Acoustical Behavior on the Spatial Characteristics of the Hindu Temples Using Computer Simulations: A Comparative Analysis.

Apoorva A. Dandge[1*] and Dr. Akshay P. Patil[1]

Department of Architecture and Planning, VNIT, Nagpur, Maharashtra, India

Abstract:

The Sanctum (Garbha Griha) and Pavilion (Mandapa) are Hindu temples' most important indoor religious locations. Several chanting rites are held within these spaces, and their acoustic quality needs to be scientifically analyzed. This study compares the acoustic behavior of two Hindu temples, which are similar in architectural features but differ in the internal sanctum ceiling, pavilion shape, and openings. The study also analyses the effect of sound source characteristics on each temple space independently and combinedly in the presence of devotees. Acoustic indicators such as Background Noise, Early Decay time (EDT), Reverberation time (T30), and Speech Transmission Index (STI) were analyzed using on-site measurements and a calibrated acoustic model. The results indicated that the combined effect of two sound excitation positions (S1:S2 inside the sanctum and center of the pavilion) slightly increased the T30 value by 67.92 % in Renuka temple and 4.87 % in Jagannath temple when compared to a sound excitation S2 in the pavilion. Speech Intelligibility in each temple case is rated 'excellent'.

Keywords: Hindu Temple Acoustics; Architectural Heritage; Acoustic Heritage; Reverberation Time; Speech Intelligibility; Acoustic Simulation.

I. INTRODUCTION

The temples are the most essential spaces of Hindu architecture and have evolved to meet the spiritual needs of the people. Various worship activities occur in the temple complex, each with different acoustical requirements. From the point of view of acoustics, the forts and temples in India are designed with great mathematical precision. The rules for producing sounds, chanting Vedas, and playing musical instruments are well-crafted [1]. In Hindu tradition, most people visit temples-built hundreds of years ago that still stand today, providing much-needed peace of mind to all devotees. Hindu temples are predominant in addition to sacraments, festivals, and spiritual practices. Acoustics are vital in worship spaces across all cultures and religions. Most temple activities involve speech and music [2]. Sound is essential to Hindu rituals because Vedic mantras help manifest the deity and sustain people's presence [3]. Generally, worship in a temple is performed by a priest on behalf of the faithful believers. However, the devotees chant Vedic mantras and pray with the chief priest during several phases of worship. Devotees and psalmodists (*kirtankars*) sing devotional songs called bhajans and kirtans. In addition to Vedic mantras and bhajans, musical instruments such as hanging bells, handbells, gongs, and conch shells enhance the spiritual experience of devotees in Hindu temples [4]. Even though temples are supreme structures in the Hindu community, the acoustic environment of Hindu temples needs more consideration in the literature. Various researchers conducted acoustical studies at worship spaces, including Churches, Mosques, Japanese temples, Monasteries, Han Chinese Buddhist temples, and Synagogues.

However, very few cases of Indian Hindu temples are considered. The non-destructive sound measurement techniques used to assess the internal structure of South Indian temple pillars were investigated by (Kumar *et al*., 2008). A study of spectral research on the sound emitted from the musical pillar at Vitthal temple, Hampi, a UNESCO world heritage site, was conducted by [5]. Changing the speaker arrangement affects speech intelligibility, and reflective surfaces from dome roofs and side surfaces increase the visible source width in Japanese Buddhist temples, as examined by [2]. The effects of design arrangement and spatial features of Han Chinese Buddhist temples on courtyard sound fields were investigated by [6]. The impact of non-similar types of pews on church acoustics was explored by [7]. Twenty-five box-shaped churches were simulated and investigated [8], concluding that length-to-width proportion notably affected C_{80} and T_s values. Sound field characteristics were analyzed for religious activities in an Indian Buddhist temple in Nagpur using the balloon burst technique and analyzed occupied and unoccupied condition based on simulation results [9]. Mosques in Lisbon performed better than Portuguese Catholic churches of comparable size when compared by [10]. The influence of mihrab geometry on the acoustics of modern mosques was studied by [11], and they found that the flat wall and Mihrab with a trapezium shape can generate a uniform polar response over the frequency range (250 Hz–4000 Hz). The sound quality of the Jingci Temple near West Lake has been studied using measurements and a questionnaire surveyed by [12]. Architectural acoustics is a complicated science and technology that includes environmental acoustics and noise control, among other things [13].

Hindu Temples are meant for group prayer, individual prayer, devoted speech, and musical performances in defined temple spaces. Hindu temples throughout India and around the world are architectural and artistic marvels. Hindu temples are necessary for performing sacraments, celebrating festivals, and developing one's faith.

The methodology used in this study is based on the on-site measurement of the acoustic impulse response and acoustic modeling of two identified Hindu temples to examine the acoustic behavior when a) a single priest chants in the sanctum (Garbha Griha), b) Psalmodist (*Kirtankar*) occasionally sings bhajan and kirtans in the center of the pavilion (Mandapa), and c) Combine effect of single priest chanting in the sanctum and psalmodist (*Kirtankar*) singing bhajan and kirtans in the presence of devotee's chant and sing in synchronization during the time of major festivals. The comparative analysis of two identified temples was performed using three indicators: Reverberation Time (T_{30}), Early Decay Time (EDT), and Speech Transmission Index (STI), and later simulated to examine all three above conditions.

II. SPATIAL CHARACTERISTICS OF THE HINDU TEMPLE

Hindu temple interior consists of three main spaces - Sanctum (Garbha Griha), Vestibule (Antarala), and Pavilion (Mandapa), as shown in Figure 1. The sanctum is considered the most sacred space in a Hindu temple; as the deity is placed inside this chamber, it faces towards the east and symbolizes the sun, the source of all energy and life, entering the sanctum and bringing blessings to the worshippers [14]. The placement of the deity within the sanctum is carefully planned according to Vastu Shastra, an ancient Indian system of architecture and design. The floor plan is typically square, representing a deity in the center so the worshippers outside can see and worship the idol. Only one priest is permitted inside this chamber to chant Vedic mantras. During worship, the priest usually rings a handbell in addition to chanting. The sanctum leads to a second space called the "Antarala," also called the vestibule, which has acoustic significance as some priests, along with the prominent priest in the sanctum, chant in synchrony and musical instruments such as conch shells, handbells, hanging bells, and gongs are played simultaneously. "Mandapa," also referred to as the Pavilion, the third sizeable congregational space, is devoted to worshipers singing devotional songs and chanting Vedic mantras along with the prominent priest in the sanctum during festivals [15]. Sanctum (Garbha Griha) and Pavilion (Mandapa) are believed to have reverberant acoustic characteristics, according to [4]. The pavilion is designed as a semi-open or enclosed space with decorated arches and intricately carved walls and ceilings, each depending upon the style of the temple.

