auditorium midline, sufficiently elevated to see the stage, and without obstructions. (Chapter 4; Jeon et al., 2008; John et al., 2007; Kawase, 2013; Russell, 1838; Sato et al., 2012; Vaupel, 1998; Veneklasen, 1975). Visual factors not directly related to the performance, such as auditorium design, also affect concert experience and perception (Chapter 3; Hyde, 2002). Furthermore, visual and auditory perception are mutually influential, especially in terms of preference and spatial perception (Cabrera et al., 2004; Chapter 3; Galiana et al., 2016; Larsson et al., 2002; Tokunaga et al., 2013; Valente & Braasch, 2010). However, in most cases visual influence on auditory perception overpowers auditory influence on visual perception (Chapter 3; Jeon et al., 2008; Zahorik, 2001).

The comfort of the seat and environment are not related to the performance but can greatly affect overall experience (Egorov, 2020; Giannis et al., 2016; Kavgic et al., 2008; Pitts, 2016). Environmental comfort, especially temperature and air quality, has been studied within the research topic of indoor environmental quality (mostly outside of the auditorium context). Seat comfort, mostly overlooked in academic research, is experienced acutely by audience members (Haithman, 2004; Lister, 2003). While people have some tolerance for concert seats, seat discomfort or tight legroom distracts and detracts from concert enjoyment.

Going with friends or family is also an important concert enjoyment factor. However, the social aspect of concerts has been considered less important than factors directly related to the quality of the performance (Pitts et al., 2013; Roose, 2008; Thompson, 2007). On the other hand, its importance varies between people (Roose, 2008; Thompson, 2007).

Other factors, including ticket price, connectedness with the audience, and ease of seat access, have also been found to affect the experience and choice of going to concerts (Pitts et al., 2013; Roose, 2008; Vaupel, 1998), but have not been systematically studied.

Most of the abovementioned literature only studied one specific aspect of concert experience, with limited comparisons between social and performance factors (Roose, 2008), acoustics and performance factors (Thompson, 2007), and slightly more information on the comparison between visual and acoustic factors (Jeon et al., 2008; Zahorik, 2001). How the factors from all aspects compare with each other in their contribution to the overall experience, and whether there are any connections between the subjective judgements, both remain unknown.

7.1.2 Audience factors

Various studies have found that opinions relating to concert enjoyment vary between people. Audience factors that have been found to affect people's appreciation of classical music concerts include engagement with concert attendance, classical music knowledge, professional background and training, and demographic background including education, social status, age, and gender. These factors are not independent, but rather are closely linked.

Concert-going frequency is one of the most studied audience characteristics. Experience with music listening can equip people with the same music appreciation capacities as professionally trained musicians (Bigand & Poulin-Charronnat, 2006). Roose (2008) categorized classical concert audience into three groups: "passers-by," "interested participants," and "inner circle," based on earlier theories of Becker (1982) and Laermans (2002, as cited in Roose, 2008). These groups were classified by concert-going frequencies, and were found to have different socio-demographic composition, concert-going motives, and aesthetic dispositions. More frequent classical concert-goers were generally older and had higher education levels, and their motives were more related to the performers ("intrinsic"), while less frequent concert-goers were more motivated by friends ("extrinsic"). More frequent concert-goers were also more demanding for innovation and more detached from music emotionally, while less frequent attendees preferred greater familiarity and wished to be emotionally moved. This is compatible with the "inverted-U model" originally proposed by Berlyne (1960), which has been the most widely accepted theory for the effect of familiarity on music preference in general (reviewed in Chmiel & Schubert, 2017). Concert-going frequency also affects the sense of belonging, which frequent concert attendees experienced more with increasing familiarity with musicians and regular attendees (Pitts et al., 2013; Pitts & Spencer, 2008). An analysis of marketing-driven data from the website Audience Finder (Bradley, 2017) showed that between 2014 to 2016, in the 113 collaborating organizations in England, 67% of people only booked one classical music concert, and only 8% booked six or more times.

Many studies report either positive correlations between age and concert-going frequency, or high average audience ages, which may be a reflection of the former (e.g., Kolb, 2001; Pitts, 2016; Roose, 2008). The sample of Roose (2008) had an average age of 56.6 with a steady increase from 54.7 to 57.0 for the three levels of concert-going frequency, over 60% of the sample of Pitts (2016) were mid-late career or retired respondents, and Kolb (2001) found that the average age of classical concert audience increased from 40 in 1982 to 46 in 1997. Data from Audience Finder in England (Bradley, 2017) showed that 79% of the audiences were over 41, almost half of whom were over 61. This has been attributed to lack of knowledge about classical music and sense of belonging in the younger generation (Dobson & Pitts, 2011; Kolb, 2000, 2001; Pitts, 2016). The imbalance and exclusiveness in the classical music workforce relating to gender, ethnicity, disability, and socio-economic status may also have contributed to the skewed audience distribution (Cox & Kilshaw, 2021).

Music playing experience may also be influential. People with music training have been found to have more accurate and detailed perception for both music and speech. This difference also appeared as faster and larger neural responses (reviewed in Strait & Kraus, 2011). More specifically, listeners with music backgrounds are more sensitive to the details in sounds, and have better attention and memory. Ohgushi (2006) found that music students could understand the intention of music performers better than psychology students, and Hargreaves et al. (1980) found that music preference of people without training was less correlated with the perceived quality of music. In the context of concert attending, Galiana et al. (2016) found that “experts” including professional musicians and acousticians could better judge the acoustics of the auditorium without the influence of architectural attributes. However, in terms of subjective preference judgements, no difference was yet found between people with music backgrounds and those without (Giménez et al., 2011; Kawase, 2013; Thompson, 2006), apart from that people with music backgrounds were more demanding of the music and acoustics, and gave lower ratings (Giménez et al., 2011).

7.1.3 Objectives

While many studies have investigated the effect of different factors affecting a concert experience separately, there is an opportunity to better understand how the factors compare and relate to each other. Therefore, the current chapter aimed to provide additional contextual information for factors that have been studied separately in different fields, by: (1) systematically comparing between the contribution of factors from different aspects to people’s concert-going decision-making and experience; and (2) revealing any relationships in people’s judgements of these factors and whether relevant background characteristics affected the judgements.

7.2 Method

7.2.1 Materials

An online survey was conducted comprising five sections: background information, matrix questions, section ranking, view rating, and additional comments. Background information collected included age, gender, country, participants’ classical concert-going frequency, any type of long-term involvement with music venues or groups, and background in music, architectural design, acoustical engineering, or audio engineering.

There were three matrix questions in total, which investigated the influence of various attributes on how participants select which concerts to attend (“Concert”), how they select seats (“Seat”), and how much they enjoy the overall experience of going to a concert (“Overall”). The selection of the attributes was based on factors previously found to affect preference (reviewed in 1.1), with the acoustics-related questions adapted mainly from Barron (1988) and Beranek (2012), and concert-going related questions adapted mainly from Roose (2008) and Thompson (2007).

For each attribute, a five-point Likert scale with individually labelled adjectives was used: *not at all important*, *slightly important*, *moderately important*, *very important*, and *extremely important*. Participants were told to select *not at all important* if that if they had never considered the option or did not know what it meant. The complete statement of each attribute and referral codes used in this paper are listed in Table 7-1.

Table 7-1 All given attributes in the matrix questions and referral codes

Question code	Attribute statement	Attribute code	Group
Concert	You like or want to see the venue	Hall	Architecture
	You like or want to see the performing musicians	Musician	Performance
	You like or want to see the repertoire	Repertoire	Performance
	Other friends/family are going	Social	Social
	Cheap ticket price	Price	Price
Seat	Distance to the stage (e.g. as close as possible, or not too close/not too far)	Distance	Visual
	Lateral location (e.g. close to the centre line)	Lateral	Visual
	Elevation position (e.g. high vantage point)	Elevation	Visual
	Good view of particular sections/musicians	SeeSection	Visual
	Good view of the auditorium	Hall	Architecture
	Expected good acoustics	Acoustics	Acoustics
	Easy access to your seat (e.g. next to an aisle or exit)	Access	Other
	In a relatively small and enclosed area (e.g. box or balcony)	Enclosed	Other
	Cheap ticket price	SeatPrice	Price
	Recommendations from ticket desks or booking websites	Recommendation	Other
Overall	You enjoy the skill of the musicians	Musician	Performance
	You enjoy the repertoire	Repertoire	Performance
	You are close to the stage and can see enough details	Distance	Visual
	You have an unobstructed view of the stage	Sightline	Visual
	You can see most or all of the musicians	SeeAllMusician	Visual
	You can see particular sections/musicians	SeeSection	Visual
	You appreciate your view of the interior architecture	Hall	Architecture
	The sound is loud enough	Loudness	Acoustics
	The sound is reverberant and lively enough	Reverberance	Acoustics
	You can hear the articulations clearly	Clarity	Acoustics
	You feel surrounded by the sound	Surround	Acoustics
	There is no or very little audible noise	Noise	Acoustics
	You feel that you can connect with the musicians	ConnectMusician	Visual
	You feel that you can connect with the other audience members	ConnectAudience	Other
	You enjoy the concert as a social event with people you know and go together	Social	Social
	You enjoy the concert as a social event to meet new people	MeetPeople	Other
	Your seat is comfortable to sit on	SeatComfort	Comfort
	The environment is comfortable (e.g. not too hot or cold, not too much wind from the air-con)	IEQ	Comfort
	Your experience before the concert is smooth (e.g. transportation, parking, finding location)	BeforeConcert	Comfort
	The auxiliary facilities are good (e.g. toilets, bars, cloakrooms)	Facilities	Comfort

There were also optional blank spaces for each question where the participants could enter other attributes that affect their experience, and an additional blank space at the end of the survey for any other comments related to the survey that they wished to share.

Before the survey was distributed, it was test-filled by five professional acousticians who were also frequent concert-goers, and was modified based on their feedback to maximize question clarity and inclusiveness.

7.2.2 Participants

The link to the online survey was distributed over a variety of public international classical music forums, and was completely anonymous. The participant information statement and consent conditions were included on the survey's cover page. Participants were able to change any previously answered questions or leave the survey and continue later before submitting the survey. Only the submitted surveys were recorded. Participants were required to be aged over 18 and to have been to at least one classical music concert. There were 153 valid returned surveys, of which 141 answered all matrix questions and 131 answered all questions. All participants gave informed consent upon submission of the survey. Participants could spend as much time as they wished on the questionnaire, and the average time spent on the survey was 11 minutes (excluding time away from the page).

Participants' ages ranged from 18 to 75 (*M*=40.6; *SD*=5.9). While the usual audience for classical music tends to lean towards older age, the participants for the current survey had a relatively even age distribution with slight skew towards the younger end. This may be due to the online questionnaire distribution, as most other studies recruited their participants among the audience of specific concerts and therefore included more people that were highly committed to concerts. For analysis, the participants were divided into three age groups of approximately the same size: 18-29 (*n*=48), 30-45 (*n*=54), and over 45 (*n*=51).

There were 96 male participants (63%), 53 female participants (35%), 3 neutral or non-binary, and 1 chose not to say. Participants came from 25 countries in terms of cultural background, of which the five countries with the highest numbers were United States (*n*=35), Australia (*n*=26), China (*n*=24), United Kingdom (*n*=16), and France (*n*=10).

7.3 Results

The results of background information, matrix questions, and additional comments are analysed separately in the following sections. Section ranking and view rating results are not included in this article.

7.3.1 Basic information results (153 answers)

The complete results for background information are given in Table 7-2.

*Table 7-2 Results for concert engagement and relevant background information (the most selected options are **bold**)*

Question	Choice	Count (n)	Percentage
Concert-going frequency (single selection)	<1 time/year	23	15%
	1-4 times/year	**75**	**49%**
	5-12 times/year	41	27%

	>12 times/year	14	9%
Membership history (multiple selections)	Mailing list	**78**	**51%**
	Paid membership	27	18%
	Regular bookings with fixed seats	13	8%
	Regular bookings without fixed seats	28	18%
	None	54	35%
Music background (single selection)	Current professional	17	11%
	Former professional	22	14%
	Amateur	**77**	**50%**
	None	37	24%
Other related professional background (multiple selection)	Acoustic engineering	30	20%
	Architecture design	9	6%
	Audio engineering	30	20%
	None	**99**	**65%**

Most participants reported relatively low concert-going frequencies, with about half going 1-4 times a year, which matches overall distribution trends found by Bradley (2017). The majority had some music background (mainly amateur), and most had no background in acoustics, architecture, or audio engineering. Because the participants could select multiple options for the membership question, answers were re-categorized into three inter-exclusive groups. People who had any forms of regular bookings and/or those who had paid memberships were categorized in “Membership” ($n=48$); people who only were part of mailing lists were categorized in “Mailing List” ($n=51$); and “None” was for none of the above ($n=54$).

To test whether the background variables were mutually independent, chi-square was calculated for each variable pair within age group, concert-going frequency, membership history, music background, and each professional background. Significant association was found between concert-going frequency and membership history ($X^2(6,N=153)=56.1, p<.001$), with higher concert-going frequency associated with higher membership engagement. Age group was associated with music background ($X^2(6,N=153)=20.4, p=.002$), with most current professional musicians being 18-29 years old, and most former profession musicians aged 30-45. Most people with an architecture background (7/9) or acoustics background (19/27) were aged 30-45($X^2(2,N=153)=6.9, p=.032$; $X^2(2,N=153)=6.9, p=.032$). Architecture and acoustics backgrounds also showed a small association ($X^2(1,N=153)=5.9, p=.015$). No association was found between concert engagement and any of the professional backgrounds investigated.

7.3.2 Matrix results (141 answers)

7.3.2.1 Agglomerative hierarchical clustering (AHC)

To categorize and reduce the variables according to their similarities, AHC (Kaufman & Rousseuw, 1990) was conducted based on Euclidean distances between attributes (Figure 7-1). The group average method was used as the results showed the highest correlation between original distances and cophenetic distances ($r=.73, p<.001$).

Attributes were manually divided into six groups based on their meaning ($R^2=.59$). From top to bottom, the attribute groups were related to visual condition and comfort (Cronbach’s alpha α=.82), ticket price (α=.88), performance and acoustic quality (α=.70), architectural design (α=.76), social event (α=.59), and other conditions (α=.50). Apart from the last two groups, all groups showed acceptable to good consistency. Visual conditions and comfort were closely linked in the evaluation and had high similarities, as were performance quality and acoustic quality. Connecting with musicians was clustered with the visual conditions, revealing the importance of view on feeling connected to the performers. The proximity of architectural design and social gathering indicated the importance of the music auditoria as part of the "event" of going to concerts. On the other hand, meeting new people and connecting with other audience members was in a group separate from social gathering, demonstrating the distinction between going with friends and meeting strangers.

The largest two groups of variables were further divided into two groups each based on the variable characteristics, separating visual condition (α=.78) and physical comfort (α=.82), performance (α=.63) and acoustics (α=.74), for analysis clarity.

At a higher hierarchical level, all attributes were divided into two groups. Performance and acoustic quality, ticket price, and visual condition and comfort were grouped (α=.79), while the other group included architectural design, social event, and other conditions (α=.72). The first group focused on attributes more related to the concert and performance, and the second focused more on other issues related to the experience of going to a concert.

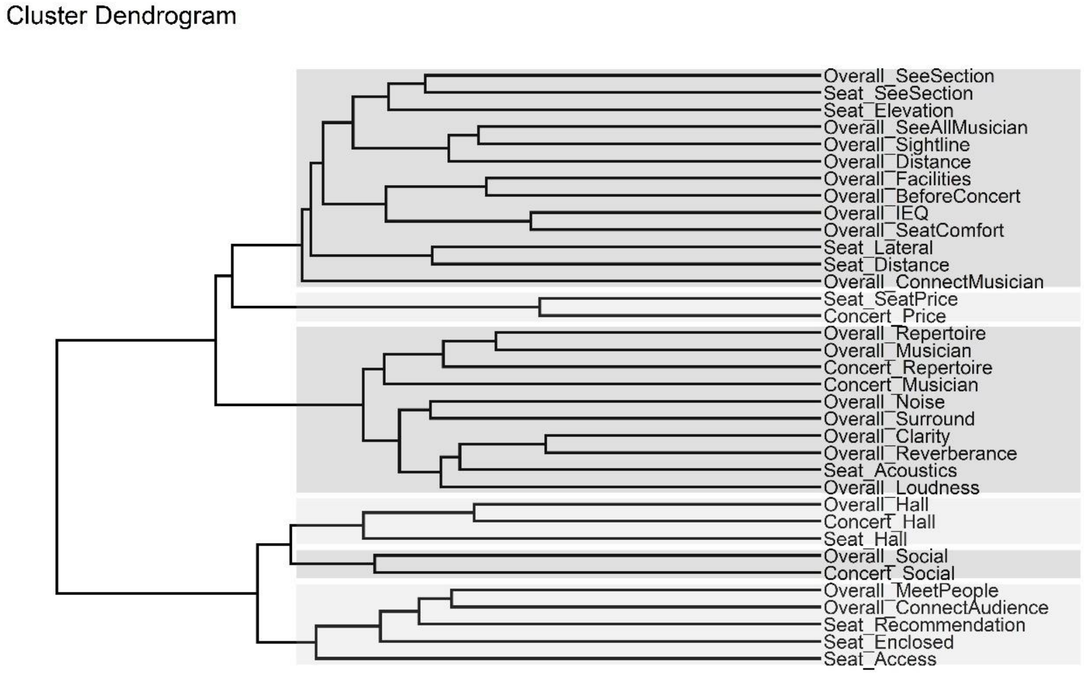


Figure 7-1 Attribute dendrogram from AHC, with the six groups indicated by shading

7.3.2.2 Principal component analysis (PCA)

While AHC grouped the variables based on their similarity, to further understand the relationships between groups and variables, PCA (Escofier & Pagès, 1994; Pagès, 2015) was also used. Original results without standardizing were used to take into account each attribute's variance. The first six components explained more than half of the variance and were chosen for further analysis (Table 7-3).

Table 7-3 PCA result: Eigenvalue and variances explained by first six components

Component	Main contributing attributes	Eigenvalue	Percentage of variance explained	Cumulative percentage of variance explained
1	Experience	5.66	18.05	18.05
2	Event *vs.* performance	2.81	8.95	27.01
3	Social, acoustics	2.33	7.41	34.42
4	Comfort, acoustics	2.00	6.38	40.80
5	Price, lateral angle, repertoire	1.95	6.23	47.03
6	Connecting with musician and audience	1.66	5.29	52.32

All attributes are plotted on the first two dimensions in Figure 7-2(A), coloured by the variable groups, with the mean of each group shown in Figure 7-2(B). The *x* and *y* values of each arrow or point represent the contribution of the attribute or group to the corresponding component, and the distances between the arrows or points represent the similarities in judgements. Circles drawn at 0.4 radius serve to better visualize the distances.

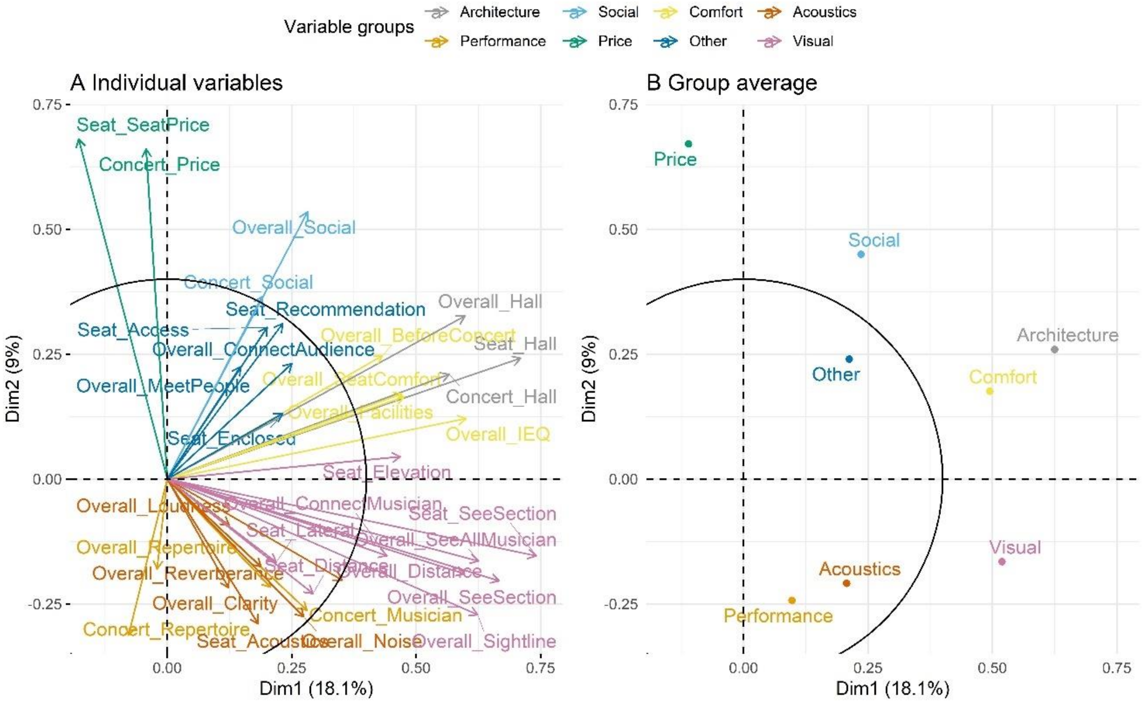


Figure 7-2 PCA variable plot of dimensions 1 and 2 (variables coloured by group)

As expected, attributes of the same group generally distributed closely on the principal component map. People who were more affected by price and social aspects of concerts tended to be less affected by the performance and acoustics. Visual condition, architectural design, and comfort were positively correlated in the subjective judgements, but relatively independent from the abovementioned attributes. Performance, acoustics, and other attributes made relatively smaller contributions to the first two dimensions compared to other variable groups, indicating that the judgements were less divided between participants. Overall, the first dimension was mostly related to the experience of concert-going (architectural design, physical comfort, and visual condition), while the second was related to performance quality in the negative direction (performance and acoustic condition), and the event of concert-going in the positive direction (price and social aspect).

In dimensions 3 to 6 (Figure 7-3), only variables with relatively high contributions (squared coordinates larger than 0.1) were selected for presentation clarity. Dimensions 3 and 4 separated visual attributes related to unobstructed view from acoustic attributes, and ease of access from the social attributes to be grouped together with comfort attributes. Dimensions 5 and 6 revealed the hidden similarities between the ratings of ticket price, repertoire, and visual attributes, and separated connecting with audience and musicians from architectural design.

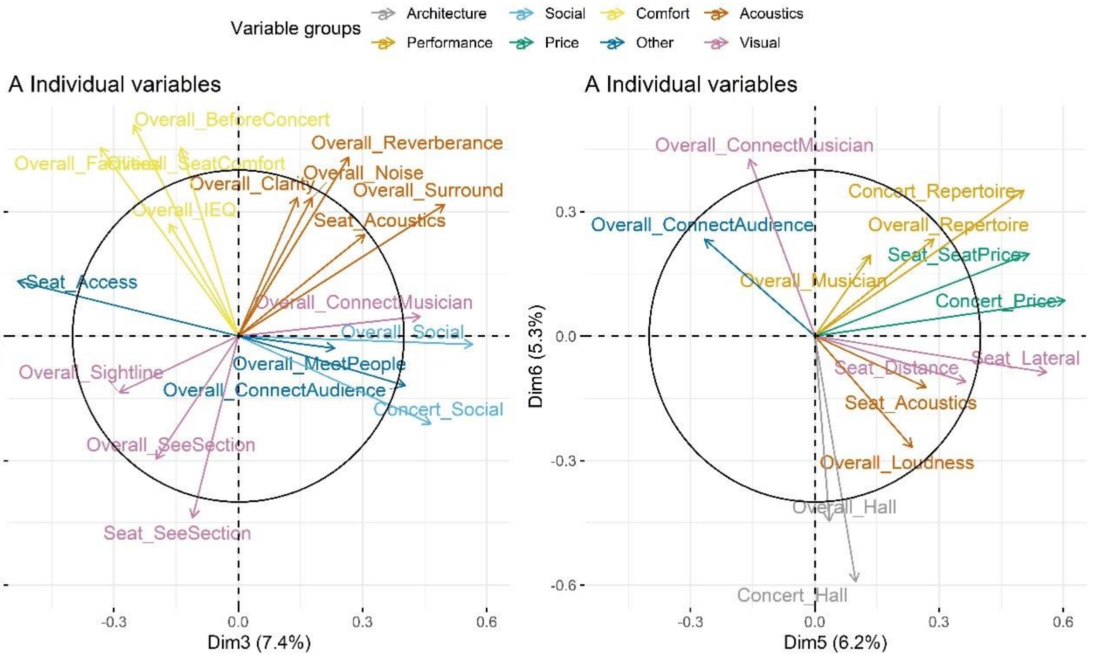


Figure 7-3 PCA variable plot of dimensions 3 to 6 (variables relatively high contribution, coloured by groups)

7.3.2.3 Results of all participants

Cronbach's α (Cronbach, 1951) was calculated for all participants and yielded 0.82, indicating good internal consistency. Average results are plotted in Figure 7-4, coloured by variable group.

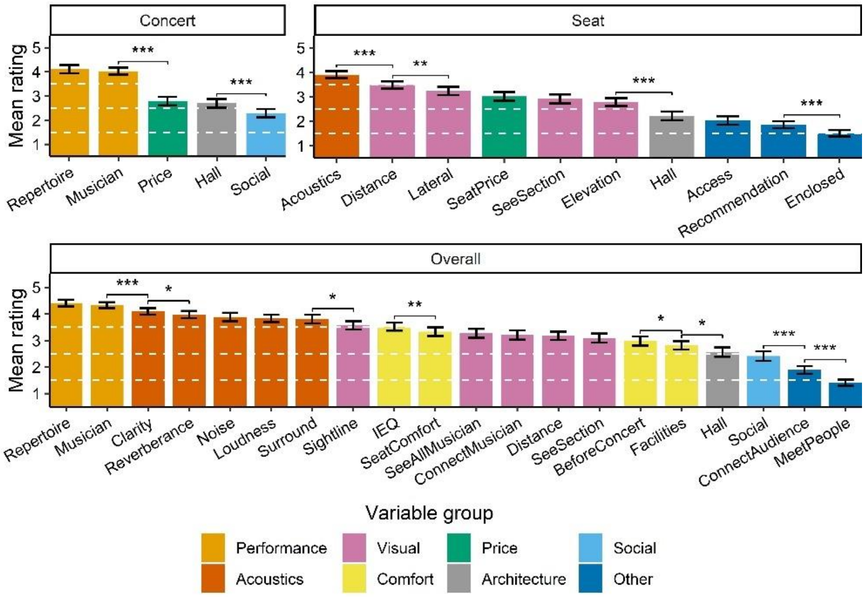


*Figure 7-4 Mean ratings and 95% confidence interval of each question for all participants with paired-sample t-tests between adjacent variables (***p<.001, **p<.01, *p<.05)*

Generally, variables of the same group had similar ratings. Concert selection mainly depended on repertoire and performing musicians. Ticket price and the host auditorium were also *moderately important*. For seat selection, expected good acoustics was considered the most important, followed by visual factors and ticket price. Overall enjoyment of the concert was also most affected by repertoire and musician, then the acoustic factors, followed by visual factors, physical comfort, and connection with the musicians. Other relevant experiences and auxiliary factors were considered less important but still *moderately important*. Connecting with or meeting other audience members were only *slightly important* to *not important*.

While repertoire and musicians were both considered *very important* in concert choice and overall enjoyment, they were more important for overall enjoyment with a mean difference (*MD*) of 0.30 for both repertoire (*t*(140)=4.47, *p*<.001) and musicians (*t*(140)=4.24, *p*<.001). Being able to see a particular section was also more important for overall enjoyment than seat selection (*MD*=0.18, *t*(140)=2.09, *p*=.039). However, distance was more important in seat selection, being the second most important factor besides expected good acoustics, but less important for overall enjoyment (*MD*=0.30, *t*(140)=3.27, *p*=.001). Being a common *moderately important* factor in both concert and seat selection, ticket price was more important for seat selection (*MD*=0.23, *t*(140)=2.09, *p*<.001). The auditorium was *moderately important* for both concert selection and overall enjoyment, but less important for seat selection (*p*<.001).

Each variable group's mean rating was calculated (Figure 7-5). Paired-sample t-tests showed significant differences between adjacent groups (*p*<.05) apart from visual condition and comfort (*p*=.671), and architecture and social aspect (*p*=.120). Performance and acoustics were both considered *very important*, followed by visual condition, comfort, and price, being *moderately important*, while architecture design, social factors, and other attributes were *slightly important*.

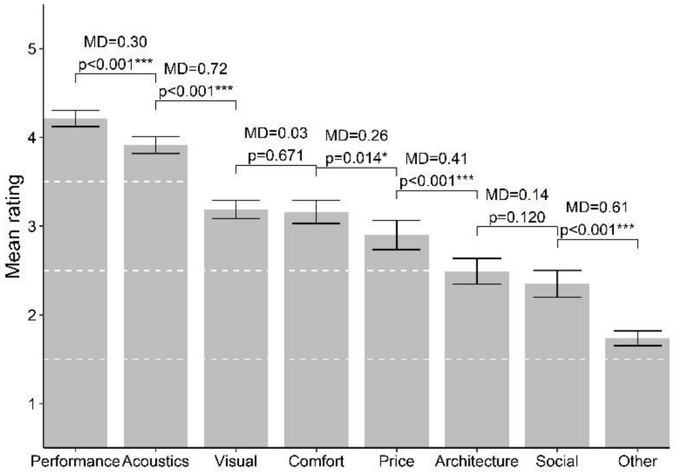


*Figure 7-5 Mean ratings and 95% confidence interval of each variable group for all participants with paired-sample t-tests between adjacent groups (***p<.001, **p<.01, *p<.05)*

7.3.2.4 Results based on participant backgrounds

The average results of each participant group separated by age group, concert-going frequency, membership history, and music background were individually calculated and compared (Figure 7-6). All groups showed acceptable consistency (α>0.7). A one-way ANOVA was also conducted for each question between each participant group and shown in the plots (****p*<.001, ***p*<.01, **p*<.05, ˙*p*<.10). Younger people attached significantly more importance to ticket price, and slightly less importance to performance. People around middle-age emphasized architecture and social factors more than younger or older groups.

More frequent concert-goers emphasized performance, and less frequent ones emphasized comfort and other attributes. Visual condition, price, architecture, and the social aspect also showed trends of being emphasized by less frequent concert-goers, though not statistically significant.

The only noticeable difference for membership history was that participants with paid membership or seasonal bookings were less affected by ticket price, probably reflecting the fact that most concerts they attend were included in the already-paid subscription. Other factors that showed significant differences relating to concert-going frequency did not show similar trends for membership history, even though membership history and concert-going frequency were significantly associated.

Participants who were current or former professional musicians emphasized performance more than those without formal music training. People who were professional musicians at the time of survey participation attached more importance than all other groups to some attributes of acoustics and view, though this contrast was not statistically significant.

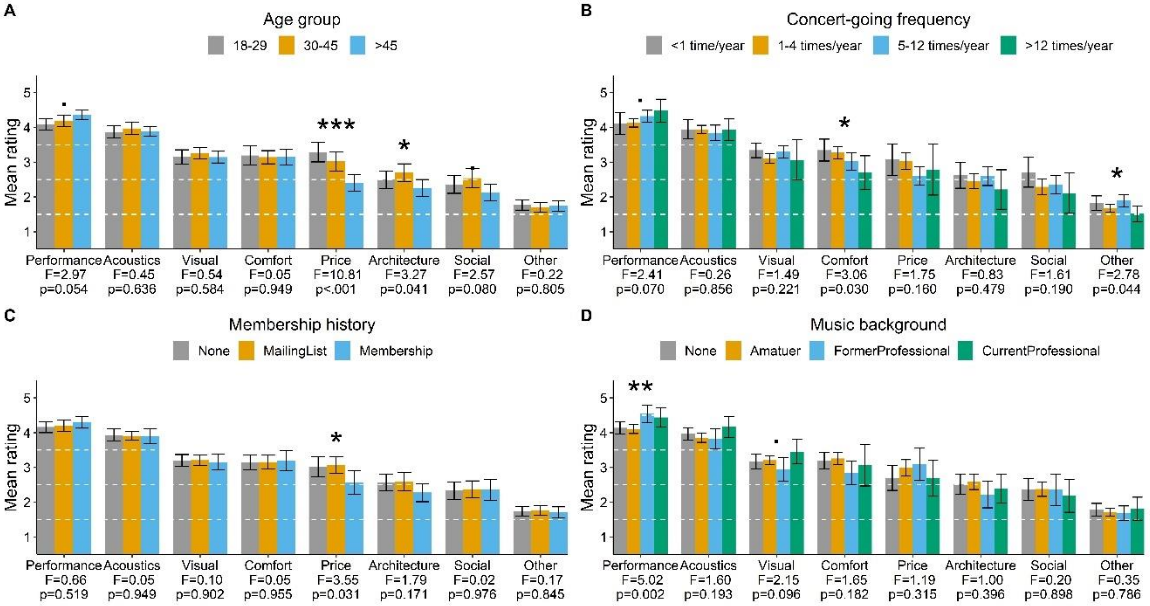


*Figure 7-6 Mean ratings and 95% confidence interval of each variable group for different background group with ANOVA results (***p<.001, **p<.01, *p<.05, ·p<.1)*

Between people with professional backgrounds in architecture, acoustics, or audio engineering and people without (Figure 7-7), an emphasis on the hosting auditorium could be seen for all three professions, especially those with an architecture background. No emphasis in acoustics was found for any of the professions. Acousticians also showed an emphasis on the social aspect of concert-going.

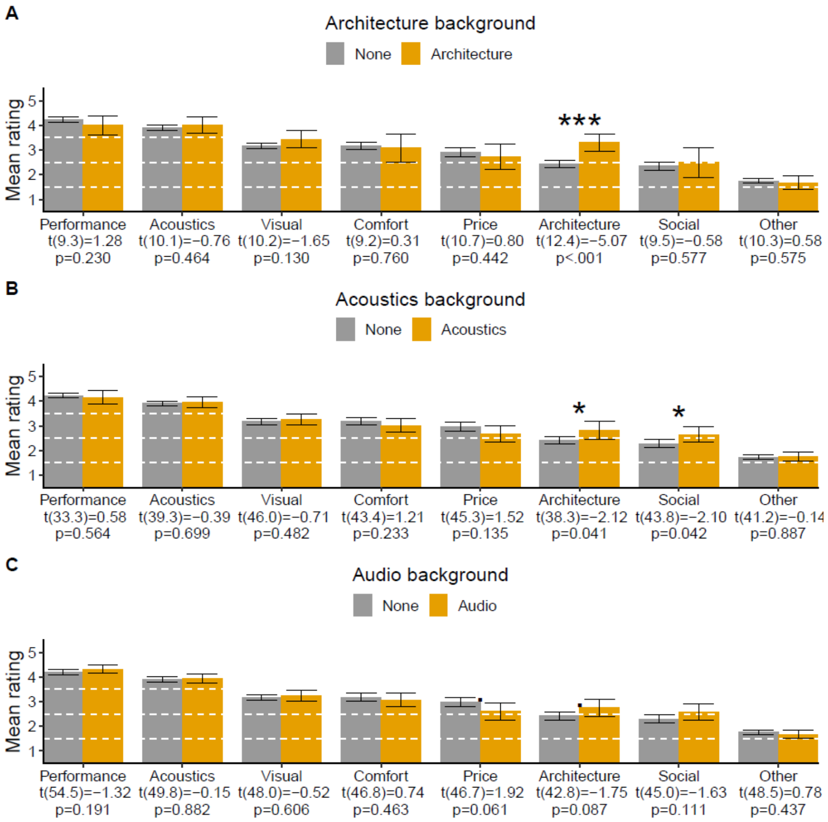


*Figure 7-7 Mean ratings and 95% confidence interval of each variable group for different professional background group with independent t-test results (***p<.001, **p<.01, *p<.05, ·p<.1)*

No significant difference was found between the results of people from different countries when comparing between the countries with sample sizes larger than ten.

7.3.2.5 Additional factors

Participants were also asked to identify any other factors that affect their selection of concerts, selection of seats, and overall enjoyment—but were not included in the survey's list of factors.

