Proceedings of the Institute of Acoustics

PRACTICAL APPLICATION AND ANALYSIS OF FULL ORCHESTRA SPATIAL IMPULSE RESPONSES IN AN OPERA HOUSE

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1 INTRODUCTION

The loudspeaker orchestra - a measurement system consisting of a large array of sources on stage - was initially proposed in IOA Auditorium Acoustics in 2008[1]. The original purpose was to create identical orchestra performances in different room-acoustic conditions. Subsequently, the loudspeaker orchestra has been developed further, improving the source directivity[2] and enhancing the quality of the anechoic music material[3]. In addition to in-situ listening and recording, the applications for the loudspeaker orchestra include measurements of both spatial and monaural room impulse responses. Despite certain violations of the ISO3382-1 standard, the loudspeaker orchestra is an efficient method for measuring a large number of impulse responses from the stage area. With a spatial microphone array as the receiver, the direction of sound arrival can be estimated in detail[4] from the measured room impulse responses. This provides data for objective spatial sound analysis methods[5], and also enables a high-quality auralisation through convolution with anechoic recordings[6]. So far these approaches have been utilised in a series of concert hall measurements in Finland[6] and Central Europe, and the data have led to novel findings in room acoustics[7].

Opera houses, in general, demand conditions that differ from concert halls, but the acoustics of opera houses have been somewhat less studied than concert halls. The research methods with both are alike with perceptual and objective studies[8], and the measurements the ISO3382-1 standard provide data for the respective objective parameters[9]. While the objective parameters lay a basis for room-acoustic analysis, the common parameters lack the power to reveal more detailed structure of the sound field. Here, we report the application of the loudspeaker orchestra and spatial analysis in an opera house - the Finnish National Opera. As an extension to the earlier concert hall measurements, the source layout included eight loudspeakers on the stage representing typical positions for opera soloists. Furthermore, the orchestra layout was adapted for the space limitations imposed by orchestra pits. This paper presents spatial sound analysis of an opera house in different parts of the audience and on-stage, in terms of both the orchestra and soloists. The results were used for evaluating, diagnosing, and suggesting improvements on the acoustic conditions in the opera hall from a consultants' perspective.

2 BACKGROUND AND OBJECTIVES

The Finnish National Opera is a horseshoe-type opera house opened in 1993. The medium-size theatre seats a combined audience of 1350 at the stalls and three tiers of balconies. The main stage has equally-sized rectangular side and back wings, and a flytower. The floor plan and side section drawing are shown in Fig. 1. The orchestra pit accommodates a typical opera orchestra, and there is no overhang below the stage. A prominent feature of the side walls of the auditorium is that most of the surfaces are in fact doors. They are angled so that they do not provide any natural early reflection patterns to the audience. Another feature of acoustic significance is that the balcony fronts are essentially smooth and tilted down towards the audience. This creates some focusing effects, which are mainly heard when the sound reinforcement system is used. Despite these observations, the acoustic conditions of the hall in general were found pleasing for the performers as well as audience since the inauguration, but also left room for improvements in the future.

A major renovation took place in 2007, when the stage mechanics and most of the audio-visual infrastructure were replaced. At the same time, the pit was enlarged to remove the pit overhang. Also the sidewalls in front of the proscenium opening were altered. The intention of this modification was to enhance early reflections from the singers and provide better support for the orchestra. The renovation gave an impression of improved acoustics, but the hall could still benefit from further improvements for some issues: missing clarity of the singers inside the auditorium; balancing the orchestra and singers; uneven sound and insufficient brilliance of the strings; and, local sound focusing in the audience area.

In 2015, the seats in the entire hall were scheduled to be replaced, and the orchestra shell, occasionally used in symphony concerts, was changed. This renovation also opened a possibility for further acoustical modifications, and it was decided to commission a re-investigation of the acoustic conditions in order to suggest improvements for the opera house. The renovation of the seats required the conventional measurements of reverberation time and other basic objective parameters in the opera house. For learning more on the room-acoustic features of the venue, we conducted spatial impulse response measurements with the loudspeaker orchestra. These measurements were studied by applying recently introduced analysis methods for visually evaluating the acoustics[5] and planning the conceivable modifications.

