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Master's Thesis Proposal

The Just Noticeable Difference of the Stage Acoustical Parameters ST_{early} and ST_{late}

I: Stimulus Preparation

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Abstract

The following proposal will provide an overview of the pending master's thesis *The Just Noticeable Difference of the Stage Acoustical Parameters ST_{early} and ST_{late} - I: Stimulus Preparation*. Those Parameters have been introduced by A.C. Gade [1, 2] and added to the annex of the ISO 3382-1 [3] subsequently. The main goal of the thesis is to provide the basis necessary for a listening test to examine the just noticeable differences of support stage parameters. This is going to be achieved by digital stage modeling and derivation of binaural room impulse responses with dynamic synthesis. The aim is to construct realistic sounding but simplified concert venues in consideration of changes in ST_{early} and ST_{late}. After an introduction, recent work on related topics will be pointed out. Subsequently, to get an overview of the work's temporal structure, a time schedule will be contributed at the very end.

1 Introduction

The acoustics concerning a musician on stage are a crucial factor for rehearsal as well as for live performance and hence for the auditive experience of the audience [4]. Nevertheless stage acoustics is in contrary to concert hall acoustics still in its infancy. Plenty of established room acoustic parameters are regarding the sound experience for the audience while there are just few to focus on the perception on stage. The most common stage parameters are ST_{early} and ST_{late}, that were proposed by A.C. Gade in 1989 [1, 2]. The parameters ST_{early} and ST_{late} try to predict subjective ensemble conditions such as the audibility of musicians hearing others, self-audibility and provided reverberant feedback by the concert hall [3]. These conditions are obtained by physical sound propagation properties, such as the direct sound and early and late reflections, derived from room impulse responses measured on stage. These are therefore highly influenced by the stage environment as well as the architectural design of the audience area.

$$ST_{early} = \frac{\int_{20ms}^{100ms} p^2(t)dt}{\int_{0ms}^{10ms} p^2(t)dt} \tag{1}$$

is represented by the relation of energy of early reflections to the energy of the direct sound pressure level $p(t)$ measured in 1 m distance and

$$ST_{late} = \frac{\int_{100ms}^{1000ms} p^2(t)dt}{\int_{0ms}^{10ms} p^2(t)dt} \tag{2}$$

by the energy of the late reflections to the same reference, respectively. These parameters have been regarded more in depth various times [5, 6, 10] and added to the annex of the ISO 3382-1 standard in 1997 [3]. As these so-called stage support parameters are described pure physically but try to predict subjective impressions a determination of just noticeable differences is common to elaborate on their psychoacoustic nature.
The just noticeable difference (JND), concerning audio, describes just audible changes of a certain parameter. JNDs are usually acquired by different methods such as the forced-choice method or method of constant stimuli which are applied in a listening test. The threshold is determined as the value where at least 50 % of participants hear a difference in two varying stimuli. There is no study on the JNDs of the support parameters yet, merely an estimation that states a value of about 2 dB [6].
In respect of stage design, measurement and an advanced evaluation of orchestral and solo musicians' conditions, it is critical to identify the JNDs of stage support parameters. To be aware of which alterations of physical stage properties like adding reflectors have to be made to achieve audible changes in the listening experience, JNDs of ST_{early} and ST_{late} are crucial. This is also important for measuring stage support. E.g. ISO 3382-1 proposes to keep stands and chairs on stage while measuring support. When a measurement of both, with and without stands and chairs results in support parameters within a maximum deviation of the JNDs, the obstacles will not change audible stage support and could be neglected for measurement. Musicians' playing conditions also change for example due to size of orchestra and audience. How big this influence is concerning stage support will be verifiable objectively with the availability of just noticeable differences.
The justification for this thesis is based beyond design and measurement on generally occurring problems concerning objective parameters derived from subjective experience. The most common one, concerning those support parameters, is occasionally the gap between