For selection of concert, the most frequently mentioned additional factors were the location's convenience (7 mentions, *moderately* to *extremely important*), and the convenience of date and time of the concert (6 mentions, *very* to *extremely important*). Five comments were related to unfamiliarity or novelty of the musicians, repertoire, or venue (*moderately* to *very important*), mostly from relatively frequent concert-goers (4 out of 5 reported going to concerts more than 5 times a year), which supports the finding of Roose (2008) that frequent listeners seek innovation more. Two mentioned concert duration. A few comments mentioned factors that required prior knowledge of the venue, including expected good acoustics, expected seat comfort, and expected audience behaviour. Two comments also mentioned COVID19-safety—a special consideration at the time of this survey.

For seat selection, the most mentioned factors were seat comfort (3 mentions) and unobstructed views (2 mentions). Three participants mentioned specific personal preferences or favourite seats. All responses required the participant to be familiar with the auditorium and be able to anticipate the conditions.

For overall enjoyment, the most mentioned factors were behaviour of other audience members (7 mentions, 5 of which were *extremely important*), especially no talking or phone usage. This could be considered as part of the given criterion "Noise." Other mentioned factors include program notes (3 mentions), food and drinks (2 mentions), and accessibility (2 mentions). People who mentioned information booklets and food and drinks were mostly frequent concert-goers (4 out of 5 at least 5-12 times a year). While program notes have been found to affect concert enjoyment, the effect was more often found to be negative (Bennett & Ginsborg, 2018; Margulis, 2010).

7.3.3 Additional comments

In the blank space for additional comments, participants shared some of their past experiences and specific personal preferences. Several participants mentioned the differences between watching or listening to music recordings from home and attending concerts in auditoria. Even though video recordings may provide even better viewing conditions, they still reported wishing to go to concerts for the live experience, the feeling of being part of a shared atmosphere, and the immersive acoustic experience. Several people mentioned that a downside of live concerts was possible disturbance from other audience members, which was also the most frequently mentioned additional factor in the previous section.

A few people mentioned that they had different seat preferences for different performances or different auditoria. Another frequently-mentioned point was that while acoustics was very important, it was difficult to predict the acoustic condition of a certain seat before the concert, hence some people tended to choose seats from previous experiences.

7.4 Discussion and conclusion

The results have revealed relationships between diverse aspects of classical concert experience, including their relative importance and differences in people's judgements. Results include some confirmatory conclusions that match previous findings of relevant complementary method studies, in addition to new discoveries of relationships not yet explicated in the current literature. The main findings are discussed below.

The most important factors for decision making and experience of classical concerts—regardless of participant background—were related to performance, followed by acoustics, view, price, and comfort. The high importance of acoustics is in line with Thompson (2007). Acoustics being judged more important than view is similar to the conclusion of Jeon et al. (2008) that auditory preference accounts for a larger proportion in overall preference. However, this conclusion is contrary to the finding by Kawase (2013) that "expected good visibility of musicians" was the primary reason participants selected a seat as their favourite or least favourite, instead of "expected good sound." This could be explained by the differences in the stimuli and questions, as the current survey asked the participants to self-report each factor's importance; Jeon et al. (2008) asked participants to rate their preference; while Kawase's study (2013) asked them to choose a seat and state the reason. This could lead to the conclusion that acoustics is more important for overall enjoyment and believed so by people, but because it is harder to quantify and predict (especially for people without relevant backgrounds), when making seat selection, people tend to use view as the main rubric as it is more predictable. This may also be why "distance to stage" was more important for decision making than overall enjoyment. While people will always try to make decisions that lead to the best experience, some factors are easier to predict and compare, which consequently have more influence on people's decision making. This hypothesis needs to be tested in future research, but it may reveal potential value of presenting more information at the decision-making stage, for example, allowing people to preview the sound and view of a seat through auralization and visualization, which has been explored in some experimental studies (Korenaga & Ando, 1993; Sato et al., 2010; Wang et al., 2017).

The result that "going to concerts for the performers" was a more important reason than "going with friends" is similar to Roose's findings (2008), but the current survey also found that the repertoire was even more important than the performing musicians, and placed the importance of ticket price and "wanting to see the auditorium" between the performers and "going with friends." For overall enjoyment, visual conditions were almost as important as acoustic conditions. This highlights a need for more research into the visual condition and preference in concert halls, as the existing literature has a heavily skewed emphasis on acoustics research in auditoria, with limited results on visual preference (Jeon et al., 2008; Kawase, 2013; Sato et al., 2012), and fewer disentangling the effect of visual preference from auditory or overall preference. The results also showed that physical comfort of the environment and seat was indeed very important for overall enjoyment of the concerts, with similar ratings as view of the performance. This calls for more academic research in the previously neglected area.

Perceived importance was closely related for performance and acoustics, view and comfort, architecture and social event. An interpretation is that performance and acoustic quality affect the sound that people hear, which is the core of a music concert. Good view and comfort ensure that people can fully enjoy the music without being distracted by annoyances. They are not what people attend a concert for, but are closely connected to how people can enjoy the performance. And lastly, the hosting venue of the performance and the social aspect of concert-going are both related to going to a concert as a special event. These are not directly related to the performance, but complete the experience of going to a concert. Price, on the other hand, was relatively independent from the other factors. Based on the relationships between the factors, a summary chart is given (Figure 7-8), with two extra factors mentioned frequently by participants (in dashed frames), although their importance was not systematically investigated. The dashed lines connecting the groups indicate that divisions between the "music," "environment," and "event" are not completely distinct. This model puts factors from different fields of research into a larger context. Naturally, the more important factors deserve more research, but those at the bottom of the list were still considered important and should not be neglected. In addition, the operation of auditoria—e.g., the intended music style and performers, the ticket price range, the audience flow before, during, and after concerts—should all be considered at the design stage, as all the factors are interconnected and contribute to the overall experience of audiences.

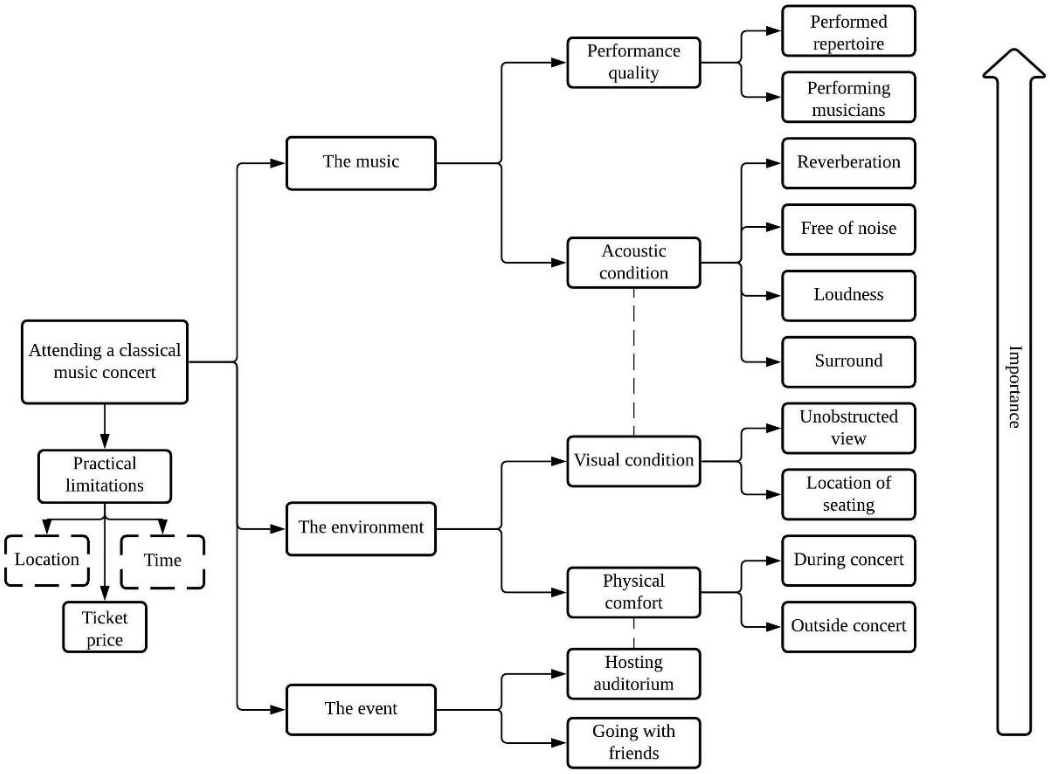


Figure 7-8 Relationships between factors affecting a concert-going experience

In terms of people's background, more frequent concert-goers emphasized repertoire slightly more, while less frequent concert-goers were more affected by non-performance factors (physical comfort, social aspect, price, and architecture), though the differences between groups of people were smaller than between factors. In other words, while most people attended concerts mainly for the music, less frequent concert-goers attached more importance to the overall experience. While this finding is in line with the conclusions from Roose (2008), Roose's study did not investigate the effect of repertoire. While the trends that less frequent concert-goers were more affected by price were also found by Roose (2008), the effect was not as significant as between age groups, suggesting that this effect may have been more related to age than concert-going frequency.

People who had past or present professional music experience emphasized the performance more than those without. However, current professional musicians or music students emphasized view more, while former professionals emphasized it less. This may be related to the findings of Giménez et al. (2011) that "music experts" were more demanding on the musicians' techniques. A possible explanation for the difference in judgement of view between current and former musicians is that people who are currently professional musicians or music students are more interested in performer playing techniques, which they could closely identify with and possibly learn from. Hence while current musicians would like to see the detailed actions and gestures of the performing musicians, former musicians no longer need to play music as their profession and seek ways to improve, and so can be more relaxed and just enjoy the music. However, this hypothesis will still need to be explored in future studies.

Price was more important for younger people, and less important for people with paid membership or seasonal bookings. The reason is likely to be mainly economic, as age is associated with income (King & Magoulas, 2015), and people with paid membership or seasonal bookings possibly already have most of the concerts included in their subscription. The concerns about price may also be part of the reason why the overall audience for classical music concerts is mainly older people, even though the young audience for classical music broadcasting has increased in recent years (Gosling, 2018). One solution may be reduced tickets for young audiences or students, which some orchestras and venues have adopted with positive effects (Pitts et al., 2013).

The hosting auditorium was more important for people with acoustics or architecture backgrounds, and social aspect was more important for acousticians, but no emphasis on the auditorium's acoustics was found, contrary to what might be expected. Although there is not much existing relevant literature, it is easy to understand that architects and acousticians are more interested in auditorium interior designs. While Giménez et al. (2011) found that acousticians (within "music experts") were more demanding of the acoustics, and Galiana (2016) found that they could better distinguish architecture variables from acoustic variables, the current results showed that they did not judge acoustics more importantly than others. The emphasis on social factors might be related to job characteristics but will need further verification.

The limitation of the research mainly lies in the questionnaire methodology, which means that results were self-reported beliefs by the participants and may not accurately reflect their actions or *in situ* experiences; and the relatively small sample size, which means that the results, especially those comparing different groups of people, could be somewhat affected by sampling. In addition, the current survey was conducted during the COVID-19 pandemic when most live music concerts had been cancelled throughout the world, and the remaining ones were carried on under special restrictions. While the survey dealt with this situation by asking the participants to refer to their experiences before COVID-19, it is uncertain whether the pandemic impacts on live music concert-attendance will continue to affect future concerts, including audience preferences and decision-making.

This survey is exploratory in nature, revealing connections and comparisons between factors from various aspects of classical concerts in their importance on audiences' decision making and enjoyment. It helped contextualize some of the previously individually studied factors, and drew attention to some important but under-studied factors that require future research. It also revealed some differences in focus between audiences and some links between seemingly unrelated factors, which may help future research consider the factors in a larger context and avoid missing some important connections.

Chapter 8 View quality prediction analysis examples of world auditoria

This chapter utilizes the proposed prediction model for visual seat preference and analyses various existing auditoria, to explore the relationships between view quality and auditorium shape and size.

8.1 Introduction

Apart from the acoustics, the visual scene in a concert hall plays an important role in the audience's concert-attending experience, and the view of the stage is a key component of the visual scene. On the one hand, visual preference contributes to the overall preference of the performance environment and experience (Chapter 4, 5, & 7; Jeon et al., 2008; Kawase, 2013; Sato et al., 2012); on the other hand, visual and auditory preference interact with and enhance each other (Chapter 3; Hyde, 2004) as an instance of cross-modal interactions that have been studied extensively in psychology (Alais et al., 2010; Stein & Meredith, 1993). In addition, some of the factors that influence auditory and visual preference are correlated. Proximity to stage is one of the major determinants of visual preference (Chapter 4 & 5); while in concert halls, due to its effect on direct sound energy, proximity is usually positively correlated with sound strength, which is positively correlated to auditory preference (Chapter 4 & 5; Jeon et al., 2008; Sato et al., 2012). Another example is floor rake in the seating area. Lower rakes usually result in visual obstruction between audience members, which negatively affects visual preference (Chapter 5). Acoustically, lower rakes are associated with more severe unwanted low-frequency attenuation in the direct sound caused by the seats, known as the seat dip effect (Tahvanainen et al., 2020).

Various studies have analysed and compared the acoustical quality or preference of a range of concert halls (Barron, 1988, 2009; Beranek, 1992, 2003, 2012; Galiana et al., 2016; Gimenez et al., 2011), but no systematic comparison has been done for the visual quality of any concert halls. The current study analyses an aspect of the visual quality of 56 concert halls that have been documented by Barron (2009) and Beranek (2012) using the quality of stage-view prediction model proposed in Chapter 5. It explores relationships between the stage-view visual quality and previously documented acoustic quality in these halls.

8.2 Method

8.2.1 Models

Auditorium models were built in Rhinoceros (Robert McNeel & Associates, 2019) using floor plans and sections provided by Barron (2009) and Beranek (2012). Only seating areas were included in the models, and all the steps within each area were simplified to constant-rake slopes (Figure 8-1).

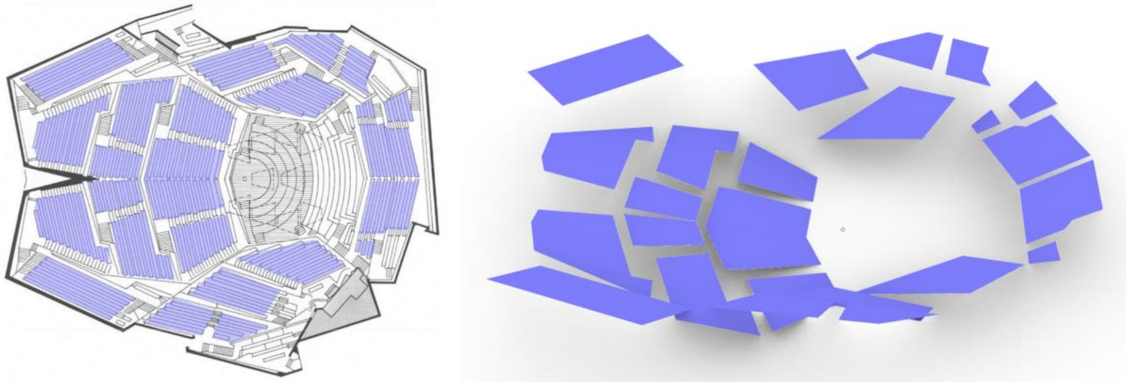


Figure 8-1 Example of audience areas used in the analysis (Berlin Philharmonie). Left: 2D view of modelled audience areas with reference to the floor plan. Right: 3D view of modelled audience area.

Points were extracted from the surfaces at approximately 0.9 m intervals, and were used for the calculation of stage view condition (Figure 8-2). A point at approximately the location of a conductor (1.2 m above the stage) was used as the reference point for distances and angles, as per the study that derived the prediction model of stage-view quality (Chapter 4). The points-of-view were at the height of 1.2 m above the floor, to represent the average eye height of seated people (Burris-Meyer & Cole, 1964).

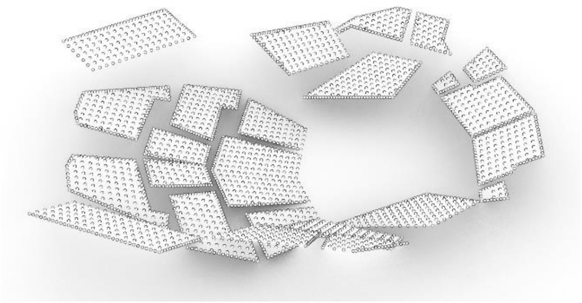


Figure 8-2 Example of audience area points (at approximately 0.9 m intervals) used in the calculation (Berlin Philharmonie).

8.2.2 Prediction equation

The full script Python for calculating the view quality in each auditorium is given in Appendix E. The view condition of each point was calculated using the prediction equation given in Chapter 5:

$$P = P_D + P_L + P_V + P_O$$

$$\begin{cases} P_D = dD \\ P_L = l|L| \\ P_V = v_1 V + v_2 V^2 \\ P_O = oVO \end{cases}$$

Equation 8-1

In which P is the seat preference prediction based on the effect of distance, lateral angle, vertical angle, and visual obstruction; P_D is the effect of distance; D is the distance from the point of focus in meters; P_L is the effect of lateral angle; L is the lateral angle from the center symmetric plane in degrees; P_V is the effect of vertical angle; V is the vertical angle from the horizontal plane in degrees; P_O is the effect of visual obstruction; VO is the amount of visual obstruction, a number between 0 and 1, which equals to the proportion of stage area that are invisible from the location; d = -0.0952; l = -0.0127; v_1 = 0.0613; v_2 = -0.0017; o = -1.92. For easier interpretation of the result values, an additional equation was used to scale the results to approximately between 0 and 100:

$$P_s = 100 \times \frac{P + 4}{3}$$

Equation 8-2

8.2.3 Visual obstruction estimation

The visual obstruction condition in realistic situations depends on the exact seating layout and occupancy and the audience members' individual seated heights, and may also be affected by architectural elements such as balcony fronts and columns, and the particular orchestra layout on stage. Due to the high complexity and variability, the visual obstruction used in this study only includes an estimate of audience obstruction.

A cuboid of 12 m wide, 7.5 m deep, and 1.8 m high was used as an approximation of an orchestra. This covers the area of a 60-piece orchestra used in precursor studies (e.g., Chapter 5). The depth of the cuboid covered from 1 m downstage of the conductor location (the target point for the location calculation) to 6.3 m upstage of the conductor location. The height was referenced to stage level (excluding risers, which were not considered in this study), and the width distributed evenly on both sides of the conductor location. Points were distributed evenly in the cuboid at approximately 0.9 m distance (14 × 9 × 3 = 378 points in total), and used as target points for the obstruction calculation. The same points used for the calculation of distance, lateral and vertical angles (1.2 m above the floor at 0.9 m intervals) were used as points-of-view for the obstruction calculation. To simulate obstruction from audience, 2 m high solid bodies were placed at the audience areas, with the upper face at 0.12 m above the points-of-view, which is the average height of the top of the seated audiences' heads (Burris-Meyer & Cole, 1964). For each point-of-view, a straight line representing a line-of-sight is connected between every target point to the point-of-view, and tested for any intersections with the audience surfaces. To account for the gaps between the rows, when testing for intersections between the lines-of-sight and the audience surfaces, a circle of 0.9 m radius (which is the average distance between rows) centring the point-of-view is excluded from the audience surfaces (Figure 8-3). In other words, if the lines-of-sight go above the surface within 0.9 m from the point-of-view (which corresponds to looking over the head of the person in front), it is considered unobstructed. In addition, in real situations, there are gaps between the audience members, and using a solid body to represent audience obstruction will always overestimate the obstruction. Therefore, the proportion of obstructed lines-of-sight (the quantity of lines-of-sight that have intersections with the audience surface divided by the total quantity of lines-of-sight from this point-of-view, 378) is multiplied by a factor of 0.2, to estimate the effect of being able to see the stage through the gaps between people's heads. This method may slightly overestimate the obstructions when there are very few rows in front of the viewer, and slightly underestimate the obstruction when there are many rows in front of the viewer, but it provides an adequate probabilistic estimate of the obstructions when detailed configurations of seat widths or the use of staggered seating are not available.

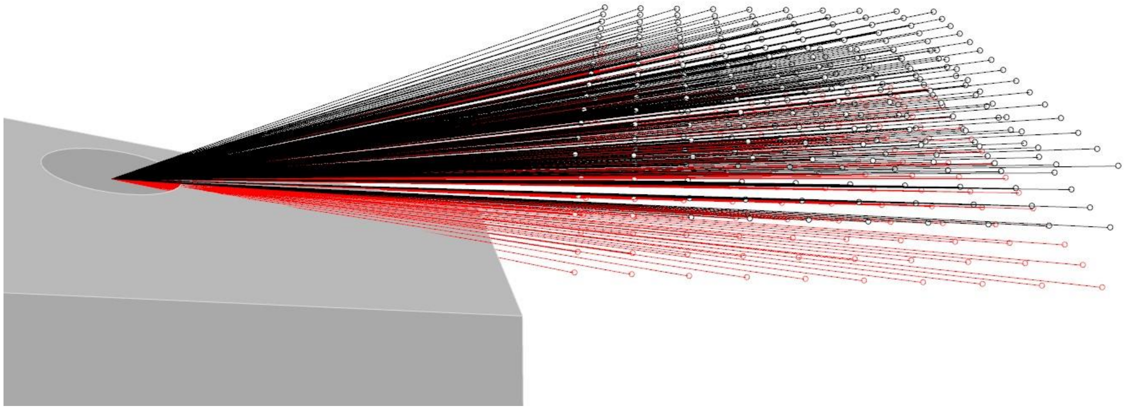


Figure 8-3 Demonstration of visual obstruction calculation. A circle of 0.9 radius is cut from the surface at the point-of-view. All lines represent lines-of-sight from the point-of-view to each target point. Red lines intersect with the audience surface or goes below, and thus are counted as obstructed by other audience members. Black lines pass through the circle without interruption, and are counted as unobstructed.

To validate the method of using whole audience surfaces for the calculation, an example, Berlin Philharmonie, was calculated using both whole audience surfaces and individually modelled audience members. The audience members were modelled according to the floor plans and section, with the height of the centre of the heads at 1.2 m, head radius of 0.12 m, shoulder width of 0.4 m, and seat width of 0.55 m (Figure 8-4). The results calculated with both methods are very similar (Figure 8-5).

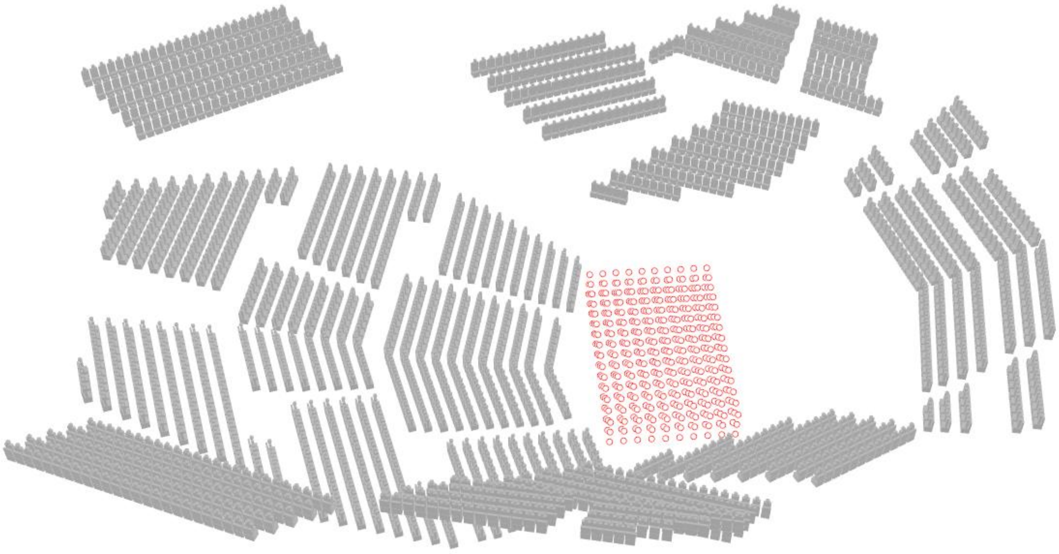
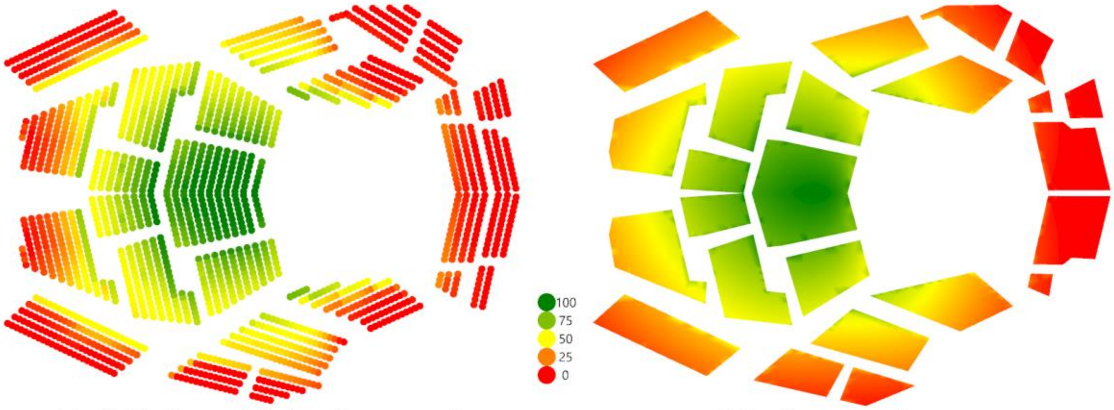


Figure 8-4 Example of individually modelled audience members (grey seated figures) and the 378 on-stage targets (red circles) (Berlin Philharmonie)



A Individually modelled audience members

B Continuous audience areas

Figure 8-5 Visual comparison of two modelling methods. A: using individually modelled audience members. B: using continuous audience areas. Colour scale shows the calculated preference results (including visual obstruction): red (0 or lower) – yellow (50) – green (100 or higher).

The difference between the calculated result at each point when using the individually modelled audience members, and the calculated result at the closest point when using the continuous audience areas, is shown in Figure 8-6 (left). As the two methods do not use the same locations, the calculated difference is between the closest locations in the two methods. The continuous audience areas return higher results at locations relatively further away from the stage (orange colour), and lower results at locations close to the stage (blue colour). This is likely due to the estimation method of visual obstruction used with the continuous audience areas as described in previous paragraphs. As when a seat is close to the stage, there are only a few rows in front of the seat, and there are more gaps between the audience members for the lines-of-sight to go through; while when a seat is further at the back, there are more rows in front of the seat and the obstruction from audience members is more severe. From the comparison scatterplot (Figure 8-6 (right)), it can be seen that the results from the two methods generally have high correlation. Considering that both methods are only estimations of the real situation, and that the locations evaluated in the two methods are also slightly different, the relatively high consistency shows that the results are relatively reliable.

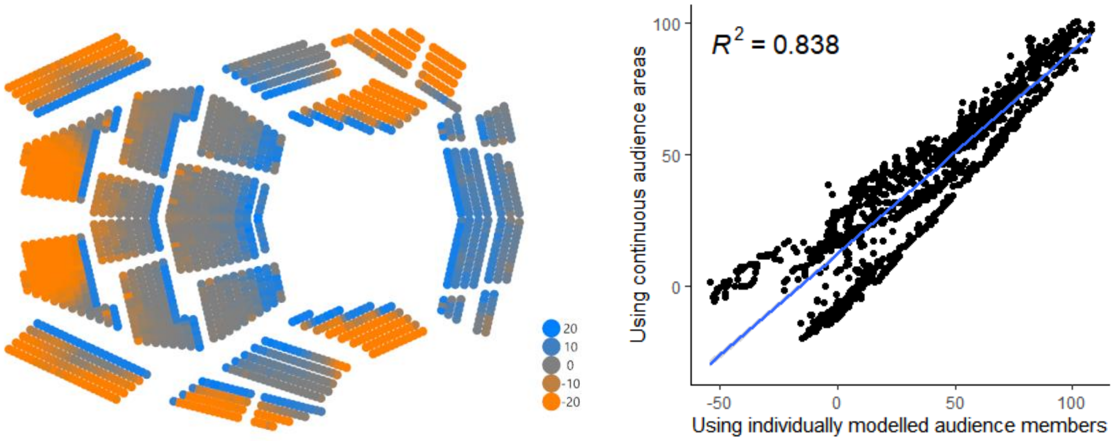


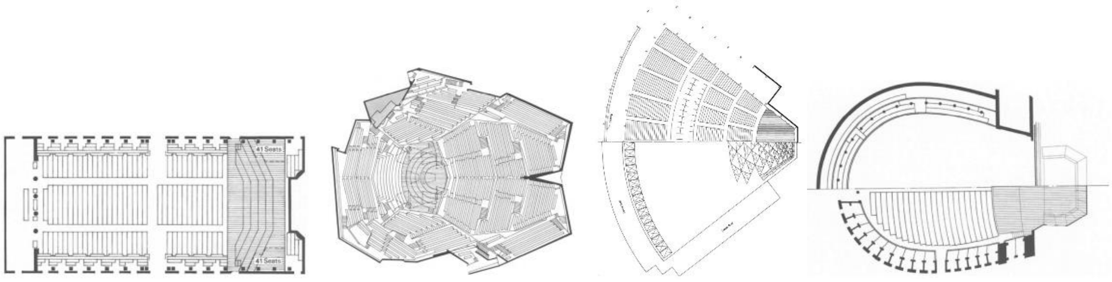
Figure 8-6 Comparison between two modelling methods. Left: difference between results from individually modelled audience members and results at closest point when using continuous audience areas, positive results show that individually modelled audience members return higher results. Right: scatterplot of two methods compared.

8.2.4 Analysed auditoria

All 16 British concert halls listed in Barron's book (2009) and 49 out of 58 concert halls listed in Beranek's concert hall ranking (2003) with corresponding drawings provided in his book (2004) were analysed. Nine auditoria are included in both lists, and the models were built based on drawings provided by Beranek whenever available, while two auditoria with drawings only provided by Barron were modelled accordingly.

The acoustic quality of the concert halls was divided into three categories: A, B, and C. The categorization for Beranek's list followed the ranking provided in the paper (2003), with the top ranked auditoria (1-20) in category A, 21 to 39 in category B, and the bottom ranked (40-58) in category C. The categorization of Barron's list was based on the descriptions of subjective characteristics in the book (2009). The halls with highly positive descriptions are in category A, those with mixed or average descriptions are in category B, and those that mainly have criticism are in category C (Table 8-1). The shapes of the auditoria were also categorized into four categories following Beranek's categorization (1996): rectangular (REC), geometric (GEO), fan-shaped (FAN), and horse-shoe shaped (HSU) (Table 8-1). The auditoria that were not included in the original categorization were categorized by the authors depending on their overall shape. The stalls' floor plan of a typical example for each shape is given in Figure 8-7.

Rectangular halls, sometimes also called "shoe-box concert halls", are the most widely used and highly rated shape of concert hall with parallel side walls that usually provide early lateral reflection that is desirable in acoustics. The halls usually have a flat or slightly raked stalls, with one or two balconies on the side and back. The number of seats that can be fitted in a rectangular hall is generally relatively small. Fan-shaped halls are designed to fit more seats, but the splayed side walls usually do not provide sufficient lateral reflections, therefore few of them have highly rated acoustics. Horse-shoe halls are used more often in old European opera houses, and usually have several vertically layered balconies surrounding flat or slightly raked stalls. Geometric halls are the halls that do not fit in any of the other shape categories. The most popular type of geometric hall is the “vineyard concert hall”, with relatively small seating sections that are stepped like vineyard terraces. The aim of the design is to fit in more seats but still providing lateral reflections using the walls enclosing each section.



A Rectangular (REC) **B Geometric (GEO)** **C Fan-shaped (FAN)** **D Horse-shoe (HSU)**

Figure 8-7 Example floor plans of the four shape categories used in the analysis (Beranek, 2012). A: rectangular hall example - Vienna Grosser Musikvereinssaal. B: geometric hall example - Berlin Philharmonie. C: fan-shaped hall example - Lenox Tanglewood Music Shed. D: Horse-shoe hall example - Buenos Aires Teatro Colon.

Table 8-1 All analysed auditoria and results

Source	Acoustic Category	Shape	Auditorium name	Total number of seats	Total seating area (m^2)	“Good” proportion	Mean score	“Good” seats	“Good” area
Beranek	A	REC	Vienna Grosser Musikvereinssaal	1598	776	0.42	50	671	326
Beranek	A	REC	Boston Symphony Hall	2625	1092	0.29	48	761	317
Beranek	A	HSU	Buenos Aires Teatro Colon	2487	1295	0.3	38	746	389
Beranek	A	REC	Berlin Konzerthaus (Schauspiethaus)	1575	775	0.47	55	740	364
Beranek	A	REC	Amsterdam Concertgebouw	2037	886	0.25	47	509	222
Beranek	A	REC	Tokyo Tokyo Opera City (TOC) Concert Hall	1632	783	0.44	50	718	345
Beranek	A	REC	Zurich Grosser Tonhallesaal	1546	632	0.54	55	835	341
Beranek	A	HSU	New York Carnegie Hall	2804	1303	0.28	37	785	365
Beranek	A	REC	Basel Stadt-Casino	1448	569	0.68	60	985	387
Beranek	A	GEO	Cardiff St. David's Hall	1952	1104	0.46	50	898	508
Beranek	A	HSU	Dallas McDermott Hall	2065	1167	0.34	43	702	397
Beranek	A	REC	Bristol Colston Hall	1940	756	0.48	53	931	363
Beranek	A	REC	Lenox Seiji Ozawa Hall	1180	463	0.59	60	696	273
Beranek	A	GEO	Costa Mesa Segerstrom Hall	2994	1623	0.24	35	719	390

Beranek	A	REC	Salt Lake City Abravanel Symphony Hall	2812	1422	0.31	39	872	441
Beranek	A	GEO	Berlin Philharmonie	2218	1124	0.38	42	843	427
Beranek	A	GEO	Tokyo Suntory Hall	2006	1116	0.34	46	682	379
Beranek	A	HSU	Brussels Palais des Beaux-Arts	2150	987	0.37	46	796	365
Beranek	A	GEO	Baltimore Joseph Meyerhoff Symphony Hall	2467	1141	0.22	42	543	251
Beranek	B	REC	Bonn Beethovenhalle	1407	843	0.13	36	183	110
Beranek	B	REC	Chicago Orchestra Hall	2530	1247	0.36	44	911	449
Beranek	B	GEO	Christchurch Town Hall	2662	1170	0.34	47	905	398
Beranek	B	HSU	Cleveland Severance Hall	2101	1235	0.38	44	798	469
Beranek	B	REC	Gothenburg Konserthus	1286	554	0.42	47	540	233
Beranek	B	FAN	Jerusalem Binyanei Ha'Oomah	3142	1576	0.13	36	408	205
Beranek	B	REC	Kyoto Concert Hall	1840	892	0.39	48	718	348
Beranek	B	GEO	Leipzig Gewandhaus	1900	1144	0.44	49	836	503
Beranek	B	FAN	Lenox Tanglewood Music Shed	5121	2330	0.06	-11	307	140
Beranek	B	REC	Osaka Symphony Hall	1702	957	0.44	51	749	421
Beranek	B	REC	Tokyo Metropolitan Art Space	2017	1022	0.4	36	807	409
Beranek	B	REC	Tokyo Orchard Hall	2150	1032	0.21	28	452	217
Beranek	B	REC	Vienna Konzerthaus	1865	666	0.31	47	578	206
Beranek	C	FAN	Salzburg Festspielhaus	2158	891	0.55	57	1187	490
Beranek	C	GEO	Stuttgart Liederhalle Grosser Saal	2000	1075	0.13	31	260	140
Beranek	C	REC	New York Avery Fisher Hall	2742	1172	0.23	37	631	270
Beranek	C	FAN	Copenhagen Radiohuset Studio 1	1081	533	0.79	62	854	421
Beranek	C	HSU	Edinburgh Usher Hall	2502	949	0.24	44	600	228
Beranek	C	REC	Glasgow Royal Concert Hall	2457	1173	0.5	50	1229	587
Beranek	C	REC	London Royal Festival Hall	2901	1445	0.27	45	783	390
Beranek	C	FAN	Liverpool Philharmonic Hall	1803	848	0.41	48	739	348
Beranek	C	REC	Manchester Free Trade Hall	2529	922	0.45	52	1138	415
Beranek	C	FAN	Paris Salle Pleyel	2386	843	0.24	42	573	202
Beranek	C	FAN	Montreal Salle Wilfrid-Pelletier	2982	1299	0.17	37	507	221
Beranek	C	FAN	Tokyo NHK Hall	3677	1467	0.12	21	441	176
Beranek	C	GEO	Sydney Opera House Concert Hall	2696	1485	0.25	34	674	371
Beranek	C	FAN	Tel Aviv Fredric R Mann Auditorium	2715	1069	0.35	44	950	374

Beranek	C	GEO	London Barbican Concert Hall	1924	1066	0.42	49	808	448
Beranek	C	FAN	Buffalo Kleinhans Music Hall	2839	1389	0.17	34	483	236
Beranek	C	GEO	London Royal Albert Hall	5222	2627	0.06	15	313	158
Barron	A	GEO	Belfast Waterfront Hall	2039	1101	0.35	47	714	385
Barron	A	REC	Bristol Colston Hall	1940	756	0.48	53	931	363
Barron	A	GEO	Cardiff St. David's Hall	1952	1104	0.46	50	898	508
Barron	A	REC	Croydon Fairfield Hall	1539	698	0.54	58	831	377
Barron	A	REC	Poole Lighthouse Concert Hall	1473	672	0.49	55	722	329
Barron	B	GEO	Birmingham Symphony Hall	1990	1174	0.35	41	697	411
Barron	B	REC	Glasgow Royal Concert Hall	2457	1173	0.5	50	1229	587
Barron	B	REC	Liverpool Philharmonic Hall	1803	848	0.41	48	739	348
Barron	B	REC	London Royal Festival Hall	2901	1445	0.27	45	783	390
Barron	B	REC	Manchester Bridgewater Hall	2127	1080	0.48	49	1021	518
Barron	B	REC	Nottingham Royal Concert Hall	2315	1200	0.41	49	949	492
Barron	B	REC	Watford Colosseum	1586	627	0.12	35	190	75
Barron	C	HSU	Edinburgh Usher Hall	2502	949	0.24	44	600	228
Barron	C	FAN	London Barbican Concert Hall	1924	1066	0.42	49	808	448
Barron	C	GEO	London Royal Albert Hall	5222	2627	0.06	15	313	158
Barron	C	REC	Manchester Free Trade Hall	2529	922	0.45	52	1138	415

8.3 Results

8.3.1 Modelled audience area vs. total number of seats

The number of seats for each auditorium was compared with the total audience area for the analysis (Figure 8-8). The number of seats and modelled area are highly correlated ($r = .936$, $p < .001$), and the relationship is consistent between the two sources of drawings, supporting the reliability of the chosen modelling method. Between the different shapes of auditoria, geometric auditoria have a slightly lower seat density than the other types. This could be related to the relatively irregular arrangements and smaller sizes of the seating areas in geometric auditoria, especially vineyard-type auditoria.