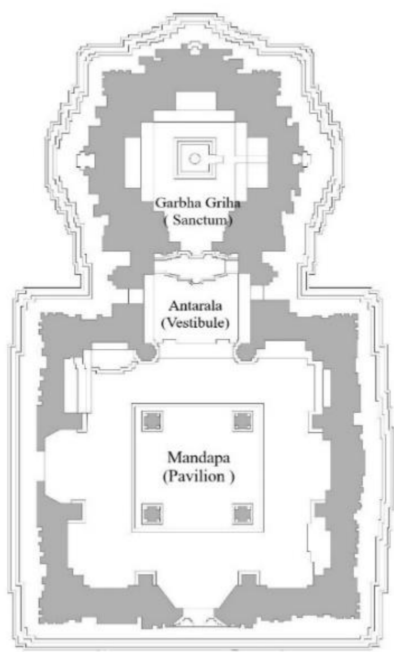

FIG. 1. Typical Hindu Temple Plan (Not to scale)

III. HISTORICAL CONTEXT OF INVESTIGATED TEMPLES

The temples investigated are part of a pilot study. These temples are examples of Hindu temple architecture in response to the need to establish several musical and speech activities in defined temple spaces. The location is a famous pilgrimage center known for historic temples and after-death rituals surrounding Ambala Lake [16]. Ambala Lake is surrounded by the hills of Ram Giri, Motha Parvat, and Narayana Tekdi, with temples and Ghats defining one of its banks, as shown in Figure 2. The temples are situated on the northeastern side, at the foothills of Ramtek in Maharashtra, India.

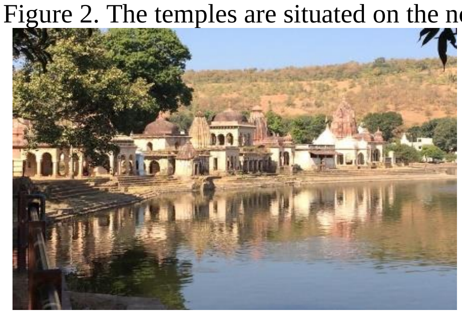

FIG.2. Heritage Temple,Ambala lake

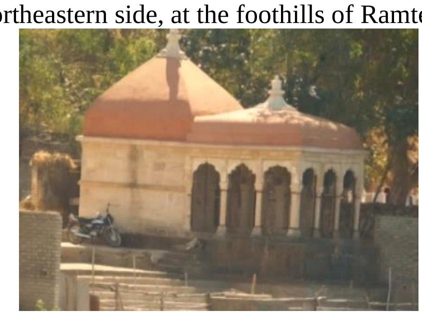

FIG. 3. Renuka Temple,Ramtek

FIG. 4. Jagannath Temples,Ramtek

The two identified temples of Renuka and Jagannath are composed on the planning principles of Vastu Purusha Mandala and were built during the 17th century, as shown in Figures 3 and 4. Because of the natural setting, this location is separated from the main town. It has evolved into one of the Hindu religion's sacred places of worship. The surrounding environment is serene and peaceful, with the sound of temple bells, chants, and prayers creating a spiritual atmosphere (Milind and Faiz, 2016). The temple complex provides a tranquil setting for visitors to connect with their spirituality while admiring ancient India's architectural marvels. Because of its mythological significance, the town was reconstructed by Raje Raghuji of Nagpur's royal Bhosale family, who laid the foundations of this pilgrim town [18]. Several other temples and ghats built by the ruler, together with its natural surroundings, gave the town a unique character (Russell R., 1908). The religious identity of Renuka temple has often been changed as its architectural elements show Mughal influence on the overall form of the temple as compared to Jagannath temple, which has an original architectural Hindu temple form. The local priest of Joshi Temple Hindu Trust manages the temples which are preserved under the State Archeology Department, Nagpur Circle. The priest performs daily chanting rituals in the temple's sanctum and organizes bhajans and kirtans in the pavilion at major festivals. During such festivals, the devotees also participate in the chanting and create a spiritual atmosphere inside the temples.

IV. GEOMETRY AND ARCHITECTURAL DETAILS

The Renuka Temple plan layout is composed of two spaces: an enclosed square sanctum (Garbha Griha) measuring 2.85 m x 3.14 m x 2.72 m with a single door opening in the square-shaped semi-open pavilion (Mandapa) of dimensions 4.11 m x 4.19 m x 3.7 m (refer to figure 5 left). Decorated with Maratha-style arches and columns surmounted by a hemispherical dome in the sanctum and a vaulted ceiling with a small dome resting on four columns in the center of the pavilion. However, the Jagannath temple slightly varies in design. It consists of a plan layout of three spaces: a square sanctum (Garbha Griha) with a tiered ceiling measuring 2.15 m x 2.15 m x 3.10 m with a door opening in the vestibule (Antarala) that measures 2.21 m x 1.04 m x 3.10 m connected to a rectangular-shaped enclosed pavilion (Mandapa) measuring 5.26 m x 8.02 m x 3.10 m with a flat ceiling resting on decorated Maratha-style columns and arches (refer figure 5 right). Elaborated Architectural details, along with sound source activities in temple space, are summarized in Table I.