subjective and objective measurement results. For instance, ISO 3382-1 connects the parameter ST_{early} with the subjective experience of *hearing others*. Hence, Lautenbach *et al.* stated differently. They conducted a study where they followed three orchestras on tour while providing questionnaires for each musician and each location. Additionally each stage was measured with ISO 3382-1 according setups. They showed that ST_{early} is rather correlated with *hearing oneself* than *hearing others* [7]. This means that there are still discrepancies occurring between support as a subjective impression and the parameters that are represented as concrete formulas. Thus this cleavage may lead to ambiguous and partially contradictory results of data gained by subjective research methods such as surveys and questionnaires and objective measurements. On account of this disagreement, the gap needs to be filled. This master's thesis shall face this matter by staging support parameter's JNDs and therefore may provide further insight to solve this problem.
Therefore an immersive environment for the listening test shall be provided. The main part of the thesis will be the generation of dynamic binaural room impulse responses (BRIRs) with the geometrical acoustic based program *RAVEN* [8]. *RAVEN* uses a hybrid method of ray-tracing and image-sourcing to calculate impulse responses of a modeled room. In this thesis's scope The BRIRs will be derived from realistic and pleasant sounding but simplified stages and audience areas modeled in *SketchUp*. The designed models will then be used in a virtual acoustic reality for a listening test to obtain the JNDs. Thus the aim is to construct simplified concert stages and audience areas in consideration of changes in ST_{early} and ST_{late} and if possible only slight changes in other known room and stage acoustic parameters to make sure to test the right parameters.
An elaborated literature research is essential for the outstanding thesis. Results from a first inquiry will show the state of the art concerning stage acoustics, support parameters, JND research of other room acoustical parameters, auralization and stage and concert hall investigations referring to influences of architectural design on acoustics.

2 State of the Art

The two stage parameters proposed by A.C. Gade [1, 2] ST_{early} and ST_{late}, have been a fundamental step for research concerning stage acoustics. Stage support parameters have subsequently been investigated many times in different aspects. For example the influence of, amongst others, support parameters for a musician on stage have been shown by Z. Schärer Kalkandjiev *et al.* [4, 9]. They predicted that ST_{late} is a strong, significant indicator for a bright and hard timbral rendition. An extension of the support parameters have been proposed by R.H.C. Wenmaekers *et al.* [10] that takes distance dependency into account and resolves some measurement restrictions introduced by A.C. Gade [5]. Additionally plenty of stage parameters like $ST2$ or ST_{total}, Clarity Stage (CS) and Early Ensemble Level (EEL) have been introduced by A.C. Gade [10]. Moreover, wide variations of the common ST_{early} and ST_{late} concerning their time intervals and their measurement methods on the reference level have been introduced. A short summary on these derived parameters is provided by C. Hak *et al.* [10]. Another extensive overview of the research on stage acoustics, especially on laboratory and field studies, their feasibility and their conclusion concerning stage design is provided once more by A.C. Gade [11]. Lautenbach *et al.* checked for stage parameters and their connection to subjective experiences in a field study [7]. A moderate correlation between stage support and sound strength and the subjective judgment on *hearing onesself*, *hearing others* and *playing in time* was concluded. They also stated contradictory results between subjective and objective measurements as described in the introductory section.