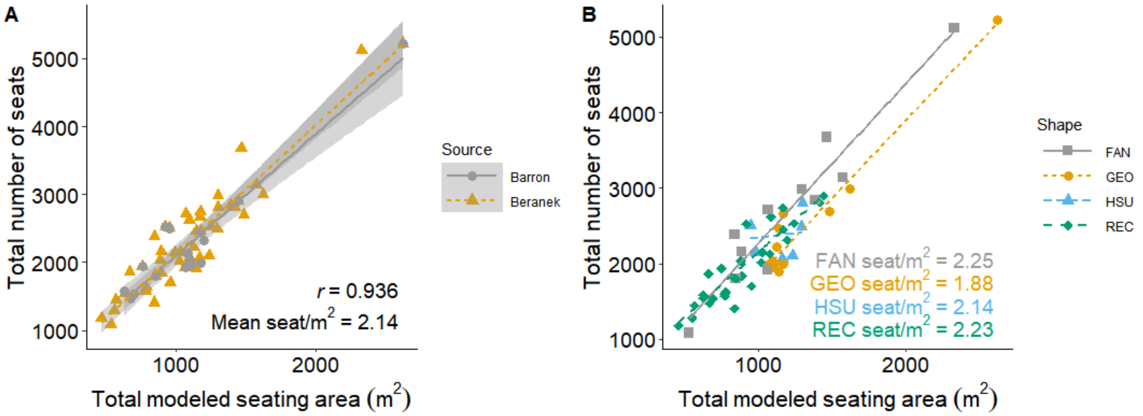


Figure 8-8 Number of seats plotted against modelled audience area. A: colour and shape separated by source. B: colour and shape separated by hall shape

8.3.2 Stage-view quality visualization over the seating areas

As the view quality of the stage is calculated for the whole seating area of each auditorium, to better visualize the results, the areas are coloured according to the calculated view scores. The colour changes gradually with three anchors: red for 0 or below, yellow for 50, and green for 100 or above. The areas with scores over 50 are highlighted with green contours. All auditoria analysed are visualized according and arranged below. The sizes of the figures are scaled to the best fit, and do not represent the size of the auditoria.

Amsterdam
Concertgebouw

Baltimore
Joseph Meyerhoff Symphony Hall

Basel
Stadt-Casino

Belfast
Waterfront Hall

Berlin
Konzerthaus (Schauspiethaus)

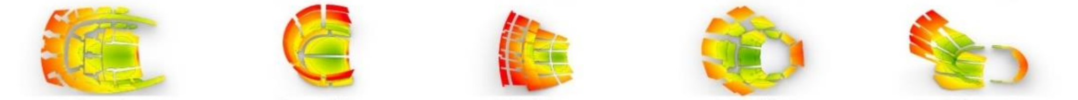
Berlin
Philharmonie

Birmingham
Symphony Hall

Bonn
Beethovenhalle

Boston
Symphony Hall

Bristol
Colston Hall



Brussels
Palais des Beaux-Arts

Buenos Aires
Teatro Colon

Buffalo
Kleinhans Music Hall

Cardiff
St. David's Hall

Chicago
Orchestra Hall

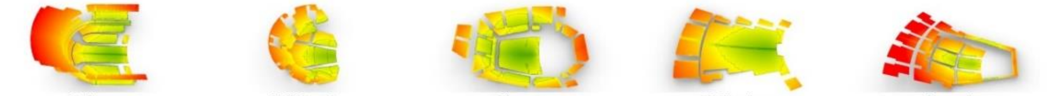
Christchurch
Town Hall

Cleveland
Severance Hall

Copenhagen
Radiohuset Studio 1

Costa Mesa
Segerstrom Hall

Croydon
Fairfield Hall



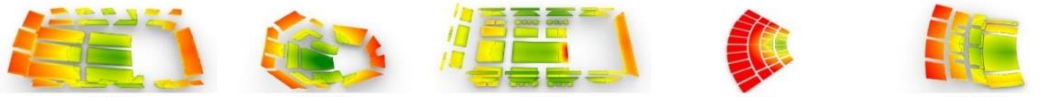
Dallas
McDermott Hall

Edinbrugh
Usher Hall

Glasgow
Royal Concert Hall

Gothenburg
Konserthus

Jerusalem
Binyanei Ha'Oomah



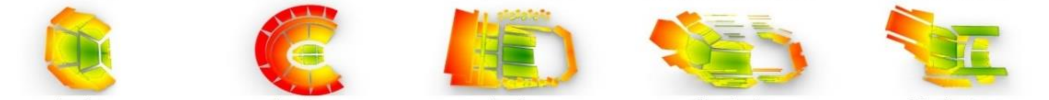
Kyoto
Concert Hall

Leipzip
Gewandhaus

Lenox
Seiji Ozawa Hall

Lenox
Tanglewood Music Shed

Liverpool
Philharmonic Hall



London
Barbican Concert Hall

London
Royal Albert Hall

London
Royal Festival Hall

Manchester
Bridgewater Hall

Manchester
Free Trade Hall

Montreal
Salle Wilfrid-Pelletier

New York
Avery Fisher Hall

New York
Carnegie Hall

Nottingham
Royal Concert Hall

Osaka
Symphony Hall

Paris
Salle Pleyel

Poole
Lighthouse Concert Hall

Salt Lake
City Abravanel Symphony Hall

Salzburg
Festspielhaus

Stuttgart
Liederhalle Grosser Saal

Sydney
Opera House Concert Hall

Tel Aviv
Fredric R Mann Auditorium

Tokyo
Metropolitan Art Space

Tokyo
NHK Hall

Tokyo
Opera City (TOC) Concert Hall

Tokyo
Orchard Hall

Tokyo
Suntory Hall

Vienna
Grosser Musikvereinssaal

Vienna
Konzerthaus

Watford
Colosseum

Zurich
Grosser Tonhallesaal

Figure 8-9 Result visualisation of all analysed auditoria. Colour scale: red (0 or below) – yellow (50) – green (100 or above). Green lines bordered areas: 50 or above. Image of halls not in scale.

8.3.3 “Good” proportion vs. mean score

Two indicators were selected to represent the overall visual condition of each auditorium: the proportion of seating area with calculated view score over 50 (“good” proportion), and the mean view score of all calculated points (mean score). The two indicators are compared. As expected, the relationship between the indicators is not linear, but it is mostly positive, which can be shown by the corresponding ranking. This means that the two indicators mostly agree with each other when comparing between auditoria. Because the points used for the analysis are not always evenly distributed on the seating areas (e.g., the points may be denser around the edges or areas with more detailed contours), and this may slightly affect the result of mean score, giving the denser areas larger weighting. Therefore, the “good” proportion is considered the better indicator and chosen for the analysis.

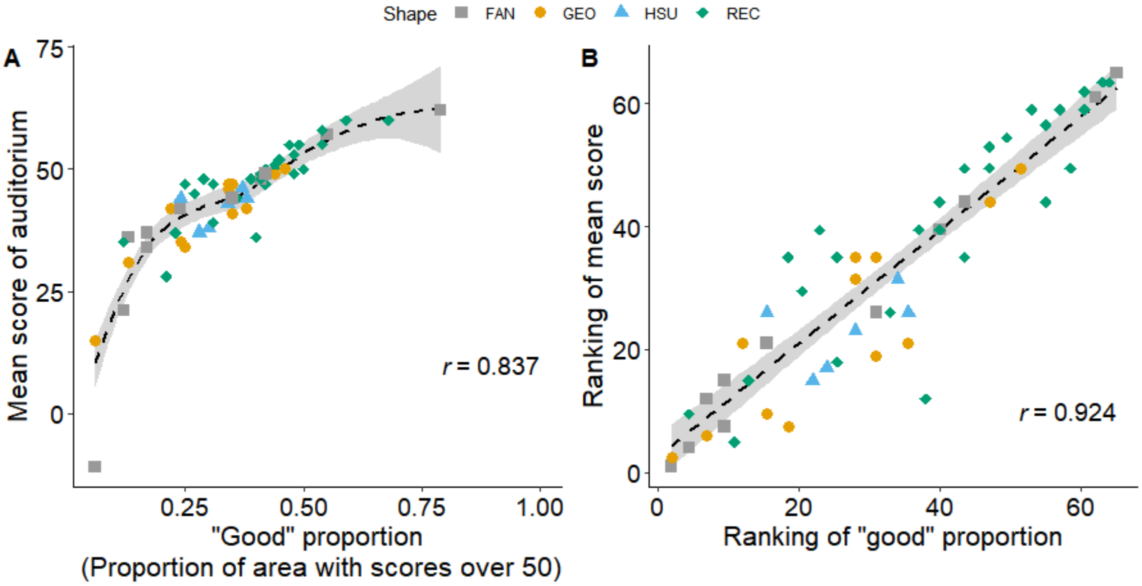


Figure 8-10 Mean score plotted against proportion of area with scores over 50. A: values. B: ranking.

However, usually the seats with good views are more important than the seats with bad views, as when the auditorium is not filled to the full capacity, the relatively “good” seats would be more likely to be taken. In some extreme cases, the seats with the worst visual and acoustic conditions in particular auditoria may never be used. Therefore, apart from the “good” proportion, the absolute number of seats with calculated view score over 50 (“good” seats) is also calculated by multiplying “good” proportion with the total number of seats.

8.3.4 Visual vs. acoustic condition

To examine whether these is general correlation between visual and acoustic conditions, one-way ANOVAs were conducted for the relationship between acoustic category and visual quality (“good” proportion and “good” seats). The results show only a weakly significant effect (at 90% confidence) for “good” proportion (*F*(2,62) = 2.74, *p* = .072), and no effect for the number of “good” seats (*F*(2,62) = 0.71, *p* = .498) between auditoria in different acoustic categories. There is a slight decreasing trend in “good” proportion when acoustics deteriorates from A to C, while

Tukey-HSD *post hoc* test shows only a weakly significant difference between A and C (p = .083). For the number of “good” seats, while the medians in the three categories are very similar, the distribution is much more concentrated in halls of category A, which means that halls with the best acoustic quality are less varied in stage-view quality than the others.

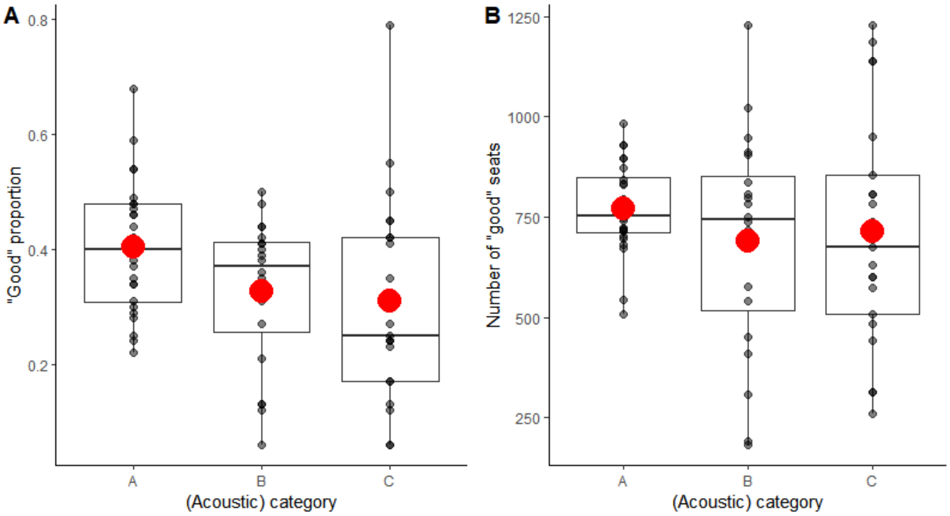


Figure 8-11 Distribution boxplots of "good" proportion (A) and number of “good” seats (B) in different acoustic categories, along with mean (red dots) and individual values (small grey dots).

8.3.5 Shape vs. visual and acoustic condition

The auditorium shape is one of the most important characteristics of concert halls that affect their acoustic condition, and most of the auditoria with best acoustics are rectangular halls because of the strong lateral reflection the side walls provide (Beranek, 2012), while fan-shaped halls usually have insufficient lateral support and are mostly poor acoustically. The chi-square calculation (X^2 = 19.98, df = 6, p = .003) and balloon plot (Figure 8-12(A)) for the relationship between shape and acoustic category aligns with this conclusion. In terms of visual condition, the proportion of “good” seats is plotted against different shapes and acoustic categories (Figure 8-12(B)). While there are no fan-shaped halls in category A, rectangular halls generally have better visual condition than geometric halls and horse-shoe halls. Fan-shaped halls with fair acoustics (category B) have much lower visual quality than other shapes, and those that have better visual quality have poor acoustics (category C). On the other hand, acoustics and visual quality have a positive relationship in geometric halls, meaning that geometric halls with good acoustics generally also have better overall visual condition. The rectangular halls that have the best acoustics also have the best visual condition. Overall, although the differences in visual condition between individual halls are more significant than between shapes, rectangular halls have the best visual quality while fan-shaped halls have the lowest, despite the usual belief that fan-shaped halls provide the better views than rectangular halls. However, this effect was only weakly significant, at 90% confidence (F(3,61) = 2.24, p = .093).

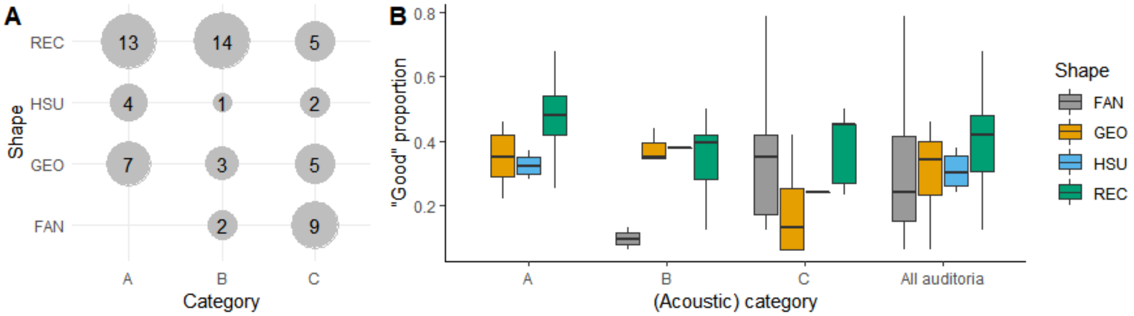


Figure 8-12 Relationship between hall shape and acoustics. A: balloon plot of shape vs. acoustic category. B: distribution boxplot of calculated "good" proportion for each shape and acoustic category

8.3.6 Size vs. acoustic and visual condition

The auditorium size is also an important factor that affects their quality. For acoustics, halls that are too large usually have insufficient sound strength due to the dispersion of sound energy in space, and seats at the back usually have lower clarity. The size of the auditorium is represented by the total number of seats, and there is a negative relationship between the number of seats and acoustic quality (Figure 8-13) (F(2,62) = 4.40, p = .016), though Tukey-HSD post hoc test shows that only the difference between category A and C reaches significance (p = .013). The auditorium shape also is significantly related to size (F(3,61) = 3.27, p = .027). Fan-shaped halls have the largest mean number of seats, and rectangular halls have the fewest, although *post hoc* test only found small significance differences (at 90% confidence) between rectangular and fan-shaped (p = .062), and rectangular and geometric (p = .077).

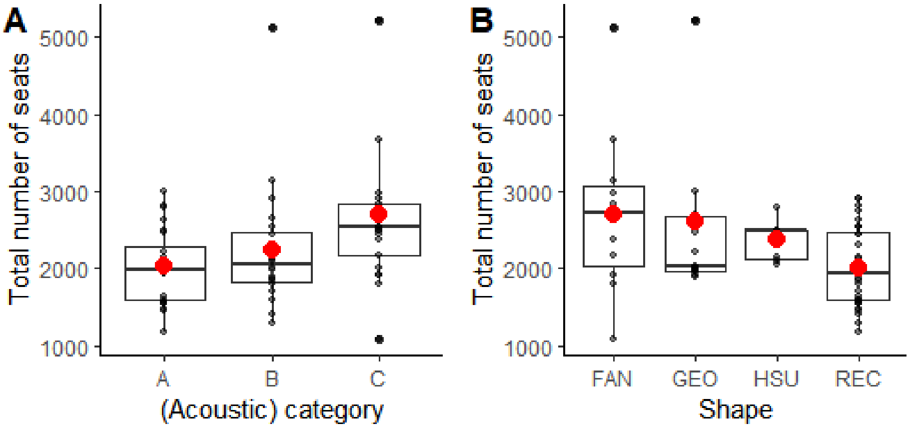


Figure 8-13 Hall size represented by total number of seats plotted against acoustic category (A) and shape (B), together with mean (red dots) and individual values (small grey dots)

Due to the negative correlation between distance to stage and visual preference, seats further away from the stage generally have lower calculated scores. As a result, larger auditoria tend to have lower overall view quality. To examine the relationship between auditorium size and overall view quality, the proportion of area with scores over 50 ("good" proportion) for each auditorium is plotted against the total number of seats of the auditorium (Figure 8-14). The auditoria are also separated by shape and acoustic quality category to reveal further relationships. While the overall quality represented by the “good” proportion generally decreases as size increases (*r* = -.68, *p* < .001), the different auditorium shapes have slightly different trends. The overall view quality in rectangular halls is affected by size the least (*r* = -.34, *p* = .059). Geometric halls are more affected by size, while usually having larger sizes (*r* = -.79, *p* < .001). Fan-shaped halls usually have good overall visual condition when the auditorium is small (e.g., less than 2500 seats), but the condition degrades the fastest as size increases, because the number of seats in each row increases as distance increases, so it includes more seats with poor visual condition when size increases compared to other shapes. Thus fan-shaped halls are the most negatively affected by size (*r* = -.84, *p* = .001). Horse-shoe halls usually have a large number of seats on the balconies around the perimeter of the halls which are usually relatively far from the stage, therefore has the least desirable overall visual condition compared to other halls with the same number of seats, while still being negatively affected by size (*r* = -.77, *p* = .041). However, while there is a general trend that the overall visual condition decreases as size increases, the visual condition can be very different between halls of similar size, especially for rectangular halls and halls with small sizes.

While the proportion of seats with good visual condition decreases with hall size, there is an optimal size of auditorium that can provide the greatest number of “good” seats at around 2000 to 2500 seats. Rectangular halls, which are generally smaller, have a positive correlation between the number of “good” seats and size (*r* = .43, *p* = .015), while the correlation is negative for geometric (*r* = -.64, *p* = .010) and fan-shaped halls (*r* = -.69, *p* = .018), which are usually bigger. When the capacity exceeds 3000, even though there are more seats in the auditorium, the number of “good” seats decreases, possibly due to the decrease of seating rake. Meanwhile, there are no auditoria with acoustic category of A with over 3000 seats. In other words, it is difficult for large auditoria with over 3000 seats to achieve either good acoustics or good stage view.

However, the auditoria with the most “good” seats are only in category C in terms of acoustics. The three auditoria with the most “good” seats are: Glasgow Royal Concert Hall (1228 out of 2457 seats), Salzburg Festspielhaus (1187 out of 2158 seats), and Manchester Free Trade Hall (1138 out of 2529 seats). A common characteristic of these halls is that they are all relatively wide with large balconies close to the stage. While the large width and balconies allow more seats to be close to the stage and increase the overall visual quality, they may result in lower lateral reflection that is undesirable in acoustics. The halls in category A that have the largest number of “good” seats are: Basel Stadt-Casino (985 out of 1448 seats), Bristol Colston Hall (931 out of 1940 seats), Cardiff St. David’s Hall (898 out of 1952 seats), Salt Lake City Abravanel Symphony Hall (872 out of 2812 seats), and Berlin Philharmonie (843 out of 2218 seats). Three out of five of these halls are around 2000 seats capacity, with one smaller (Basel Stadt-Casino, 1448) and one larger (Abravanel Symphony Hall, 2812). This may suggest that around 2000 may be an optimal size for concert halls to achieve both good acoustics and maximum number of seats with good view. Two of these halls are geometric, both of which are vineyard-shaped, while the rest are rectangular.

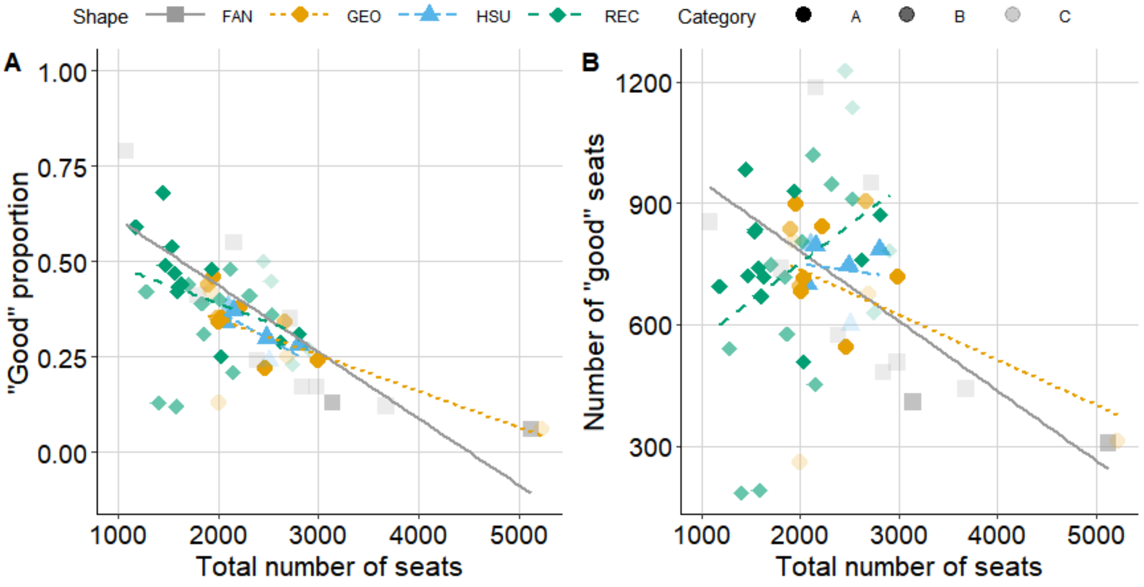


Figure 8-14 View quality (proportion and number of seats with scores over 50) vs. total number of seats

8.4 Discussion and conclusion

This chapter analyses the predicted view quality of whole seating areas in some of the acoustically ranked world auditoria using the prediction model proposed in this thesis. The main findings are discussed below.

In general, halls with the best acoustics have less varied stage view qualities compared to others. While halls with average or poor acoustic quality may have very good or very poor view quality, the halls with good acoustics generally have medium to good view quality. This may mean that there are certain rules that a hall needs to comply with to achieve good acoustics, and the same rules also confine the view quality.

For different hall shapes, when the acoustic qualities are in the same category, rectangular halls generally have the best view qualities, especially in the halls with the best acoustics. This is contrary to general belief that other shapes, especially geometric and fan-shaped halls, have better view qualities than rectangular halls. Geometric halls have relatively good view quality when acoustics is also good, but there are some halls that have both low acoustical and view quality. Due to the very small sample size of horse-shoe halls, they are not analysed in detail.

Generally smaller halls have both better acoustics and better view qualities (in terms of proportion) compared to larger halls. This is easy to understand as smaller halls have smaller source-receiver distances, and smaller distance both correspond to larger image and higher detail resolution, which leads to higher visual preference, and to higher sound pressure level and higher intimacy, which lead to higher auditory preference.

In terms of providing the largest number of seats with "good" view quality, there is an optimal size of auditorium at around 2000 to 2500 seats. While smaller halls can have a higher proportion of seats with good view, the total number is small and limits the number of “good” seats. Larger halls with more than 3000 seats generally need to sacrifice seating rake to fit in the number, which in turn deteriorates view quality in the area where the best view quality should be achieved. However, this does not guarantee that all halls around that size have “good” view quality as the view quality varies greatly for the same size and even same hall type, pointing to the need of design optimization regarding view quality, which is a sparsely-documented aspect of the concert hall design process.

While it is widely accepted that fan-shaped halls generally have medium to poor acoustics due to the lack of lateral reflection (Barron, 2009; Beranek, 2012; Lokki, 2014), they are still built in some cases in the belief of achieving better viewing conditions. However, the results in this analysis show that it is not the case, especially for large halls. While they may fit more seats within an acceptable lateral angle, there are more seats that are further away from the stage and fewer that are close to the stage, and distance is one of the main influential factors for view quality.

This analysis is based on the proposed prediction model and simplified architecture models, and does not take into account detailed seating layout including row widths and staggered seating. It only estimates the view obstructions using the proposed simplified method, and does not include obstructions from architecture elements (such as balcony railings). Only a single point on stage is used in the location calculation, so it does not include the effect of different stage setups (e.g., having riser steps on stage). However, the results show some general statistical trends of a number of halls, which may be of interest to some readers.

Chapter 9 Conclusions

This thesis examines the subjective preference in music auditoria with an emphasis on the less-studied visual preference, using the method of virtual reality subjective evaluation. The main conclusions are discussed in this chapter.

A prediction model for within-auditorium seat preference was constructed through orthogonally controlled factors, and verified through realistic auditoria simulations. The model accounts for distance to stage (negative effect), lateral angle from centre line (negative effect), vertical angle from stage level (polynomial effect with optimal value), obstruction of stage view (negative effect), and sound strength (positive effect). The model can accurately predict the average subjective overall audiovisual seat preference in the virtual reality auditorium simulations used in this thesis. A simplified analysis tool for view quality (excluding the effect of sound strength) was created, and a range of world auditoria was analysed using the tool, showing that rectangular halls have the best average view quality, with an optimal size (greatest number of "good" seats) of around 2000 seats capacity.

When comparing between different auditoria, interior design (e.g., colour, shape) of auditoria affects preference for auditoria and all seats within the auditoria, but preference differences between seats are generally larger than between halls. Red, the most commonly featured colour in existing auditoria, is also the most preferred colour for auditorium design. Obstructions from audience members are more tolerated than obstructions from architectural elements, and the effects will need to be quantified in future research.

When comparing with other factors of a concert-going experience, apart from the performance quality, acoustic and view quality are the most important factors, followed by comfort, price, hosting auditorium and social aspect. More frequent concert-goers are more influenced by performance and acoustics, while less frequent audiences emphasize the event more.

This thesis is the first to quantify the effect of view on seat preference using orthogonal methods, and to construct a prediction model that may be applicable to all music auditoria. It is also the first to examine the effect of interior design on auditorium preference, and compare various aspects of the concert-going experience under a same frame of context. It reveals the importance of view quality for the overall preference of concert experiences, and calls for more research into this previously under-studied area.

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Appendix A Acoustic measurement of Verbrugghen Hall

The measurement was done on 1st of August 2019 in the Verbrugghen Hall. The Verbrugghen Hall has a capacity up to 528, and is frequently used for concerts, music practices, and other purposes. It's approximately 7000 m^3 in volume.

A.1 Equipment

The equipment used for the measurement includes 2 types of loudspeakers and 3 types of microphones. For the first set of measurements, the dodecahedron speaker and the multichannel microphone were used. For the second set of measurements, both speakers and both dummy head and omni-directional microphone were used.

A.1.1 Loudspeakers

The loudspeakers used in the measurement are:

- Dodecahedron Speaker - Brüel & Kjær OmniPower 4292 with Brüel & Kjær Power Amplifier Type 2734;
- Studio Monitor - Genelec 8030A Bi-amplified Monitoring System.

The dodecahedron speaker is used as an omni-directional sound source in compliance with ISO 3382-1 (2009). The studio monitor is used as a more directional sound source that resembles human voice or directional instruments.

A.1.2 Microphones

The loudspeakers used in the measurement are:

- Multichannel Microphone - mh acoustics EM32 Eigenmike® microphone array (32 Channels)
- Dummy Head (2 Channels) - Neumann KU 100 Dummy Head system
- Omni-directional Microphone – Brüel & Kjær Hand-held Analyzer Type 2270 (1 Channel)

The multichannel microphone is used to record the received signal with spatial information, that can be turned into Ambisonic impulse responses. It also allows the measurement of lateral energy fraction, used in the calculation of early lateral energy fraction (J_{LF} or J_{LFC}) and late lateral sound level (L_J) which are used to determine apparent source width (ASW) and listener envelopment (LEV), respectively. The dummy head is used for binaural measurements including inter-aural cross correlation coefficients (IACC) that determines "spatial impression". The omni-directional microphone is used for absolute level calibration.

A.2 Source and receiver positions

For the first set of measurements (dodecahedron speaker x multichannel microphone), 5 source positions on stage x 18 microphone positions in the audience were chosen. For the second set of measurements (dodecahedron/directional speakers x dummy head/omni-directional microphone), the same 5 source positions on stage x 6 microphone positions in the audience were used.

A.2.1 Source positions

5 source positions on stage at the height of 1.5 meters for both sets of measurements (Figure A-1): S1 (-1.5, -3), S2 (-4, -2), S3 (-4, 2), S4 (-1.5, 3), and S5 (-3, 0). S1 – 4 were chosen in accordance with an existing measurement for stage support in the same concert hall, as the locations were chosen for a reasonable string quartet arrangement (Panton, Yadav, Cabrera, & Holloway, 2019). The main purpose of these four source positions was to be used for auralization. S5 were chosen on the symmetry axis for general analysis. When the directional speaker was used, it was oriented towards the positive direction of the x axis.

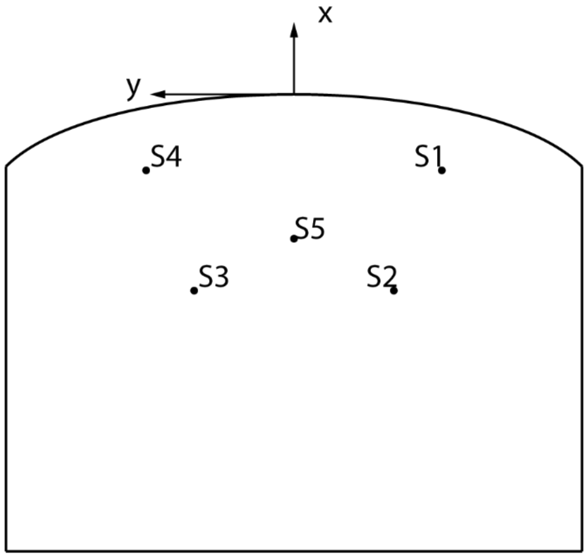

Figure A-1 Source locations for the measurement of Verbrugghen Hall

A.2.2 Receiver positions

18 microphone positions in the audience for the first set of measurements at the height of 1.2 meters:

- 6 in the Front Stalls: D12, D19, I12, I19, M12, M19;
- 2 in the Back Stalls: O10, O19;
- 3 in the North Stalls: NS3, NS8, NS12;
- 4 in the Balcony: BA10, BB17, BD10, BD17;
- 3 in the North Gallery: NG1, NG7, NG12.

6 microphone positions in the audience for the second set of measurements at the height of 1.2 meters:

- 6 in the Front Stalls: D12, D19, I12, I19, M12, M19.

The seat numbers of receiver positions are marked in Figure A-2. The microphones are positioned at the projection centre of each measured seat. For the multichannel microphone and the dummy head, the orientations of the microphones are pointed towards the stage, parallel to the symmetry axis of the auditorium.

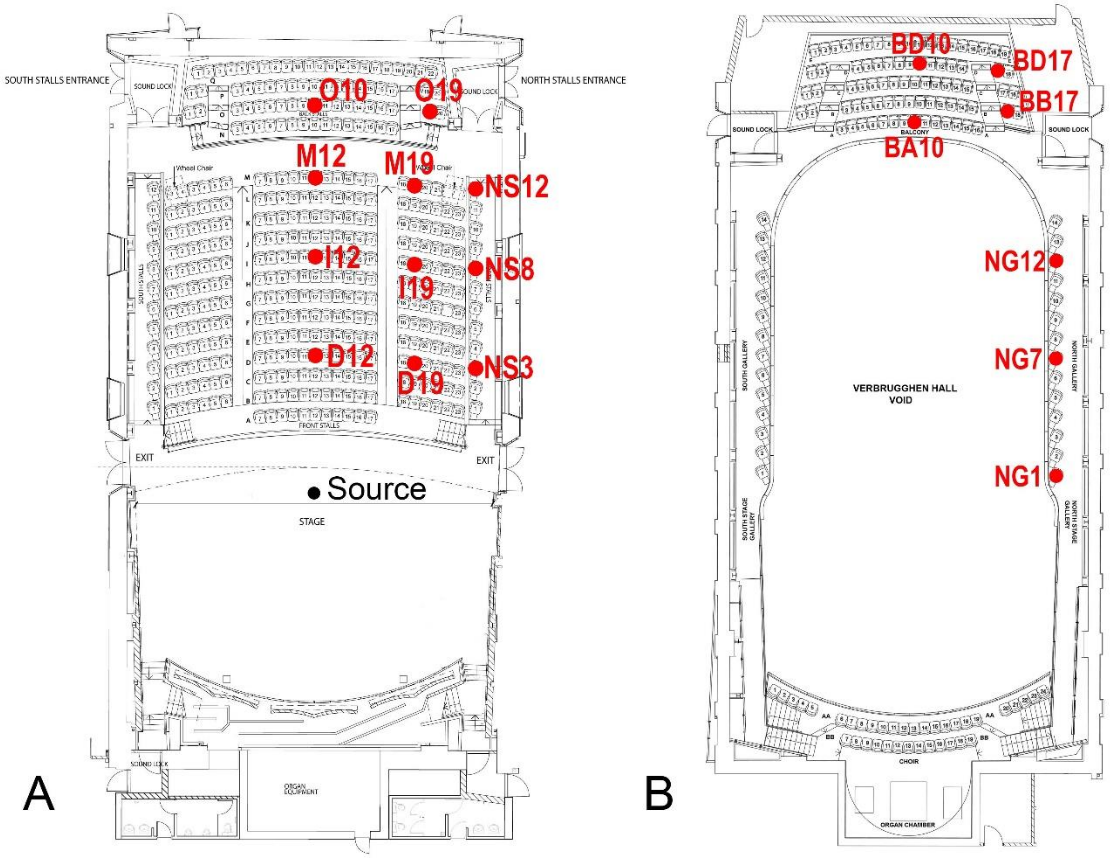

Figure A-2 Receiver locations for the measurement of Verbrugghen Hall

A.3 Measurement procedure

A.3.1 Test signal

The test signal used in the measurement is a computer-generated exponential sine-sweep of 30 seconds from 20 Hz to 20 kHz.