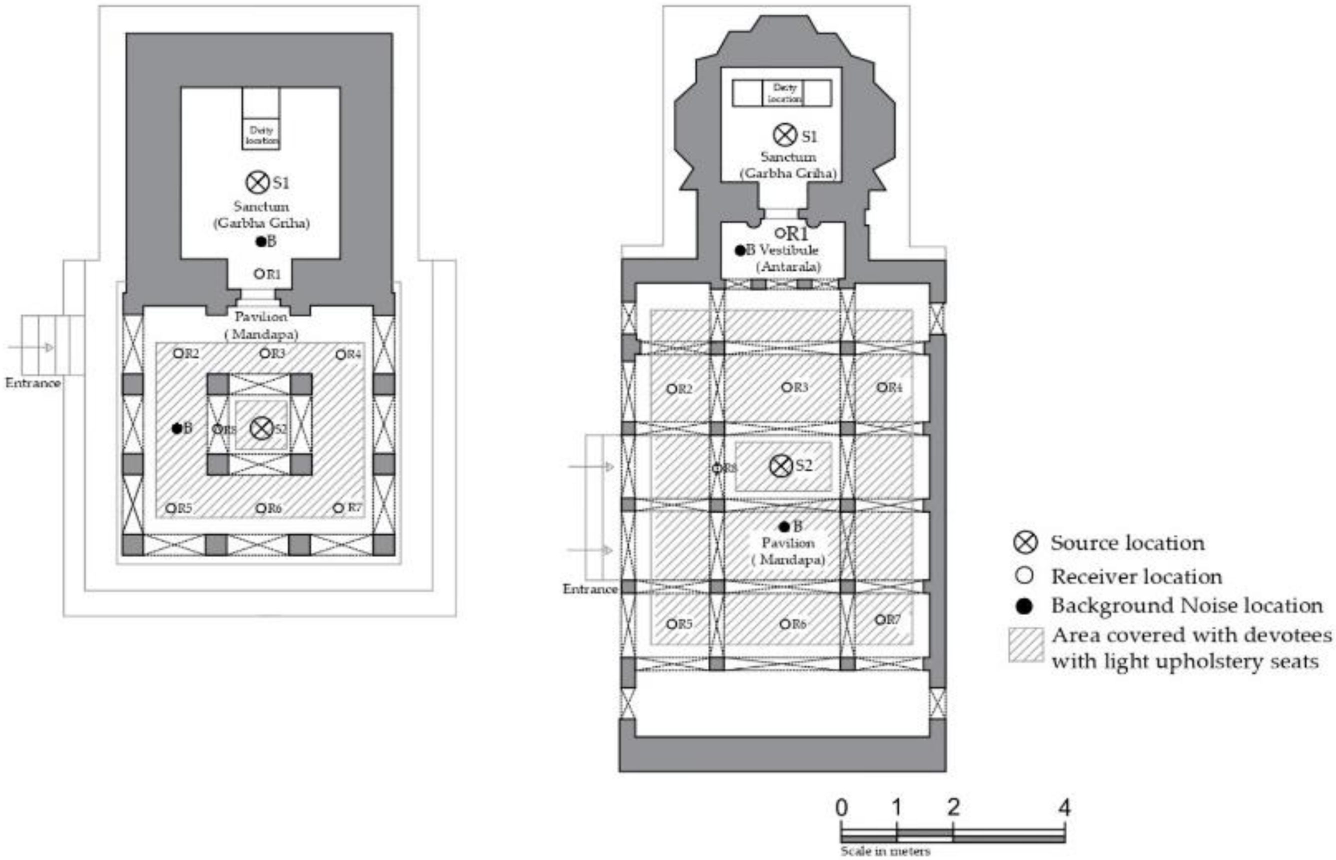

FIG. 5. Floor plan of Renuka temple (left) and Jagannath temple (right) including the sound source (S1: inside the sanctum. S2: center of the Pavilion), receiver position (R1-R8) and Background Noise location, with hatched area showcasing occupied by devotees.

TABLE I. Architectural details and sound activity inside Renuka and Jagannath temple.

	Temple Space	**Internal Volume (m^3)**	**Type of Ceiling**	**Material of construction**	**Type of sound activity**
Renuka Temple	Sanctum (Garbha-Griha)	33.11	Hemispherical dome		Single priest chanting daily
	Pavilion (Mandapa)	63.71	Vaulted ceiling with a small dome in the center of the pavilion	Yellow sandstone with lime plaster	Psalmodists (*Kirtankars)* sing bhajan and kirtans occasionally.
	Combined Space	96.82	–		Single Priest, Devotees and Psalmodist sing and chant together during the festivals.
Jagannath Temple	Sanctum (Garbha-Griha)	14.32	Tiered		Single priest chanting daily

	Vestibule (Antarala)	7.12	Flat	Yellow sandstone with lime plaster	Two or three priest chants along with main priest.
	Pavilion (Mandapa)	130.77	Flat		Psalmodist (*Kirtankars)* sing bhajan and kirtans occasionally.
	Combined Space	152.21	–		Single Priest, Devotees and Psalmodist sing and chant together during the festivals.

V. METHODOLOGY

The on-site measurement chain followed the aim of calculating Room Impulse Response (RIR) using the Balloon Burst technique adopted by [20][21]. Omnidirectional speakers are the best choice for this type of acoustic measurement as recommended by [22]. However, this measurement technique was impossible due to an inability to connect to the electric grid in the temple space. Hand clap, the firecracker burst, is another method for measuring reverberation time and frequency decay. However, it has certain drawbacks, as low frequencies below 300 Hz are unreliable in the hand clap method, and a firecracker burst causes disturbance in the temple's sanctity. Throughout the measurement process, balloons with a diameter of 40-42 cm and a constant inflation level were used. The larger the balloon size, the more energy it emits, and the higher the inflation level, the better the high-frequency content [9]. The results have been measured with the help of the Brüel & Kjær Handheld Analyser 2250 and calibrated microphone 4189.

Sound Source and Receiver positions

On-site measurements of acoustic impulse response were carried out in the empty temples for two sound excitation positions (S1: inside sanctum and S2: Center of Pavilion) and placed at a height of 1.5 m from the floor as recommended by [22]. Eight characteristic receiver positions (R1: inside sanctum where actual priest chants Vedic mantra), (R2-R8: Inside pavilion where devotees and psalmodist (*Kirtankars*) occupy seats during festivals (refer to figure 5). While there is no standardized placement for sound sources in Hindu temple religious practice, sound is considered an essential aspect of worship. It is often strategically placed to enhance the spiritual experience. Ultimately, it is up to the priest and the specific temple tradition to determine the placement and use of sound sources during worship; therefore, for this research, sound excitation and receiver positions were based on the suggestions of the temple priest. The receiver's position was 1.2 m above the floor, one-fourth wavelength from the reflecting surfaces, and half wavelength from each receiver as per [22]. For sound field simulation, a 3D model of the temple's interior was created in Autodesk 3D and was imported into ODEON 12.10 (Auditorium), room acoustic software. The model was calibrated following the on-site impulse response measurement, as discussed later in this paper.

VI. ACOUSTIC INDICATORS

In this frame of reference, Indian Hindu temple architecture serves as a repository of knowledge, art, architecture, culture, and a place of worship. Numerous indicators that describe an enclosure's acoustic quality are defined by [22]. However, many other researchers have experimented with acoustical parameters for halls intended for verbal or musical auditions [23]. Guidelines for acoustical measurements in churches were established by [7]. Several acoustical measurements and prediction methods for cathedral acoustics have recently been stated [24] [25]. There still needs to be a concrete agreement on a set of parameters that should be considered while describing the acoustical quality of a Hindu temple enclosure. This research analysis of the acoustic behavior of Hindu temples is intended to measure objective indicators such as reverberation time (T_{30}), early decay time (EDT), and speech transmission index (STI) as described below.