A.C. Gade dedicates an article to this equivocality by proposing a consistent set of objective and subjective measurement results and uniform questionnaires [12]. Besides research on support there also had been JND studies on acoustic parameters in the last decades.
Meanwhile JNDs of most common room acoustic parameters have been detected [13]. For example J.S. Bradley showed that JNDs of the speech clarity parameter C_{50} is about 1 dB [14]. The influence of experimental design and different listening test methods have been investigated by M.C. Vigeant *et al.* and indicated a great variance of JNDs of C_{80}, the clarity index for music [15]. The variation of JNDs in this study ranged for almost 4 dB for different test setups. This finding points out the importance of the test method and setup that will be chosen for the listening test.
Deriving BRIRs by digitally designed room models has been done before various times. E.g. by S. Pelzer *et al.* who presented their work on this topic in 2013 and provided a solid basis for interactive state of the art room modeling and its auralization [16]. Quality assessments of the room auralization software *RAVEN* was conducted by S. Pelzer *et al.* [17] to provide reliability on *RAVEN's* measurement results. In this article a modeled room was compared to a real-world test environment. The comparison showed similar results for the combination of two common auralization methods used in *RAVEN*. A suitable tool for a dynamic integration of *SketchUp* into *RAVEN* has been provided [18] which will make dynamic changes of the acoustic environment possible and therefore enables a feasible listening test setup for the master's thesis's purpose.
Concert hall and stage design criteria resulting from likes and dislikes of musicians as well as objective computer model based assessments have been investigated throughout the last decenniums. D.C. Bruck observed the musicians' preferences on different stage enclosure types [19]. The musicians were asked for subjective judgments on *ease of ensemble*, *ability to hear oneself* and *ability to hear other players* in varying environments. These attributes are closely related to the meaning of ST_{early} and ST_{late}. Among other things, the study showed clear stage type preferences concerning *ability to hear oneself*. A.H. Marshall *et al.* also tested proposals on *ease of ensemble* and soloist conditions in a controlled test environment [20]. The same literature also hinted at the perception of imbalances of reflections and and changes of reflection patterns with varying stage size. Acoustical design of stages with large plane surfaces in rectangular recital halls were observed in respect to stage parameters in a computer model [21]. Decisive factors for stage support in this paper were wall and ceiling inclination angles, the stage volume and attachment of reflectors. A clearly arranged overview of findings in stage acoustics applying to stage enclosure, reflectors/-canopies, floor/risers as well as preferred distribution of direct sound, early reflections and late reflections can be found in literature [22].
The insights of the articles and studies dealing with support parameters, room auralization and concert hall design presented above will be used to achieve the goal of the thesis in a convenient way. The methods used to conduct the thesis will be introduced subsequently.

3 Method

As described in the introduction section, this master's thesis will provide the preparatory work for a listening test conducted in the scope of the subsequent work. This section gives a short summary of the listening test's setup to understand what has to be done as preparatory work to conduct such, followed by a more in depth explanation of the modeling process and its guidelines and preparations.
In the actual listening test up to four performers will be placed in an anechoic room and

invited to play certain classical pieces of music. The players will wear acoustically almost completely transparent headphones and will be recorded with a microphone attached directly to the instrument. At the same time their head movements will be registered with a head tracking system. The recording will be used as input signal for simulation and will be convolved with BRIRs matching head positions of the performer and precalculated room models. The product of the convolution will then be played back through the participants' headphones without the direct sound. The underlying room models of the BRIRs will be altered to provide different stimuli.

The models will represent realistic sounding room acoustical environments with adequate variance in support parameters and only minimal variance in other room acoustical properties using the software *Sketchup* and *RAVEN*. Controlled changes of support parameters could be realized by different approaches like varying dimensions, volume and/or material properties of stage and audience area environment. The design and evaluation process will show which of these approaches are feasible. Furthermore stages with different dimensions and comparable support are of relevance for the following listening test. A better insight of subjects' judgment thus can be provided, as the sound of those models will differ with respect to constant support parameters. This can be seen as a kind of a test variable which could ensure that just the JNDs of ST_{early} and ST_{late} are evaluated and not the ones of other room acoustic parameters such as the reverberation time. The reliability of the test's results could thereby rise. Different stage and audience area types will be observed to provide a broad set of data for the listening test to find a convenient way to alter ST_{early} and ST_{late} values. The variation of both ST_{early} and ST_{late} should be accomplished with an equal step size of each parameter. As Gade's estimation for stage support parameters' JNDs is about 2 dB [6] a step width of 1 dB will be sufficiently accurate. A bunch of other known room acoustic parameters that are implemented in $RAVEN$ like reverberation time $T30$, early decay time EDT, sound strength G, clarity C_{50} and C_{80} and the lateral fraction LF should not exceed their JNDs while varying support parameters. Nevertheless, the early-to-direct energy ratio ($ED80$) that is for most measurement occasions highly correlated with ST_{early} shows that this is unlikely to be possible for all observed parameters.