3 HALL MEASUREMENTS

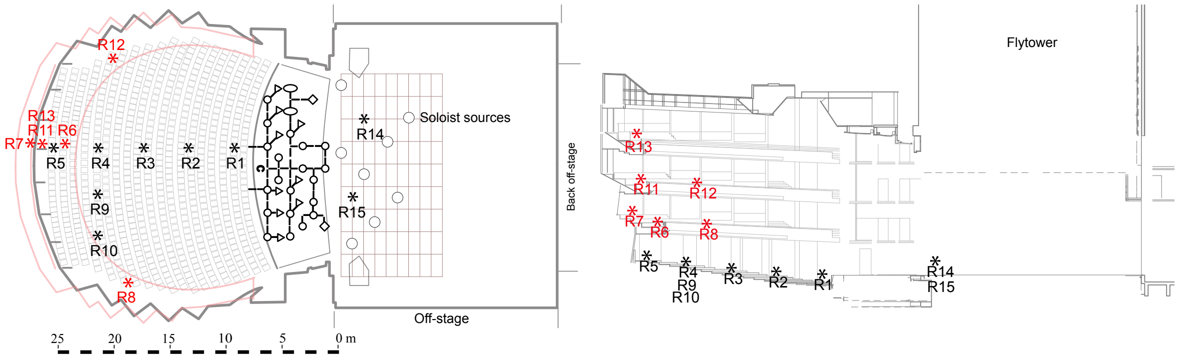
Two sets of room acoustic measurements were conducted in the national opera. First, we measured the room impulse responses according the ISO 3382-1:2009 standard, utilizing a omni-directional source in the orchestra pit and on stage. The receiver in these measurements was a calibrated B&K measuring microphone, and we estimated the monaural objective parameters from the measured room impulse responses. These measurements served mainly the calibration of the computer model for the seat renovation.

Second, we applied the loudspeaker orchestra[2], adapted and extended for opera measurements, and spatial microphone array with six omni-directional capsules (G.R.A.S. Type 50-VI) for the spatial analysis of the acoustics. Previously, the loudspeaker orchestra has included 34 loudspeakers connected to 25 individual signal channels[5]. For the opera purposes, the original soloist source along with seven additional soloist positions were added on-stage to represent different singer positions during performance. In total, the spatial room impulse responses were measured from 32 source channels to each receiver position. In contrast to the previous applications of the loudspeaker orchestra, the most notable change in the orchestra layout was the position of the 2nd violins on the opposite side to the 1st violins. This is also the seating arrangement of the resident opera orchestra, and also many other opera orchestras rely on this layout.

The impulse responses from the orchestra sources were measured with two different pit depths: 1.9 m and 2.3 m below the stage level. Due to the ongoing rehearsal period, the loudspeakers were set up among the chairs, music stands, and other orchestra equipment. However, we consider that the effect by the extra equipment in the pit on the measurements is marginal, since most receiver positions receive mainly reflected sound from the orchestra anyway. The walls between the empty stage, and side and back wings were closed in the measurements.

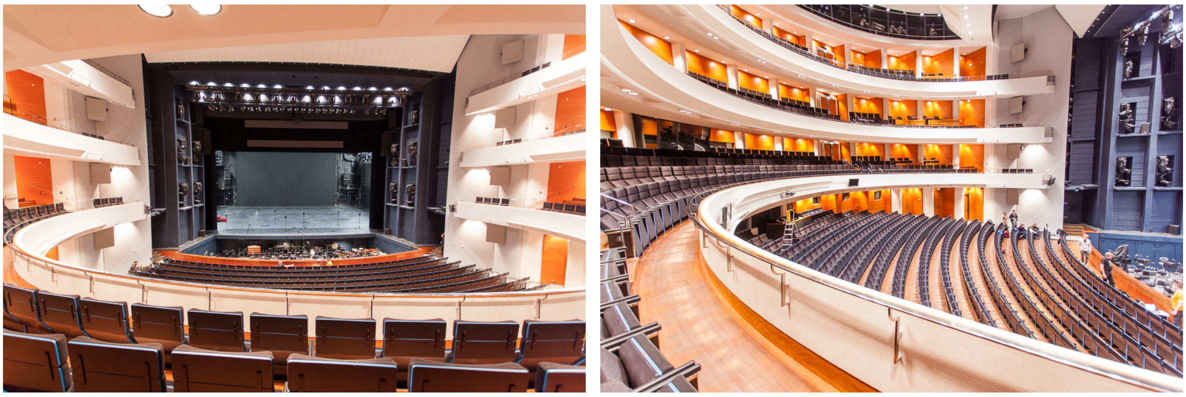
4 SPATIAL SOUND ANALYSIS

The key to the spatial sound analysis is the estimation of the direction of the arriving sound. Due to the differences in the sound propagation paths from the measurement source to the six microphones in the array, each sound event in the room impulse response is captured at a slightly different time



a) b)