A. Objective indicator: Reverberation Parameters: T_{30} and EDT.

In a simple single volume, energy dissipates exponentially (or linearly on a logarithmic scale), and the reverberation time (T_{60}) is classically defined as the time it takes for the sound level to drop by 60 dB from the initial level [26]. At mid-frequencies (average of octaves 500 Hz, 1000 Hz, and 2000 Hz) are associated with the sensation of 'liveliness' [27]. Reverberation time (T_{30}) has been assessed in this paper. (T_{30}) is defined as the reverberation time of the room evaluated over a 30 dB decay ranging from −5 to −35 dB [23]. The Sabine formula relates the RT to the properties of the room.

$$T = 0.161V/\alpha S \quad (1)$$

B. Early Decay Time (EDT): It is based on an initial decay of 0 to 10 dB. It is influenced by early reflections and is dependent on measuring the source-receiver position and room geometry [28]. This indicator is calculated individually for each frequency in the octave band [29].

$$\mathrm{EDT} = \mathrm{RT}_{0,-10}(\mathrm{sec}) \quad (2)$$

C. Speech Transmission Index (STI): With a value ranging from zero to one, the speech transmission index (STI) is an objective indicator that specifies speech transmission quality and is related to speech intelligibility. STI is a function of RT and Background Noise (Paini, *et al.*, 2006).

Table II. Shows STI scale as a numeric representation as expressed in [31]

STI Value	Speech Intelligibility Rating
< 0.3	Bad
0.3 – 0.45	Poor
0.45 – 0.60	Fair
0.60 – 0.75	Good
>0.75	Excellent

VII. ACOUSTIC MODEL CALIBRATION

Indian Hindu temples are elaborately carved from the outside and inside; every element inside the temple is carved with stories from the Vedic scriptures. According to [32], more than intricate geometric models are needed to ensure higher precision in calculating acoustic indicators, and a simpler geometric model with accurate acoustic features gives satisfactory results. The model of the temples was created in Autodesk 3D and the dxf. the file was imported into the ODEON 12.10 -Auditorium, as shown in Figures 6 and 7. The main objective of the on-site acoustic measurements was to investigate the acoustic indicators defined by the series of standards ISO 3382- Part 1, analyze the essential sound field characteristics further, and compare them with the values of the acoustic parameters obtained by acoustic model simulations. The investigated temples are entirely built with yellow sandstone and bonded using lime mortar, the absorption coefficients used in the study were first assigned using standard literature values, which were then combined with those obtained from previous studies for similar material (Nieves *et al.*, 2014). As each structure is unique and specific features are frequently hidden or difficult to grasp through simple visual inspection, an iterative adjustment process was carried out beginning with the absorption coefficients of the most unusual or uncertain surfaces, potentially covering large areas, so that minor variations from the assigned initially values could lead to better agreement between simulated and measured parameters [34].

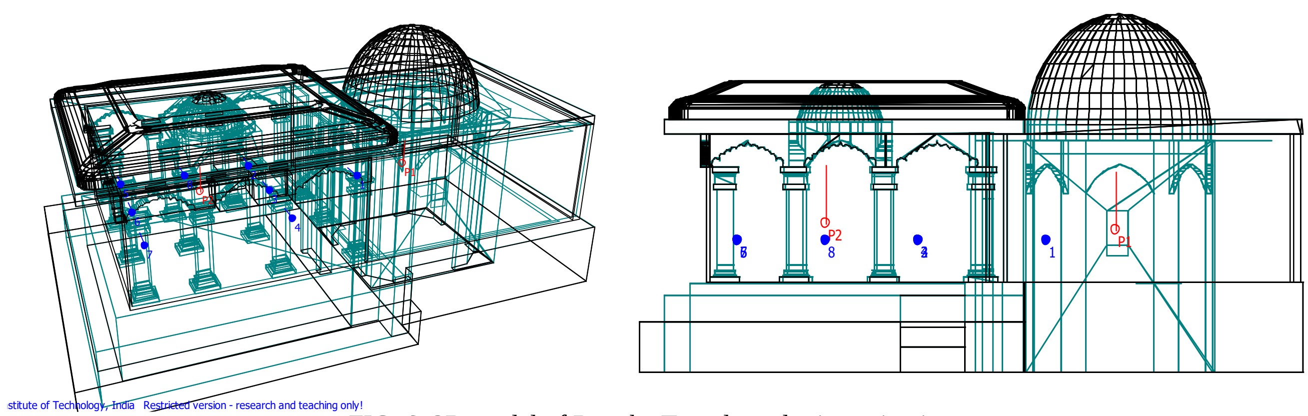

FIG. 6. 3D model of Renuka Temple under investigation.

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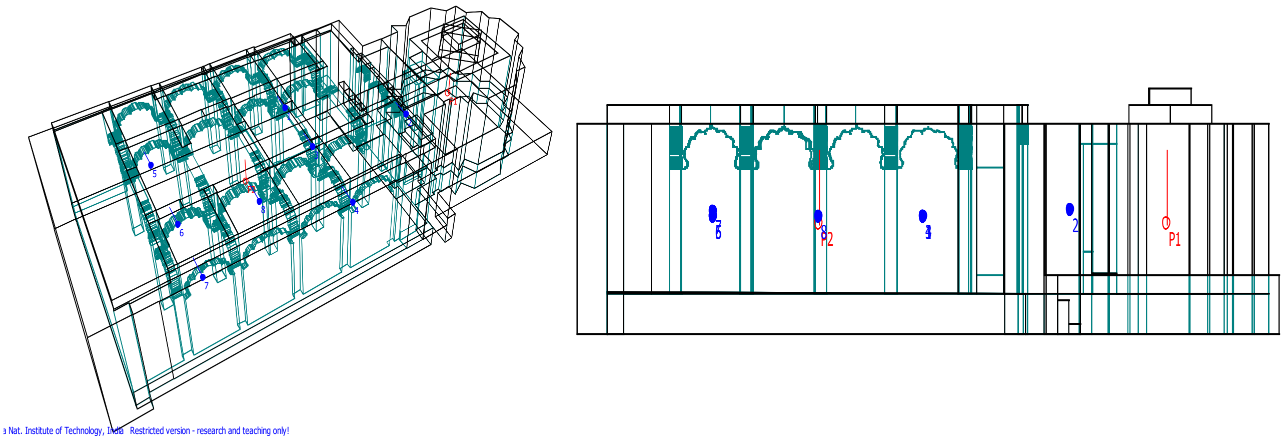


FIG. 7. 3D model of Jagannath Temple under investigation.

As mentioned in Table III, the scattering coefficients were expressed as a component of the actual dimension of the surface irregularities in the temples (Martellotta *et al*. 2018). On-site (T_{30}) measurement results are then compared with simulation results as it is necessary to calibrate and validate the acoustic model. The calculation settings of each temple model were set to ‘precision mode’. The reverberation time (T_{30}) value of each temple was checked using quick and global estimate functions, and finally, results were estimated from the regular ODEON 12.1O Simulation Process.