Before starting with the design process, it is important to be aware that support parameters are not implemented in $RAVEN$. Therefore $RAVEN's\ Matlab$ interface will be enhanced with early and late support from the ISO 3382-1 [3] standard as well as Wenmaekers's distance dependent modification [10]. To investigate early support in a listening test which is according to ISO 3382-1 a measure for ensemble conditions, at least one secondary source has to be present on stage. Wenmaekers' extension on support parameters enable the possibility to measure support with different source to receiver distances which is useful for such occasion. Late support, which predicts hearing oneself and judges the reverberant feedback of the hall, does not depend on distance [10] and thus can be measured in 1 m distance suitable to ISO 3382-1.

To use the full capability of *RAVEN* and enhance the auditive realism of listening test experience, one might think stage modeling should include a certain amount of details such as risers, stands and chairs which have to be present during measurement [3]. In addition, when stage design is kept too simple, the reflection pattern might be dominated by strong singular reflections to achieve high ST_{early}. This could result in an unpleasant sound experience [20]. But as *RAVEN* is based on geometrical acoustics with ray-tracing and image sourcing a high level of details is likely to make results unpredictable. Objects should have a certain size to ensure that they get hit by a ray. If objects are too small and the amount of rays is not sufficient the object will appear acoustically invisible. Plus, smaller obstacles

have a higher probability of diffracting the sound wave but diffraction is at the moment not in a finished stadium in *RAVEN* and therefore should be avoided. A high level of details is not relevant regarding the audience area as those minutiae will be further away from the listener's on stage position. Moreover, late reflections are most likely to be diffuse and therefore do not provide critical clues on sound directivity. Nevertheless, some crucial design criteria have to be taken into account to prevent, for example, single strong reflections from the audience area. For instance a diffusive or tilted rear wall of the concert hall is therefore obligatory. Altogether stages and concert hall models should underlay different design criteria according to the findings on musicians preferences stated in e.g. the work of D.C. Bruck [19], M. Barron *et al.* [22] and A.H. Marshall *et al.*[20] to make them sound realistic and pleasant to listening test's subjects. Overhead reflectors' heights are preferred by musicians in 7–10 m and should consist of many small reflectors instead of one large [22], reflections between 0,5 kHz and 2 kHz seem to be decisive concerning ensemble playing, below 0,5 kHz they may be detrimental [20] and stage volume is preferably at least 1000 m^3 when a stage shell is considered [22] to name some of the guidelines.
With understanding the listening test's conditions that were explained briefly and a more profound comprehension of the modeling process, its guidelines and preparations, the main scope of this thesis should be clarified and ready to be executed.
To ensure that the work will be accomplished in time, a time table is proposed in the following and last section.

4 Time Schedule

Date	Task
03.10 - 04.10	Creating a Mindmap and begin writing a Proposal
07.10 - 11.10	Finishing the Proposal and starting Literature Research
14.10 - 08.11	Finalizing Literature Research
11.11 - 22.11	Adjusting to *SketchUp* and Creating first Models
25.11 - 29.11	Adjusting to RAVEN
02.12 - 20.12	Creating first BRIRs
23.12 - 03.01	Creating final Stage Models
06.01 - 20.01	Creating final BRIRs
04.02 - 11.02	Checking the BRIRs on their Accuracy
14.02 - 19.02	Finalizing the Stage Models and the BRIRs
21.02 - 30.03	Writing the Thesis

References

[1] A.C. Gade. Investigations on musician's room acoustic conditions in concert halls - part i: Methods and laboratory experiments. *Acustica*, 69:193–203, 1989.