A.3.2 Recording software

The recording software used is AARAE (Release 9) for MATLAB.

A.3.3 Measurement setup

First set of measurements (dodecahedron speaker x multichannel microphone)

The measurement set up is shown in Figure A-3.

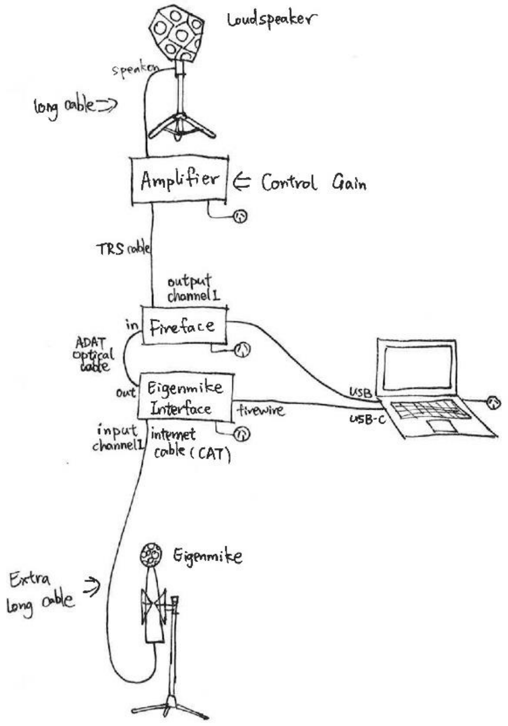

Figure A-3 Measurement equipment setup

The RME Fireface UCX and EM32 Eigenmike® Array Interface Box are synchronized using ADAT optical cable, both of which are connected to a laptop with AARAE running. The Fireface transfers signal to the loudspeaker's amplifier. A fixed gain was used through out the whole measurement. The Eigenmike Interface is connected to the Eigenmike through a CAT-5 cable.

For each of the 18 microphone positions in the audience, all 5 speaker positions on the stage were measured.

Second set of measurements (dodecahedron/directional speakers x dummy head/omni-directional microphone)

The RME Fireface UCX is connected to a laptop with AARAE running. The dodecahedron speaker and studio monitor are connected to the output channel 1 and 2 of the Fireface. The dummy head and the omni-directional speaker are connected to the input channel 1 and 2 of the Fireface.

Each test signal is played through the dodecahedron first, then after 5 seconds of interval, through the studio monitor. For each of the 6 microphone positions in the audience, both microphones have been tested at the location with both speakers placed at each of 5 positions on stage.

A.4 Calibration procedure

A.4.1 Calibration environment

The calibration of the equipment was done in a diffused reverberation chamber of the acoustic lab in the University of Sydney, with a volume of 130 m^3.

A.4.1.1 Speaker calibration for sound strength

In ISO 3382-1 (2009), the sound strength, G, is defined by as the logarithmic ratio of the sound energy (squared and integrated sound pressure) of the measured impulse response to that of the response measured in a free field at a distance of 10 m from the sound source. To calculate G, the speakers were calibrated using the following method.

6 omni-directional microphones were distributed randomly in the reverberation chamber. All of the microphones were calibrated to a 1000 Hz, 94 dB pure tone. 3 speaker positions were tested for each of the speakers. None of the microphones or speakers were located within 2 meters from the wall or 1 meter from each other. The test signal was the same sine sweep used in the measurement. The sound energy received at each microphone for each of the speaker positions was averaged to get the mean sound energy level of the signal in diffused field.

Then the sound energy level (sound power level in usual context) of the test signal can be calculated through the equations given in ISO 3741 (2010), from which the sound energy level at 10 meters from the source in a free field can then be calculated.

A.4.1.2 Eigenmike calibration

Due to the special structure of Eigenmike, no regular calibrator can be used for its calibration. Therefore, a calibration process was conducted.

Two recordings were made at the exact same position with the same test signal – exponential sine sweep, one of which made by Eigenmike with the same settings used in the measurement, the other by a calibrated omni-directional microphone. The sound energy level of two recordings were compared, so the calibration offset of the Eigenmike can be calculated from the calibration offset of the omni-directional microphone plus the difference between the two sound energy level results.

A.5 Results and analysis

The recorded signals were convolved with the inverse filter of the test signal to be turned into impulse responses. The multichannel recordings (32 channels) from the multichannel microphone were converted into second order Ambisonics (9 channels). The acoustic attributes given in ISO 3382-1 (2009) were calculated from the impulse responses using the methods given in the standard, including reverberation time (T_{20} or T_{30}), sound strength (G), early decay time (EDT), clarity (C_{80}), definition (D_{50}), centre time (T_s), early lateral energy fraction (J_{LF} or J_{LFC}), late lateral sound level (L_J), and inter-aural cross correlation coefficients (IACC) (Table A-1). Apart from IACC which was calculated using the measurement results from the dummy head (and therefore averaged between the 6 receiver locations in the second set of measurements), all the other results were calculated using the results from the multichannel microphone. The full results are shown in Appendix B.

Table A-1 Measured parameters of Verbrugghen Hall (octave band values and average)

Acoustic Attribute		Unit	Octave Bands Centre Frequencies						Average
			125	250	500	1k	2k	4k	
Reverberation Time	T_{20}	s	2.20	2.21	2.12	2.05	1.87	1.52	2.09
	T_{30}	s	2.19	2.18	2.13	2.05	1.87	1.52	2.09
Early Decay Time	EDT	s	2.18	2.21	2.17	2.08	1.92	1.54	2.13
Clarity	C_{80}	dB	-2.61	-2.16	-1.39	-0.98	-0.50	0.94	-1.18
Definition	D_{50}	/	0.24	0.28	0.31	0.33	0.34	0.41	0.32
Centre Time	T_s	ms	0.16	0.16	0.16	0.16	0.14	0.11	0.16
Sound Strength	G	dB	12.27	10.64	9.61	6.80	4.57	8.66	8.43
Early Lateral Energy Fraction	J_{LF}	/	0.04	0.19	0.44	0.68	0.47	0.06	0.34
	J_{LFC}	/	0.08	0.14	0.21	0.25	0.21	0.08	0.17
Late Lateral Sound Level	L_J	dB	1.81	6.53	9.83	8.71	4.45	-0.92	7.61
Inter-aural Cross Correlation Coefficients (6 locations in stalls)	$IACC_A$	/	0.91	0.73	0.25	0.20	0.16	0.18	0.40

The overall results measured in the Verbrugghen Hall are compared with the results from a few other shoe-box shaped concert halls. Table A-2 shows the measurement results from Grosser Musikvereinssaal (1680 seats, 15000 m^3) in Vienna, Austria (Beranek, 2012). Grosser Musikvereinssaal is one of the world's most famous shoe-box concert halls, and considered to have very high quality acoustics (Long, 2009).

Table A-2 Measured parameters of Grosser Musikvereinssaal (octave band values and average) (Source: Beranek 2012)

Acoustic Attribute		Unit	Octave Bands Centre Frequencies						Average
			125	250	500	1k	2k	4k	
Reverberation Time	RT	s	2.97	3.03	**3.06**	**3.05**	2.67	2.10	3.06
Sound Strength	G	dB	6.10	6.04	**5.97**	**6.57**	6.04	4.51	6.27
Early Decay Time	EDT	s	2.96	3.04	**3.05**	**3.01**	2.71	2.09	3.03
Clarity	C_{80}	dB	-5.28	-5.47	**-4.72**	**-3.95**	-3.32	-1.57	-4.34
Early Lateral Energy Fraction	J_{LF}	/	**0.13**	**0.17**	**0.19**	**0.17**	0.12	0.21	0.17
Inter-aural Cross Correlation Coefficients	$IACC_A$	/	**0.89**	**0.68**	**0.20**	**0.11**	**0.17**	**0.26**	0.39

Table A-3 shows the measurement results from Hamarikyu Asahi Hall (552 seats, 5800 m^3) in Tokyo, Japan. It's a small shoe-box shaped recital hall that has similar number of seats as the

Verbrugghen Hall. The acoustics of the Hamarikyu Asahi Hall was reported to be desirable (Beranek, 2012).

Table A-3 Measured parameters of Hamarikyu Asahi Hall (octave band values and average) (Source: Beranek 2012)

Acoustic Attribute		Unit	Octave Bands Centre Frequencies						Average
			125	250	500	1k	2k	4k	
Reverberation Time	RT	s	1.63	1.68	**1.83**	**1.93**	1.90	1.71	1.88
Sound Strength	G	dB	7.50	7.60	**9.80**	**10.00**	10.80	11.30	9.90
Early Decay Time	EDT	s	1.53	1.72	**1.82**	**1.80**	1.75	1.62	1.81
Clarity	C_{80}	dB	-0.30	-1.90	**-1.20**	**0.00**	0.60	0.30	-0.60
Inter-aural Cross Correlation Coefficients	$IACC_A$	/	/	/	**0.22**	**0.15**	**0.12**	**0.11**	0.15

Table A-4 shows the measurement results from Dai-ichi Seimei Hall (714 seats, 6800 m^3) in Tokyo, Japan. It's a small shoe-box shaped recital hall that has similar volume as the Verbrugghen Hall (Beranek, 2012).

Table A-4 Measured parameters of Dai-ichi Seimei Hall (octave band values and average) (Source: Beranek 2012)

Acoustic Attribute		Unit	Octave Bands Centre Frequencies						Average
			125	250	500	1k	2k	4k	
Reverberation Time	RT	s	2.02	1.87	**1.78**	**1.89**	1.88	1.72	1.84
Sound Strength	G	dB	8.80	8.80	**8.10**	**9.00**	9.90	9.40	8.55
Early Decay Time	EDT	s	1.91	1.79	**1.75**	**1.85**	1.84	1.70	1.80
Clarity	C_{80}	dB	-2.20	-1.20	**-0.70**	**-0.30**	-0.30	-0.80	-0.50
Inter-aural Cross Correlation Coefficients	$IACC_A$	/	/	/	**0.26**	**0.14**	**0.10**	**0.17**	0.17

The seat M12, which is located in the middle of the last row of the front stalls is chosen as the base location for the subjective testing in auditorium colour experiment because it's located close to the back to the auditorium and therefore able to see the most of the auditorium, but not under the balcony or on the balcony which may affect the subjective experience. It can get a relatively balanced and typical visual and auditory experience of the auditorium.

The measurement results of seat M12 are given in Table A-5 in octave bands:

Table A-5 Measured parameters at seat M12 of Verbrugghen Hall (octave band values and average)

Acoustic Attribute		Unit	Octave Bands Centre Frequencies						Average
			125	250	500	1k	2k	4k	
Reverberation Time	T20	s	1.94	2.26	**2.11**	**2.04**	1.91	1.55	2.07
	T30	s	2.05	2.21	**2.12**	**2.05**	1.88	1.51	2.08

Sound Strength	G	dB	14.74	11.74	**10.05**	**7.11**	4.03	7.87	8.58
Early Decay Time	EDT	s	2.29	1.74	**2.10**	**1.75**	1.92	1.51	1.92
Clarity	C_{80}	dB	-0.20	-2.74	**-1.34**	**-1.90**	-1.32	0.42	-1.62
Definition	D_{50}	/	0.31	0.10	**0.25**	**0.25**	0.29	0.36	0.25
Centre Time	T_s	ms	0.14	0.14	**0.15**	**0.15**	0.15	0.11	0.15
Early lateral energy fraction	J_{LF}	/	**-17.79**	**-13.93**	**-6.59**	**0.51**	1.76	-6.80	-9.45
	J_{LFC}	/	**-9.78**	**-8.81**	**-5.71**	**-1.97**	-1.60	-6.14	-6.57
Late lateral sound level	L_J	dB	-2.98	3.27	8.01	8.05	4.23	-1.45	4.09
Inter-aural cross correlation coefficients	$IACC_A$	/	**0.91**	**0.75**	**0.22**	**0.19**	**0.17**	**0.14**	0.40

*Note that in all tables, the values that are used to calculate the average values are marked with bold letters.

Compared to other concert halls of similar sizes, Verbrugghen Hall has significantly less seats, partly because of the relatively large stage. It has a reasonable reverberation time for its size, and sufficient sound strength and lateral energy.

Appendix B Complete measurement results of Verbrugghen Hall (1 August 2019)

Table B-1 Octave bands reverberation parameters measured with dodecahedron speaker and multichannel microphone

Source	Receiver	Frequency	EDT (s)	T_{20} (s)	T_{30} (s)	T_{10} (s)	C_{50} (dB)	C_{80} (dB)	D_{50}	D_{80}	T_s (s)
S1	BA10	125	2.623	2.210	2.189	2.368	-5.115	-1.031	0.249	0.447	0.150
S1	BA10	250	2.115	2.323	2.359	2.318	-3.767	-1.927	0.312	0.399	0.148
S1	BA10	500	2.396	2.197	2.234	2.234	-2.992	-1.158	0.347	0.437	0.160
S1	BA10	1000	2.266	2.037	2.045	1.950	-3.888	-2.167	0.290	0.378	0.172
S1	BA10	2000	2.047	1.858	1.843	1.931	-4.241	-1.960	0.282	0.392	0.154
S1	BA10	4000	1.676	1.510	1.512	1.608	-3.001	-0.391	0.335	0.478	0.124
S1	BA10	8000	1.059	0.935	0.930	0.918	0.445	2.447	0.524	0.630	0.073
S1	BB17	125	2.423	2.040	1.992	2.075	-6.971	-3.397	0.186	0.318	0.155
S1	BB17	250	1.973	2.287	2.234	2.284	-4.122	-2.114	0.292	0.385	0.156
S1	BB17	500	2.158	2.153	2.176	2.320	-6.319	-3.700	0.191	0.299	0.174
S1	BB17	1000	2.027	2.038	2.041	1.874	-6.517	-3.038	0.187	0.333	0.164
S1	BB17	2000	1.981	1.850	1.873	1.818	-4.138	-1.274	0.280	0.428	0.149
S1	BB17	4000	1.546	1.571	1.552	1.558	-3.623	-0.863	0.307	0.452	0.122
S1	BB17	8000	0.851	0.952	0.940	0.905	2.070	4.591	0.614	0.735	0.063
S1	BD10	125	1.668	2.214	2.268	1.873	-3.280	-2.424	0.328	0.369	0.156
S1	BD10	250	2.122	2.217	2.182	2.274	-2.743	-0.904	0.351	0.449	0.150
S1	BD10	500	2.101	2.176	2.118	2.087	-4.101	-1.226	0.282	0.431	0.148
S1	BD10	1000	2.220	2.011	2.061	1.902	-2.428	-1.044	0.365	0.440	0.150
S1	BD10	2000	1.896	1.861	1.876	1.953	0.375	2.108	0.522	0.619	0.117
S1	BD10	4000	1.662	1.543	1.524	1.574	0.450	2.100	0.526	0.618	0.100
S1	BD10	8000	0.925	0.963	0.942	0.973	4.449	6.592	0.732	0.814	0.044
S1	BD17	125	2.381	2.200	2.078	2.356	-4.906	-2.972	0.257	0.343	0.193
S1	BD17	250	2.246	2.265	2.154	2.483	-3.524	-0.456	0.317	0.477	0.148
S1	BD17	500	2.270	2.039	2.149	1.875	-4.932	-2.348	0.243	0.369	0.174
S1	BD17	1000	2.028	2.099	2.055	2.172	-2.648	0.191	0.355	0.511	0.135
S1	BD17	2000	1.956	1.870	1.852	1.909	-1.517	0.225	0.414	0.513	0.124
S1	BD17	4000	1.636	1.557	1.534	1.539	-1.157	0.561	0.434	0.532	0.106
S1	BD17	8000	0.899	0.922	0.931	0.897	0.705	3.300	0.540	0.679	0.064
S1	BSide1	125	2.236	2.059	2.164	2.147	-0.476	-0.096	0.473	0.496	0.190
S1	BSide1	250	2.020	2.026	2.103	2.118	-1.467	-0.404	0.418	0.478	0.177
S1	BSide1	500	2.371	2.158	2.151	2.273	-1.861	-0.494	0.397	0.472	0.189
S1	BSide1	1000	2.171	2.066	2.030	2.019	-1.888	-0.274	0.393	0.484	0.164
S1	BSide1	2000	1.973	1.815	1.852	1.843	-3.285	-1.721	0.320	0.403	0.150
S1	BSide1	4000	1.566	1.510	1.486	1.555	-1.331	1.411	0.428	0.576	0.112
S1	BSide1	8000	1.060	0.927	0.914	0.965	4.819	6.899	0.736	0.808	0.044
S1	BSide7	125	2.721	2.441	2.132	3.165	-3.362	1.080	0.369	0.560	0.169
S1	BSide7	250	2.181	2.240	2.205	2.473	-3.080	-1.613	0.335	0.409	0.175
S1	BSide7	500	2.056	2.157	2.150	2.167	-4.867	-2.624	0.247	0.356	0.176
S1	BSide7	1000	2.142	2.050	2.033	2.226	-6.658	-3.873	0.180	0.292	0.184
S1	BSide7	2000	1.861	1.900	1.892	1.840	-4.010	-2.079	0.287	0.383	0.156
S1	BSide7	4000	1.627	1.519	1.536	1.588	-3.682	-1.854	0.308	0.397	0.133
S1	BSide7	8000	1.135	0.910	0.918	0.891	-0.105	2.458	0.496	0.625	0.077
S1	BSide12	125	1.556	2.413	2.377	2.040	-4.635	-2.926	0.275	0.350	0.145
S1	BSide12	250	2.451	2.164	2.093	2.444	-3.847	-2.815	0.293	0.345	0.185
S1	BSide12	500	2.710	2.041	2.083	2.088	-6.811	-3.703	0.174	0.302	0.203

S1	BSide12	1000	2.241	2.047	2.122	2.236	-6.067	-3.702	0.200	0.299	0.185
S1	BSide12	2000	1.981	1.868	1.870	1.848	-4.846	-2.812	0.247	0.344	0.164
S1	BSide12	4000	1.661	1.536	1.519	1.554	-4.934	-2.514	0.250	0.363	0.143
S1	BSide12	8000	1.089	0.926	0.901	0.966	0.714	3.016	0.540	0.661	0.072
S1	D12	125	2.337	2.096	2.043	1.659	-5.438	-3.169	0.269	0.348	0.176
S1	D12	250	2.494	2.164	2.166	2.113	1.161	2.325	0.566	0.628	0.171
S1	D12	500	2.145	2.104	2.097	2.364	0.131	1.850	0.507	0.603	0.164
S1	D12	1000	1.951	2.045	2.084	1.965	1.270	3.115	0.572	0.669	0.135
S1	D12	2000	1.798	1.886	1.888	1.839	2.619	4.421	0.645	0.732	0.133
S1	D12	4000	1.519	1.494	1.494	1.515	2.781	4.932	0.655	0.757	0.086
S1	D12	8000	0.823	0.873	0.874	0.852	7.490	10.645	0.848	0.919	0.023
S1	D19	125	2.676	2.294	2.156	2.564	-3.944	-2.248	0.322	0.382	0.165
S1	D19	250	2.175	2.201	2.124	2.392	2.192	2.947	0.620	0.661	0.170
S1	D19	500	2.501	2.056	2.133	2.063	2.405	3.380	0.630	0.681	0.156
S1	D19	1000	2.086	2.045	2.035	2.051	3.750	4.529	0.701	0.737	0.114
S1	D19	2000	1.869	1.862	1.852	1.890	5.602	6.734	0.784	0.824	0.093
S1	D19	4000	1.359	1.486	1.495	1.543	5.776	7.525	0.786	0.845	0.056
S1	D19	8000	0.383	0.850	0.869	0.736	10.113	12.996	0.910	0.952	0.016
S1	I12	125	2.168	2.354	2.194	2.296	-3.722	-1.988	0.299	0.388	0.162
S1	I12	250	2.100	2.236	2.165	2.297	-4.675	-1.077	0.275	0.443	0.159
S1	I12	500	2.176	2.113	2.074	2.179	-3.213	-1.687	0.327	0.406	0.177
S1	I12	1000	2.217	2.043	2.091	2.131	-2.624	-0.412	0.354	0.477	0.169
S1	I12	2000	1.862	1.838	1.829	1.802	-5.633	-1.982	0.216	0.388	0.158
S1	I12	4000	1.666	1.477	1.505	1.501	-3.072	-0.105	0.338	0.495	0.123
S1	I12	8000	0.936	0.894	0.899	0.907	0.580	4.583	0.533	0.739	0.060
S1	I19	125	1.852	2.231	2.298	2.285	-6.558	-2.121	0.191	0.389	0.137
S1	I19	250	2.336	2.248	2.227	2.400	-2.985	-1.665	0.338	0.406	0.187
S1	I19	500	2.089	2.099	2.139	2.132	-3.880	-1.575	0.291	0.411	0.174
S1	I19	1000	2.113	1.993	2.061	2.016	-0.924	0.248	0.453	0.515	0.159
S1	I19	2000	2.115	1.821	1.847	1.832	0.506	1.681	0.529	0.596	0.144
S1	I19	4000	1.656	1.497	1.507	1.470	0.809	2.260	0.546	0.627	0.097
S1	I19	8000	0.832	0.930	0.911	0.963	7.038	8.991	0.817	0.873	0.031
S1	M12	125	2.643	2.095	2.057	2.518	-3.368	-0.443	0.341	0.476	0.185
S1	M12	250	2.302	2.182	2.094	2.404	-7.547	-4.728	0.195	0.275	0.187
S1	M12	500	2.202	2.248	2.178	2.152	-4.385	-2.107	0.269	0.385	0.164
S1	M12	1000	2.137	2.096	2.073	1.909	-3.974	-2.403	0.286	0.365	0.173
S1	M12	2000	2.018	1.852	1.859	1.758	-4.018	-1.669	0.285	0.407	0.155
S1	M12	4000	1.580	1.519	1.526	1.551	-1.575	0.411	0.411	0.524	0.112
S1	M12	8000	0.903	0.929	0.923	0.940	1.241	4.792	0.571	0.747	0.062
S1	M19	125	1.909	2.427	2.253	2.865	-12.996	-6.146	0.076	0.203	0.157
S1	M19	250	2.287	2.081	2.111	2.362	-8.123	-3.257	0.150	0.325	0.176
S1	M19	500	2.266	2.094	2.138	2.044	-4.011	-2.639	0.285	0.353	0.183
S1	M19	1000	2.089	2.061	2.062	2.120	-4.027	-1.977	0.288	0.390	0.162
S1	M19	2000	1.908	1.847	1.873	1.806	-2.338	-0.759	0.370	0.457	0.144
S1	M19	4000	1.596	1.538	1.520	1.529	-2.486	-0.105	0.361	0.494	0.115
S1	M19	8000	0.938	0.926	0.927	0.864	1.299	4.143	0.567	0.705	0.060
S1	O10	125	2.126	2.316	2.215	2.357	-5.799	-3.795	0.270	0.343	0.155
S1	O10	250	2.266	2.241	2.143	2.352	-4.776	-3.067	0.254	0.334	0.178
S1	O10	500	2.025	2.121	2.178	2.068	-2.586	-0.712	0.359	0.460	0.145
S1	O10	1000	2.018	2.130	2.102	2.304	-1.738	0.415	0.402	0.524	0.139
S1	O10	2000	1.882	1.894	1.891	1.880	-3.506	-1.362	0.309	0.423	0.139
S1	O10	4000	1.513	1.517	1.512	1.510	-0.762	1.375	0.457	0.576	0.102
S1	O10	8000	0.774	0.938	0.943	0.918	3.233	6.217	0.677	0.804	0.049
S1	O19	125	2.069	2.181	2.254	2.282	-8.454	-4.913	0.128	0.248	0.154

S1	O19	250	2.490	2.021	2.097	2.117	-4.567	-2.944	0.265	0.345	0.179
S1	O19	500	2.329	2.168	2.142	2.289	-3.558	-1.756	0.306	0.400	0.176
S1	O19	1000	2.142	2.064	2.052	2.129	-2.963	-0.679	0.340	0.462	0.164
S1	O19	2000	1.827	1.909	1.886	1.968	-4.022	-0.676	0.285	0.461	0.137
S1	O19	4000	1.410	1.555	1.562	1.499	-2.326	0.493	0.369	0.528	0.109
S1	O19	8000	0.889	0.918	0.911	0.915	1.285	4.589	0.570	0.736	0.057
S1	Side3	125	2.390	2.021	2.134	2.064	2.107	2.476	0.616	0.636	0.220
S1	Side3	250	2.268	2.298	2.225	2.163	0.685	1.216	0.538	0.567	0.163
S1	Side3	500	2.247	2.102	2.110	2.436	1.767	2.545	0.600	0.642	0.136
S1	Side3	1000	2.057	2.056	2.071	1.993	1.221	2.199	0.569	0.623	0.121
S1	Side3	2000	1.923	1.890	1.872	1.943	0.721	1.998	0.541	0.612	0.114
S1	Side3	4000	1.614	1.528	1.494	1.549	2.651	3.815	0.647	0.705	0.075
S1	Side3	8000	0.933	0.933	0.914	0.973	4.708	6.514	0.737	0.806	0.041
S1	Side8	125	1.975	2.224	2.186	2.146	-9.999	-5.879	0.122	0.212	0.139
S1	Side8	250	2.350	2.243	2.176	2.343	-2.059	-0.456	0.390	0.474	0.201
S1	Side8	500	2.098	2.278	2.252	2.272	-1.730	-0.318	0.404	0.482	0.172
S1	Side8	1000	2.037	2.059	2.091	2.068	-3.302	-1.456	0.327	0.419	0.163
S1	Side8	2000	1.929	1.882	1.876	1.779	-1.840	0.075	0.399	0.504	0.144
S1	Side8	4000	1.747	1.543	1.525	1.650	0.792	2.291	0.543	0.624	0.091
S1	Side8	8000	1.040	0.944	0.935	0.979	2.166	5.167	0.617	0.765	0.052
S1	Side12	125	1.926	2.188	2.207	2.067	-11.337	-5.009	0.087	0.244	0.145
S1	Side12	250	2.483	2.268	2.117	2.149	-4.590	-1.690	0.263	0.405	0.189
S1	Side12	500	2.496	2.062	2.097	1.984	-2.715	-1.389	0.349	0.421	0.183
S1	Side12	1000	1.924	2.070	2.092	2.017	-3.933	-1.324	0.290	0.426	0.154
S1	Side12	2000	2.043	1.848	1.841	1.900	-4.971	-2.386	0.243	0.367	0.155
S1	Side12	4000	1.598	1.527	1.518	1.573	-2.210	-0.252	0.376	0.486	0.113
S1	Side12	8000	0.940	0.923	0.924	0.898	0.426	4.091	0.524	0.714	0.064
S2	BA10	125	2.203	2.226	2.146	2.495	-7.127	-4.034	0.174	0.284	0.156
S2	BA10	250	2.441	2.170	2.146	1.959	-4.052	-2.830	0.287	0.345	0.170
S2	BA10	500	2.122	2.094	2.103	2.212	-5.018	-1.829	0.243	0.397	0.165
S2	BA10	1000	2.180	2.186	2.118	2.139	-5.630	-1.995	0.215	0.389	0.166
S2	BA10	2000	2.066	1.824	1.863	1.853	-5.454	-2.057	0.228	0.385	0.157
S2	BA10	4000	1.506	1.544	1.518	1.532	-4.659	-0.892	0.262	0.449	0.123
S2	BA10	8000	0.967	0.919	0.931	0.938	-0.049	2.765	0.497	0.653	0.075
S2	BB17	125	2.217	2.073	2.227	2.026	-5.789	-0.949	0.235	0.447	0.149
S2	BB17	250	2.087	2.326	2.198	2.356	-5.231	-2.187	0.254	0.379	0.147
S2	BB17	500	2.139	2.131	2.149	2.325	-3.206	-0.858	0.330	0.452	0.137
S2	BB17	1000	2.216	1.991	2.037	2.059	-5.592	-2.820	0.219	0.346	0.168
S2	BB17	2000	1.957	1.831	1.868	1.855	-4.049	-1.229	0.288	0.430	0.150
S2	BB17	4000	1.549	1.541	1.544	1.469	-2.302	0.186	0.371	0.511	0.118
S2	BB17	8000	0.954	0.919	0.914	0.937	-1.188	2.129	0.435	0.616	0.080
S2	BD10	125	1.901	2.616	2.361	2.465	-4.396	-2.370	0.269	0.371	0.157
S2	BD10	250	2.296	2.071	2.128	1.922	-4.322	-1.556	0.271	0.412	0.160
S2	BD10	500	2.507	2.075	2.111	2.207	-3.371	-0.310	0.319	0.482	0.151
S2	BD10	1000	2.218	1.968	2.022	2.026	-6.107	-2.884	0.198	0.341	0.161
S2	BD10	2000	1.842	1.919	1.894	1.899	-3.630	-0.450	0.307	0.474	0.133
S2	BD10	4000	1.561	1.524	1.521	1.621	-2.119	0.076	0.381	0.504	0.112
S2	BD10	8000	0.870	0.949	0.939	0.930	-0.258	3.510	0.485	0.686	0.069
S2	BD17	125	2.404	2.095	2.123	2.193	-6.377	-1.914	0.208	0.393	0.170
S2	BD17	250	2.188	2.021	2.084	2.098	-4.867	-1.825	0.252	0.403	0.149
S2	BD17	500	2.230	2.102	2.099	2.190	-4.399	-1.096	0.268	0.440	0.156
S2	BD17	1000	2.038	2.161	2.052	2.023	-4.893	-1.850	0.245	0.396	0.156
S2	BD17	2000	1.892	1.875	1.856	1.981	-1.833	0.545	0.396	0.531	0.127
S2	BD17	4000	1.582	1.494	1.510	1.481	-2.033	0.604	0.387	0.534	0.108

S2	BD17	8000	0.957	0.925	0.928	0.964	0.126	3.401	0.507	0.680	0.069
S2	BSide1	125	2.055	2.321	2.235	2.486	-1.724	0.773	0.410	0.542	0.158
S2	BSide1	250	2.095	2.150	2.160	2.057	-3.506	-2.954	0.319	0.346	0.193
S2	BSide1	500	2.085	2.052	2.135	2.147	-2.705	-0.192	0.352	0.489	0.159
S2	BSide1	1000	1.989	2.088	2.067	2.207	-3.326	-0.895	0.319	0.449	0.149
S2	BSide1	2000	1.856	1.932	1.891	1.775	-2.646	0.084	0.353	0.505	0.151
S2	BSide1	4000	1.543	1.532	1.525	1.496	-0.603	2.315	0.471	0.620	0.094
S2	BSide1	8000	0.883	0.909	0.909	0.990	2.275	6.493	0.627	0.810	0.048
S2	BSide7	125	2.184	2.179	2.195	2.102	-9.154	-4.155	0.131	0.297	0.159
S2	BSide7	250	2.276	2.224	2.177	2.198	-3.592	-1.750	0.307	0.402	0.187
S2	BSide7	500	2.237	2.122	2.146	1.911	-4.025	-2.525	0.289	0.361	0.182
S2	BSide7	1000	2.092	2.071	2.064	2.009	-4.872	-3.294	0.246	0.320	0.175
S2	BSide7	2000	2.007	1.833	1.831	1.845	-6.804	-3.075	0.175	0.330	0.166
S2	BSide7	4000	1.595	1.537	1.532	1.470	-3.631	-0.211	0.309	0.488	0.124
S2	BSide7	8000	1.083	0.944	0.922	0.986	4.137	6.509	0.703	0.796	0.045
S2	BSide12	125	2.169	2.253	2.132	2.382	-6.391	-1.960	0.196	0.394	0.165
S2	BSide12	250	2.482	2.167	2.212	2.277	-5.890	-2.964	0.208	0.338	0.184
S2	BSide12	500	2.045	2.094	2.148	2.129	-4.917	-2.819	0.251	0.344	0.162
S2	BSide12	1000	2.100	2.067	2.100	1.989	-4.976	-2.896	0.244	0.341	0.165
S2	BSide12	2000	1.906	1.903	1.913	1.877	-6.423	-3.433	0.186	0.312	0.164
S2	BSide12	4000	1.622	1.532	1.502	1.545	-4.164	-1.249	0.282	0.430	0.131
S2	BSide12	8000	0.970	0.921	0.928	0.972	-0.789	1.963	0.456	0.609	0.083
S2	D12	125	1.736	2.009	2.154	1.927	-8.237	-1.476	0.205	0.422	0.128
S2	D12	250	2.334	2.203	2.202	2.246	-2.244	-1.133	0.375	0.437	0.171
S2	D12	500	2.129	2.120	2.118	2.022	-2.551	-0.680	0.359	0.462	0.161
S2	D12	1000	2.142	2.000	1.997	2.059	-1.486	-0.123	0.416	0.493	0.170
S2	D12	2000	1.911	1.882	1.862	1.888	-5.062	-2.745	0.238	0.348	0.159
S2	D12	4000	1.575	1.519	1.506	1.544	-3.279	-0.759	0.328	0.458	0.124
S2	D12	8000	0.906	0.912	0.901	0.938	3.965	6.156	0.708	0.798	0.051
S2	D19	125	2.205	2.144	2.222	2.069	-2.721	0.985	0.361	0.554	0.138
S2	D19	250	1.926	2.266	2.283	2.460	-0.586	0.233	0.467	0.513	0.139
S2	D19	500	2.504	2.064	2.031	2.067	0.522	1.999	0.529	0.609	0.148
S2	D19	1000	2.111	2.007	2.013	2.126	-1.244	0.619	0.429	0.536	0.138
S2	D19	2000	1.875	1.895	1.899	1.855	-2.733	0.200	0.348	0.511	0.137
S2	D19	4000	1.538	1.484	1.500	1.522	-1.805	0.993	0.399	0.555	0.111
S2	D19	8000	1.044	0.921	0.898	0.937	4.528	6.379	0.737	0.809	0.042
S2	I12	125	2.653	2.053	2.137	1.879	-4.215	-1.107	0.291	0.441	0.158
S2	I12	250	2.161	2.162	2.148	2.279	-8.235	-4.464	0.146	0.271	0.171
S2	I12	500	1.944	2.208	2.143	2.225	-5.796	-2.890	0.214	0.346	0.164
S2	I12	1000	1.909	2.167	2.137	2.075	-3.624	-0.843	0.303	0.452	0.155
S2	I12	2000	1.817	1.879	1.874	1.914	-4.519	-1.973	0.262	0.389	0.149
S2	I12	4000	1.553	1.563	1.515	1.607	-1.874	0.723	0.396	0.541	0.109
S2	I12	8000	0.934	0.902	0.904	0.919	1.181	4.427	0.566	0.730	0.062
S2	I19	125	1.655	2.208	2.328	2.212	-6.899	-1.382	0.181	0.424	0.128
S2	I19	250	2.262	2.180	2.187	2.207	-5.665	-4.332	0.217	0.270	0.184
S2	I19	500	2.286	2.123	2.120	2.130	-4.384	-1.970	0.267	0.389	0.180
S2	I19	1000	2.232	1.976	2.017	2.159	-3.300	-1.263	0.319	0.428	0.172
S2	I19	2000	1.941	1.856	1.863	1.845	-2.644	-0.746	0.353	0.457	0.137
S2	I19	4000	1.496	1.557	1.531	1.476	-2.636	-0.148	0.353	0.492	0.113
S2	I19	8000	0.895	0.905	0.918	0.931	3.827	6.772	0.690	0.806	0.045
S2	M12	125	2.280	2.143	2.291	1.787	-2.402	1.406	0.412	0.580	0.142
S2	M12	250	2.472	2.264	2.210	2.444	-8.991	-4.727	0.115	0.258	0.168
S2	M12	500	2.080	2.100	2.153	2.024	-5.190	-2.463	0.239	0.367	0.164
S2	M12	1000	2.137	2.063	2.069	2.013	-4.691	-1.928	0.255	0.393	0.171