Figure 1 Plan (a) and section (b) of the Finnish National Opera house with the measurement sources and receiver positions in the post-2007 configuration. Each of the dashed lines between sources in the pit denote 1 m distance, and the grid on-stage is 1 m × 2 m.



a) b)

Figure 2 Photographs of the Finnish National Opera house interior from the first balcony to the stage (a) and across the auditorium (b).

instant in the capsules of the array. We assume that at each instant in the impulse response, only one plane wave arrives at the microphone array. Based on the time differences-of-arrival variations in the measured responses, we can then estimate the direction for each sample in the room impulse response in short time-windows. This approach, named Spatial Decomposition Method (SDM), has been described in detail in the seminal publication[4], and based on the experiences gathered from analyzed spaces ranging from small rooms[10] to concert halls, we consider this method valid also for opera houses[*]. SDM yields omnidirectional pressure from one of the microphones in the array, accompanied by the estimated direction-of-arrival for each sample.

To study the opera acoustics in detail, we used the SDM data with wide-band spatiotemporal visualization[5]. In short, this technique forward-integrates the directional sound energy beginning from the initial direct sound, and visualizes the cumulating energy in expanding sets of histogram curves in selected time resolution. In other words, the method reveals from which directions and when the prominent reflections arrive in the receiver position and how they contribute to the overall sound field. Overlaid with the halls' drawings, this method can link together the geometry and the resulting acoustic effects for intuitive analysis.

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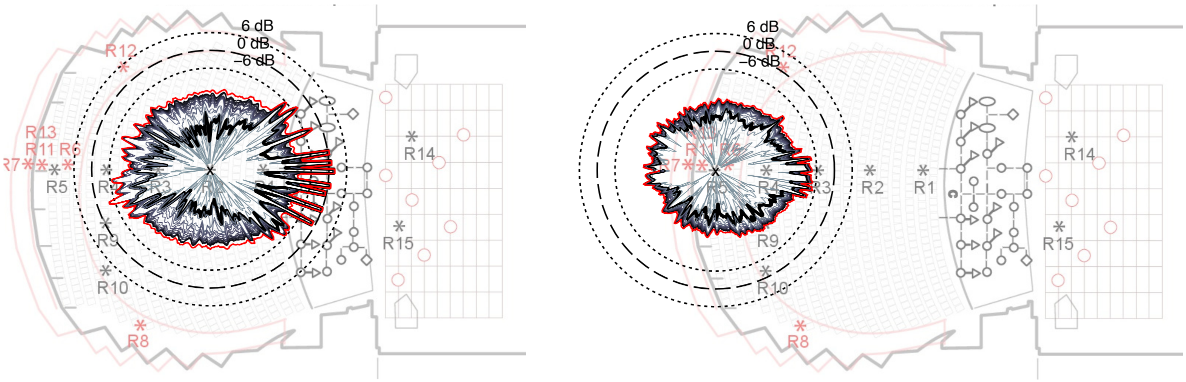
[*] The assumption of a single plane-wave is valid up to approximately 100 ms for room impulse responses of concert halls. In case of multiple simultaneous plane waves, the direction estimate is a weighted average of the directions within the analysis window.



a) Position R2, Stage sources only

b) Position R5, Stage sources only

Figure 3 Spatiotemporal visualization of the responses from eight source positions on stage.