Table III. Absorption and scattering coefficient of materials used in the simulated model built in Odeon.

Material Name	**Scattering Coefficient**	**Absorption Coefficient of Material**					
		125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Hard stone	0.05	0.02	0.03	0.03	0.04	0.05	0.05
Devotees with lightly upholstery seats	0.05	0.51	0.64	0.75	0.80	0.82	0.83

Figure 8 shows the measured and simulated octave value of the T_{30} indicator for spatially averaged all measurement points for sound excitation (S1: inside sanctum) for Renuka and Jagannath temple. Just Noticeable Difference (JND) for reverberation time corresponds to 5% of the reference value, according to [22]. The assessment was carried out at each octave band, averaging all receiver positions for sound excitation at S1 in Renuka and Jagannath temple, and the results showed that the simulated and measured values differed by no more than one just noticeable difference (JND). Exceeding 1 JND would entail a change of listeners perception of reverberation [36]. Therefore multiple ‘trial and error’ combinations helped to achieve such precise result in each temple case.

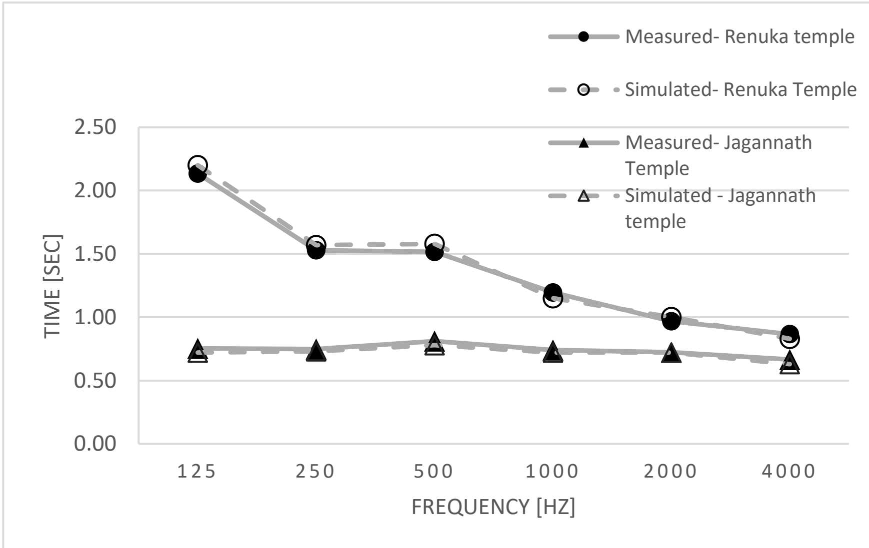


FIG. 8. Shows the measured and simulated octave value of T_{30} indicator for spatially averaged all measurement points in the case of sound excitation S1 versus frequency for Renuka and Jagannath temple.

In this research, we have use T_{30} value to analyze reverberation time indicator, because it can be challenging to generate enough sound in a room to measure T_{60} directly. For T_{30}, we frequently extrapolate it using only a portion of the decay using (time taken for loss, -5 to -35 dB); therefore, average background noise per frequency was measured for each receiver point for two spaces in the temples as mentioned in Figure 9. The average values measured were 41.46 dBA and 34.99 dBA at 1kHz for Renuka and Jagannath temple, respectively. A loud noise was measured in a 500 Hz and 1 kHz frequency band. In particular, the Renuka Temple Pavilion is a semi-open space with slightly high background noise compared to the enclosed Pavilion of Jagannath Temple, which is far from the main chaos observed in the surrounding.

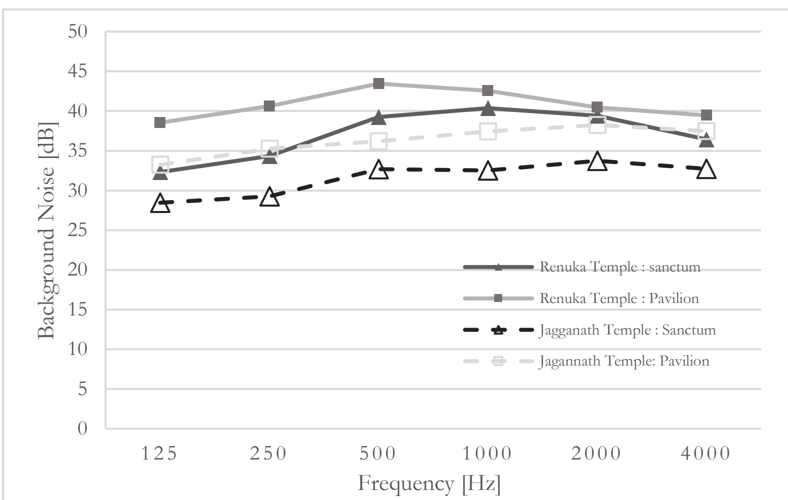


FIG. 9. Background Noise inside sanctum (Garbha Griha) and center of the Pavilion (Mandapa) for Renuka and Jagannath temple.

VIII. EXAMINATION OF ACOUSTIC MODEL

The study conducted in this research is to examine the acoustical behaviour of Hindu temples with the effect 1) a Single priest chanting inside the sanctum 2) Psalmodist (*Kirtankars*) occasionally singing devotional songs known as Bhajan and Kirtans in the center of the pavilion and 3) Combine effect of a single priest chanting (inside sanctum) and simultaneously Psalmodist (*Kirtankars*) singing and playing a musical instrument in the center of the pavilion in the presence of seated devotees' chant and sing in sync gathered during major festivals. All three cases simulate real-life situations when devotees and priests are present inside the temple. Seated devotees using light upholstery seats with a density of 1.40 per/m^2 approximately, spacing of about 1 m, corresponds to have one person every 72 cm,i.e., a full occupation) were considered based on the study conducted by [37]. Depending on the design and size of the investigated temples, twelve devotees and thirty devotees approximately could occupy the pavilion space in the case of the Renuka and Jagannath temples, respectively (refer to Figure 5). Then, acoustic indicator T_{30} and EDT for octave range values were measured on-site and compared for empty conditions, graphically presented in Figure 10. The similarities between T_{30} and EDT, energy decay curves, could be observed in the Renuka temple. Detailed observations are later discussed in the results and discussion section.