S2	M12	2000	1.943	1.846	1.884	1.774	-4.053	-1.002	0.283	0.443	0.151
S2	M12	4000	1.533	1.502	1.516	1.515	-2.825	0.054	0.343	0.503	0.117
S2	M12	8000	0.881	0.902	0.898	0.928	2.825	5.932	0.648	0.782	0.051
S2	M19	125	1.949	2.233	2.158	2.222	-5.410	-2.039	0.224	0.388	0.142
S2	M19	250	2.487	2.114	2.145	2.290	-5.548	-2.512	0.224	0.361	0.179
S2	M19	500	1.995	2.212	2.144	2.395	-5.197	-2.113	0.234	0.381	0.154
S2	M19	1000	2.030	2.067	2.069	2.162	-5.413	-3.221	0.223	0.323	0.168
S2	M19	2000	1.872	1.908	1.904	2.016	-3.036	-0.158	0.336	0.492	0.140
S2	M19	4000	1.501	1.475	1.512	1.490	-1.250	1.077	0.429	0.561	0.104
S2	M19	8000	0.927	0.908	0.920	0.939	2.736	5.273	0.641	0.755	0.052
S2	O10	125	2.168	2.149	2.107	1.906	-9.616	-3.952	0.100	0.308	0.147
S2	O10	250	2.193	2.305	2.230	2.200	-3.441	-1.450	0.315	0.418	0.156
S2	O10	500	2.241	2.147	2.149	2.175	-4.038	-1.479	0.287	0.417	0.156
S2	O10	1000	1.908	2.047	2.055	2.078	-1.995	0.589	0.390	0.534	0.135
S2	O10	2000	1.896	1.895	1.873	1.889	-3.599	-1.154	0.304	0.434	0.142
S2	O10	4000	1.387	1.565	1.549	1.602	-1.670	1.398	0.407	0.578	0.103
S2	O10	8000	0.758	0.887	0.912	0.894	2.186	6.077	0.619	0.794	0.052
S2	O19	125	2.344	2.254	2.254	2.478	-7.888	-6.147	0.174	0.231	0.179
S2	O19	250	2.457	2.236	2.179	2.245	-7.100	-3.886	0.172	0.292	0.183
S2	O19	500	2.059	2.076	2.103	2.035	-6.008	-2.921	0.203	0.341	0.171
S2	O19	1000	2.197	2.016	2.010	2.191	-5.160	-2.046	0.241	0.385	0.167
S2	O19	2000	1.793	1.898	1.864	1.910	-4.720	-1.099	0.253	0.437	0.135
S2	O19	4000	1.441	1.507	1.521	1.653	-5.090	-0.457	0.237	0.474	0.119
S2	O19	8000	0.914	0.901	0.904	0.884	0.049	3.656	0.503	0.694	0.067
S2	Side3	125	1.786	2.417	2.281	2.247	-4.403	-4.184	0.304	0.323	0.160
S2	Side3	250	2.275	2.166	2.222	2.371	0.688	1.107	0.537	0.559	0.135
S2	Side3	500	2.054	2.221	2.217	1.995	-1.841	0.012	0.399	0.500	0.147
S2	Side3	1000	1.964	2.144	2.085	1.971	-1.043	-0.120	0.442	0.493	0.136
S2	Side3	2000	2.039	1.890	1.875	1.843	1.118	1.996	0.562	0.609	0.106
S2	Side3	4000	1.716	1.485	1.494	1.479	1.131	2.582	0.564	0.641	0.086
S2	Side3	8000	1.013	0.868	0.892	0.801	2.118	3.791	0.619	0.704	0.051
S2	Side8	125	1.995	2.283	2.113	2.465	-10.276	-6.828	0.091	0.185	0.167
S2	Side8	250	1.909	2.184	2.183	2.354	-4.136	-2.089	0.308	0.388	0.169
S2	Side8	500	2.209	2.065	2.072	2.168	-2.568	-1.519	0.356	0.413	0.166
S2	Side8	1000	1.929	2.087	2.030	2.201	-3.403	-1.166	0.322	0.434	0.152
S2	Side8	2000	2.003	1.875	1.868	1.953	-1.999	0.236	0.388	0.513	0.135
S2	Side8	4000	1.708	1.534	1.504	1.523	0.918	2.728	0.551	0.648	0.085
S2	Side8	8000	0.918	0.925	0.922	0.946	-0.594	3.820	0.468	0.705	0.063
S2	Side12	125	2.090	2.509	2.295	1.820	-5.439	-2.045	0.259	0.396	0.167
S2	Side12	250	2.155	2.204	2.147	2.103	-7.540	-5.649	0.165	0.218	0.187
S2	Side12	500	2.115	2.232	2.192	2.270	-5.837	-3.873	0.217	0.297	0.182
S2	Side12	1000	2.167	2.031	2.029	1.980	-3.351	-0.721	0.321	0.459	0.157
S2	Side12	2000	1.903	1.856	1.859	1.895	-4.171	-1.388	0.278	0.422	0.142
S2	Side12	4000	1.533	1.533	1.529	1.531	-1.742	0.728	0.404	0.541	0.107
S2	Side12	8000	0.840	0.927	0.925	0.887	2.364	5.491	0.627	0.766	0.055
S3	BA10	125	2.705	2.365	2.316	2.709	-3.957	-2.546	0.306	0.365	0.178
S3	BA10	250	1.947	2.218	2.256	2.206	-3.902	-2.485	0.290	0.362	0.147
S3	BA10	500	2.274	2.241	2.203	2.213	-3.211	-1.504	0.327	0.416	0.154
S3	BA10	1000	2.135	2.010	2.056	2.012	-5.322	-2.279	0.228	0.372	0.166
S3	BA10	2000	1.946	1.877	1.843	1.847	-3.789	-0.682	0.296	0.461	0.144
S3	BA10	4000	1.484	1.554	1.543	1.490	-3.165	-0.291	0.325	0.483	0.116
S3	BA10	8000	0.960	0.950	0.939	0.967	0.638	3.415	0.536	0.684	0.069
S3	BB17	125	2.780	1.908	2.204	2.307	-5.202	-2.507	0.243	0.360	0.170
S3	BB17	250	1.971	2.321	2.300	2.484	-5.055	-3.075	0.258	0.344	0.140

S3	BB17	500	2.233	2.052	2.074	2.188	-6.072	-3.399	0.203	0.318	0.169
S3	BB17	1000	2.174	1.955	1.985	2.017	-3.898	-1.739	0.294	0.404	0.164
S3	BB17	2000	1.858	1.878	1.916	1.754	-2.506	0.209	0.360	0.512	0.133
S3	BB17	4000	1.450	1.575	1.548	1.565	-1.012	1.598	0.443	0.590	0.102
S3	BB17	8000	0.884	0.934	0.937	0.902	2.604	4.967	0.643	0.755	0.055
S3	BD10	125	1.463	2.633	2.381	2.835	-3.903	-2.433	0.291	0.364	0.147
S3	BD10	250	2.486	2.243	2.180	2.566	-1.260	0.036	0.430	0.503	0.169
S3	BD10	500	2.003	2.158	2.158	2.343	-3.510	-0.695	0.315	0.461	0.138
S3	BD10	1000	2.112	2.031	2.014	2.039	-3.121	-0.916	0.331	0.448	0.144
S3	BD10	2000	1.990	1.914	1.874	1.891	-2.783	-0.437	0.346	0.475	0.137
S3	BD10	4000	1.446	1.533	1.548	1.550	-2.075	0.401	0.383	0.523	0.104
S3	BD10	8000	0.886	0.963	0.929	0.940	1.255	4.196	0.570	0.714	0.063
S3	BD17	125	2.606	2.085	2.163	2.283	-3.751	0.639	0.318	0.537	0.147
S3	BD17	250	1.673	2.331	2.225	2.266	-4.290	-1.492	0.277	0.418	0.121
S3	BD17	500	2.202	2.102	2.123	2.124	-1.295	0.302	0.427	0.517	0.132
S3	BD17	1000	2.247	2.003	1.991	1.980	-4.523	-1.638	0.263	0.407	0.164
S3	BD17	2000	1.913	1.851	1.858	1.826	-2.871	-0.218	0.341	0.488	0.132
S3	BD17	4000	1.432	1.497	1.536	1.479	-1.448	1.293	0.418	0.574	0.097
S3	BD17	8000	0.861	0.944	0.924	0.973	1.092	3.673	0.561	0.698	0.060
S3	BSide1	125	2.061	2.179	2.182	2.515	-7.273	-5.199	0.167	0.235	0.152
S3	BSide1	250	2.223	2.343	2.226	2.168	-3.843	-0.927	0.322	0.451	0.155
S3	BSide1	500	2.087	2.161	2.157	2.168	-3.010	-0.075	0.337	0.496	0.147
S3	BSide1	1000	2.130	2.052	2.012	2.070	-2.816	-0.661	0.347	0.462	0.152
S3	BSide1	2000	1.837	1.901	1.894	1.942	-0.562	1.711	0.468	0.597	0.123
S3	BSide1	4000	1.596	1.478	1.494	1.484	-0.380	1.700	0.478	0.596	0.108
S3	BSide1	8000	0.784	0.919	0.907	1.011	2.987	5.936	0.654	0.782	0.055
S3	BSide7	125	2.120	2.085	2.156	2.655	-9.585	-0.114	0.106	0.496	0.111
S3	BSide7	250	2.258	2.213	2.166	2.057	-3.882	-2.421	0.299	0.370	0.169
S3	BSide7	500	1.893	2.099	2.149	2.196	-3.419	-1.787	0.313	0.399	0.147
S3	BSide7	1000	1.913	2.051	2.042	2.133	-3.099	-1.187	0.339	0.435	0.146
S3	BSide7	2000	1.820	1.882	1.882	1.882	-1.744	0.347	0.401	0.520	0.134
S3	BSide7	4000	1.530	1.489	1.517	1.433	-0.533	1.542	0.470	0.586	0.102
S3	BSide7	8000	0.859	0.914	0.916	0.914	2.982	5.267	0.663	0.768	0.054
S3	BSide12	125	1.806	2.196	2.256	1.889	-7.474	-2.786	0.209	0.351	0.136
S3	BSide12	250	2.539	2.077	2.189	2.226	-2.316	-0.993	0.374	0.444	0.145
S3	BSide12	500	2.108	2.036	2.081	2.033	-5.039	-2.040	0.254	0.386	0.166
S3	BSide12	1000	2.000	2.145	2.108	2.040	-3.103	-0.716	0.330	0.459	0.148
S3	BSide12	2000	1.990	1.893	1.870	1.893	-3.928	-1.060	0.291	0.440	0.148
S3	BSide12	4000	1.546	1.554	1.514	1.537	-1.911	0.889	0.393	0.551	0.109
S3	BSide12	8000	0.876	0.934	0.919	0.976	1.191	4.134	0.563	0.711	0.062
S3	D12	125	1.843	1.716	1.916	1.709	-9.578	-2.620	0.176	0.361	0.147
S3	D12	250	2.285	2.102	2.203	2.394	-3.313	-1.733	0.321	0.407	0.172
S3	D12	500	2.303	2.085	2.137	1.983	-2.795	-0.634	0.348	0.464	0.184
S3	D12	1000	2.106	2.039	2.017	2.001	0.226	1.262	0.513	0.572	0.155
S3	D12	2000	2.042	1.820	1.809	1.880	-0.434	0.895	0.475	0.551	0.152
S3	D12	4000	1.553	1.501	1.498	1.530	1.138	2.526	0.565	0.641	0.096
S3	D12	8000	0.997	0.884	0.893	0.901	5.178	7.125	0.759	0.830	0.034
S3	D19	125	2.548	2.170	2.092	2.581	-4.091	-0.876	0.298	0.453	0.164
S3	D19	250	2.180	2.217	2.138	2.135	-4.550	-2.568	0.264	0.359	0.184
S3	D19	500	2.216	2.133	2.136	2.271	-2.367	-0.631	0.368	0.464	0.170
S3	D19	1000	2.027	2.000	2.032	1.982	-0.878	0.241	0.451	0.513	0.146
S3	D19	2000	1.848	1.848	1.836	1.863	0.165	1.901	0.509	0.608	0.117
S3	D19	4000	1.490	1.497	1.499	1.567	0.963	2.906	0.555	0.661	0.089
S3	D19	8000	0.777	0.900	0.912	0.909	4.254	7.253	0.726	0.841	0.042

S3	I12	125	2.458	2.330	2.481	1.759	-3.932	-0.809	0.305	0.458	0.143
S3	I12	250	1.995	2.411	2.202	2.382	-7.718	-4.575	0.162	0.259	0.162
S3	I12	500	2.117	2.134	2.108	2.066	-5.873	-2.455	0.218	0.365	0.172
S3	I12	1000	2.129	2.039	2.007	2.191	-2.577	0.075	0.360	0.504	0.159
S3	I12	2000	1.944	1.907	1.895	1.922	-3.528	-0.402	0.313	0.477	0.141
S3	I12	4000	1.607	1.451	1.487	1.465	-2.339	0.656	0.369	0.537	0.112
S3	I12	8000	0.837	0.913	0.903	0.878	2.276	6.276	0.616	0.791	0.050
S3	I19	125	2.045	2.285	2.176	2.286	-6.038	-4.299	0.269	0.309	0.176
S3	I19	250	2.669	2.061	2.097	2.542	-11.282	-6.538	0.073	0.194	0.204
S3	I19	500	2.389	1.989	2.071	2.214	-4.771	-0.901	0.250	0.449	0.172
S3	I19	1000	2.105	2.071	1.991	2.232	-3.454	-0.965	0.312	0.445	0.153
S3	I19	2000	1.919	1.882	1.860	1.804	-3.640	-0.322	0.304	0.482	0.140
S3	I19	4000	1.458	1.528	1.504	1.525	-2.104	1.186	0.383	0.566	0.104
S3	I19	8000	0.783	0.906	0.905	0.936	-0.607	5.083	0.466	0.744	0.063
S3	M12	125	2.335	2.288	2.250	1.969	-2.064	1.792	0.425	0.602	0.154
S3	M12	250	2.504	2.225	2.122	2.133	-7.879	-3.259	0.149	0.323	0.165
S3	M12	500	2.215	2.266	2.165	2.230	-4.916	-2.033	0.258	0.387	0.159
S3	M12	1000	2.066	2.054	2.049	2.105	-4.460	-1.642	0.271	0.408	0.170
S3	M12	2000	1.967	1.859	1.856	1.932	-2.501	-0.160	0.360	0.491	0.147
S3	M12	4000	1.407	1.522	1.505	1.497	-1.370	1.408	0.422	0.580	0.104
S3	M12	8000	0.887	0.868	0.896	0.832	2.065	5.035	0.614	0.754	0.056
S3	M19	125	1.773	2.174	2.244	1.970	-9.209	-5.469	0.127	0.232	0.136
S3	M19	250	2.157	2.205	2.074	2.631	-8.528	-3.728	0.138	0.299	0.169
S3	M19	500	2.109	2.149	2.214	2.076	-4.911	-1.850	0.246	0.396	0.161
S3	M19	1000	2.049	2.092	2.047	2.169	-3.274	-0.811	0.324	0.454	0.149
S3	M19	2000	1.918	1.914	1.883	1.899	-3.915	-1.063	0.294	0.440	0.151
S3	M19	4000	1.556	1.519	1.534	1.590	-3.066	0.080	0.342	0.503	0.117
S3	M19	8000	0.774	0.913	0.915	0.898	-0.403	5.333	0.477	0.765	0.061
S3	O10	125	1.986	2.078	2.193	1.782	-9.564	-5.499	0.100	0.250	0.154
S3	O10	250	2.256	2.182	2.174	2.411	-4.323	-1.449	0.281	0.419	0.146
S3	O10	500	2.201	2.091	2.136	2.188	-3.248	-1.805	0.324	0.398	0.159
S3	O10	1000	2.010	2.071	2.048	2.036	-3.183	-0.982	0.326	0.444	0.146
S3	O10	2000	1.919	1.856	1.875	1.873	-4.264	-1.587	0.273	0.410	0.140
S3	O10	4000	1.435	1.554	1.541	1.556	-3.026	1.419	0.333	0.581	0.105
S3	O10	8000	0.855	0.913	0.923	0.934	1.695	4.923	0.595	0.747	0.063
S3	O19	125	2.017	1.995	2.155	1.893	-13.414	-10.509	0.059	0.087	0.165
S3	O19	250	2.087	2.349	2.190	2.386	-8.138	-2.066	0.146	0.395	0.146
S3	O19	500	2.263	2.055	2.077	2.094	-5.132	-2.741	0.245	0.349	0.175
S3	O19	1000	2.098	2.030	2.027	2.048	-2.900	-0.757	0.346	0.458	0.141
S3	O19	2000	1.949	1.880	1.860	1.828	-2.922	-0.613	0.338	0.465	0.140
S3	O19	4000	1.495	1.527	1.556	1.574	-2.446	0.086	0.365	0.505	0.110
S3	O19	8000	0.821	0.873	0.901	0.829	-0.123	4.341	0.493	0.719	0.064
S3	Side3	125	2.211	2.007	2.328	1.677	-2.267	-0.508	0.386	0.472	0.145
S3	Side3	250	1.924	2.262	2.262	2.464	-1.791	-0.223	0.399	0.487	0.163
S3	Side3	500	2.273	2.119	2.093	2.374	-3.076	-0.891	0.330	0.449	0.150
S3	Side3	1000	1.916	2.125	2.121	2.055	-3.376	-1.199	0.317	0.433	0.156
S3	Side3	2000	1.983	1.845	1.841	1.854	-2.214	-0.209	0.375	0.488	0.138
S3	Side3	4000	1.509	1.491	1.493	1.454	-1.986	-0.201	0.388	0.488	0.109
S3	Side3	8000	1.010	0.888	0.909	0.843	1.020	3.661	0.558	0.697	0.064
S3	Side8	125	2.290	2.251	2.122	1.843	-10.234	-3.835	0.098	0.332	0.150
S3	Side8	250	2.550	2.284	2.291	2.127	-6.296	-2.312	0.209	0.371	0.165
S3	Side8	500	2.225	2.151	2.131	2.141	-2.927	-1.822	0.340	0.398	0.168
S3	Side8	1000	1.989	2.106	2.091	2.189	-3.578	-1.737	0.309	0.402	0.150
S3	Side8	2000	1.969	1.800	1.858	1.840	-4.061	-1.290	0.283	0.426	0.147

S3	Side8	4000	1.542	1.516	1.517	1.470	-2.068	0.753	0.386	0.543	0.107
S3	Side8	8000	0.805	0.901	0.904	0.914	2.433	4.976	0.634	0.752	0.061
S3	Side12	125	1.739	2.067	2.107	1.800	-11.691	-8.320	0.068	0.142	0.152
S3	Side12	250	2.163	2.257	2.246	2.376	-7.065	-3.804	0.190	0.306	0.165
S3	Side12	500	2.187	2.207	2.198	2.255	-6.112	-2.481	0.198	0.362	0.169
S3	Side12	1000	2.096	2.076	2.038	2.087	-4.692	-1.409	0.263	0.420	0.159
S3	Side12	2000	1.858	1.852	1.856	1.821	-5.048	-1.250	0.248	0.431	0.143
S3	Side12	4000	1.444	1.527	1.538	1.525	-1.342	1.865	0.427	0.603	0.095
S3	Side12	8000	0.821	0.927	0.919	0.907	0.102	3.632	0.506	0.696	0.064
S4	BA10	125	2.185	2.479	2.220	2.415	-5.607	-3.883	0.227	0.327	0.173
S4	BA10	250	2.238	2.189	2.203	2.204	-5.668	-3.308	0.222	0.319	0.169
S4	BA10	500	2.285	2.238	2.068	2.187	-3.981	-1.773	0.291	0.401	0.166
S4	BA10	1000	2.182	2.090	2.019	2.102	-4.884	-2.899	0.246	0.341	0.176
S4	BA10	2000	1.825	1.912	1.904	1.866	-4.120	-1.828	0.279	0.396	0.151
S4	BA10	4000	1.544	1.571	1.512	1.570	-2.174	-0.095	0.379	0.495	0.118
S4	BA10	8000	1.030	0.913	0.917	0.912	-0.781	1.947	0.456	0.608	0.081
S4	BB17	125	2.506	2.376	2.297	2.470	-5.913	-1.803	0.229	0.398	0.211
S4	BB17	250	2.181	2.111	2.142	2.356	-5.936	-4.383	0.211	0.269	0.161
S4	BB17	500	2.226	2.129	2.186	2.230	-2.907	-1.382	0.345	0.423	0.147
S4	BB17	1000	2.050	2.085	2.070	2.054	-5.385	-2.834	0.229	0.343	0.158
S4	BB17	2000	1.920	1.908	1.876	1.910	-2.103	-0.066	0.382	0.496	0.129
S4	BB17	4000	1.502	1.545	1.498	1.627	-0.603	1.297	0.465	0.574	0.103
S4	BB17	8000	0.992	0.901	0.913	0.933	0.572	2.999	0.531	0.659	0.070
S4	BD10	125	2.125	2.310	2.335	2.418	-5.561	-3.310	0.231	0.321	0.192
S4	BD10	250	2.296	2.135	2.217	2.066	-2.145	-0.991	0.391	0.448	0.153
S4	BD10	500	2.142	2.101	2.187	2.143	-4.017	-1.943	0.296	0.391	0.160
S4	BD10	1000	2.086	2.051	2.048	2.194	-1.345	-0.003	0.423	0.500	0.128
S4	BD10	2000	1.946	1.882	1.872	1.837	-1.062	0.269	0.440	0.515	0.124
S4	BD10	4000	1.670	1.517	1.520	1.573	-0.723	0.810	0.458	0.546	0.108
S4	BD10	8000	0.867	0.940	0.935	1.013	3.562	5.563	0.689	0.774	0.056
S4	BD17	125	2.906	1.999	2.187	2.140	-0.516	0.528	0.472	0.530	0.214
S4	BD17	250	2.060	2.169	2.226	2.297	-3.974	-1.774	0.295	0.406	0.144
S4	BD17	500	2.103	2.114	2.145	2.004	-3.324	-1.362	0.318	0.423	0.157
S4	BD17	1000	2.030	2.145	2.081	2.118	-3.773	-1.276	0.299	0.427	0.149
S4	BD17	2000	1.917	1.888	1.876	1.844	-1.030	0.818	0.442	0.546	0.121
S4	BD17	4000	1.505	1.516	1.528	1.455	0.439	2.239	0.524	0.624	0.092
S4	BD17	8000	0.987	0.935	0.935	0.948	1.715	4.321	0.596	0.727	0.061
S4	BSide1	125	2.287	2.116	2.085	2.037	-8.338	-4.769	0.150	0.272	0.176
S4	BSide1	250	2.238	2.387	2.181	2.422	-1.685	-0.263	0.408	0.484	0.178
S4	BSide1	500	2.171	2.116	2.144	2.245	-2.210	-0.171	0.381	0.490	0.153
S4	BSide1	1000	2.051	2.115	2.102	2.084	-3.561	-1.323	0.308	0.425	0.167
S4	BSide1	2000	1.845	1.868	1.858	1.775	-2.011	-0.162	0.387	0.491	0.137
S4	BSide1	4000	1.498	1.529	1.518	1.447	-1.945	1.036	0.390	0.559	0.110
S4	BSide1	8000	0.928	0.910	0.914	0.973	1.531	4.650	0.587	0.743	0.065
S4	BSide7	125	2.692	2.215	2.155	2.692	-4.017	-0.118	0.286	0.494	0.162
S4	BSide7	250	2.226	2.241	2.197	2.447	-3.566	-2.309	0.368	0.413	0.154
S4	BSide7	500	1.976	2.127	2.037	2.303	-5.006	-0.878	0.250	0.450	0.151
S4	BSide7	1000	2.177	2.068	2.031	2.141	-3.112	-1.200	0.329	0.432	0.170
S4	BSide7	2000	1.865	1.876	1.870	1.846	-2.941	0.112	0.341	0.506	0.134
S4	BSide7	4000	1.556	1.484	1.511	1.575	-2.960	0.275	0.345	0.514	0.121
S4	BSide7	8000	0.910	0.909	0.923	0.936	2.461	5.455	0.635	0.770	0.059
S4	BSide12	125	2.302	2.108	2.206	2.194	-8.009	-4.272	0.161	0.281	0.169
S4	BSide12	250	2.095	2.124	2.251	2.026	-4.308	-3.724	0.272	0.299	0.183
S4	BSide12	500	1.923	2.164	2.196	2.243	-6.436	-3.248	0.186	0.323	0.164

S4	BSide12	1000	1.970	2.103	2.069	2.029	-3.895	-0.960	0.292	0.445	0.149
S4	BSide12	2000	1.861	1.900	1.898	1.920	-2.974	-0.397	0.335	0.477	0.140
S4	BSide12	4000	1.553	1.524	1.520	1.601	-1.683	1.011	0.405	0.558	0.115
S4	BSide12	8000	0.927	0.926	0.924	0.957	-0.266	3.468	0.485	0.686	0.072
S4	D12	125	2.604	2.124	2.131	2.054	-3.964	-0.947	0.324	0.447	0.170
S4	D12	250	2.064	2.199	2.150	2.400	0.254	1.089	0.514	0.559	0.162
S4	D12	500	2.173	2.061	2.102	1.882	0.084	1.262	0.505	0.571	0.166
S4	D12	1000	2.042	2.086	2.077	2.166	1.028	2.994	0.559	0.665	0.145
S4	D12	2000	1.870	1.841	1.862	1.815	1.500	3.399	0.584	0.684	0.139
S4	D12	4000	1.423	1.483	1.505	1.493	2.578	4.824	0.644	0.752	0.084
S4	D12	8000	0.834	0.893	0.902	0.845	5.371	8.748	0.772	0.881	0.031
S4	D19	125	1.733	2.271	2.051	2.435	-3.035	-0.281	0.342	0.484	0.126
S4	D19	250	1.870	2.201	2.221	2.263	-5.971	-3.209	0.205	0.327	0.152
S4	D19	500	2.139	2.056	2.123	2.109	-2.923	0.892	0.341	0.551	0.162
S4	D19	1000	1.973	2.042	2.020	2.171	-1.750	0.708	0.402	0.540	0.145
S4	D19	2000	1.908	1.836	1.875	1.902	-1.067	1.050	0.441	0.559	0.127
S4	D19	4000	1.420	1.554	1.544	1.481	0.814	3.232	0.546	0.677	0.090
S4	D19	8000	0.821	0.880	0.887	0.888	1.334	5.724	0.574	0.770	0.062
S4	I12	125	1.985	2.489	2.310	2.075	-3.836	-2.299	0.299	0.371	0.157
S4	I12	250	1.824	2.381	2.283	2.389	-4.961	-2.268	0.244	0.373	0.158
S4	I12	500	2.270	2.138	2.130	2.159	-3.645	-1.274	0.305	0.429	0.182
S4	I12	1000	2.234	1.975	2.006	1.984	-1.187	0.241	0.434	0.514	0.176
S4	I12	2000	1.928	1.821	1.839	1.841	-1.788	0.266	0.399	0.515	0.162
S4	I12	4000	1.643	1.494	1.508	1.556	0.547	3.377	0.527	0.680	0.091
S4	I12	8000	1.004	0.887	0.883	0.870	3.237	6.452	0.669	0.795	0.044
S4	I19	125	1.797	2.186	2.255	2.177	-6.438	-0.279	0.244	0.478	0.128
S4	I19	250	2.287	2.213	2.184	2.212	-8.350	-2.614	0.131	0.359	0.161
S4	I19	500	2.118	2.157	2.144	2.112	-4.479	-1.437	0.270	0.421	0.172
S4	I19	1000	2.071	2.079	2.103	2.044	-2.060	-0.236	0.387	0.488	0.161
S4	I19	2000	1.880	1.857	1.876	1.922	-2.407	0.372	0.367	0.521	0.132
S4	I19	4000	1.584	1.558	1.532	1.564	-0.255	1.969	0.485	0.610	0.099
S4	I19	8000	0.863	0.922	0.910	0.959	2.405	6.564	0.630	0.814	0.053
S4	M12	125	2.561	2.339	2.263	2.462	-4.025	-0.504	0.314	0.471	0.168
S4	M12	250	2.158	2.376	2.140	2.552	-6.185	-2.497	0.221	0.368	0.164
S4	M12	500	2.236	2.114	2.115	2.246	-5.952	-3.984	0.214	0.294	0.177
S4	M12	1000	2.121	2.164	2.088	2.125	-3.917	-1.459	0.292	0.417	0.167
S4	M12	2000	1.921	1.866	1.893	1.917	-4.791	-0.790	0.250	0.455	0.145
S4	M12	4000	1.542	1.493	1.501	1.588	-2.383	0.020	0.367	0.501	0.120
S4	M12	8000	0.903	0.897	0.894	0.914	2.561	5.492	0.637	0.770	0.056
S4	M19	125	2.008	2.255	2.204	2.542	-6.218	-4.268	0.203	0.278	0.157
S4	M19	250	2.213	2.404	2.200	2.282	-7.410	-3.983	0.158	0.292	0.170
S4	M19	500	2.358	2.125	2.140	2.089	-3.771	-2.869	0.296	0.341	0.177
S4	M19	1000	2.077	2.070	2.059	2.100	-4.588	-1.876	0.270	0.399	0.166
S4	M19	2000	1.920	1.845	1.885	1.810	-3.699	-0.878	0.303	0.450	0.153
S4	M19	4000	1.524	1.480	1.507	1.455	-2.514	1.813	0.364	0.601	0.107
S4	M19	8000	0.906	0.935	0.916	0.995	0.903	4.813	0.550	0.745	0.064
S4	O10	125	2.206	2.401	2.376	2.514	-4.931	-3.556	0.296	0.354	0.155
S4	O10	250	2.185	2.368	2.277	2.575	-4.123	-2.319	0.279	0.370	0.168
S4	O10	500	2.186	2.115	2.097	2.292	-2.297	-0.532	0.371	0.469	0.153
S4	O10	1000	2.103	1.915	2.013	2.014	-2.152	-0.662	0.379	0.462	0.151
S4	O10	2000	1.928	1.828	1.867	1.895	-4.092	-1.452	0.281	0.418	0.140
S4	O10	4000	1.528	1.547	1.526	1.553	-1.459	0.870	0.423	0.549	0.106
S4	O10	8000	0.786	0.921	0.932	0.914	4.170	6.705	0.715	0.816	0.047
S4	O19	125	1.823	2.165	2.132	2.056	-8.822	-8.176	0.154	0.162	0.162

S4	O19	250	2.081	2.167	2.244	2.047	-6.051	-2.729	0.200	0.349	0.167
S4	O19	500	2.311	2.193	2.135	2.274	-2.870	-1.429	0.347	0.420	0.160
S4	O19	1000	2.152	2.083	2.091	2.162	-3.488	-1.225	0.311	0.430	0.159
S4	O19	2000	1.900	1.864	1.852	1.985	-3.195	-1.672	0.326	0.406	0.146
S4	O19	4000	1.540	1.533	1.518	1.547	-2.074	0.400	0.388	0.522	0.111
S4	O19	8000	0.914	0.917	0.917	0.915	0.806	3.935	0.546	0.711	0.064
S4	Side3	125	2.299	2.328	2.256	2.384	-3.830	0.159	0.303	0.501	0.143
S4	Side3	250	2.343	2.282	2.232	2.221	-1.303	1.481	0.426	0.583	0.146
S4	Side3	500	2.095	2.087	2.112	2.000	-4.129	-1.668	0.281	0.406	0.171
S4	Side3	1000	2.043	2.156	2.108	2.293	-3.070	-1.019	0.331	0.442	0.157
S4	Side3	2000	1.945	1.864	1.862	1.774	-0.937	0.734	0.447	0.542	0.131
S4	Side3	4000	1.411	1.506	1.527	1.509	0.904	2.537	0.551	0.641	0.085
S4	Side3	8000	0.925	0.895	0.909	0.919	2.764	5.074	0.653	0.760	0.053
S4	Side8	125	2.317	2.061	2.210	1.997	-6.071	-3.124	0.201	0.330	0.160
S4	Side8	250	2.250	2.348	2.239	2.495	-4.393	-1.428	0.268	0.419	0.154
S4	Side8	500	1.930	2.142	2.120	2.294	-3.291	-1.158	0.320	0.434	0.161
S4	Side8	1000	2.105	2.072	2.044	2.057	-4.841	-1.940	0.248	0.391	0.163
S4	Side8	2000	1.921	1.949	1.928	1.862	-3.874	-1.110	0.292	0.437	0.146
S4	Side8	4000	1.462	1.542	1.528	1.476	-1.474	1.115	0.418	0.563	0.103
S4	Side8	8000	0.906	0.902	0.905	0.909	-0.850	3.885	0.451	0.705	0.067
S4	Side12	125	2.265	2.037	2.075	1.803	-5.350	-1.166	0.258	0.433	0.158
S4	Side12	250	2.725	2.215	2.213	2.036	-6.291	-4.188	0.191	0.278	0.199
S4	Side12	500	2.000	2.182	2.230	2.069	-3.505	-2.112	0.311	0.382	0.166
S4	Side12	1000	2.082	2.017	2.063	1.998	-4.281	-1.779	0.278	0.400	0.158
S4	Side12	2000	1.813	1.912	1.896	1.897	-3.894	-1.089	0.291	0.439	0.138
S4	Side12	4000	1.468	1.530	1.531	1.553	-3.844	0.210	0.293	0.512	0.114
S4	Side12	8000	0.912	0.911	0.926	0.899	0.809	4.137	0.546	0.717	0.067
S5	BA10	125	2.607	2.222	2.164	2.265	-6.794	-2.430	0.182	0.368	0.155
S5	BA10	250	2.204	2.100	2.146	1.925	-4.521	-2.357	0.266	0.368	0.162
S5	BA10	500	2.223	2.235	2.199	2.211	-5.903	-2.650	0.215	0.353	0.179
S5	BA10	1000	1.995	2.032	2.050	1.949	-5.231	-2.319	0.232	0.371	0.165
S5	BA10	2000	1.828	1.906	1.912	1.879	-5.837	-3.177	0.207	0.325	0.152
S5	BA10	4000	1.627	1.529	1.511	1.474	-4.491	-1.678	0.265	0.405	0.133
S5	BA10	8000	0.952	0.923	0.938	0.968	-0.624	3.105	0.465	0.667	0.079
S5	BB17	125	2.446	2.152	2.137	2.066	-3.748	-1.551	0.308	0.413	0.157
S5	BB17	250	2.091	1.977	2.144	2.220	-4.572	-0.571	0.268	0.468	0.134
S5	BB17	500	2.310	2.129	2.150	2.067	-3.824	-1.841	0.298	0.397	0.158
S5	BB17	1000	2.030	2.037	2.049	2.022	-4.753	-2.365	0.251	0.367	0.163
S5	BB17	2000	1.846	1.912	1.878	1.906	-5.038	-1.998	0.239	0.388	0.144
S5	BB17	4000	1.525	1.506	1.523	1.515	-2.697	-0.567	0.351	0.468	0.118
S5	BB17	8000	0.935	0.898	0.919	0.882	0.980	3.352	0.555	0.681	0.069
S5	BD10	125	2.432	2.347	2.053	2.850	-0.344	0.308	0.481	0.518	0.187
S5	BD10	250	2.437	2.132	2.207	2.008	-4.591	-1.766	0.265	0.402	0.175
S5	BD10	500	1.984	2.107	2.128	2.038	-5.133	-1.315	0.247	0.427	0.140
S5	BD10	1000	2.187	1.992	2.025	2.002	-5.179	-2.370	0.241	0.368	0.159
S5	BD10	2000	1.965	1.827	1.852	1.885	-3.832	-1.478	0.296	0.416	0.144
S5	BD10	4000	1.604	1.509	1.536	1.566	-2.186	0.358	0.377	0.521	0.109
S5	BD10	8000	0.925	0.949	0.945	0.958	-0.132	2.367	0.492	0.631	0.071
S5	BD17	125	2.018	2.319	2.241	2.636	-2.874	-1.646	0.343	0.407	0.147
S5	BD17	250	2.228	2.116	2.202	2.260	-5.652	-5.515	0.262	0.268	0.169
S5	BD17	500	2.185	2.082	2.119	2.029	-3.858	-1.964	0.293	0.392	0.168
S5	BD17	1000	2.158	2.070	2.060	1.962	-3.349	-0.940	0.319	0.447	0.155
S5	BD17	2000	2.004	1.873	1.866	1.783	-4.778	-1.848	0.253	0.396	0.150
S5	BD17	4000	1.539	1.504	1.542	1.413	-3.251	-0.444	0.326	0.475	0.117