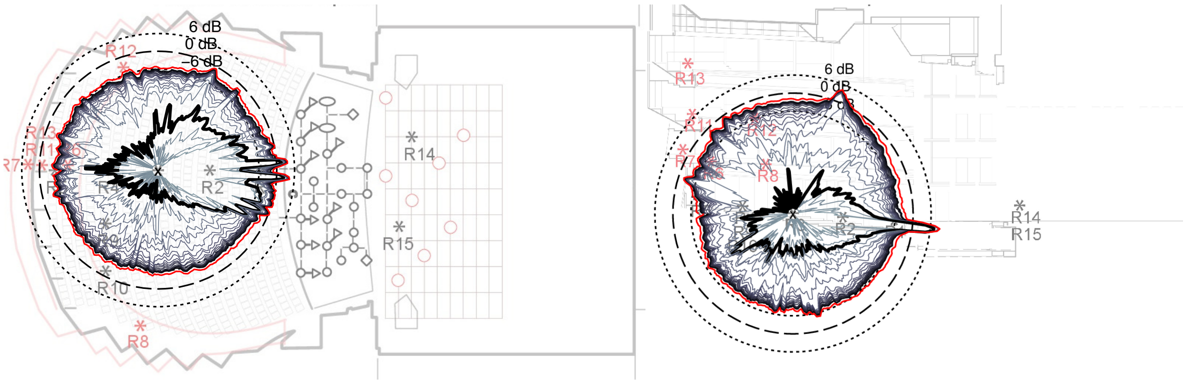
4.1 Visualization results

The visualizations show the development of the spatial sound energy over time. Each of the outward expanding curve accumulate the directional energy from the initial direct sound to 5, 10, 20, 30 (bolded), 40 ms etc. up to 200 ms. The outermost red curve represents the spatial distribution of the entire impulse responses. Note that the curves are averaged over source positions included in each visualization. A detailed description is available in Ref.[5].

First, we inspect the response of the stage sources. Figure 3 shows the analysis in two receiver positions in the stalls. In R2, the direct sounds are easily distinguishable in the directions of the sources on stage as sharp spikes (see Fig. 3a). The few spikes outside the source positions suggests that the proscenium provides distinct reflections with only certain soloist positions. The effect of any lateral reflections disappears when moving to a further distance (see Fig. 3b). The shape of this visualization resembles strongly to what the authors have found earlier in the wider non-shoebox concert halls[11,12]. The condition in R5 is also similar to several positions on the balconies.

Together with visual inspection of the floor plan, these interpretations promote a conclusion that the wall geometry after the proscenium causes the surfaces to function effectively as a wide fan-shape with respect to the audience area. In addition, the recessed doorway at the sides of the front seating rows is a choice difficult to reason with room-acoustic arguments. According to the uneven reflections - if any - seen with the stage source positions, it is likely that the singers do not receive enough support for their voice to carry over the audience area. After all, the bare direct sound suffers the most from attenuation over distance, when compared to a direct sound assisted by early reflections[13].

A corresponding analysis for the sources representing the orchestra in the pit is shown in Fig. 4. In the lateral plane (Fig. 4a) we see that the example receiver position has a line-of-sight into only few source positions, and the unobstructed direct sound is shown as the strong spikes in the respective directions. The first wavefronts from the remaining sources arrive via diffraction from non-transparent barrier in front of the first seat row. The space between curves on the left rear side suggests reflected energy between 30-40 ms after the direct sound, but there is very little evidence for proper early lateral reflections. This is natural, since the image sources for the first order reflections are not visible. The pit and the audience area are separated by a solid barrier approximately 0.8 m high. The median plane visualization also shows how the initial sound arrives from the top edge of this barrier. This view reveals that the inclined balcony front indeed creates a strong reflection at 40 ms, which can be heard as focusing. Also, the rear wall produces a reflection at 50 ms. Yet another notable source of reflections is the flat ceiling area between the lighting bridges. In this position, the ceiling reflection arrives between 50-70 ms after the direct sound. The same ceiling reflection is visible the all positions in the stalls. Higher balcony positions receive similar reflections from other parts of the ceiling.



a) Lateral plane, Pit sources only

b) Median plane, Pit sources only

Figure 4 Spatiotemporal visualization of the responses from loudspeaker orchestra in the pit.

Considering the conditions on stage, the downstage positions (R14 and R15 in Fig. 1) receive a prominent orchestra reflection from the ceiling above the pit. The same receiver positions suggest that the conductor's end in the pit and the pit floor yield a cat-eye reflection back to the stage. The stage itself provides little energy within 200 ms, but the flytower returns prominent late reverberant energy.