[2] A.C. Gade. Investigations on musician's room acoustic conditions in concert halls - part ii: Field experiments and synthesis of results. *Acustica*, 69:249–262, 1989.

[3] IDT. Acoustics – measurement of room acoustic parameters – performance spaces. (ISO 3382 - 1), 2009.

[4] Z. Schärer Kalkandjiev and S. Weinzierl. The influence of room acoustics on solo music performance: An experimental study. *Psychomusicology: Music, Mind, and Brain*, 25:195–207, 2015.

[5] A.C. Gade. Practical aspects of room acoustic measurements on orchestra plattforms. In *Proc. of the 14th ICA*, 1992.

[6] C. C. J. M. Hak and R.H.C Wenmaekers. The sound power as a reference for sound strength (g), speech level (l) and support (st): Uncertainty of laboratory and in-situ calibration. *Acta Acoustica United with Acustica*, 101:892–907, 2015.

[7] M. Lautenbach and M. Vercammen. Stage acoustics, iso 3382 and beyond. *Proceedings of the International Symposium on Room Acoustics*, 2013.

[8] D. Schröder and M. Vorländer. Raven: A real-time framework for the auralization of interactive virtual environments. In *Forum Acusticum 2011*, pages 1541–1546, Aalborg, 2011.

[9] Z. Schärer Kalkandjiev and S. Weinzierl. The influence of room acoustics on solo music performance: An empirical case study. *Acta Acoustica United with Acustica*, 99:433–441, 2013.

[10] Wenmaekers R.H.C, C. C. J. M. Hak, and L.C.J. Luxemburg. On measurements of stage acoustic parameters: Time interval limits and various source–receiver distances. *Acta Acustica United with Acustica*, 98:776–789, 2012.

[11] A.C. Gade. Acoustics for symphony orchestras; status after three decades of experimental research. *Building Acoustics*, 18:181–206, 2011.

[12] A. C. Gade. Subjective and objective measures of relevance for the description of acoustics conditions on orchestra stages. *Proceedings of the International Symposium on Room Acoustics*, 2013.

[13] C. C. J. M. Hak, R.H.C. Wenmaekers, and L.C.J. Luxemburg. Measuring room impulse responses: Impact of the decay range on derived room acoustic parameters. *Acta Acustica United with Acustica*, 98:907–915, 2012.

[14] J.S. Bradley. A just noticeable difference in c50 for speech. *Applied Acoustics 58(2)*, pages 99–108, 1999.

[15] M. C. Vigeant and R. D. Celmer. Effect of experimental design on the results of clarity-index just-noticeable-difference listening tests. In *Proceedings of 20th International Congress on Acoustics,*, Sydney, 2010.

[16] S. Pelzer. Interactive real-time simulation and auralization for modifiable rooms. In *Proc. of the ISRA*, Toronto, 2013.

[17] S. Pelzer, M. Aretz, and M. Vorländer. Quality assessment of room acoustic simulation tools by comparing binaural measurements and simulations in an optimized test scenario. *Acta Acustica United with Acustica*, 97:1529–1534, 2011.

[18] L. Aspöck, S. Pelzer, M. Vorländer, and F. Wefers. A real-time auralization plugin for architectural design and education. In *Proceedings of the EAA Joint Symposium on Auralization and Ambisonics*, Berlin, 2014.

[19] D. C. Bruck. Musician's preference for concert stage acoustics. *Acoustical Society of America Journal*, 88:S184, 1990.

[20] A. H. Marshall, D. Gottlob, and H. Alrutz. Acoustical conditions preferred for ensemble. *Acoustical Society of America Journal*, 64:1437–1442, November 1978.

[21] Weihwa Chiang and Yan kuan Shu. Acoustical design of stages with large plane surfaces in rectangular recital halls. *Applied Acoustics*, 64(9):863 – 884, 2003.

[22] M. Barron and J. J. Dammerud. Stage acoustics in concert halls – early investigations. *Proceedings of the Institute of Acoustics*, 28, 2006.