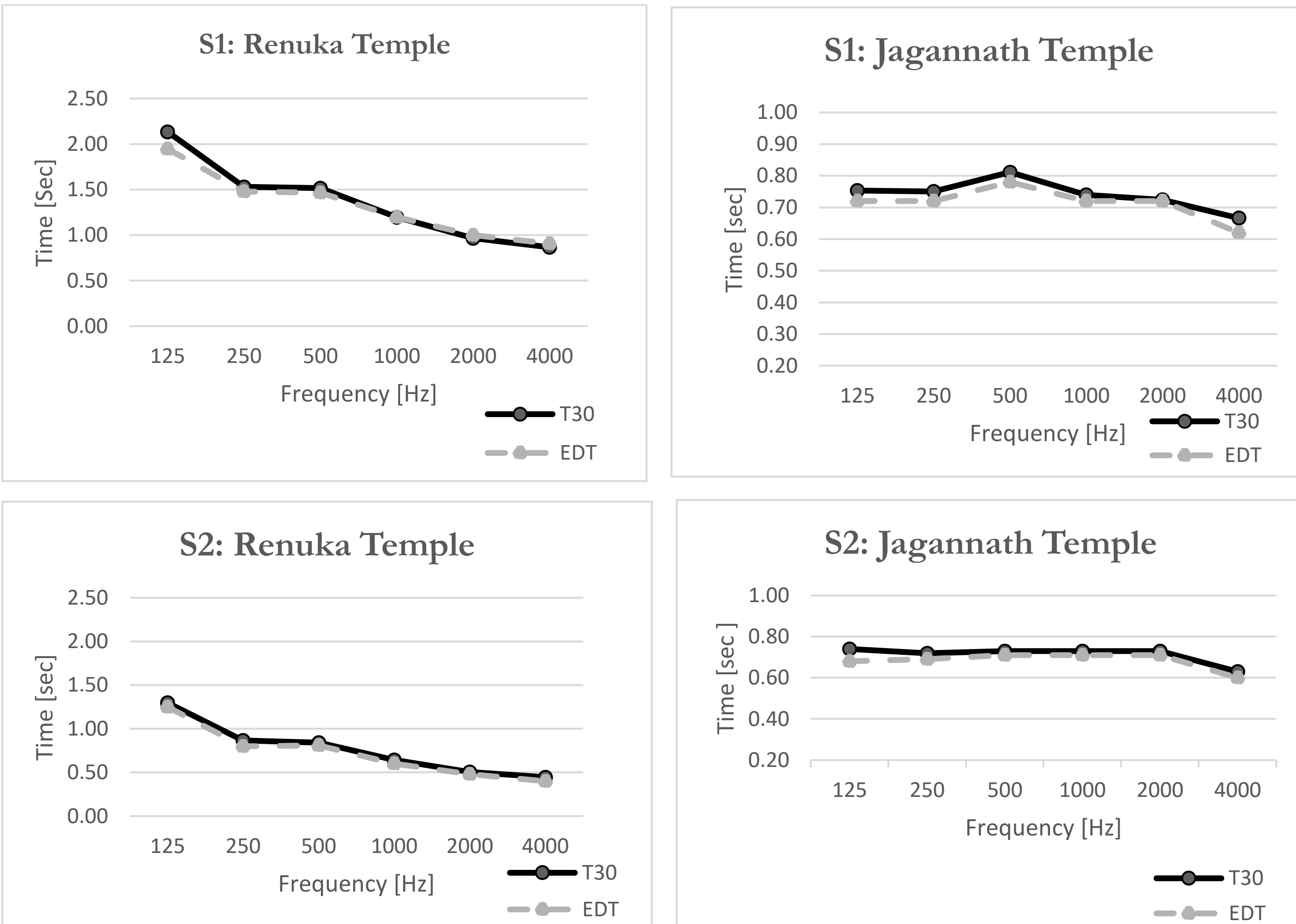


FIG. 10. The octave range values for reverberation time (T_{30}) and early decay time (EDT) indicators measured on-site at two sound excitation positions S1 and S2, spatially averaged a crossed eight receiver positions for Renuka temple (left) and Jagannath temple (right).

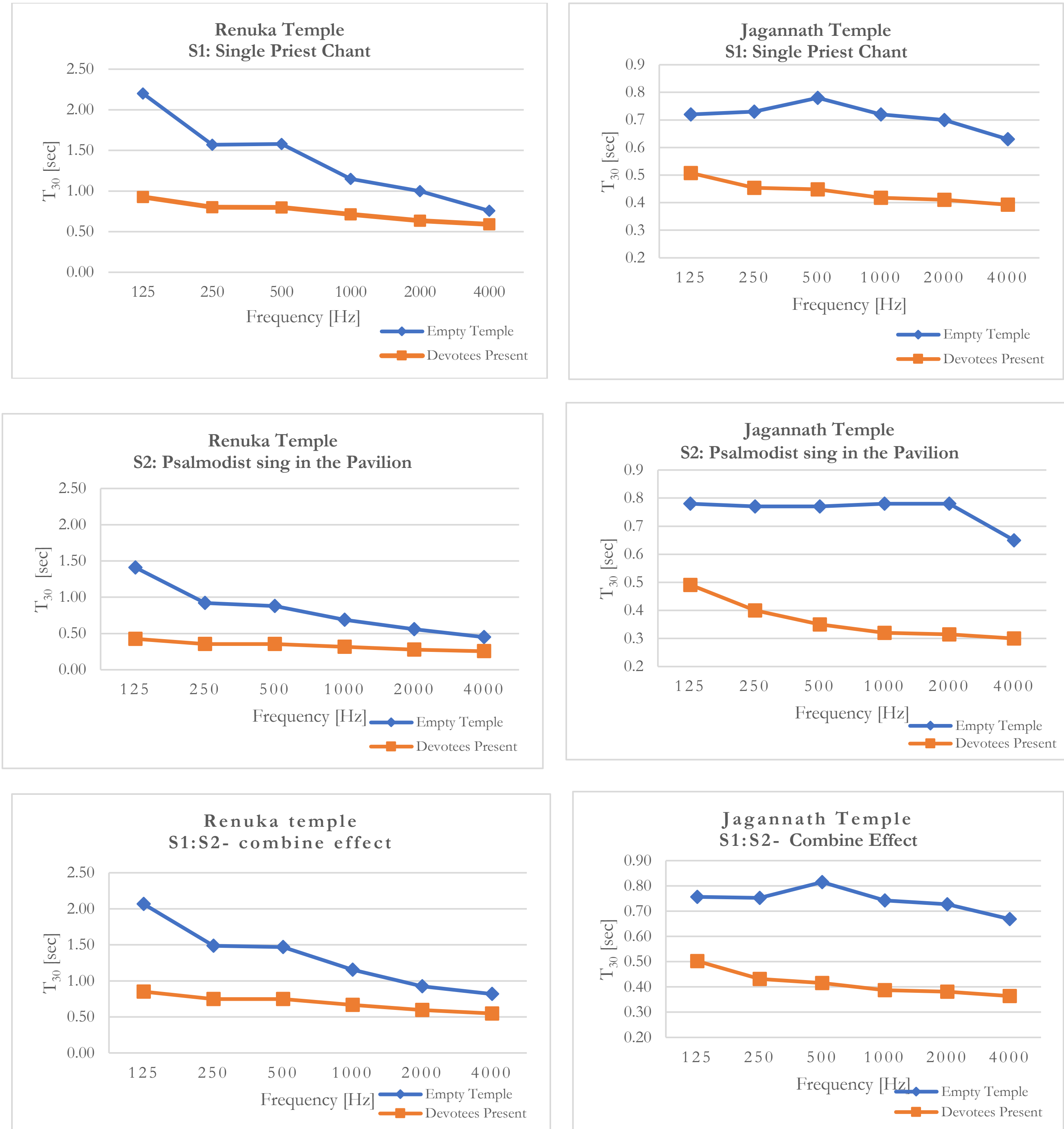
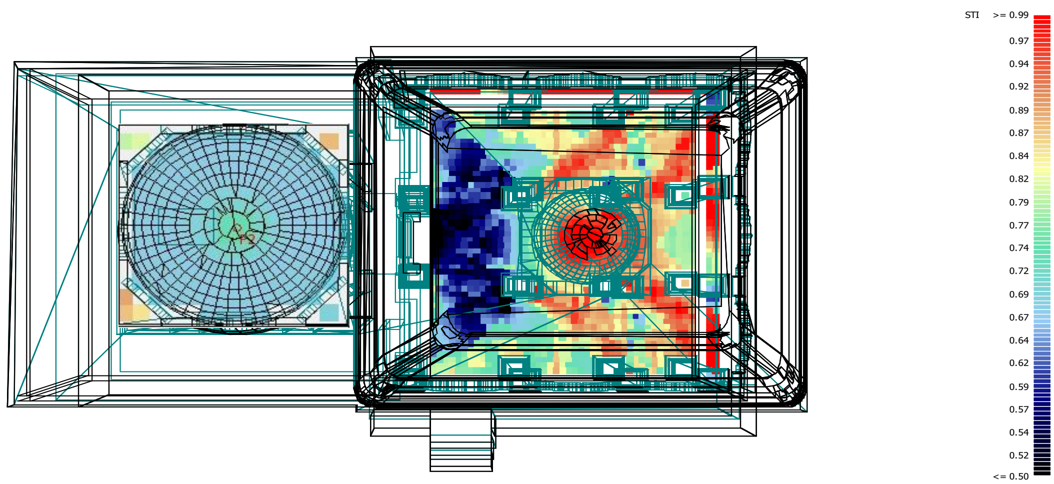