This analysis agrees with the observations outlined in the objectives: the acoustic support for voices on stage is sparse, and the sound of the instruments in the pit do not have reflections equally. Furthermore, the prominent ceiling reflection has been found to render a constricted sound image[14]. Although the change in the pit height has small audible differences both in-situ listening and experimental auralizations, the visualizations show only marginal variation between the analyzed pit heights.

5 ACOUSTIC MODIFICATIONS

Based on the analyses, we proposed mainly two improvements for the room acoustics. First, we selected the extension of proscenium wall on both sides of the pit as the primary modification (see dashed area in Fig. 5). The intended effect was to significantly reduce the open area near the pit sides, and to improve the efficiency for lateral reflections mainly from the stage to the audience area. Furthermore, the transmission of the orchestra sound would benefit from the closer reflective surface. The height of the extension was limited by the sightlines for the spotlights embedded behind the light-colored wall segment. The augmented side walls were built by the in-house set construction department. Initially, the walls were erected experimentally for gathering experiences with such a modified proscenium. Depending on the possible improvement in the acoustic quality, more permanent structures would be constructed at a later time. The material used for the side wall extension is a board structure with a total weight of about 23 kg/m^3.

Second, the ceiling section above front stalls was designed to feature rigid extruded elements that would distribute the reflections to a larger area both in width and depth. The redesigned ceiling would then avoid reflecting the sound specularly to the audience absorption. Instead, the redirected energy would be more lateral through varying propagation paths when reaching the audience. The shape of the elements was chosen importantly not to diffuse the sound, but only to redirect the incident sound without modifying its temporal structure. We chose a mixture of two element sizes: 0.5x0.5 m and 1.0x1.0 m. They were arranged in a quasi-random order with a relative coverage of 50%. The height of the sphere cutaway-shape elements was 0.1 m. In order to further increase the rigidity and to avoid absorption at low frequencies, all elements were filled with polyurehane foam. Installation of the ceiling elements was completed at the time of writing this paper.

Other modifications regarding the room geometry were limited, as the principal wall structures are

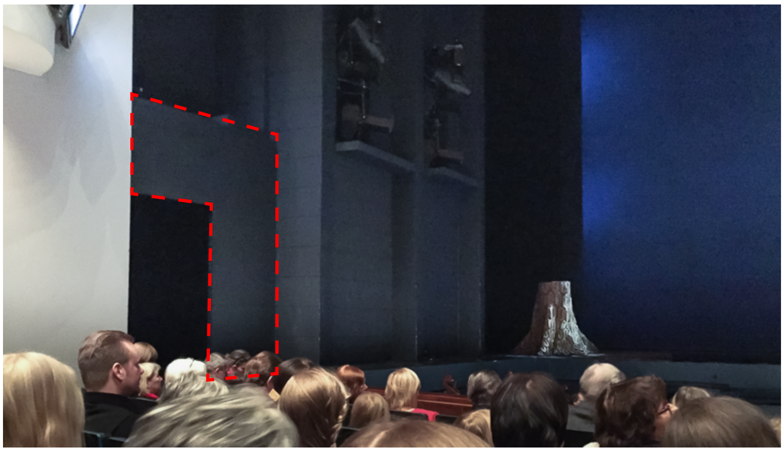


Figure 5 Picture of the wall extension on the left side.

painted concrete. The various technical equipment impose limitations on the possible solutions. Modification of the balcony front is planned, but postponed to a later time. In addition, replacing the solid barrier in front of the pit partially with an acoustically more transparent alternative is considered.

6 INFOMAL LISTENING EXPERIMENT

The extended proscenium walls were constructed first, which allowed to conduct a subjective evaluation before and after the modification. The administration of the opera organized listening events during a scheduled performance of a late-Romantic opera. The members of an evaluation panel, consisting of a small group of performers, technical staff, and management, attended the performance for assessing the current acoustic conditions in the audience area prior to any modifications. Later, another performance of the same opera piece was heard after the construction of the extended walls. The panel members occupied exactly the same seats on both times. These particular performances were held in a timeframe of two weeks. One of the authors also attended these events.

In addition to the discussion and comments gathered by the Finnish National Opera representative, the authors conducted a brief written survey after the second performance. The questions were related to perceptual changes in the overall acoustics, and the participants were instructed to avoid discussing their observations prior to completing the questionnaire.