S5	BD17	8000	0.986	0.948	0.927	0.971	1.648	4.916	0.593	0.750	0.057
S5	BSide1	125	2.335	2.146	2.255	2.072	-5.423	-3.824	0.271	0.328	0.187
S5	BSide1	250	2.336	2.318	2.129	2.628	-1.967	-1.042	0.408	0.451	0.174
S5	BSide1	500	2.279	2.148	2.129	2.195	-2.569	-0.950	0.358	0.446	0.175
S5	BSide1	1000	2.273	1.938	2.045	2.204	-2.855	-0.156	0.342	0.491	0.159
S5	BSide1	2000	1.976	1.858	1.859	1.865	-1.279	0.817	0.427	0.547	0.135
S5	BSide1	4000	1.582	1.482	1.505	1.358	-2.528	-0.643	0.360	0.463	0.122
S5	BSide1	8000	1.011	0.916	0.914	0.971	1.403	4.004	0.572	0.696	0.065
S5	BSide7	125	1.467	2.160	2.202	2.376	-10.849	-6.134	0.095	0.206	0.146
S5	BSide7	250	2.044	2.210	2.306	2.073	-3.280	-1.085	0.322	0.438	0.166
S5	BSide7	500	2.161	2.139	2.075	2.259	-5.691	-3.421	0.229	0.323	0.169
S5	BSide7	1000	1.939	2.086	2.072	2.078	-4.036	-1.867	0.287	0.395	0.152
S5	BSide7	2000	1.950	1.837	1.875	1.883	-6.005	-3.220	0.203	0.324	0.156
S5	BSide7	4000	1.488	1.539	1.524	1.521	-2.937	-0.533	0.345	0.470	0.120
S5	BSide7	8000	0.911	0.935	0.914	0.957	2.588	5.955	0.637	0.785	0.053
S5	BSide12	125	2.153	2.118	2.055	2.767	-7.401	-2.525	0.175	0.361	0.143
S5	BSide12	250	2.039	2.162	2.129	2.217	-6.420	-4.183	0.190	0.293	0.166
S5	BSide12	500	2.026	2.040	2.102	2.158	-5.330	-2.667	0.231	0.354	0.165
S5	BSide12	1000	2.273	2.074	2.068	2.071	-5.015	-2.560	0.243	0.358	0.168
S5	BSide12	2000	1.966	1.880	1.881	1.911	-3.789	-1.537	0.299	0.413	0.156
S5	BSide12	4000	1.559	1.524	1.531	1.474	-1.373	0.937	0.422	0.553	0.115
S5	BSide12	8000	0.948	0.931	0.939	0.943	-0.035	2.321	0.499	0.623	0.076
S5	D12	125	1.878	2.209	2.101	2.197	-5.076	-3.095	0.259	0.333	0.146
S5	D12	250	2.102	2.023	2.095	2.206	-0.553	1.552	0.468	0.588	0.135
S5	D12	500	1.981	1.992	2.035	2.035	-2.544	0.800	0.360	0.545	0.144
S5	D12	1000	1.920	1.923	1.994	1.903	-1.310	2.138	0.426	0.619	0.136
S5	D12	2000	1.778	1.864	1.869	1.813	-2.104	1.561	0.383	0.588	0.125
S5	D12	4000	1.491	1.479	1.496	1.540	-3.331	0.717	0.319	0.541	0.113
S5	D12	8000	0.879	0.893	0.887	0.894	2.295	5.827	0.628	0.787	0.060
S5	D19	125	1.949	2.170	2.132	2.535	-7.062	-3.428	0.230	0.341	0.161
S5	D19	250	2.020	2.211	2.266	2.060	-4.891	-3.065	0.273	0.345	0.160
S5	D19	500	1.952	2.156	2.196	2.014	-1.397	-0.095	0.422	0.495	0.162
S5	D19	1000	2.127	2.032	1.986	2.040	-1.800	-0.272	0.399	0.485	0.152
S5	D19	2000	2.055	1.805	1.849	1.748	-1.440	0.363	0.419	0.521	0.145
S5	D19	4000	1.520	1.520	1.515	1.489	-1.251	1.194	0.429	0.568	0.113
S5	D19	8000	0.940	0.915	0.906	0.890	1.798	5.464	0.601	0.778	0.054
S5	I12	125	2.101	2.025	2.088	1.975	-5.948	-3.837	0.240	0.307	0.170
S5	I12	250	2.059	2.112	2.077	2.041	-8.109	-2.560	0.141	0.357	0.153
S5	I12	500	1.950	1.993	2.100	1.949	-3.237	-0.116	0.328	0.495	0.141
S5	I12	1000	2.052	1.970	1.982	2.001	-3.802	-0.716	0.297	0.459	0.161
S5	I12	2000	1.790	1.860	1.864	1.883	-2.847	0.025	0.348	0.502	0.139
S5	I12	4000	1.529	1.473	1.499	1.478	-0.121	1.745	0.493	0.598	0.098
S5	I12	8000	0.884	0.894	0.903	0.888	-0.603	4.663	0.476	0.719	0.065
S5	I19	125	2.435	1.899	2.141	1.617	-7.195	-1.723	0.212	0.419	0.157
S5	I19	250	2.370	1.983	2.061	2.195	-8.767	-6.824	0.118	0.174	0.183
S5	I19	500	2.203	2.096	2.138	2.018	-3.713	-1.995	0.305	0.390	0.184
S5	I19	1000	2.071	2.014	2.018	2.094	-1.970	-0.358	0.389	0.479	0.147
S5	I19	2000	1.804	1.928	1.884	2.020	-2.396	-0.678	0.367	0.462	0.130
S5	I19	4000	1.599	1.493	1.508	1.449	-1.902	0.135	0.393	0.507	0.115
S5	I19	8000	0.906	0.935	0.916	0.952	4.550	7.633	0.731	0.843	0.038
S5	M12	125	2.288	1.939	2.048	2.177	-3.558	-0.204	0.313	0.489	0.139
S5	M12	250	1.741	2.259	2.215	2.225	-9.582	-2.735	0.103	0.368	0.144
S5	M12	500	2.099	2.107	2.119	2.111	-4.824	-1.340	0.251	0.426	0.146
S5	M12	1000	1.748	2.037	2.048	1.959	-4.917	-1.903	0.246	0.394	0.149

S5	M12	2000	1.924	1.908	1.885	1.930	-3.983	-1.319	0.288	0.425	0.149
S5	M12	4000	1.509	1.548	1.512	1.591	-2.444	0.423	0.365	0.524	0.111
S5	M12	8000	0.793	0.896	0.908	0.900	-0.474	5.189	0.474	0.747	0.063
S5	M19	125	2.340	2.123	2.175	2.032	-5.496	-1.076	0.230	0.443	0.159
S5	M19	250	2.299	2.253	2.198	2.066	-8.332	-3.623	0.138	0.305	0.174
S5	M19	500	2.110	2.132	2.164	2.064	-5.119	-1.805	0.236	0.399	0.160
S5	M19	1000	2.036	2.091	2.047	2.154	-4.306	-0.807	0.275	0.454	0.158
S5	M19	2000	1.911	1.863	1.876	1.841	-3.940	-0.903	0.288	0.448	0.147
S5	M19	4000	1.478	1.546	1.543	1.519	-2.655	1.315	0.354	0.574	0.107
S5	M19	8000	0.840	0.921	0.919	0.888	1.207	4.937	0.566	0.749	0.058
S5	O10	125	2.256	2.295	2.220	2.136	-8.195	-3.242	0.144	0.367	0.150
S5	O10	250	1.969	2.102	2.067	2.291	-5.650	-1.958	0.236	0.395	0.133
S5	O10	500	1.994	2.067	2.088	2.145	-3.753	-0.940	0.299	0.446	0.143
S5	O10	1000	1.860	2.012	2.056	2.068	-0.726	0.808	0.458	0.546	0.130
S5	O10	2000	1.657	1.884	1.878	1.941	-2.487	0.255	0.364	0.514	0.124
S5	O10	4000	1.425	1.534	1.542	1.483	-1.296	1.565	0.427	0.588	0.101
S5	O10	8000	0.743	0.916	0.924	0.895	2.615	6.381	0.643	0.810	0.050
S5	O19	125	2.266	2.085	2.168	2.086	-7.590	-3.566	0.202	0.316	0.158
S5	O19	250	2.386	2.177	2.124	2.202	-6.907	-2.113	0.179	0.384	0.165
S5	O19	500	2.185	2.269	2.214	2.209	-4.705	-2.468	0.253	0.363	0.163
S5	O19	1000	2.027	2.084	2.046	1.980	-1.871	-0.253	0.395	0.486	0.140
S5	O19	2000	1.788	1.952	1.918	1.913	-1.819	0.406	0.397	0.523	0.126
S5	O19	4000	1.452	1.488	1.534	1.457	-1.052	1.446	0.440	0.582	0.103
S5	O19	8000	0.751	0.908	0.903	0.844	3.733	6.617	0.695	0.811	0.047
S5	Side3	125	1.873	2.199	2.298	2.189	-1.932	0.168	0.391	0.507	0.143
S5	Side3	250	2.143	2.278	2.262	2.502	-0.554	0.373	0.469	0.521	0.157
S5	Side3	500	2.058	2.120	2.116	2.165	-1.607	-0.450	0.409	0.474	0.154
S5	Side3	1000	2.076	2.056	2.050	2.097	-2.449	-0.691	0.365	0.461	0.147
S5	Side3	2000	1.928	1.912	1.882	1.835	-1.514	0.127	0.415	0.507	0.136
S5	Side3	4000	1.610	1.545	1.524	1.524	-0.063	1.859	0.496	0.603	0.097
S5	Side3	8000	1.031	0.884	0.914	0.854	0.399	3.939	0.521	0.707	0.059
S5	Side8	125	2.304	2.299	2.205	2.718	-8.875	-5.149	0.120	0.241	0.181
S5	Side8	250	2.056	2.144	2.078	1.967	-8.047	-5.738	0.173	0.230	0.178
S5	Side8	500	2.166	2.183	2.167	2.279	-2.834	-0.794	0.346	0.454	0.177
S5	Side8	1000	2.089	2.088	2.062	2.271	-3.818	-1.383	0.293	0.422	0.159
S5	Side8	2000	2.050	1.891	1.882	1.872	-4.004	-1.878	0.285	0.394	0.158
S5	Side8	4000	1.591	1.557	1.537	1.496	-1.198	0.803	0.432	0.546	0.109
S5	Side8	8000	1.033	0.946	0.921	0.947	4.349	6.351	0.721	0.802	0.040
S5	Side12	125	3.210	2.189	2.138	2.388	-4.213	-3.182	0.280	0.330	0.248
S5	Side12	250	2.133	2.250	2.280	2.370	-5.458	-3.366	0.228	0.318	0.173
S5	Side12	500	2.003	2.145	2.156	2.122	-5.633	-2.752	0.222	0.350	0.160
S5	Side12	1000	2.216	1.991	2.033	1.939	-3.578	-1.096	0.305	0.437	0.164
S5	Side12	2000	1.962	1.869	1.868	1.844	-4.303	-2.068	0.278	0.386	0.147
S5	Side12	4000	1.661	1.479	1.514	1.458	-2.988	-0.377	0.341	0.479	0.124
S5	Side12	8000	0.955	0.965	0.942	0.924	1.307	4.090	0.571	0.708	0.066

Octave bands strength and lateral parameters measured with dodecahedron speaker and multichannel microphone

Source	Receiver	Frequency	*G* (dB)	L_J (dB)	J_{LF}	J_{LFC}
S1	BA10	125	10.59	1.75	0.019	0.060
S1	BA10	250	9.59	5.81	0.137	0.121
S1	BA10	500	7.64	7.95	0.575	0.258
S1	BA10	1000	4.78	8.49	0.685	0.272

S1	BA10	2000	2.88	3.56	0.445	0.220
S1	BA10	4000	5.98	-2.39	0.053	0.074
S1	BA10	8000	-4.49	-2.95	NA	NA
S1	BB17	125	11.70	1.28	0.042	0.078
S1	BB17	250	9.91	5.94	0.142	0.137
S1	BB17	500	7.83	8.69	0.567	0.246
S1	BB17	1000	5.07	8.00	0.937	0.323
S1	BB17	2000	2.48	3.21	0.461	0.214
S1	BB17	4000	6.03	-2.02	0.082	0.093
S1	BB17	8000	-3.24	-2.94	NA	NA
S1	BD10	125	13.29	1.02	0.021	0.055
S1	BD10	250	9.79	5.36	0.193	0.172
S1	BD10	500	7.28	8.20	0.454	0.234
S1	BD10	1000	4.82	6.35	0.749	0.270
S1	BD10	2000	3.86	2.48	0.211	0.125
S1	BD10	4000	6.92	-2.57	0.040	0.058
S1	BD10	8000	-2.09	-3.75	NA	NA
S1	BD17	125	9.53	3.80	0.037	0.062
S1	BD17	250	9.75	6.02	0.215	0.168
S1	BD17	500	7.55	8.83	0.452	0.240
S1	BD17	1000	5.08	6.76	0.519	0.255
S1	BD17	2000	2.92	2.59	0.457	0.217
S1	BD17	4000	6.21	-2.36	0.079	0.092
S1	BD17	8000	-3.58	-3.09	NA	NA
S1	BSide1	125	15.79	3.80	0.023	0.057
S1	BSide1	250	12.97	8.49	0.208	0.148
S1	BSide1	500	10.94	11.94	0.511	0.271
S1	BSide1	1000	7.75	10.65	0.571	0.241
S1	BSide1	2000	5.34	6.08	0.450	0.219
S1	BSide1	4000	9.55	0.72	0.068	0.074
S1	BSide1	8000	1.27	0.17	NA	NA
S1	BSide7	125	12.39	2.49	0.026	0.060
S1	BSide7	250	11.20	9.01	0.176	0.110
S1	BSide7	500	10.00	10.56	0.438	0.182
S1	BSide7	1000	6.19	9.30	1.068	0.365
S1	BSide7	2000	4.30	4.96	0.305	0.171
S1	BSide7	4000	7.82	-0.61	0.042	0.063
S1	BSide7	8000	-2.34	-0.53	NA	NA
S1	BSide12	125	12.81	2.96	0.019	0.048
S1	BSide12	250	9.24	6.61	0.190	0.121
S1	BSide12	500	8.07	10.24	0.561	0.241
S1	BSide12	1000	5.15	8.94	0.760	0.275
S1	BSide12	2000	3.31	3.70	0.284	0.172
S1	BSide12	4000	6.58	-1.35	0.063	0.080
S1	BSide12	8000	-2.65	-1.73	NA	NA
S1	D12	125	13.50	4.27	0.067	0.116
S1	D12	250	12.84	7.44	0.089	0.075
S1	D12	500	12.11	10.46	0.304	0.142
S1	D12	1000	10.20	10.13	0.409	0.167
S1	D12	2000	8.58	6.14	0.270	0.098
S1	D12	4000	12.68	0.94	0.046	0.048
S1	D12	8000	6.96	1.57	NA	NA
S1	D19	125	12.65	2.77	0.055	0.091
S1	D19	250	14.44	6.50	0.086	0.054

S1	D19	500	12.61	10.97	0.428	0.185
S1	D19	1000	11.31	10.80	0.492	0.152
S1	D19	2000	10.51	6.52	0.220	0.074
S1	D19	4000	15.58	1.21	0.035	0.031
S1	D19	8000	9.60	2.64	NA	NA
S1	I12	125	12.67	1.88	0.055	0.103
S1	I12	250	10.95	5.84	0.146	0.121
S1	I12	500	10.02	11.11	0.435	0.199
S1	I12	1000	6.91	9.29	0.629	0.222
S1	I12	2000	4.42	4.83	0.443	0.205
S1	I12	4000	7.84	-0.73	0.074	0.077
S1	I12	8000	0.14	-0.23	NA	NA
S1	I19	125	13.12	3.01	0.029	0.080
S1	I19	250	10.15	5.84	0.232	0.167
S1	I19	500	10.60	9.96	0.291	0.159
S1	I19	1000	8.12	9.09	0.366	0.136
S1	I19	2000	5.81	5.01	0.251	0.096
S1	I19	4000	10.42	-0.29	0.033	0.036
S1	I19	8000	2.66	0.42	NA	NA
S1	M12	125	10.79	1.53	0.078	0.108
S1	M12	250	9.57	6.35	0.202	0.168
S1	M12	500	8.83	9.33	0.324	0.210
S1	M12	1000	5.96	8.95	0.598	0.270
S1	M12	2000	3.81	4.44	0.431	0.231
S1	M12	4000	7.53	-1.06	0.074	0.096
S1	M12	8000	-1.02	-1.76	NA	NA
S1	M19	125	11.82	2.00	0.068	0.109
S1	M19	250	9.75	5.53	0.200	0.150
S1	M19	500	8.67	9.18	0.535	0.215
S1	M19	1000	6.24	8.68	0.553	0.236
S1	M19	2000	4.65	4.48	0.328	0.154
S1	M19	4000	7.91	-1.03	0.057	0.063
S1	M19	8000	-1.71	-1.03	NA	NA
S1	O10	125	11.26	1.91	0.028	0.067
S1	O10	250	9.41	5.33	0.221	0.157
S1	O10	500	8.67	9.36	0.328	0.178
S1	O10	1000	6.00	7.76	0.600	0.243
S1	O10	2000	3.37	3.62	0.502	0.252
S1	O10	4000	7.76	-1.90	0.070	0.092
S1	O10	8000	-0.45	-2.06	NA	NA
S1	O19	125	8.86	1.78	0.092	0.107
S1	O19	250	9.48	6.08	0.127	0.130
S1	O19	500	8.29	9.17	0.385	0.201
S1	O19	1000	5.85	7.93	0.491	0.189
S1	O19	2000	3.52	4.04	0.413	0.188
S1	O19	4000	7.84	-1.70	0.042	0.060
S1	O19	8000	-1.83	-1.27	NA	NA
S1	Side3	125	13.89	2.44	0.008	0.031
S1	Side3	250	12.68	8.82	0.133	0.128
S1	Side3	500	12.34	11.79	0.345	0.180
S1	Side3	1000	9.17	10.19	0.675	0.252
S1	Side3	2000	6.80	6.25	0.413	0.185
S1	Side3	4000	11.03	1.44	0.055	0.057
S1	Side3	8000	1.46	1.96	NA	NA

S1	Side8	125	14.10	4.24	0.007	0.038
S1	Side8	250	11.46	7.06	0.154	0.119
S1	Side8	500	10.05	10.43	0.269	0.141
S1	Side8	1000	7.09	9.90	0.561	0.210
S1	Side8	2000	4.83	5.43	0.313	0.149
S1	Side8	4000	8.70	-0.15	0.030	0.042
S1	Side8	8000	0.51	-0.59	NA	NA
S1	Side12	125	12.29	3.36	0.044	0.072
S1	Side12	250	10.49	5.98	0.134	0.117
S1	Side12	500	9.05	10.56	0.330	0.172
S1	Side12	1000	6.83	9.94	0.555	0.227
S1	Side12	2000	3.42	4.95	0.503	0.217
S1	Side12	4000	7.60	-0.23	0.049	0.063
S1	Side12	8000	-2.22	-0.45	NA	NA
S2	BA10	125	11.71	1.45	0.030	0.065
S2	BA10	250	9.35	6.97	0.246	0.169
S2	BA10	500	8.60	9.42	0.617	0.263
S2	BA10	1000	4.54	8.10	0.846	0.307
S2	BA10	2000	2.43	3.91	0.458	0.241
S2	BA10	4000	6.18	-2.00	0.068	0.087
S2	BA10	8000	-3.52	-2.80	NA	NA
S2	BB17	125	11.20	1.70	0.044	0.086
S2	BB17	250	9.63	6.61	0.171	0.160
S2	BB17	500	9.01	8.79	0.441	0.233
S2	BB17	1000	4.80	8.40	0.944	0.325
S2	BB17	2000	2.71	3.71	0.541	0.230
S2	BB17	4000	6.49	-2.03	0.055	0.073
S2	BB17	8000	-4.60	-2.18	NA	NA
S2	BD10	125	11.89	0.25	0.041	0.077
S2	BD10	250	9.48	5.90	0.190	0.173
S2	BD10	500	7.63	7.42	0.393	0.238
S2	BD10	1000	4.33	6.99	0.938	0.302
S2	BD10	2000	2.62	2.83	0.607	0.256
S2	BD10	4000	6.17	-2.59	0.079	0.097
S2	BD10	8000	-4.12	-3.66	NA	NA
S2	BD17	125	10.29	1.42	0.013	0.038
S2	BD17	250	10.24	5.61	0.178	0.154
S2	BD17	500	7.82	8.28	0.599	0.254
S2	BD17	1000	4.59	7.37	0.785	0.297
S2	BD17	2000	3.20	2.83	0.490	0.207
S2	BD17	4000	6.96	-2.24	0.068	0.077
S2	BD17	8000	-4.05	-3.33	NA	NA
S2	BSide1	125	14.23	1.59	0.020	0.048
S2	BSide1	250	12.01	8.19	0.309	0.167
S2	BSide1	500	11.32	11.21	0.352	0.209
S2	BSide1	1000	8.00	9.98	0.674	0.260
S2	BSide1	2000	6.00	5.68	0.378	0.176
S2	BSide1	4000	10.04	0.32	0.044	0.049
S2	BSide1	8000	1.70	-0.01	NA	NA
S2	BSide7	125	12.78	1.69	0.034	0.066
S2	BSide7	250	10.98	6.41	0.149	0.116
S2	BSide7	500	9.91	10.69	0.497	0.246
S2	BSide7	1000	6.60	9.27	0.550	0.257
S2	BSide7	2000	3.85	5.14	0.604	0.254

S2	BSide7	4000	8.03	-1.23	0.079	0.083
S2	BSide7	8000	-0.25	-0.67	NA	NA
S2	BSide12	125	11.53	1.04	0.019	0.050
S2	BSide12	250	8.84	6.18	0.148	0.156
S2	BSide12	500	9.39	9.89	0.278	0.182
S2	BSide12	1000	5.81	8.42	0.677	0.275
S2	BSide12	2000	3.06	4.35	0.473	0.219
S2	BSide12	4000	6.96	-1.55	0.050	0.073
S2	BSide12	8000	-2.94	-2.39	NA	NA
S2	D12	125	14.76	3.40	0.032	0.060
S2	D12	250	11.69	7.60	0.124	0.096
S2	D12	500	11.40	10.77	0.480	0.206
S2	D12	1000	8.16	9.89	0.653	0.185
S2	D12	2000	5.09	5.80	0.489	0.222
S2	D12	4000	9.18	0.92	0.097	0.107
S2	D12	8000	2.43	1.35	NA	NA
S2	D19	125	14.15	2.82	0.042	0.087
S2	D19	250	12.43	7.92	0.146	0.147
S2	D19	500	11.77	10.31	0.440	0.218
S2	D19	1000	8.56	10.15	0.806	0.269
S2	D19	2000	5.69	5.67	0.634	0.269
S2	D19	4000	9.89	0.42	0.090	0.093
S2	D19	8000	2.79	0.94	NA	NA
S2	I12	125	12.52	2.85	0.025	0.064
S2	I12	250	10.53	7.75	0.133	0.119
S2	I12	500	9.73	10.40	0.367	0.167
S2	I12	1000	7.33	8.68	0.769	0.259
S2	I12	2000	4.60	4.86	0.674	0.295
S2	I12	4000	8.33	-0.86	0.091	0.101
S2	I12	8000	-0.20	-0.28	NA	NA
S2	I19	125	12.44	1.77	0.030	0.076
S2	I19	250	10.06	7.13	0.315	0.195
S2	I19	500	9.46	10.69	0.428	0.204
S2	I19	1000	6.95	8.80	0.521	0.206
S2	I19	2000	4.78	4.74	0.428	0.193
S2	I19	4000	8.89	-0.88	0.075	0.065
S2	I19	8000	0.24	-0.73	NA	NA
S2	M12	125	12.92	1.12	0.030	0.066
S2	M12	250	9.32	6.72	0.140	0.129
S2	M12	500	9.15	10.05	0.306	0.207
S2	M12	1000	6.14	8.56	0.497	0.215
S2	M12	2000	3.94	4.36	0.396	0.197
S2	M12	4000	7.98	-0.83	0.061	0.075
S2	M12	8000	-0.84	-0.84	NA	NA
S2	M19	125	11.47	1.57	0.052	0.082
S2	M19	250	9.28	7.22	0.223	0.172
S2	M19	500	9.52	9.59	0.325	0.195
S2	M19	1000	5.97	9.41	0.918	0.278
S2	M19	2000	4.39	4.56	0.375	0.188
S2	M19	4000	8.67	-1.20	0.048	0.064
S2	M19	8000	-0.92	-1.85	NA	NA
S2	O10	125	11.38	1.37	0.021	0.055
S2	O10	250	9.39	5.27	0.150	0.118
S2	O10	500	8.37	8.61	0.401	0.216

S2	O10	1000	6.56	7.90	0.531	0.227
S2	O10	2000	3.61	3.29	0.461	0.225
S2	O10	4000	7.89	-1.96	0.046	0.062
S2	O10	8000	-1.01	-1.57	NA	NA
S2	O19	125	10.38	1.78	0.045	0.087
S2	O19	250	8.58	5.21	0.197	0.158
S2	O19	500	8.27	9.81	0.419	0.176
S2	O19	1000	5.35	8.00	0.781	0.306
S2	O19	2000	3.63	3.77	0.401	0.212
S2	O19	4000	7.12	-1.49	0.055	0.076
S2	O19	8000	-2.45	-1.53	NA	NA
S2	Side3	125	13.15	2.44	0.076	0.124
S2	Side3	250	13.26	8.39	0.117	0.136
S2	Side3	500	11.05	11.35	0.506	0.257
S2	Side3	1000	8.75	10.57	0.582	0.229
S2	Side3	2000	6.95	5.57	0.409	0.215
S2	Side3	4000	10.33	1.38	0.070	0.087
S2	Side3	8000	1.75	3.26	NA	NA
S2	Side8	125	11.70	2.28	0.067	0.115
S2	Side8	250	11.10	7.33	0.118	0.111
S2	Side8	500	9.71	10.46	0.355	0.193
S2	Side8	1000	7.13	9.22	0.496	0.213
S2	Side8	2000	4.62	5.36	0.374	0.182
S2	Side8	4000	9.74	0.06	0.031	0.044
S2	Side8	8000	-1.33	-0.15	NA	NA
S2	Side12	125	11.58	1.98	0.035	0.076
S2	Side12	250	10.08	7.54	0.231	0.144
S2	Side12	500	8.30	9.94	0.409	0.181
S2	Side12	1000	6.74	9.41	0.516	0.193
S2	Side12	2000	4.01	4.81	0.408	0.204
S2	Side12	4000	7.70	-0.70	0.042	0.063
S2	Side12	8000	-1.48	-0.52	NA	NA
S3	BA10	125	9.24	2.23	0.025	0.055
S3	BA10	250	10.09	5.89	0.185	0.171
S3	BA10	500	7.62	9.74	0.576	0.269
S3	BA10	1000	4.87	7.95	0.744	0.323
S3	BA10	2000	3.02	3.73	0.413	0.202
S3	BA10	4000	6.77	-2.01	0.068	0.086
S3	BA10	8000	-3.96	-2.80	NA	NA
S3	BB17	125	9.32	0.42	0.040	0.094
S3	BB17	250	9.90	7.29	0.263	0.201
S3	BB17	500	8.20	8.90	0.589	0.270
S3	BB17	1000	5.27	8.11	0.801	0.281
S3	BB17	2000	3.38	3.34	0.390	0.181
S3	BB17	4000	7.18	-1.96	0.055	0.068
S3	BB17	8000	-2.85	-3.51	NA	NA
S3	BD10	125	11.72	0.69	0.032	0.067
S3	BD10	250	8.52	5.46	0.144	0.138
S3	BD10	500	7.37	7.45	0.465	0.246
S3	BD10	1000	4.68	7.09	0.591	0.259
S3	BD10	2000	2.44	2.60	0.513	0.247
S3	BD10	4000	6.52	-2.46	0.076	0.095
S3	BD10	8000	-4.04	-3.79	NA	NA
S3	BD17	125	11.30	3.93	0.043	0.075

S3	BD17	250	10.27	5.55	0.129	0.129
S3	BD17	500	8.36	7.67	0.293	0.178
S3	BD17	1000	4.70	6.57	0.856	0.300
S3	BD17	2000	2.96	2.96	0.402	0.197
S3	BD17	4000	7.27	-2.19	0.057	0.074
S3	BD17	8000	-3.61	-2.38	NA	NA
S3	BSide1	125	11.80	1.88	0.068	0.092
S3	BSide1	250	12.17	7.63	0.270	0.165
S3	BSide1	500	10.87	10.82	0.478	0.246
S3	BSide1	1000	7.79	10.04	0.699	0.293
S3	BSide1	2000	6.20	4.95	0.352	0.161
S3	BSide1	4000	9.44	-0.25	0.092	0.082
S3	BSide1	8000	0.34	-0.46	NA	NA
S3	BSide7	125	13.01	1.42	0.024	0.055
S3	BSide7	250	10.88	7.98	0.226	0.161
S3	BSide7	500	10.95	10.69	0.533	0.234
S3	BSide7	1000	7.46	8.24	0.762	0.335
S3	BSide7	2000	4.94	4.35	0.381	0.190
S3	BSide7	4000	8.71	-1.08	0.061	0.074
S3	BSide7	8000	-0.31	-1.24	NA	NA
S3	BSide12	125	13.21	2.27	0.031	0.067
S3	BSide12	250	10.47	6.37	0.087	0.098
S3	BSide12	500	9.64	8.70	0.299	0.197
S3	BSide12	1000	6.32	8.03	0.435	0.205
S3	BSide12	2000	3.69	3.89	0.357	0.193
S3	BSide12	4000	7.59	-2.20	0.044	0.072
S3	BSide12	8000	-2.34	-2.22	NA	NA
S3	D12	125	14.53	2.23	0.043	0.079
S3	D12	250	11.78	6.45	0.112	0.082
S3	D12	500	10.75	11.28	0.506	0.187
S3	D12	1000	8.99	10.18	0.655	0.181
S3	D12	2000	6.44	5.92	0.328	0.127
S3	D12	4000	11.36	0.63	0.043	0.046
S3	D12	8000	3.49	2.32	NA	NA
S3	D19	125	11.95	2.66	0.058	0.087
S3	D19	250	10.52	6.57	0.220	0.145
S3	D19	500	10.59	10.84	0.431	0.175
S3	D19	1000	8.41	9.67	1.048	0.311
S3	D19	2000	6.62	5.63	0.793	0.248
S3	D19	4000	11.08	0.18	0.080	0.074
S3	D19	8000	2.98	0.36	NA	NA
S3	I12	125	12.50	2.77	0.023	0.062
S3	I12	250	10.30	6.78	0.116	0.113
S3	I12	500	9.74	10.10	0.447	0.199
S3	I12	1000	7.23	8.79	0.660	0.221
S3	I12	2000	4.42	4.90	0.494	0.198
S3	I12	4000	8.84	-0.89	0.088	0.081
S3	I12	8000	0.27	-0.90	NA	NA
S3	I19	125	11.18	2.39	0.122	0.148
S3	I19	250	9.22	6.47	0.304	0.215
S3	I19	500	9.21	9.67	0.358	0.216
S3	I19	1000	6.89	8.67	0.850	0.276
S3	I19	2000	4.65	4.56	0.596	0.229
S3	I19	4000	8.68	-0.90	0.074	0.089

S3	I19	8000	-0.83	-0.98	NA	NA
S3	M12	125	12.40	1.29	0.013	0.044
S3	M12	250	9.57	6.55	0.129	0.134
S3	M12	500	9.18	10.56	0.297	0.207
S3	M12	1000	6.23	8.48	0.567	0.229
S3	M12	2000	4.35	4.37	0.379	0.189
S3	M12	4000	9.00	-1.01	0.052	0.068
S3	M12	8000	-0.75	-0.75	NA	NA
S3	M19	125	12.92	2.19	0.062	0.082
S3	M19	250	10.18	7.04	0.167	0.149
S3	M19	500	9.12	9.84	0.273	0.165
S3	M19	1000	6.26	8.84	0.633	0.252
S3	M19	2000	3.98	4.10	0.308	0.166
S3	M19	4000	7.22	-1.51	0.063	0.085
S3	M19	8000	-1.09	-2.41	NA	NA
S3	O10	125	12.37	-0.07	0.033	0.073
S3	O10	250	9.52	4.91	0.144	0.139
S3	O10	500	8.14	8.55	0.417	0.189
S3	O10	1000	5.91	7.54	0.679	0.264
S3	O10	2000	3.49	3.64	0.627	0.285
S3	O10	4000	7.95	-1.67	0.059	0.088
S3	O10	8000	-2.34	-1.91	NA	NA
S3	O19	125	11.06	1.45	0.097	0.131
S3	O19	250	9.46	4.21	0.105	0.123
S3	O19	500	8.45	9.31	0.360	0.191
S3	O19	1000	5.97	8.05	0.515	0.231
S3	O19	2000	3.20	4.25	0.397	0.195
S3	O19	4000	6.95	-1.51	0.061	0.079
S3	O19	8000	-2.06	-1.13	NA	NA
S3	Side3	125	12.81	3.28	0.026	0.055
S3	Side3	250	11.27	7.67	0.088	0.089
S3	Side3	500	10.61	11.02	0.367	0.222
S3	Side3	1000	7.35	9.71	0.925	0.292
S3	Side3	2000	5.14	5.61	0.691	0.297
S3	Side3	4000	8.94	0.55	0.103	0.103
S3	Side3	8000	-0.31	1.20	NA	NA
S3	Side8	125	11.94	0.82	0.020	0.059
S3	Side8	250	9.98	6.86	0.261	0.189
S3	Side8	500	9.35	9.64	0.469	0.210
S3	Side8	1000	6.66	9.32	1.135	0.322
S3	Side8	2000	4.06	4.61	0.679	0.315
S3	Side8	4000	8.22	-0.61	0.075	0.088
S3	Side8	8000	-1.30	-0.56	NA	NA
S3	Side12	125	11.26	1.03	0.080	0.105
S3	Side12	250	9.46	6.65	0.306	0.206
S3	Side12	500	8.64	10.36	0.414	0.199
S3	Side12	1000	6.21	9.26	0.799	0.293
S3	Side12	2000	4.13	4.25	0.413	0.212
S3	Side12	4000	8.32	-1.16	0.050	0.071
S3	Side12	8000	-2.06	-0.90	NA	NA
S4	BA10	125	10.55	0.31	0.016	0.042
S4	BA10	250	9.09	5.27	0.292	0.171
S4	BA10	500	7.90	9.15	0.511	0.224
S4	BA10	1000	4.54	7.21	0.912	0.321

S4	BA10	2000	2.78	3.37	0.440	0.189
S4	BA10	4000	6.87	-2.06	0.044	0.060
S4	BA10	8000	-4.29	-2.91	NA	NA
S4	BB17	125	7.92	0.65	0.116	0.118
S4	BB17	250	10.10	5.67	0.309	0.204
S4	BB17	500	8.36	8.44	0.407	0.232
S4	BB17	1000	5.03	7.52	0.996	0.334
S4	BB17	2000	3.09	3.40	0.493	0.213
S4	BB17	4000	7.35	-1.90	0.070	0.089
S4	BB17	8000	-3.91	-2.47	NA	NA
S4	BD10	125	10.40	1.44	0.082	0.118
S4	BD10	250	9.79	5.14	0.287	0.205
S4	BD10	500	6.61	7.99	0.846	0.287
S4	BD10	1000	5.15	7.17	0.967	0.303
S4	BD10	2000	2.73	2.55	0.638	0.207
S4	BD10	4000	6.16	-2.67	0.086	0.092
S4	BD10	8000	-2.98	-3.35	NA	NA
S4	BD17	125	9.51	0.30	0.041	0.078
S4	BD17	250	9.45	5.82	0.223	0.194
S4	BD17	500	7.92	7.66	0.459	0.244
S4	BD17	1000	4.48	6.84	0.642	0.269
S4	BD17	2000	3.64	2.57	0.381	0.176
S4	BD17	4000	7.88	-2.39	0.053	0.067
S4	BD17	8000	-3.58	-3.59	NA	NA
S4	BSide1	125	12.30	1.98	0.092	0.109
S4	BSide1	250	11.50	7.37	0.278	0.151
S4	BSide1	500	10.22	10.36	1.192	0.427
S4	BSide1	1000	7.17	9.06	0.912	0.300
S4	BSide1	2000	5.26	5.30	0.532	0.221
S4	BSide1	4000	8.92	-0.48	0.086	0.097
S4	BSide1	8000	-0.46	-1.37	NA	NA
S4	BSide7	125	12.37	1.77	0.021	0.056
S4	BSide7	250	10.02	6.22	0.281	0.158
S4	BSide7	500	10.06	10.27	0.454	0.228
S4	BSide7	1000	6.62	8.45	0.810	0.283
S4	BSide7	2000	4.36	3.52	0.681	0.263
S4	BSide7	4000	7.50	-1.24	0.111	0.117
S4	BSide7	8000	-0.50	-2.01	NA	NA
S4	BSide12	125	12.72	1.82	0.055	0.082
S4	BSide12	250	10.25	7.01	0.103	0.097
S4	BSide12	500	9.24	9.57	0.307	0.192
S4	BSide12	1000	6.30	8.18	0.691	0.298
S4	BSide12	2000	4.09	3.44	0.460	0.201
S4	BSide12	4000	7.41	-2.40	0.056	0.065
S4	BSide12	8000	-2.80	-3.10	NA	NA
S4	D12	125	13.18	3.07	0.029	0.072
S4	D12	250	13.14	7.17	0.110	0.073
S4	D12	500	12.08	10.82	0.358	0.137
S4	D12	1000	9.62	10.27	0.617	0.170
S4	D12	2000	7.96	6.46	0.385	0.122
S4	D12	4000	12.76	0.63	0.047	0.041
S4	D12	8000	5.53	2.48	NA	NA
S4	D19	125	13.96	2.16	0.034	0.073
S4	D19	250	11.64	7.83	0.120	0.119

