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Exploring conceptual framework of the soundscape of Derinkuyu Underground City

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This research aims to facilitate the experience of the cultural heritage of the ancient Derinkuyu Underground City, one of the largest ancient underground cities in the world, through audio-visual virtual reality (VR) representations of past life in the city; with a focus on defining its acoustics characteristics and soundscape of the past. The objective of this particular study is to define the conceptual framework of the soundscape in the Derinkuyu Underground City based on soundscape standards. The focus is on three spaces: the church used for religious ceremonies; the living area for resting; and the kitchen for food preparation and service. The spatial functions of the church, kitchen, and living spaces were analyzed, sound sources were classified, and the acoustic environment was characterized, considering daily tasks, defining sound sources, establishing reverberation time values by measurements and simulations and describing absorption properties of surfaces. The results showed limitations in describing context due to a lack of literature and historical records. The temporal ambiguity, interconnected spaces, and absence of clear boundaries in Derinkuyu Underground City created a timeless environment where the shared soundscape heightened auditory sensitivity, supporting survival and security needs.

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1. INTRODUCTION

Sounds are an integral part of the identity of spaces and are defined as a component of the physical environment. To the best knowledge of the authors of this paper, there is limited or no literature on ancient underground cities in terms of their acoustics and soundscapes. The doctoral research focuses on describing acoustic characteristics of Derinkuyu underground city in terms of reverberation time and noise levels; while focusing on collecting fundamental data necessary for preserving the existing acoustic environment of the world's largest known underground city, the Derinkuyu Underground City, as a cultural heritage site. To fulfill this objective, it also aims to recreate and define its spatial and auditory environment through virtual reality, while generating valuable insights into the design and construction of future underground cities. The first phase of the doctoral research, consisting of architectural and acoustical surveys, has been completed. The spatial typologies of the underground city were identified, the architecturally different spaces were documented, and reverberation times and sound absorption coefficients of tuff stone of specific spaces were determined. This study constitutes the second phase of the doctoral research which aims to define the conceptual soundscape of the city. By doing so, it is aimed to understand how acoustics contribute to the identity of these spaces and to explore the unique auditory experience within the city.

Located in Cappadocia, Turkey, the Derinkuyu Underground City is one of the largest ancient underground cities in the world and a unique cultural heritage site [1]. This Underground city, which has housed numerous civilizations over thousands of years, consists of seven levels, extends approximately 85 meters deep, and spans an area of 4.5 square kilometers [2]. The city is large enough to accommodate around 20,000 people along with their animals and food supplies [1]. It contains various spaces such as stables, kitchens, food storage rooms, schools, churches, living quarters, cemeteries, and wine production areas [3].

In the city, as first phase of the study, Specific typologies have been documented and architecturally modelled, acoustic measurements have been conducted and acoustic simulations of various spaces were made, and sound absorption coefficients and reverberation times have been calculated.

As the second phase of the study, the study attempts to define the conceptual framework of the soundscape of the city according to ISO 12913-1:2014 Acoustics — Soundscape Part 1: Definition and Conceptual Framework [4]. This includes establishing context, identification of Sound sources will be identified, and creation of taxonomy of these sources, referring to ISO/TS 12913-2:2018 Acoustics — Soundscape Part 2: Data Collection and Reporting Requirements [5]. Based on this taxonomy the acoustic environment will be defined.

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2. METHODOLOGY

In this study, only context, sound sources, and the acoustic environment have been considered in defining the parameters of the conceptual framework of the soundscape, while the identification of other elements within the parameter has not been included in the scope of this research. To achieve the study's objectives, the method first involves defining the context of the soundscape (Figure 1). This was done by reviewing the spatial functions of Derinkuyu Underground City in the literature and conducting historical analyses of the three typologies to be examined in the study. According to the definition in ISO 12913-1:2014, "the context includes the interrelationships between person and activity, and place, in space and time". Accordingly, within Derinkuyu Underground City, the relationships of person and activity, person and place, and space and time have been defined for three different typologies: church, kitchen, and living spaces. Subsequently, potential sound sources within the church, living areas, and kitchen were identified through a literature review, and a taxonomy of these sources was created by the Sound Source Taxonomy specified in ISO/TS 12913-2:2018.

Following the definition of context and identification of sound sources, the acoustic environment was characterized as per ISO 12913-1:2014. According to ISO 12913-1:2014, the acoustic environment encompasses sounds from all sound sources modified by the environment. The parameters of meteorological conditions, absorption, diffraction, reverberation, and reflection, which may alter the environment, were used to define the acoustic environment. A procedure to determine reverberation time of each room was applied. The procedure consists of recording a sweep signal of 4 s. at 3 or 5 (depending on the size of the rooms) in at least 3 different locations in each room and then converting recorded signals to impulse responses in Voxengo Deconvolver program [6] and processing impulse responses in ODEON Room Acoustics software [7] to derive reverberation time values. Three dimensional acoustic models of three rooms were also made in 3Ds Max software [8], imported to ODEON and rooms were calibrated based on measurement results. The acoustic absorption

characteristics of the tuff stone in each room was estimated/predicted during the calibration of the 3D acoustic models.