FIG. 11. T_{30} Octave values for three sound excitation effects in sanctum (S1), pavilion (S2), and combine (S1:S2) in empty and in the presence of devotees at Renuka Temple (left) and Jagannath temple (right).

As mentioned earlier, the speech transmission Index (STI) measures speech transmission quality. Table IV shows, STI Values for all three sound excitation positions. Figure 12 shows the Mapping of the Speech Transmission Index (STI) indicator for the combine effect of sound source (S1:S2) Position in the presence of devotees in the Pavilion spaces of Renuka Temple (top) and Jagannath Temple (bottom).

Table IV. Shows STI Values for all three sound excitation positions in presence of devotees.

Speech Transmission Index (STI)									
Sound source position	Receiver points	R1	R2	R3	R4	R5	R6	R7	R8
Renuka Temple	Inside sanctum	0.65	0.66	0.61	0.61	0.62	0.60	0.61	0.61
	Center of Pavilion	0.70	0.84	0.85	0.92	0.96	0.98	0.96	0.97
	Combine effect	0.66	0.55	0.56	0.57	0.92	0.95	0.93	0.94
Jagannath temple	Inside sanctum	0.72	0.63	0.67	0.63	0.48	0.49	0.47	0.54
	Center of Pavilion	0.76	0.78	0.78	0.83	0.82	0.83	0.83	0.90
	Combine effect	0.78	0.78	0.84	0.84	0.84	0.86	0.84	0.93



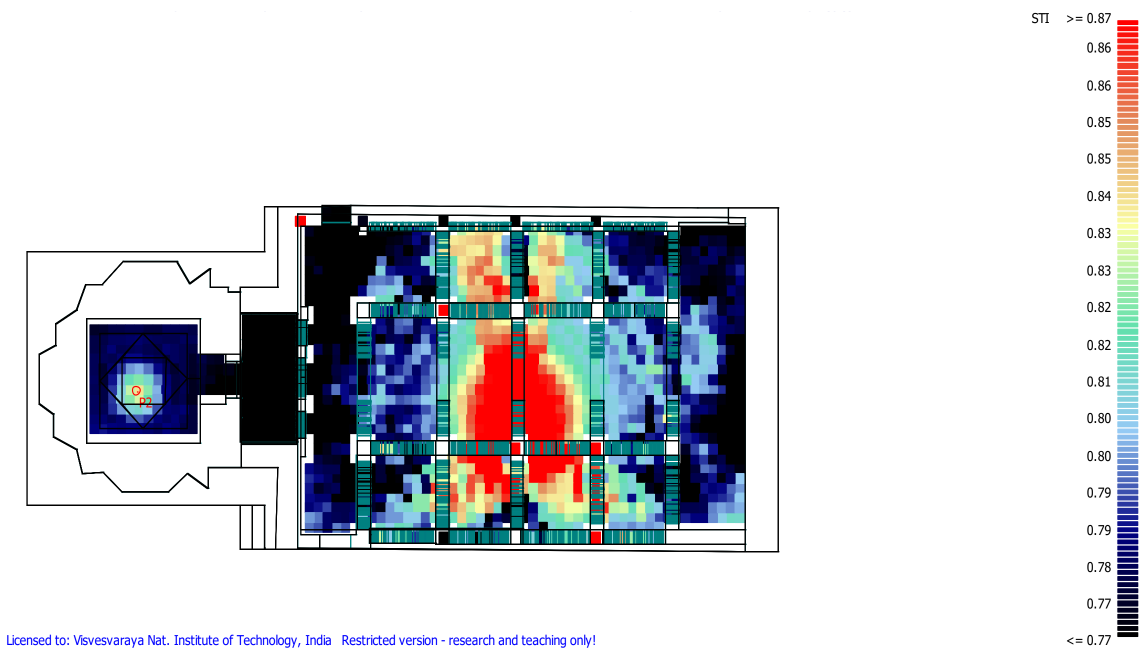


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Fig. 12. Mapping of speech transmission index (STI) indicator for the combine effect of sound source (S1:S2) position in the presence of devotees for the pavilion space at Renuka temple (top) and Jagannath temple (bottom).