S4	D19	500	10.98	11.14	0.375	0.166
S4	D19	1000	7.94	9.68	0.953	0.287
S4	D19	2000	5.96	5.19	0.760	0.314
S4	D19	4000	10.94	0.11	0.064	0.065
S4	D19	8000	0.90	0.40	NA	NA
S4	I12	125	12.56	1.52	0.055	0.081
S4	I12	250	10.94	6.46	0.099	0.089
S4	I12	500	9.71	10.72	0.256	0.145
S4	I12	1000	7.53	8.86	0.409	0.147
S4	I12	2000	5.45	4.73	0.297	0.111
S4	I12	4000	11.05	-0.17	0.023	0.026
S4	I12	8000	1.10	0.83	NA	NA
S4	I19	125	12.77	0.98	0.063	0.106
S4	I19	250	10.32	6.85	0.200	0.166
S4	I19	500	9.78	8.59	0.407	0.173
S4	I19	1000	7.16	8.59	0.676	0.250
S4	I19	2000	4.84	4.10	0.698	0.265
S4	I19	4000	9.03	-0.66	0.083	0.087
S4	I19	8000	-0.13	-1.61	NA	NA
S4	M12	125	10.60	1.92	0.097	0.117
S4	M12	250	9.66	7.22	0.168	0.144
S4	M12	500	8.99	9.82	0.434	0.195
S4	M12	1000	5.64	8.20	0.452	0.203
S4	M12	2000	3.85	4.15	0.403	0.207
S4	M12	4000	7.91	-0.86	0.070	0.082
S4	M12	8000	-0.66	-0.63	NA	NA
S4	M19	125	11.32	1.78	0.063	0.063
S4	M19	250	8.81	6.09	0.165	0.157
S4	M19	500	8.55	10.10	0.622	0.262
S4	M19	1000	6.21	8.22	0.656	0.239
S4	M19	2000	3.74	4.00	0.528	0.219
S4	M19	4000	8.06	-1.54	0.053	0.078
S4	M19	8000	-1.78	-2.55	NA	NA
S4	O10	125	11.06	0.52	0.043	0.078
S4	O10	250	9.15	5.67	0.281	0.153
S4	O10	500	8.52	9.20	0.371	0.207
S4	O10	1000	6.17	7.26	0.603	0.232
S4	O10	2000	3.54	3.03	0.580	0.253
S4	O10	4000	7.42	-1.79	0.055	0.080
S4	O10	8000	-0.92	-1.93	NA	NA
S4	O19	125	9.55	2.02	0.092	0.087
S4	O19	250	9.80	5.72	0.149	0.148
S4	O19	500	8.21	9.42	0.292	0.172
S4	O19	1000	5.32	7.82	0.527	0.227
S4	O19	2000	3.15	4.06	0.440	0.202
S4	O19	4000	6.77	-1.75	0.069	0.080
S4	O19	8000	-2.20	-1.58	NA	NA
S4	Side3	125	10.34	0.99	0.071	0.100
S4	Side3	250	11.54	7.02	0.189	0.147
S4	Side3	500	10.11	10.77	0.978	0.347
S4	Side3	1000	6.99	9.23	1.190	0.367
S4	Side3	2000	5.41	5.14	0.790	0.267
S4	Side3	4000	10.14	0.62	0.106	0.092
S4	Side3	8000	0.54	1.53	NA	NA

S4	Side8	125	11.44	-0.38	0.029	0.068
S4	Side8	250	10.58	7.53	0.233	0.175
S4	Side8	500	10.20	10.89	0.552	0.218
S4	Side8	1000	6.34	8.88	0.906	0.301
S4	Side8	2000	3.64	4.93	0.680	0.320
S4	Side8	4000	8.22	-0.19	0.091	0.105
S4	Side8	8000	-1.90	-0.10	NA	NA
S4	Side12	125	11.40	1.56	0.024	0.053
S4	Side12	250	8.50	5.89	0.387	0.206
S4	Side12	500	9.15	10.21	0.613	0.208
S4	Side12	1000	6.16	8.91	0.812	0.290
S4	Side12	2000	3.71	4.33	0.582	0.260
S4	Side12	4000	7.73	-0.86	0.069	0.091
S4	Side12	8000	-2.50	-2.03	NA	NA
S5	BA10	125	12.05	-2.13	0.014	0.040
S5	BA10	250	9.91	6.20	0.222	0.159
S5	BA10	500	6.93	9.69	1.140	0.358
S5	BA10	1000	5.25	7.49	0.750	0.268
S5	BA10	2000	2.59	3.20	0.593	0.264
S5	BA10	4000	5.87	-2.28	0.073	0.095
S5	BA10	8000	-3.87	-2.87	NA	NA
S5	BB17	125	8.99	0.60	0.043	0.081
S5	BB17	250	10.73	6.10	0.111	0.129
S5	BB17	500	7.85	9.38	0.579	0.268
S5	BB17	1000	5.17	8.21	0.803	0.298
S5	BB17	2000	2.74	3.43	0.463	0.239
S5	BB17	4000	6.37	-2.18	0.087	0.096
S5	BB17	8000	-3.80	-2.40	NA	NA
S5	BD10	125	11.72	1.75	0.043	0.090
S5	BD10	250	8.45	7.04	0.431	0.228
S5	BD10	500	7.95	8.80	0.529	0.267
S5	BD10	1000	4.31	6.32	0.757	0.305
S5	BD10	2000	2.39	2.62	0.490	0.222
S5	BD10	4000	6.23	-2.43	0.065	0.079
S5	BD10	8000	-4.39	-3.31	NA	NA
S5	BD17	125	11.86	2.11	0.017	0.054
S5	BD17	250	9.19	4.65	0.278	0.170
S5	BD17	500	7.93	8.61	0.657	0.265
S5	BD17	1000	4.83	7.51	0.571	0.253
S5	BD17	2000	2.01	2.49	0.561	0.252
S5	BD17	4000	6.00	-2.68	0.076	0.095
S5	BD17	8000	-3.06	-3.30	NA	NA
S5	BSide1	125	13.20	2.83	0.059	0.091
S5	BSide1	250	11.90	7.65	0.278	0.186
S5	BSide1	500	10.73	11.54	0.486	0.278
S5	BSide1	1000	7.58	10.02	0.741	0.272
S5	BSide1	2000	5.83	5.49	0.447	0.220
S5	BSide1	4000	8.92	-0.42	0.097	0.112
S5	BSide1	8000	-0.83	-1.29	NA	NA
S5	BSide7	125	13.55	1.96	0.029	0.052
S5	BSide7	250	11.03	7.41	0.303	0.178
S5	BSide7	500	10.42	10.37	0.567	0.217
S5	BSide7	1000	7.42	9.17	0.531	0.218
S5	BSide7	2000	4.06	5.88	0.530	0.272

S5	BSide7	4000	7.87	-0.33	0.093	0.097
S5	BSide7	8000	-0.15	-2.07	NA	NA
S5	BSide12	125	12.46	1.37	0.020	0.055
S5	BSide12	250	10.55	5.83	0.160	0.127
S5	BSide12	500	9.55	9.80	0.396	0.212
S5	BSide12	1000	5.67	8.01	0.750	0.302
S5	BSide12	2000	3.69	3.88	0.312	0.171
S5	BSide12	4000	7.84	-1.61	0.034	0.054
S5	BSide12	8000	-3.29	-2.71	NA	NA
S5	D12	125	14.70	-1.34	0.012	0.041
S5	D12	250	14.29	4.64	0.026	0.058
S5	D12	500	13.08	8.93	0.086	0.092
S5	D12	1000	10.01	8.92	0.155	0.100
S5	D12	2000	6.85	5.71	0.285	0.145
S5	D12	4000	10.08	0.50	0.083	0.094
S5	D12	8000	2.96	1.05	NA	NA
S5	D19	125	12.63	2.21	0.083	0.108
S5	D19	250	12.06	7.26	0.214	0.143
S5	D19	500	11.64	10.45	0.370	0.159
S5	D19	1000	8.34	10.09	0.922	0.293
S5	D19	2000	5.99	5.52	0.497	0.190
S5	D19	4000	10.23	0.35	0.063	0.066
S5	D19	8000	1.62	0.96	NA	NA
S5	I12	125	14.45	-0.38	0.006	0.037
S5	I12	250	12.70	2.89	0.016	0.047
S5	I12	500	11.56	7.98	0.091	0.109
S5	I12	1000	7.71	8.53	0.224	0.144
S5	I12	2000	5.30	4.81	0.257	0.145
S5	I12	4000	9.91	-0.59	0.046	0.061
S5	I12	8000	-0.92	-0.31	NA	NA
S5	I19	125	12.01	2.15	0.092	0.112
S5	I19	250	10.37	6.84	0.455	0.235
S5	I19	500	9.92	9.69	0.292	0.160
S5	I19	1000	7.51	9.11	0.753	0.266
S5	I19	2000	4.88	4.88	0.710	0.216
S5	I19	4000	8.34	-0.80	0.105	0.092
S5	I19	8000	1.05	-0.51	NA	NA
S5	M12	125	14.74	-2.98	0.006	0.035
S5	M12	250	11.74	3.27	0.013	0.044
S5	M12	500	10.05	8.01	0.073	0.089
S5	M12	1000	7.11	8.05	0.373	0.211
S5	M12	2000	4.04	4.23	0.497	0.229
S5	M12	4000	7.87	-1.45	0.069	0.080
S5	M12	8000	-1.04	-0.99	NA	NA
S5	M19	125	11.16	1.46	0.064	0.090
S5	M19	250	9.49	6.44	0.210	0.163
S5	M19	500	9.52	10.32	0.338	0.234
S5	M19	1000	6.45	8.51	0.379	0.177
S5	M19	2000	3.85	4.31	0.412	0.192
S5	M19	4000	8.04	-1.16	0.044	0.068
S5	M19	8000	-1.22	-2.31	NA	NA
S5	O10	125	12.88	-4.01	0.006	0.033
S5	O10	250	11.43	2.58	0.030	0.060
S5	O10	500	9.19	6.74	0.095	0.095

S5	O10	1000	7.24	6.76	0.295	0.148
S5	O10	2000	4.52	3.44	0.202	0.139
S5	O10	4000	8.50	-2.07	0.034	0.052
S5	O10	8000	-0.62	-2.46	NA	NA
S5	O19	125	9.96	1.25	0.024	0.061
S5	O19	250	9.09	5.52	0.132	0.134
S5	O19	500	8.29	9.38	0.356	0.178
S5	O19	1000	6.67	8.05	0.533	0.196
S5	O19	2000	3.99	4.21	0.349	0.179
S5	O19	4000	7.69	-1.27	0.049	0.068
S5	O19	8000	-0.65	-1.17	NA	NA
S5	Side3	125	12.90	3.62	0.038	0.068
S5	Side3	250	11.74	8.17	0.082	0.082
S5	Side3	500	11.02	11.06	0.410	0.194
S5	Side3	1000	7.92	10.17	1.037	0.300
S5	Side3	2000	5.71	5.68	0.420	0.199
S5	Side3	4000	9.67	0.76	0.060	0.060
S5	Side3	8000	0.51	1.70	NA	NA
S5	Side8	125	10.98	0.05	0.083	0.108
S5	Side8	250	11.91	8.91	0.185	0.140
S5	Side8	500	9.53	10.57	0.338	0.175
S5	Side8	1000	6.54	10.23	0.734	0.290
S5	Side8	2000	3.55	5.40	0.468	0.220
S5	Side8	4000	7.79	-0.13	0.053	0.073
S5	Side8	8000	0.27	0.34	NA	NA
S5	Side12	125	8.07	0.08	0.074	0.089
S5	Side12	250	9.85	7.81	0.272	0.173
S5	Side12	500	9.19	9.95	0.332	0.163
S5	Side12	1000	6.39	9.37	0.569	0.229
S5	Side12	2000	3.59	5.50	0.450	0.203
S5	Side12	4000	6.58	-0.71	0.079	0.087
S5	Side12	8000	-2.86	-1.38	NA	NA

Octave bands interaural parameters measured with dodecahedron speaker and dummy head

Source	Receiver	Frequency	$\mathrm{IACC}_{\mathrm{Early}}$	$\mathrm{IACC}_{\mathrm{Late}}$	$\mathrm{IACC}_{\mathrm{All}}$	τ_{Early} (ms)	τ_{Late} (ms)	τ_{All} (ms)	$\mathrm{ILD}_{\mathrm{Early}}$ (dB)	$\mathrm{ILD}_{\mathrm{Late}}$ (dB)	$\mathrm{ILD}_{\mathrm{All}}$ (dB)
S5	M19	125	0.919	0.879	0.893	0.229	0.000	0.104	-1.033	-0.679	-0.845
S5	M19	250	0.628	0.654	0.647	-0.063	0.000	-0.021	-1.356	-1.479	-1.449
S5	M19	500	0.371	0.090	0.148	-0.063	0.542	-0.063	-1.257	-0.659	-0.861
S5	M19	1000	0.112	0.089	0.058	-0.104	0.271	-0.833	-0.409	-0.970	-0.752
S5	M19	2000	0.277	0.086	0.137	0.167	-0.854	0.167	-1.915	-1.789	-1.852
S5	M19	4000	0.346	0.047	0.223	0.167	-0.729	0.167	-1.382	-1.228	-1.326
S1	D12	125	0.934	0.907	0.900	-0.313	0.104	0.000	0.463	-0.328	-0.141
S1	D12	250	0.910	0.718	0.772	-0.438	0.021	-0.271	-0.058	-0.392	-0.217
S1	D12	500	0.731	0.140	0.447	-0.521	0.229	-0.500	1.617	0.160	1.016
S1	D12	1000	0.370	0.066	0.232	0.146	0.000	0.125	3.132	-1.402	1.295
S1	D12	2000	0.273	0.104	0.174	-0.313	0.042	-0.292	2.089	-1.640	0.478
S1	D12	4000	0.434	0.063	0.299	-0.292	0.417	-0.292	5.412	-1.338	3.553
S1	D19	125	0.897	0.888	0.885	-0.063	0.208	0.104	-0.348	-1.203	-0.887
S1	D19	250	0.815	0.747	0.785	0.188	0.083	0.146	-0.602	-1.708	-1.028
S1	D19	500	0.281	0.113	0.215	0.208	1.021	0.229	-1.386	-1.880	-1.557
S1	D19	1000	0.367	0.106	0.260	-0.250	0.688	-0.271	1.002	-1.699	0.139
S1	D19	2000	0.270	0.089	0.204	0.167	0.271	0.167	0.967	-2.087	0.316

S1	D19	4000	0.283	0.079	0.244	0.167	0.271	0.167	-0.246	-1.633	-0.474
S1	I12	125	0.900	0.899	0.897	-0.146	-0.021	-0.063	-0.401	-1.337	-1.000
S1	I12	250	0.879	0.737	0.761	-0.292	0.083	-0.125	0.300	-0.734	-0.316
S1	I12	500	0.558	0.079	0.254	-0.417	0.667	-0.458	0.880	-0.510	0.048
S1	I12	1000	0.410	0.113	0.237	-0.167	0.125	0.229	1.477	-0.668	0.406
S1	I12	2000	0.282	0.049	0.131	-0.167	-0.938	-0.167	0.301	-1.043	-0.445
S1	I12	4000	0.275	0.052	0.171	-0.188	0.104	-0.188	2.024	-1.124	0.656
S1	I19	125	0.932	0.916	0.912	-0.188	0.021	-0.021	-2.412	-0.322	-0.859
S1	I19	250	0.717	0.656	0.670	-0.167	0.021	-0.063	0.138	-0.807	-0.447
S1	I19	500	0.421	0.159	0.240	0.104	0.458	0.188	-0.480	-1.256	-0.938
S1	I19	1000	0.485	0.107	0.277	0.042	-0.854	0.021	-0.917	-1.360	-1.113
S1	I19	2000	0.458	0.072	0.274	0.063	1.000	0.042	-0.718	-1.523	-1.070
S1	I19	4000	0.387	0.060	0.221	0.063	0.313	0.063	-0.046	-1.120	-0.465
S1	M12	125	0.850	0.859	0.847	-0.354	-0.021	-0.146	-1.801	-1.451	-1.593
S1	M12	250	0.787	0.695	0.711	-0.188	0.021	-0.042	-1.900	-1.717	-1.764
S1	M12	500	0.411	0.079	0.170	-0.292	-0.583	-0.396	-1.487	-0.614	-0.891
S1	M12	1000	0.384	0.070	0.176	-0.125	0.833	0.271	0.632	-1.152	-0.333
S1	M12	2000	0.343	0.070	0.187	-0.063	0.146	-0.083	1.043	-1.872	-0.505
S1	M12	4000	0.363	0.078	0.193	-0.063	-0.875	-0.083	1.437	-0.931	0.350
S1	M19	125	0.850	0.919	0.908	0.021	-0.021	-0.021	-1.490	-0.657	-0.778
S1	M19	250	0.707	0.764	0.744	-0.083	0.063	0.021	-1.988	-0.964	-1.235
S1	M19	500	0.348	0.120	0.100	0.021	-0.625	0.000	-0.905	-1.128	-1.055
S1	M19	1000	0.408	0.090	0.162	0.083	0.792	-0.292	-2.820	-1.501	-2.068
S1	M19	2000	0.301	0.076	0.163	0.083	-0.146	0.083	-1.552	-1.325	-1.417
S1	M19	4000	0.206	0.082	0.131	0.083	1.021	0.063	-0.410	-1.229	-0.842
S2	D12	125	0.921	0.938	0.927	-0.146	0.083	0.021	-2.064	-0.953	-1.286
S2	D12	250	0.798	0.662	0.707	-0.208	0.021	-0.083	-1.125	-1.924	-1.590
S2	D12	500	0.432	0.153	0.219	-0.396	0.229	-0.292	-0.346	-0.745	-0.561
S2	D12	1000	0.404	0.126	0.175	0.354	-0.792	0.354	0.865	-1.215	-0.256
S2	D12	2000	0.235	0.052	0.105	-0.333	1.021	-0.354	-0.403	-1.452	-0.978
S2	D12	4000	0.355	0.075	0.199	-0.125	1.021	-0.125	0.396	-1.051	-0.198
S2	D19	125	0.937	0.887	0.909	-0.167	-0.021	-0.104	-1.326	-1.133	-1.225
S2	D19	250	0.759	0.668	0.705	-0.063	0.167	0.042	-0.694	-0.640	-0.668
S2	D19	500	0.141	0.252	0.146	-0.333	0.542	0.479	-0.514	-2.672	-1.409
S2	D19	1000	0.283	0.103	0.177	0.188	-0.729	-0.229	-0.424	-1.963	-1.115
S2	D19	2000	0.250	0.073	0.128	-0.458	-0.104	-0.458	3.108	-2.029	0.727
S2	D19	4000	0.195	0.040	0.127	0.292	0.896	0.542	0.662	-1.498	-0.125
S2	I12	125	0.965	0.851	0.902	-0.063	-0.083	-0.063	-0.408	-0.496	-0.457
S2	I12	250	0.818	0.693	0.728	0.000	-0.021	0.000	-0.269	-0.268	-0.268
S2	I12	500	0.365	0.127	0.204	-0.146	-0.271	-0.188	0.001	-1.149	-0.762
S2	I12	1000	0.294	0.120	0.171	-0.104	0.688	0.271	0.797	-0.766	-0.005
S2	I12	2000	0.283	0.066	0.125	0.250	-0.479	0.250	-0.088	-0.793	-0.467
S2	I12	4000	0.268	0.071	0.163	-0.104	-0.021	0.021	0.188	-0.550	-0.144
S2	I19	125	0.949	0.882	0.899	0.042	0.146	0.125	-2.928	-0.845	-1.579
S2	I19	250	0.672	0.694	0.654	-0.313	0.188	0.063	-1.107	-1.312	-1.262
S2	I19	500	0.244	0.201	0.166	0.104	0.604	0.458	-1.457	-1.471	-1.466
S2	I19	1000	0.457	0.195	0.224	0.458	-0.729	0.854	-1.533	-1.562	-1.548
S2	I19	2000	0.345	0.078	0.160	0.083	0.500	0.083	-1.295	-1.640	-1.465
S2	I19	4000	0.233	0.063	0.140	0.063	0.146	0.063	0.025	-1.366	-0.561
S2	M12	125	0.966	0.899	0.933	0.021	-0.021	0.000	-0.290	-1.211	-0.728
S2	M12	250	0.831	0.698	0.724	-0.083	0.167	0.083	-0.938	-0.670	-0.746
S2	M12	500	0.498	0.083	0.232	-0.229	-0.417	-0.271	-0.283	-1.486	-1.037
S2	M12	1000	0.362	0.112	0.185	-0.042	0.771	0.354	-0.142	-0.989	-0.634
S2	M12	2000	0.192	0.067	0.089	-0.042	0.708	-0.063	-1.459	-1.066	-1.224

S2	M12	4000	0.126	0.098	0.109	0.063	-0.229	0.063	0.970	-1.040	0.022
S2	M19	125	0.895	0.894	0.892	0.063	0.000	0.021	-1.670	-0.527	-0.989
S2	M19	250	0.816	0.594	0.664	-0.146	-0.063	-0.083	-2.104	-0.567	-1.075
S2	M19	500	0.392	0.195	0.204	-0.042	0.396	0.146	0.438	-0.885	-0.454
S2	M19	1000	0.433	0.097	0.184	0.063	-0.833	0.083	-1.621	-0.945	-1.239
S2	M19	2000	0.407	0.078	0.199	0.083	0.854	0.083	-2.298	-1.789	-2.033
S2	M19	4000	0.250	0.041	0.137	0.063	-0.979	0.063	-1.577	-1.141	-1.383
S3	D12	125	0.915	0.943	0.933	0.146	0.000	0.042	0.264	-0.536	-0.314
S3	D12	250	0.805	0.776	0.779	0.188	0.021	0.083	-1.135	-0.793	-0.916
S3	D12	500	0.410	0.172	0.189	0.458	-0.646	0.521	-2.674	-1.146	-1.820
S3	D12	1000	0.329	0.093	0.184	-0.250	-0.813	-0.250	-3.505	-0.956	-2.259
S3	D12	2000	0.241	0.103	0.126	0.354	-0.542	0.146	-1.546	-0.455	-0.970
S3	D12	4000	0.225	0.073	0.120	0.146	-0.958	0.167	-1.477	-1.001	-1.292
S3	D19	125	0.835	0.889	0.871	0.042	-0.021	0.000	-0.219	0.203	0.063
S3	D19	250	0.557	0.749	0.682	0.208	0.021	0.104	-0.424	-0.513	-0.484
S3	D19	500	0.422	0.099	0.235	0.667	0.417	0.604	-1.774	-0.327	-0.994
S3	D19	1000	0.250	0.061	0.151	-0.063	-0.667	-0.063	-2.194	-1.667	-1.931
S3	D19	2000	0.244	0.070	0.145	0.417	-0.375	0.417	-2.658	-1.141	-1.947
S3	D19	4000	0.217	0.041	0.147	0.250	-0.979	0.250	-4.936	-0.537	-3.325
S3	I12	125	0.967	0.850	0.902	0.125	0.104	0.125	-1.047	-0.686	-0.845
S3	I12	250	0.864	0.716	0.756	0.021	0.000	0.000	-1.690	-0.825	-1.065
S3	I12	500	0.245	0.125	0.152	0.042	1.021	0.000	-2.063	-0.593	-1.106
S3	I12	1000	0.345	0.101	0.190	0.063	0.833	-0.354	-1.754	-1.180	-1.471
S3	I12	2000	0.164	0.071	0.072	0.021	0.896	0.854	-0.766	-1.150	-0.976
S3	I12	4000	0.193	0.055	0.128	0.063	0.083	0.063	-1.824	-0.424	-1.205
S3	I19	125	0.799	0.877	0.852	0.042	-0.167	-0.125	0.841	-1.189	-0.706
S3	I19	250	0.614	0.672	0.660	0.083	0.042	0.063	0.381	-0.884	-0.643
S3	I19	500	0.433	0.095	0.189	0.333	-0.354	0.313	-2.046	-0.886	-1.304
S3	I19	1000	0.309	0.086	0.156	0.208	-0.667	-0.208	-1.265	-1.609	-1.443
S3	I19	2000	0.167	0.066	0.103	0.188	-0.896	0.188	-1.785	-1.452	-1.641
S3	I19	4000	0.122	0.098	0.085	0.333	0.271	0.458	-3.244	-1.101	-2.475
S3	M12	125	0.969	0.881	0.928	0.104	0.104	0.104	-1.356	-0.373	-0.914
S3	M12	250	0.838	0.638	0.697	0.167	0.000	0.063	-2.044	-0.759	-1.187
S3	M12	500	0.351	0.128	0.125	0.146	-0.563	-0.979	-2.579	0.315	-0.732
S3	M12	1000	0.379	0.135	0.221	-0.271	-0.104	-0.250	-1.241	-1.276	-1.260
S3	M12	2000	0.386	0.075	0.176	0.083	1.000	0.104	-2.103	-0.590	-1.305
S3	M12	4000	0.239	0.106	0.113	0.083	0.688	-0.063	-2.019	-0.521	-1.343
S3	M19	125	0.849	0.932	0.911	0.083	0.000	0.021	-2.214	-0.572	-0.920
S3	M19	250	0.797	0.650	0.691	-0.083	0.000	-0.042	-0.745	-0.966	-0.903
S3	M19	500	0.397	0.089	0.161	1.021	0.604	0.229	-0.484	-0.263	-0.346
S3	M19	1000	0.345	0.113	0.150	-0.188	0.563	-0.188	-2.287	-1.760	-1.990
S3	M19	2000	0.259	0.078	0.100	0.146	0.458	0.125	-0.938	-1.381	-1.166
S3	M19	4000	0.109	0.065	0.063	-0.854	-0.792	-0.875	-1.131	-0.574	-0.900
S4	D12	125	0.953	0.893	0.897	0.375	-0.021	0.083	-1.826	-0.982	-1.246
S4	D12	250	0.895	0.734	0.770	0.500	0.042	0.333	-1.027	-1.007	-1.017
S4	D12	500	0.678	0.110	0.396	0.542	-0.354	0.521	-3.291	-0.983	-2.303
S4	D12	1000	0.425	0.097	0.227	0.375	0.750	0.396	-3.716	-1.021	-2.579
S4	D12	2000	0.408	0.039	0.282	0.313	0.438	0.313	-4.446	-0.894	-3.369
S4	D12	4000	0.494	0.111	0.394	0.292	0.938	0.292	-5.385	-0.266	-4.428
S4	D19	125	0.874	0.924	0.905	0.104	0.063	0.104	-1.670	-0.871	-1.184
S4	D19	250	0.686	0.736	0.687	0.458	0.063	0.188	-1.403	0.018	-0.460
S4	D19	500	0.480	0.098	0.288	0.729	0.583	0.708	-1.865	-1.251	-1.568
S4	D19	1000	0.305	0.076	0.194	0.688	0.833	0.708	-2.301	-1.757	-2.064
S4	D19	2000	0.194	0.069	0.120	-0.354	0.292	-0.333	-0.903	-1.884	-1.366

S4	D19	4000	0.144	0.059	0.082	0.813	-0.583	0.938	-1.436	-1.227	-1.353
S4	I12	125	0.888	0.912	0.903	0.188	0.104	0.125	-0.859	-0.479	-0.601
S4	I12	250	0.851	0.721	0.746	0.271	-0.021	0.104	-2.290	-0.326	-1.047
S4	I12	500	0.593	0.162	0.279	0.313	0.667	0.438	-1.279	-0.913	-1.050
S4	I12	1000	0.560	0.127	0.306	0.167	0.750	-0.250	-2.756	-1.046	-1.975
S4	I12	2000	0.400	0.098	0.204	0.146	-0.792	0.146	-2.281	-0.878	-1.612
S4	I12	4000	0.448	0.084	0.280	0.146	0.083	0.125	-3.255	-1.367	-2.500
S4	I19	125	0.900	0.920	0.905	-0.167	0.125	0.021	-0.598	-1.183	-0.953
S4	I19	250	0.689	0.661	0.668	0.063	0.063	0.063	0.222	-1.430	-0.863
S4	I19	500	0.451	0.115	0.261	0.521	-0.979	0.500	-1.080	-1.177	-1.132
S4	I19	1000	0.231	0.113	0.111	0.354	0.771	-0.729	-2.817	-1.777	-2.211
S4	I19	2000	0.242	0.068	0.118	0.646	-0.979	0.875	-2.545	-1.038	-1.734
S4	I19	4000	0.148	0.079	0.109	0.833	0.563	0.563	-1.631	-1.444	-1.545
S4	M12	125	0.829	0.862	0.839	0.417	0.083	0.229	-1.024	-0.725	-0.853
S4	M12	250	0.836	0.616	0.688	0.167	0.021	0.083	-0.767	0.312	-0.070
S4	M12	500	0.377	0.064	0.141	0.458	-0.979	0.479	-0.995	-0.491	-0.646
S4	M12	1000	0.409	0.092	0.112	0.146	0.125	0.146	-3.445	-0.940	-1.964
S4	M12	2000	0.354	0.061	0.153	0.146	-0.625	0.146	-3.198	-1.008	-1.967
S4	M12	4000	0.220	0.045	0.110	0.125	-0.958	0.125	-3.486	-0.718	-2.148
S4	M19	125	0.900	0.906	0.900	0.083	-0.021	0.000	-1.934	-0.314	-0.813
S4	M19	250	0.728	0.654	0.672	0.063	0.042	0.042	-1.317	0.367	-0.112
S4	M19	500	0.383	0.110	0.138	0.521	-0.500	0.542	-0.362	-0.577	-0.497
S4	M19	1000	0.182	0.041	0.075	0.375	-0.771	-0.813	-1.896	-1.377	-1.568
S4	M19	2000	0.250	0.054	0.108	0.292	0.208	0.292	-3.406	-1.279	-2.317
S4	M19	4000	0.169	0.058	0.089	0.167	-0.313	0.167	-4.435	-1.085	-2.909
S5	D12	125	0.997	0.988	0.990	0.021	0.042	0.042	-0.529	-0.981	-0.859
S5	D12	250	0.981	0.893	0.940	0.042	0.000	0.021	-0.707	-0.963	-0.824
S5	D12	500	0.844	0.429	0.643	0.000	0.021	0.021	-1.198	-1.759	-1.469
S5	D12	1000	0.856	0.169	0.583	0.021	0.021	0.021	-2.108	-1.104	-1.710
S5	D12	2000	0.376	0.078	0.234	0.000	0.021	0.000	-1.628	-0.981	-1.321
S5	D12	4000	0.455	0.084	0.311	0.000	0.021	0.000	-1.682	-0.584	-1.259
S5	D19	125	0.811	0.910	0.881	0.313	0.063	0.125	-0.609	-0.874	-0.805
S5	D19	250	0.588	0.795	0.702	0.375	0.000	0.104	-1.376	-0.584	-0.838
S5	D19	500	0.373	0.170	0.258	0.583	0.396	0.521	-2.287	-1.255	-1.753
S5	D19	1000	0.343	0.169	0.166	-0.125	0.750	-0.146	-1.921	-0.727	-1.331
S5	D19	2000	0.366	0.081	0.214	0.354	0.771	0.354	-4.851	-1.516	-3.408
S5	D19	4000	0.361	0.052	0.232	0.333	-0.063	0.333	-4.803	-0.929	-3.404
S5	I12	125	0.999	0.984	0.988	0.021	0.042	0.042	-0.536	-0.635	-0.611
S5	I12	250	0.975	0.915	0.934	-0.021	0.021	0.000	-0.165	-1.022	-0.729
S5	I12	500	0.659	0.437	0.523	-0.042	-0.083	-0.063	0.979	-1.262	-0.339
S5	I12	1000	0.534	0.068	0.312	0.021	-0.021	0.021	-1.495	-0.519	-1.035
S5	I12	2000	0.485	0.076	0.239	-0.021	0.417	-0.021	-0.925	-0.715	-0.823
S5	I12	4000	0.517	0.090	0.331	-0.021	-0.354	-0.021	-0.472	-1.056	-0.681
S5	I19	125	0.823	0.889	0.863	0.042	0.000	0.021	-2.418	-0.520	-1.138
S5	I19	250	0.484	0.724	0.670	-0.083	0.000	-0.021	-0.022	-0.543	-0.427
S5	I19	500	0.578	0.233	0.352	0.271	0.250	0.250	-2.009	-1.385	-1.603
S5	I19	1000	0.155	0.124	0.089	0.292	-0.771	-0.271	-1.449	-1.463	-1.456
S5	I19	2000	0.150	0.042	0.067	0.375	0.833	0.167	-0.496	-1.106	-0.779
S5	I19	4000	0.340	0.067	0.201	0.167	-0.458	0.167	-1.406	-0.724	-1.153
S5	M12	125	0.998	0.986	0.991	0.042	0.042	0.042	-0.764	-0.625	-0.685
S5	M12	250	0.972	0.884	0.916	0.000	0.021	0.021	-1.049	-0.262	-0.557
S5	M12	500	0.722	0.315	0.442	0.104	0.042	0.083	-0.336	-1.052	-0.821
S5	M12	1000	0.488	0.154	0.279	0.042	-0.438	0.021	-1.342	-1.202	-1.263
S5	M12	2000	0.443	0.065	0.226	0.042	-0.104	0.021	-1.574	-0.935	-1.251

S5	M12	4000	0.370	0.086	0.197	0.021	-0.938	0.021	-0.730	-0.830	-0.774
S5	M19	125	0.919	0.879	0.893	0.229	0.000	0.104	-1.033	-0.679	-0.845
S5	M19	250	0.628	0.654	0.647	-0.063	0.000	-0.021	-1.356	-1.479	-1.449
S5	M19	500	0.371	0.090	0.148	-0.063	0.542	-0.063	-1.257	-0.659	-0.861
S5	M19	1000	0.112	0.089	0.058	-0.104	0.271	-0.833	-0.409	-0.970	-0.752
S5	M19	2000	0.277	0.086	0.137	0.167	-0.854	0.167	-1.915	-1.789	-1.852
S5	M19	4000	0.346	0.047	0.223	0.167	-0.729	0.167	-1.382	-1.228	-1.326

Appendix C HRTF decoding methods testing

In order to get the best play back results of the sound in auditorium using headphones, real-time HRTF decoding is needed with head-tracking information from the VR headset. Two methods of real-time HRTF decoding was found suitable for this research: 1) Facebook 360 Spatial Workstation Plugin for Reaper, and 2) SPAT~ Plugin for Max/MSP/Jitter. The two methods were analyzed and tested separately, and SPAT~ Plugin for Max/MSP/Jitter was chosen for the experiment.

C.1 Decoding procedure

C.1.1 Facebook 360 Spatial Workstation Plugin for Reaper

The workflow of the decoding procedure of Facebook 360 Spatial Workstation plugin for Reaper is demonstrated in Figure C-1.