6.1 Results

The opinions based on the questionnaire answers were unanimously in favour for the sound with the extended proscenium walls. Four panel members, excluding the authors, returned the anonymous answer sheet, and on average they found that the new walls had a quite strong effect on the acoustics (mean 4.5; 1 = no effect; 7 = a very large effect). They indicated that the orchestra gained *richness* and *brilliance* in their sound, particularly for the strings, and hearing the singers was improved. They also found that the change in the acoustic quality was of the desired kind (mean 5.25; 1 = opposite change, 7 = correct change). Also the magnitude of the change was somewhat larger than anticipated (mean 4.25; 1 = much smaller, 7 = much larger). According to the panelists, the overall change should be also slightly more substantial (mean 4.5). The self-assessed reliability of the subjective evaluation was considered moderate (mean 4.25; 1 = very unreliable, 7 = entirely reliable) despite the time span between the two performances.

Although the extended proscenium walls were originally intended as an experiment, the panel members evaluated the change satisfactory enough to decide for preserve the temporary structures, and only add finishing details to the appearance to blend in with the original walls seamlessly.

The ceiling reflectors required an extended period for their installation, and therefore the work was not completed until the autumn opening. At the time of writing, the installation was still under way. Therefore the overall combined effect by the two modifications remain still to be evaluated. Measurements for objective studies on the acoustic changes are planned.

7 DISCUSSION

The spatiotemporal visualizations provided detailed information on the acoustics in the measured positions. The feasibility of the plan for extending the proscenium walls was evaluated against the interpretation of the visual analyses, and the results initiated also the modification of the ceiling geometry.

Earlier, the loudspeaker orchestra measurement and spatial analysis have been used only with concert halls, and the Finnish National Opera remains currently as the only opera measurement. Therefore, points of reference are absent in order to compare the acoustic conditions through visualizations. Facilitated by SDM data, we computed auralizations from all receiver positions using a Mozart opera aria, and compared the acoustics with a number of previously studied concert halls through 3D spatial sound reproduction in a dedicated listening room. Although a direct comparison is not entirely fair, an informal listening experiment revealed prominent difference between opera and concert configurations for soloist singers. With an orchestra pit in between, the increased distance to the stage sets the opera soloists into a prominent disadvantage with regard to the overall balance. At the same time, the pit reduces the definition of the orchestra sound.

The comments voiced by the evaluation panel on the extended side walls were surprisingly unanimous. Considering that the total altered surface area is relatively small, all panel members described a positive change in the overall acoustic quality. Although the time between evaluations before and after the modification was rather long, all panelists had extensive experience on the sound in national opera, and on this basis a reliable evaluation is possible.

Later brief tests with a reduced height (0.4 m) of the orchestra pit barrier suggested that unblocking of the direct sound paths has a beneficial effect on the instruments' sound and richness without increasing the sound level out of proportion. This effect is plausibly caused by the reduction in diffraction, which would treat frequency bands differently. With less diffraction in the direct sound, the harmonic structure and the timbre remain unaltered, rendering the sound more natural or pure.

In the opera measurements the stage was empty. In contrast to concert halls, most opera productions have custom-built structures or other staging that alter the acoustics without a doubt. The acoustic conditions may vary greatly for the positive or negative depending on the set materials. Yet, there is currently no common approaches for standardizing the stage conditions in opera measurements. This issue should be carefully considered before possible future opera measurements. Also, the authors did not include any source positions on stage for a choir. While the choir has a notable part in many opera pieces, the increase in the number of sources would be substantial, and this would increase the practical complexity of the measurement. In addition, the selection of applicable anechoic operatic choir material is very scarce.

8 CONCLUSIONS

We applied the loudspeaker orchestra, extended with a set of soloist positions, and the spatiotemporal visualization technique in a measurement and analysis of the Finnish National Opera. Previously, the combination of these methods has been used only with concert halls. The visualizations were used for evaluating the feasibility of planned acoustic modifications, and to support subjective observations on the acoustic quality. Following the analyses, modifications for the side walls and the ceiling were suggested. Based on first subjective evaluations during opera performances, the extended side walls produce a perceivable change in the acoustics in the desired direction.

Acknowledgments: The research leading to these results has received funding from the Academy of Finland, project nos. [289300 and 257099]. The authors wish to thank the personnel of the Finnish National Opera.

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