IX. RESULT AND DISCUSSION

This research aims to compare the acoustic behavior of three sound source positions in two Hindu temple space. The objective indicators that are considered in this research are the Reverberation Time (T_{30}) and Early Decay Time (EDT), which have been analyzed based on on-site measurements and simulations on calibrated acoustic model. Speech Transmission Index (STI) indicators were included because they present qualifying scales for word intelligibility in the temple space.

Figure 10 shows on-site measured EDT and T_{30} indicators for sound excitation S1 and S2 in each empty temple case, spatially averaged across all receiver position versus frequency octave band. In the case of empty Renuka temple, Early Decay Time (EDT) and Reverberation time (T_{30}) indicators are very similar, which indicates steady decay of energy when the sound excitation (S1: is inside the sanctum) and (S2: is placed in the center of the Pavilion). On the other hand, in the case of empty Jagannath temple, EDT is slightly shorter than T_{30} when sound excitation from S1 and S2 which indicates early reflections are strong. T_{30} value observed inside empty sanctum is 1.33s and 0.74s for Pavilion in Renuka temple, significantly higher than the T_{30} value observed in Jagannath temple, which is 0.77s (inside empty sanctum) and 0.73s (inside pavilion) represented as single number frequency arithmetical average for the mid frequency octave band (500 Hz to 1kHz). A hemispherical dome in the sanctum of Renuka Temple has a significant impact on the T_{30} value. A semi-open pavilion allows some sound energy to escape, reducing the number of reflections and leading to a shorter reverberation time than a fully enclosed space as seen when sound excitation S2 is place in the center of pavilion in case of Renuka Temple. The sanctum and Pavilion are two different spaces interlinked with the vestibule (Antarala) in the Jagannath temple, making them acoustically coupled spaces. In such a case, the sound energy decay curve in the receiving room (room without the sound source: Pavilion) is assumed to have a relatively slow early decay rate. A comparison of the on-site measurement results of EDT and T_{30} showed that T_{30} is longer in the case of the Renuka temple than in the Jagannath temple for S1 and S2 sound source position. For the sound field simulation conducted in ODEON 12.10 Software, besides the case of sound excitation from sanctum S1 and Pavilion S2, the combine effect of S1:S2 was analyzed in empty temples, and when a priest chants inside the sanctum in the presence of psalmodist (*Kirtankar*) and devotees during festival.

Figure 11 indicates that in both temples, ($T_{30)}$ value has been reduced considerably in the presence of devotees, as expected. Increased absorption, in particular, reduced the overall reflected energy, resulting in a consistent decrease in T_{30} values. The effect of source (S1: when placed in the sanctum), the occupied T_{30} value in Renuka temple is 0.75s at mid-frequency octave band, almost twice than in the case of Jagannath temple which is 0.43s. Considering the time indicator, it was expected that the tiered ceiling inside the sanctum in Jagannath Temple had reduced reverberation time (T_{30}) values than the focusing effect of concave surfaces increased in reverberation time (T_{30}) in the sanctum of the Renuka Temple. Examining the effect of the sound source (S2: placed in the center of the Pavilion), T_{30} shows an equal value of 0.35s in each temple at the mid-frequency octave band and slightly higher value of 0.43s and 0.49s at low frequency in Renuka and Jagannath temple respectively. The influence of devotees' increased absorption of the floor area by simulating the audience using light upholstery seat have affected the overall reverberation time. Combine effect of excitation S1:S2 inside sanctum and in the center of the pavilion shows surprising results of increase of T_{30} value by of 67.92 % and 4.87 % when compared with sound S2 values at mid-frequency octave band in case of Renuka and Jagannath temple respectively.

Speech intelligibility (STI) is an important indicator necessary for Hindu temples as explained earlier. In the case of sound excitation S1 from the sanctum, the value observed is 0.62, rated as good in Renuka temple and 0.57, rated as fair in Jagannath temple spatially averaged a crossed all receiver position (refer table IV). Overall sound excitation from the Pavilion S2 and combine effect S1:S2 spatially averaged can be rated excellent in both temple case. Since the overall volume of the temples is small, the listener's position is close to the speaker. Therefore, speech intelligibility is not affected much in case of Renuka temple.

X. CONCLUSION

An acoustic simulation process using the ODEON 12.10 auditorium room acoustic software was used to investigate the effect of sound source position on the acoustic behavior of two identified Hindu temples. The acoustic model was calibrated using the on-site measurements as a reference to ensure that the results were fully comparable. Sound excitation was characterized based on real-life scenarios in the Hindu temple for eight significant receiver positions. The acoustic effect of these combinations is assessed using acoustic indicators such as reverberation time (T_{30}), Early Decay Time (EDT), and Speech Transmission Index (STI).

Acoustics play a significant role in Hindu temples as they enhance the spiritual experience of the devotees. From these results, it is concluded that the dome inside the Sanctum of Renuka temple was a consequence of increased reverberation time (T_{30}) when compared to the T_{30} value of Jagannath temple with the tiered ceiling for sound excitation S1 position, i.e., single priest chanting. The significance of the hemispherical dome inside the Sanctum of the Renuka temple cannot be overstated. It enhances the acoustics of the Sanctum, but only for the spiritual experience of the priest rather than for the devotees, as they cannot enter the Sanctum. The prolonged reverberation time allows chants, prayers, and other sounds to resonate and linger, creating a spiritual experience inside the Sanctum, where only a single priest is allowed. However, the tiered ceiling inside the Sanctum of Jagannath Temple and enclosed Pavilion proved more effective than the semi open Pavilion in Renuka as far as the overall geometry of the temple is concerned. Speech intelligibility in Jagannath Temple was affected for receivers R5, R6, and R7 in Jagannath temple. The source-receiver distance in the rectangular-shaped Pavilion has increased compared to the square-shaped Pavilion in Renuka Temple. Although Enclosed Pavilion design tends to create a more controlled acoustic environment with reduced external noise interference and gives peaceful environment for the devotees.

When the sound source S2 was at the center of the Pavilion in the presence of devotees, both temples offered better subjective reverberation and the best intelligibility results were observed and spatially averaged for all receiver positions. The combine effect of S1: S2 has slightly increased the T_{30} value in both temples, which may be due to coupled volume; overall, this would not affect the acoustical behavior of the temple. Overall, Speech intelligibility is not affected much because of the small volume of the temples.

Hence, the acoustical parameters analyzed for sound excitation, S1, and S2, are appropriate for chanting and musical activities in defined temple spaces, respectively.

The findings of this study emphasize the importance of careful sound excitation placement within the Hindu temple space to understand the audience's auditory experience.

Further research and experimentation can be conducted to explore the specific acoustic indicators and psychoacoustic phenomena for different temple volumes that contribute to the observed results in a Hindu temple space.

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