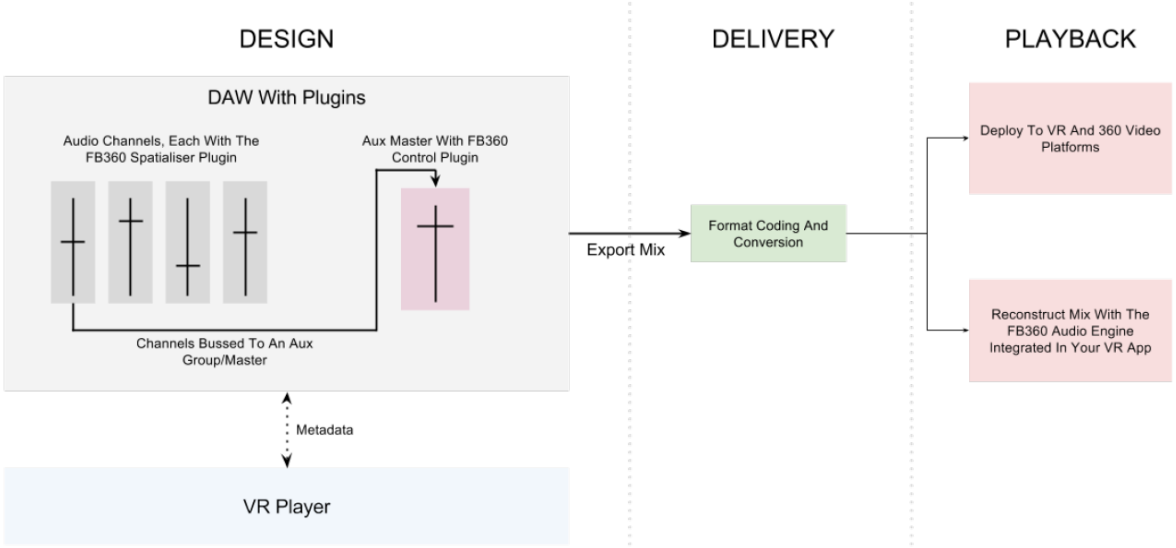

Figure C-1 Facebook 360 Spatial Workstation Plugin Workflow ("Facebook 360 Spatial Workstation User Guide," 2018)

The Facebook 360 Spatial Workstation Plugin for Reaper include several separate plugins with different functions. The input audio signals are imported in Reaper and encoded using “FB360 Spatialiser” plugin. If the input signals are B-format or higher order ambisonic files, they can be aligned to proper 3D orientation; if the input signals are single track audio files, they can be defined in a 3D location with distance and 3D angle (Euler angle). All the tracks are then routed to a master control track with “FB360 Control” plugin, then exported through the “Render” command into a multitrack WAV file. Then the WAV file is encoded in “FB Encoder”, a standalone encoder app, into a TBE file. In Unity, the “Audio 360 SDK” plugin can decode and playback the TBE file into headphones in real time, automatically using the headtracking data acquired by VR headset.

C.1.2 SPAT~ Plugin for Max/MSP/Jitter

The workflow of the decoding procedure of SPAT~ plugin for Max/MSP/Jitter is demonstrated in Figure C-2.

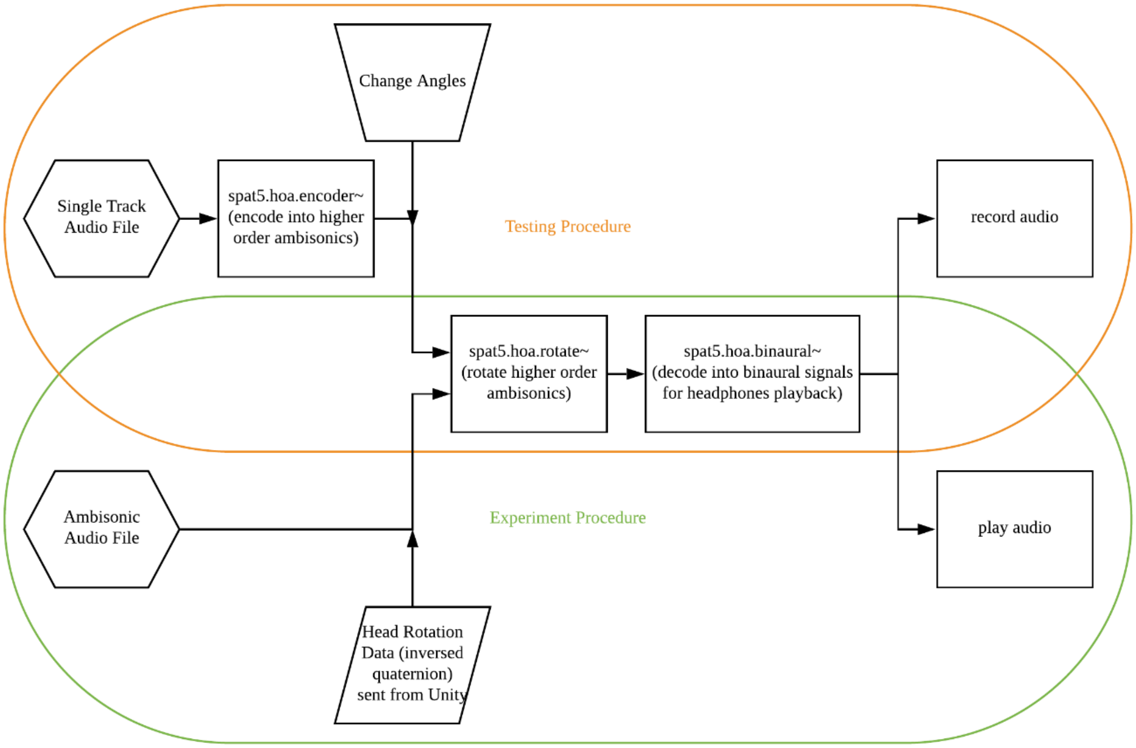

Figure C-2 Workflow of the testing procedure and experiment procedure for Ambisonic decoding

The input audio signals are opened in Max. If the input signals are single track audio files, they can be encoded into multitrack ambisonic signals using “SPAT higher order ambisonics encoder” object with a defined distance and 3D angle. The encoded or imported higher order ambisonic files (determined by the imported signal characteristics) can be rotated using “SPAT higher order ambisonics rotate” object. The rotation can either be manually input, or automatically programmed in Max, or imported real-time from Unity. The rotated ambisonic signals are then decoded by “SPAT higher order ambisonics binaural” object into headphones.

C.2 Eligibility Test

Due to the commercial nature of Facebook360 Spatial Workstation Plugin, the HRTF it used is not published or available at any resources. The HRTF used in SPAT for Max/MSP/Jitter can be changed or uploaded by the user, with a default setting of using Kemar HRTF.

To test and compare the eligibility of the two methods, a testing procedure was conducted.

C.2.1 Test signal

A 0.5 seconds linear sweep signal from 20 Hz to 20 kHz was generated using MATLAB and saved into a WAV file.

C.2.2 Test setup

C.2.2.1 Facebook 360 Spatial Workstation Plugin for Reaper

The test signal was imported into Reaper and encoded with “FB360 Spatialiser” plugin. The location of the sound source was set to be 1 meter away from the centre receiver with different 3D angles (yaw and pitch). Then it was decoded into binaural signals using the built-in decoder in “FB360 Control” plugin. For each angle, the decoded two-channel outputs were recorded within Reaper and rendered into a WAV file. 8 locations were tested, the Euler angle of which are given in the table below:

Table C-1 Angles used for HRTF testing

No.	Yaw	Pitch	Roll
1	0	0	0
2	45	0	0
3	90	0	0
4	135	0	0
5	180	0	0
6	0	45	0
7	0	90	0
8	0	135	0

Only yaw and pitch are changed with a step of 45 degrees, because when the point sound source is located at 0 degree in the front, changes in roll don’t affect the binaural signals. The angle of 180 degrees pitch is not tested because it’s theoretically the same as 180 degrees yaw, in which the sound source is located at 0 degree in the back.

C.2.2.2 SPAT~ Plugin for Max/MSP/Jitter

The test signal was opened in Max/MSP/Jitter and encoded with “SPAT higher order ambisonics encoder” object. The location of the sound source was set to be 1 meter away from the centre receiver. Different 3D angles (yaw and pitch) were set through “SPAT higher order ambisonics rotate” object. Then it was decoded into binaural signals using “SPAT higher order ambisonics binaural” object. For each angle, the decoded two-channel outputs were recorded within Max/MSP/Jitter and saved into a WAV file. Due to the better programming environment in Max/MSP/Jitter, more angles could be tested using an automated system. For each single angle of a Euler angle (yaw, pitch and roll), the tested angles were all the angles from 0 to 180 degrees with a step of 10 degrees.

C.2.3 Result analysis

The recorded two-channel WAV files were imported into AARAE for MATLAB. Cross-correlation was calculated between the test recordings and the test signal to generate the impulse responses. Figures of sound pressure level (dB) as a function of frequency (Hz) and sound pressure level (dB) as a function of time (ms) were plotted.

C.2.3.1 Facebook 360 Spatial Workstation Plugin for Reaper

Frequency response:

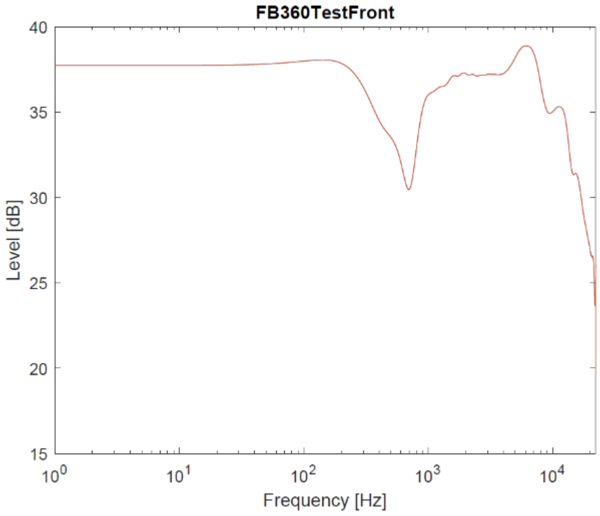

Figure C-3 Frequency response (sound pressure level vs frequency) at the angle of 0 degree in the front using Facebook 360 Spatial Workstation Plugin for Reaper

From Figure C-3 it can be seen that there is an obvious dip in the curve around 700 Hz. The reason for this is unclear but it may be related to the diffraction around the head. The frequency response in higher frequencies (above 1 kHz) is simplified compared to commonly used HRTFs.

Time response:

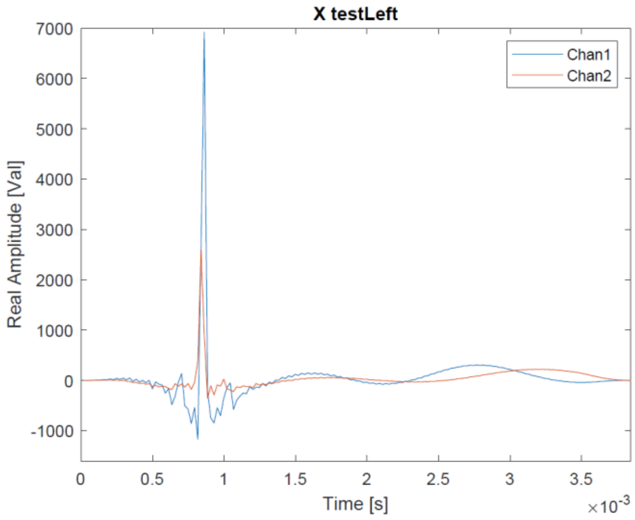

Figure C-4 Cross-correlation result at yaw = -90 degrees (left) using Facebook 360 Spatial Workstation Plugin for Reaper

The interaural time difference is given in the Table C-2.

Table C-2 Interaural time difference at yaw = -90 degrees (left) for each octave band using Facebook 360 Spatial Workstation Plugin for Reaper

Frequency (Hz)	125	250	500	1000	2000
ITD (ms)	-0.49887	-0.40816	-0.34014	0.43084	0.045351

The ITD below 500 Hz is around 0.4 ms, and at the 1000 Hz octave band, the ITD is reversed. No ITD was observed for 2000 Hz octave band.

Location response:

The sound pressure level (dB) - frequency (Hz) curve is exactly the same for different angles on the plane of symmetry of the head, i.e. when the sound source is at the front, top, back or bottom of the head.

Conclusion:

The HRTF used in Facebook 360 Spatial Workstation plugin for Reaper is overly simplified and thus considered not suitable for use in scientific research.

C.2.3.2 SPAT~ Plugin for Max/MSP/Jitter

Frequency response:

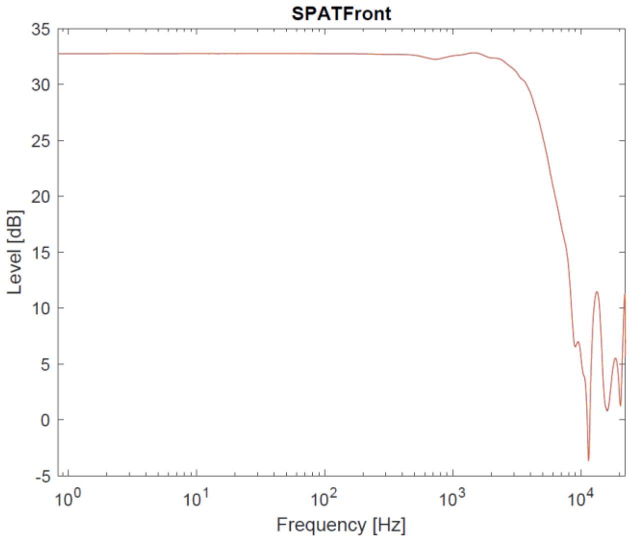

Figure C-5 Frequency response (sound pressure level vs frequency) at the angle of 0 degree in the front using SPAT~ Plugin for Max/MSP/Jitter

The curve is relatively flat below 1 kHz, and has several peaks (13 kHz, 18 kHz) and notches (11 kHz, 16 kHz). The form of the curve looks pretty normal compared to commonly used HRTFs.

Time response:

Table C-3 Interaural time difference at yaw = 90 degrees (right) for each octave band using SPAT~ Plugin for Max/MSP/Jitter

Frequency (Hz)	125	250	500	1000	2000
ITD (ms)	-0.43084	-0.43084	-0.40816	-0.38549	-0.06803

Table C-3 shows tha the ITD below 1000 Hz is around 0.4 ms, but no ITD is observed for 2000 Hz frequency band.

Figure C-6 Frequency response (sound pressure level vs frequency) at various yaw angles using SPAT~ Plugin for Max/MSP/Jitter

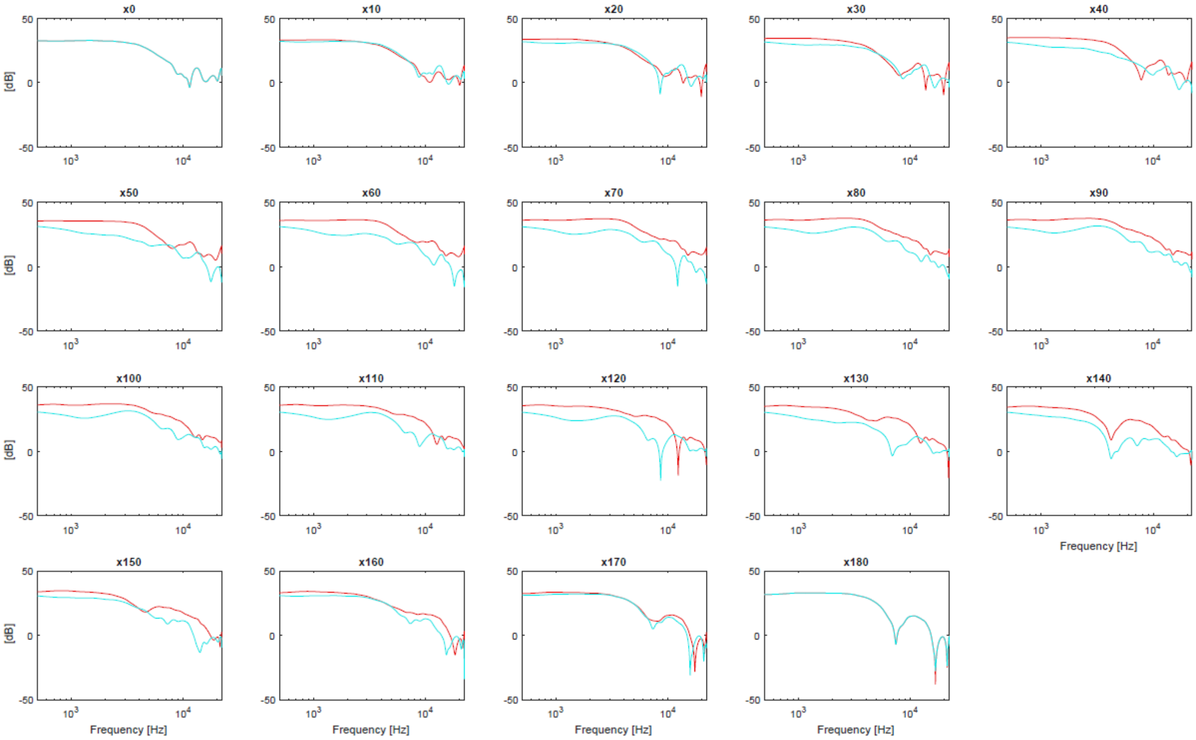

Figure C-7 Frequency response (sound pressure level vs frequency) at various roll angles using SPAT~ Plugin for Max/MSP/Jitter

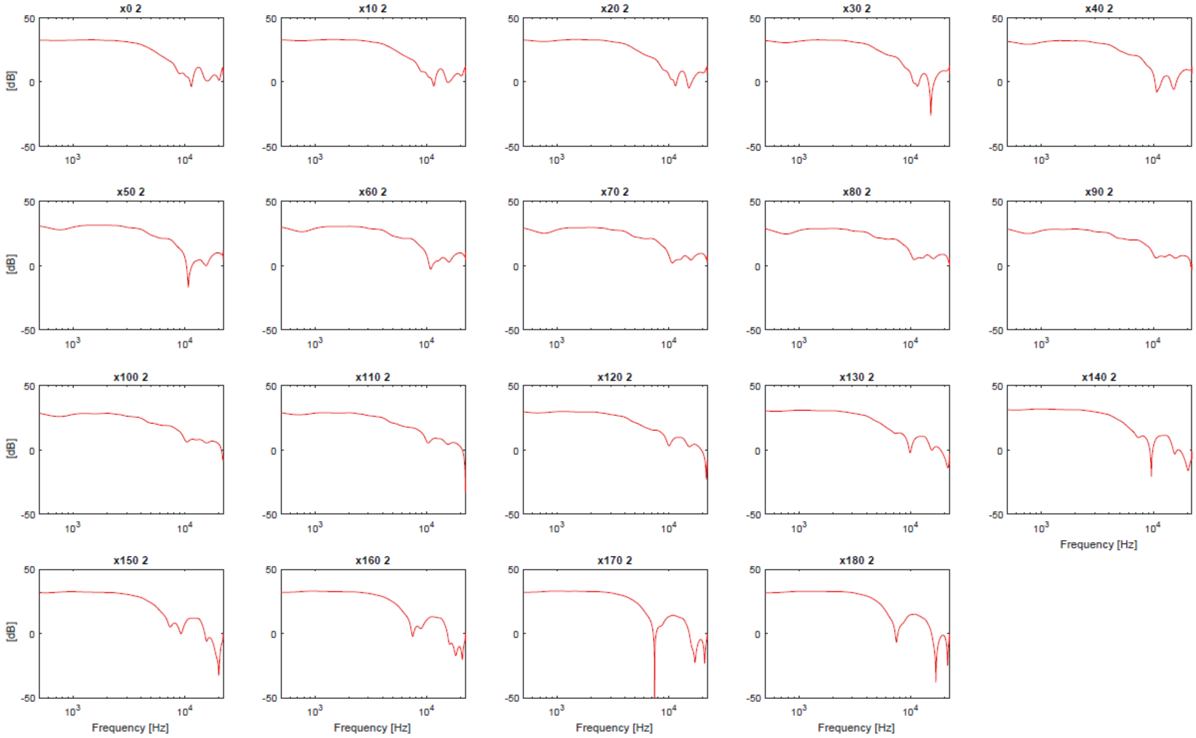

Figure C-6 and Figure C-7 shows that the sound pressure level (dB) - frequency (Hz) curve has reasonable changes when the yaw and roll is changed. No difference is observed between different pitches.

Conclusion:

The HRTF used in SPAT~ Plugin for Max/MSP/Jitter is reasonably credible and thus considered suitable for this research. Two things that need consideration: 1) the definitions of roll and pitch are exchanged; 2) no ITD is used in higher frequencies, in which sound localization mainly depends on interaural level difference.

Appendix D Hall names and image sources for Figure 3-13

Hall names and image sources of all 100 sub-images in Figure 3-13 are listed in Appendix D, along with the referral number in the figure.

1. Amsterdam, Concertgebouw: u/spiffyjj. (2011). Concertgebouw (Dutch for "Concert Building"), Adolf Leonard van Gendt, Amsterdam, Netherlands [Online Image]. Reddit. https://www.reddit.com/r/ArchitecturePorn/comments/pj248/concertgebouw_dutch_for_concert_building_adolf/

2. Aspen, Colorado, Benedict Music Tent: Benedict Music Tent (Aspen) [Online Image]. Commercial Specialists, Inc.. https://cswcfire.com/hospital.html

3. Athens, Megaron, Concert Hall: Lefteriotisf, Marios. (2017). The Athens Concert Hall [Online Image]. Google Maps. https://www.google.com/maps/uv?hl=en&pb=!1s0x14a1bd5100ae96b3%3A0x2efa440dcf5a2ce7!3m1!7e115!4shttps%3A%2F%2Flh5.googleusercontent.com%2Fp%2FAF1QipNOi6Q_AN308g4_wJqUUA5-_5ED2x9SEJrg48Sd%3Dw235-h160-k-no!5sMegaron%2C%20Concert%20Hall%20-%20Google%20Search!15sCgIgARICCAI&imagekey=!1e10!2sAF1QipOZ_Q8CmoKTy5CM8ans5KR1EsrQ7vL7cVOScAdJ&sa=X&ved=2ahUKEwjix77D1-TpAhUJQH0KHa_kAMkQoiowE3oECBcQBg

4. Baden-Baden Festspielhaus: Festspielhaus, Baden Baden, Germany [Online Image]. (2013). Audio Ease. https://www.audioease.com/IR/VenuePages/festspielhaus-badenbaden.html

5. Baltimore, Joseph Meyerhoff Symphony Hall: Arifin-Fazio, Ira. Joseph Meyerhoff symphony hall. Baltimore, Maryland [Online Image]. Pinterest. https://www.pinterest.com/pin/405253666442090164/

6. Basel, Stadt-Casino: Zwei Welten verschmelzen Stadtcasino Basel [Online Image]. Reflexion. http://reflexion.ch/werkschau/kultur/stadtcasino-basel

7. Bayreuth, Festspielhaus: The Bayreuth Festspielhaus auditorium [Online Image]. The Opera 101. https://www.theopera101.com/operahouses/bayreuth/

8. Belfast, Waterfront Hall: waterfront-025 [Online Image]. Gilbert-Ash. https://gilbert-ash.com/projects/arts-culture

9. Berlin, Kammermusiksaal der Philharmonie: Hotta, Masanori. Berliner Philharmoniker [Online Image]. Berliner Philharmoniker. https://www.berliner-philharmoniker.de/en/concerts/calendar/details/52635/

10. Berlin, Konzerthaus (Schauspielhaus): Schauspielhaus Berlin [Online Image]. Pinterest. https://www.pinterest.com/pin/52213676912672768/

11. Berlin, Philharmonie: Philharmonie Berlin [Online Image]. Blink. https://www.blinktravel.guide/berlin/philharmonie-berlin-auditorium

12. Birmingham, Symphony Hall: Birmingham International Convention Centre and Symphony Hall [Online Image].

Institution of Civil Engineers. https://www.ice.org.uk/what-is-civil-engineering/what-do-civil-engineers-do/birmingham-international-convention-centre"

13. Bonn, Beethovenhalle: Roland, Rossner. Beethovenhalle [Online Image]. Deutsche Stiftung Denkmalschutz. https://www.denkmalschutz.de/denkmal/beethovenhalle-bonn.html

14. Boston, Symphony Hall: BSO-Final-2 [Online Image]. WSDG. https://wsdg.com/boston-symphony-orchestra-unveils-wsdg-redesigned-control-room/

15. Brussels, Palais des Beaux-Arts: BOZAR_Salle-Henry-Le-Boeuf-05Michael-Falke-copie [Online Image]. Brussels Museums. https://www.brusselsmuseums.be/en/museums/bozar-centre-for-fine-arts

16. Budapest, Magyar Allami Operahaz: Casas, Jose Manuel. Hungarian State Opera House [Online Image]. Minube. https://www.minube.net/place/opera-house-budapest--a80496

17. Budapest, Patria Hall: Pàtria Budapest Hotel [Online Image]. Budapest Congress Center. https://www.bcc.hu/meeting_room/patria/

18. Buenos Aires, Teatro Colón: Teatro Colón [Online Image]. Must See Places. https://mustseeplaces.eu/wp-content/uploads/2016/03/teatro-colon.jpg

19. Buffalo, Kleinhans Music Hall: Phu, Chuong. (2019). Kleinhans Music Hall [Online Image]. Google Maps. https://www.google.com/maps/uv?hl=en&pb=!1s0x89d312556ad4ef4d%3A0x80371f56c4411107!3m1!7e115!4shttps%3A%2F%2Flh5.googleusercontent.com%2Fp%2FAF1QipPHjIbLwTyTqVtUkBQ04VDvz_b0EUl5SGtJCaNj%3Dw409-h160-k-no!5sBuffalo%2C%20Kleinhans%20Music%20Hall%20-%20Google%20Search!15sCgIgARICCAI&imagekey=!1e10!2sAF1QipNxaE6MZ304BefVbvZTuBQYrzZrDBYujRsfQAAm&sa=X&ved=2ahUKEwiM3-v91-TpAhVHb30KHfuHBF0QoiowC3oECBUQBg

20. Caracas, Aula Magna: Aula Magna [Online Image]. Pinterest. https://www.pinterest.com/pin/544161567445437987/

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Appendix E View quality calculation Python script for Rhinoceros 3D

The following Python script was used in Chapter 8 for view quality prediction of an auditorium model.

Usage

`CalculateSeatPreference(BasePoint, Direction, AudienceAreas, Bake =` True, Resolution = 0.9, Limit = 50)

Arguments

`BasePoint`

    A point at the conductor location at stage level

`Direction`

    A horizontal line starting at BasePoint, pointing towards the audience along the main axis of the auditorium

`AudienceAreas`

    Surfaces for audience areas at floor level

`Bake` (default is True)

    A boolean value indicating whether the resulting colour map and curves will be baked as Rhino geometries

`Resolution` (default is 0.9)

    A number for the standard unit size (in m) for the division of audience surfaces

`Limit` (default is 50)

    A number for the score limit above which is considered “good” areas

Return Values

`coloredMesh`

    A gradient mesh of the audience areas coloured by calculated view scores. Red for 0 or below, yellow for 50, green for 100 or above

`bestSeatBorders`

    Curves on the audience areas that encircles areas with scores higher than the set Limit

`stats`

    A list consists of `[totalArea, goodArea, goodRatio, mean, stdDev, median]`

    `totalArea`

        The total area of the input audience areas in m^2

    `goodArea`

        The area in m^2 of the audience areas with scores higher than the set Limit

    `good`Ratio

        The result of goodArea divided by totalArea

    `mean`

        The mean score of all calculated points

    `stdDev`

        The standard deviation of scores of all calculated points

    `median`

        The median of scores of all calculated points

Full script

```
import rhinoscriptsyntax as rs
import math
from Rhino.Geometry import *
from Rhino.Input import RhinoGet
from Rhino.DocObjects import ObjectType
from scriptcontext import doc, escape_test
import random
from ghpythonlib import parallel
import statistics

def Breps2Meshs(breps, res):
    """Converts input breps to one mesh and vertices"""
    print "Dividing audience area..."
    oMesh = Mesh()
    MeshParam = MeshingParameters.Default
    MeshParam.MaximumEdgeLength = res
    pts = []
    for i in range(len(breps)):
        brep = breps[i]
        meshes = Mesh.CreateFromBrep(brep, MeshParam)
        for mesh in meshes:
            oMesh.Append(mesh)
            pts = pts + list(mesh.Vertices)
    return oMesh, pts

def LocationInfo(bPt, dir, Pts):
    """Calculates the distance, lateral angle, and vertical angle
of points"""
    print "Calculating location information..."
    Distance = []
    Lateral = []
    Vertical = []
    for point in Pts:
        escape_test()
        d = rs.Distance(bPt, point)
        Distance.append(d)
        projectPoint = [point.X, point.Y, bPt.Z]
        l,_ = rs.Angle2(dir,(bPt, projectPoint))
        Lateral.append(l)
        v,_ = rs.Angle2((bPt, projectPoint),(bPt, point))
        if point.Z < bPt.Z:
            v = -v
        Vertical.append(v)
    return Distance, Lateral, Vertical

def StagePointsGen(bPt, dir, res, depth = 7.5, width = 12, height
= 1.8):
    """Generates point cloud on stage as target points"""
    print "Generating stage points..."
    xDiv = int(math.ceil(depth/res))
```

```
    yDiv = int(math.ceil(width/res))
    zDiv = int(math.ceil(height/res))
    PtCl = PointCloud()
    for x in range(xDiv+1):
        for y in range(yDiv+1):
            for z in range(zDiv+1):
                pt = Point3d(x*depth/xDiv, y*width/yDiv,
z*height/zDiv)
                PtCl.Add(pt)
    PtCl.Translate(Vector3d(1-depth, -width/2, -1.2))
    PtCl.Rotate(Vector3d.VectorAngle(Vector3d.XAxis,
Vector3d(dir[1]-dir[0]), Plane.WorldXY),Vector3d.ZAxis,
Point3d.Origin)
    PtCl.Translate(Vector3d(bPt))
    Points = list(PointCloud.GetPoints(PtCl))
    return Points

def MeshRayIntersect(target):
    """Intersects mesh and rays - for parallel computing"""
    ray = Ray3d(GlobalPoint, Vector3d(target - GlobalPoint))
    par = Intersect.Intersection.MeshRay(GlobalMesh, ray)
    if (par > 0) & (par < 1):
        pt = Ray3d.PointAt(ray, par)
        return pt

def MeshRayIntersect2(target):
    """Intersects mesh and rays - for parallel computing"""
    virtualView = GlobalPoint + 0.9 * (target - GlobalPoint) /
rs.Distance(target, GlobalPoint)
    ray = Ray3d(GlobalPoint, Vector3d(target - GlobalPoint))
    par = Intersect.Intersection.MeshRay(GlobalMesh, ray)
    if (par > 0) & (par < 1):
        pt = Ray3d.PointAt(ray, par)
        return pt

def ObstructionCalc(viewPts, targetPts, obsMesh):
    """Estimates view obstruction - using parallel computing"""
    print "Calculating view obstructions..."
    Obstruction = []
    global GlobalMesh
    GlobalMesh = Mesh()
    GlobalMesh.CopyFrom(obsMesh)
    GlobalMesh.Translate(Vector3d(0, 0, 0.12))
    meshEdges = GlobalMesh.GetNakedEdges()
    for edge in meshEdges:
        extrusion = Surface.CreateExtrusion(PolylineCurve(edge),
Vector3d(0,0,-2))
        mesh = Mesh.CreateFromSurface(extrusion)
        GlobalMesh.Append(mesh)
    BottomMesh = Mesh()
    BottomMesh.CopyFrom(GlobalMesh)
```

```
    BottomMesh.Translate(Vector3d(0,0,-2))
    GlobalMesh.Append(BottomMesh)
    for viewPt in viewPts:
        escape_test()
        global GlobalPoint
        GlobalPoint = Point3d(viewPt.X, viewPt.Y, viewPt.Z)
        Intersections = parallel.run(MeshRayIntersect2,
targetPts, False)
        IntersectionsClean = [i for i in Intersections if i]
        obs = len(IntersectionsClean)/len(targetPts) * 0.2
        Obstruction.append(obs)
    return Obstruction

def PreferencePredict(D, L, V, O):
    """Calculates predicted preference using the model"""
    print "Calculating preference scores..."
    score = []
    score1 = []
    score100 = []
    for d, l, v, o in zip(D, L, V, O):
        s = -0.0952*d - 0.0127*l + 0.0613*v - 0.0017*(v**2) -
1.92*o
        score.append(s)
        score1.append((s + 4)/3)
        score100.append(100*((s + 4)/3))
    return score, score1, score100

def MeshColoring(mesh, scores):
    """Colors audience area based on preference prediction"""
    print "Coloring the audience area..."
    colors = mesh.VertexColors
    for i in range(len(scores)):
        score = scores[i]
        if score > 1: score = 1
        elif score < 0: score = 0
        if score < 0.5:
            colorR = 255
            colorG = 255 * score/0.5
        else:
            colorR = 255 * (1-score)/0.5
            colorG = 255 * ((1-score)+0.5)
        colorB = 0
        colors.SetColor(i,colorR, colorG, colorB)
    return mesh

def CirclingBest(pts, score100, limit, mesh):
    """Outlines the seats with preference scores over the
limit"""
    print "Finding the best seats..."
    escape_test()
    bestSeatBorders = []
```

```
    # Select points with scores above the limit
    selPts = []
    selInds = []
    for pt, score in zip(pts,  score100):
        if score >= limit:
            selPts.append(pt)
    # Select mesh faces with all vertices above the limit
    selMesh = Mesh()
    mesh.Unweld(0,True)
    submeshes = mesh.ExplodeAtUnweldedEdges()
    for submesh in submeshes:
        escape_test()
        submeshVertices = submesh.Vertices
        select = True
        for vert in submeshVertices:
            if vert not in selPts:
                select = False
        if select == True:
            selMesh.Append(submesh)
    # Draw borders around the selected mesh
    bestSeatBorders = selMesh.GetNakedEdges()
    return bestSeatBorders, selMesh

def PreferenceStats(meshTotal, meshSel, scores):
    print "Calculating descriptive stats..."
    """Calculates descriptive stats for the scores"""
    totalArea = AreaMassProperties.Compute(meshTotal).Area
    goodArea = AreaMassProperties.Compute(meshSel).Area
    goodRatio = goodArea/totalArea
    mean = statistics.mean(scores)
    stdDev = statistics.stdev(scores)
    median = statistics.median(scores)
    return totalArea, goodArea, goodRatio, mean, stdDev, median

# Main function
def CalculateSeatPreference(BasePoint = None, Direction = None, 
AudienceAreas = None, Bake = True, Resolution = 0.9, Limit = 50):
    # Check for input data, prompt to select if empty
    if BasePoint is None:
        BasePoint = rs.GetPoint("Define base point on stage 
(conductor location, stage level)")
        if BasePoint == None:
            print "Calculation canceled"
            return
    if Direction is None:
        Direction = rs.GetLine(1,BasePoint, message3 = "Define 
direction of main axis (looking towards the audience)")
        if Direction == None:
            print "Calculation canceled"
            return
    Direction[1].Z = Direction[0].Z
    if AudienceAreas is None:
```

```
        rc, objRefs = RhinoGet.GetMultipleObjects("Select
surfaces for audience areas (floor level)", True,
ObjectType.Surface | ObjectType.PolysrfFilter)
        if objRefs == None or len(objRefs) == 0:
            print "Calculation canceled"
            return
        AudienceAreas = [objRef.Brep() for objRef in objRefs]

    # Convert breps to meshs and points
    audienceMesh, audiencePoints = Breps2Meshs(AudienceAreas,
Resolution)

    # Calculate distance and angles
    Distance, Lateral, Vertical = LocationInfo(BasePoint,
Direction, audiencePoints)

    # Calculate stage view obstruction
    stagePoints = StagePointsGen(BasePoint, Direction,
Resolution)
    Obstruction = ObstructionCalc(audiencePoints, stagePoints,
audienceMesh)

    # Calculate the preference scores of each point
    _, ScoreDisplay, Score100 = PreferencePredict(Distance,
Lateral, Vertical, Obstruction)

    # Color audience areas according to the scores
    coloredMesh = MeshColoring(audienceMesh, ScoreDisplay)

    # Draw convex hull of points above the limit on each surface
    bestSeatBorders, bestSeatMesh = CirclingBest(audiencePoints,
Score100, Limit, audienceMesh)

    # Calculate statistics
    stats = PreferenceStats(audienceMesh, bestSeatMesh, Score100)
    print "Average preference score: {:.0f}".format(stats[3])
    print "Percentage of seats above {:}: {:}%".format(Limit,
round(stats[2],2))

    if Bake == True:
        doc.ActiveDoc.Objects.AddMesh(coloredMesh)
        for border in bestSeatBorders:
            doc.ActiveDoc.Objects.AddPolyline(border)
            doc.ActiveDoc.Views.Redraw()

    return coloredMesh, bestSeatBorders, stats

if __name__ == '__main__':
    CalculateSeatPreference()
```