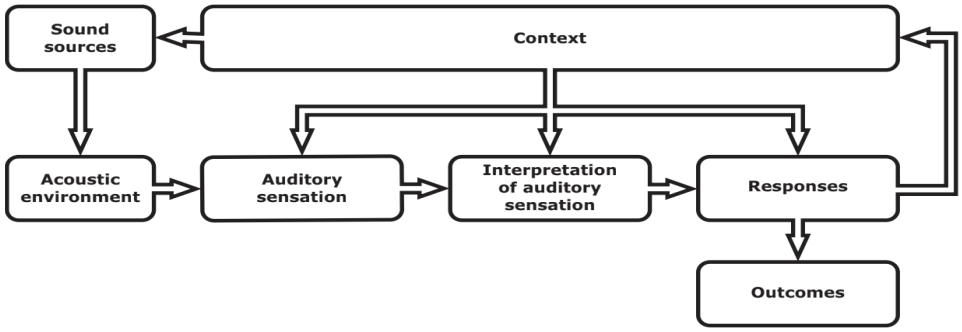


Figure 1. Elements in the perceptual construct of soundscape [4].

3. RESULT AND DISCUSSION

In this article, we applied the soundscape methodology to investigate the perceptual components of the soundscape in the church (a public space), living area (private space), and kitchen spaces (semi-public space) selected for study.

Through this methodology, we aimed to describe the parameters of the context, sound sources, and acoustic environment.

A. CONTEX

Historical studies in the literature have revealed that the Derinkuyu Underground City, listed as a UNESCO World Heritage site [9], is the largest underground city in the world, capable of accommodating 20,000 people at an urban scale and containing a variety of spatial typologies. In this city, the church selected as a sample space is used for religious ceremonies and gatherings. The living area serves as a space for sleeping and resting, while the kitchen functions as an area for food preparation, cooking, and service activities. The church has an approximate capacity of 80 people, the living area accommodates a maximum of 10 people, and the kitchen can host up to 20 people (Figure 2).



Figure 2. Actions and numbers of people in typologies.

Given its underground location and its lack of connections to the surface beyond its entrance and exit, the temporal/spatial relationship necessary for defining the soundscape's context is absent. It can be argued that this underground city exists beyond the confines of time, as a timeless space (Figure 3). The very fact that it is always dark and there is no day, and nighttime distinction might be contributing to this timelessness.

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Figure 3. Living images of the church, living room and kitchen [10].

B. SOUND SOURCES

Sound sources were determined based on the relationships of space/action and space/person, which define the contextual components according to the spatial typologies and architectural characteristics. A taxonomy of these sound sources was created, and auditory scenarios were developed accordingly.

In the church, it was observed that approximately 80 people gathered for religious activities. Based on the activities occurring in this space and its relationship with adjacent spaces, the presumed sound sources include footsteps, speech, bell sounds, music, and singing.

The living area, a private and relatively isolated space, accommodates up to 10 people in sleeping and resting areas. Considering the architectural location and spatial adjacency of this area, the presumed sound sources are footsteps and speech.

In the kitchen, a service and utility space, approximately 20 people from different groups are involved in food preparation, cooking, and serving. According to the results of the analysis and structural features of this space, the sound sources include fire sounds, footsteps, sounds of metal/stone/wooden kitchen tools, grinding, and boiling (Figure 4).

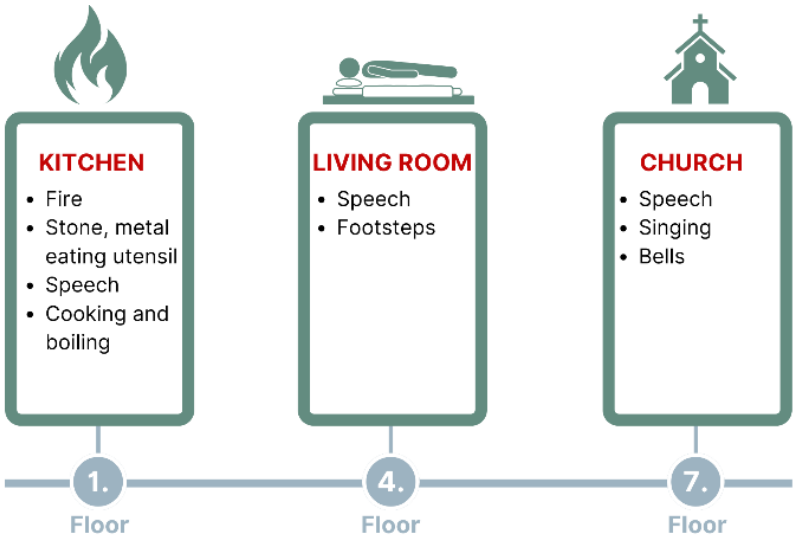


Figure 4. Sound sources according to activities in the typology of space.

For each space, a taxonomy of identified sound sources was developed. Accordingly, in Derinkuyu Underground City, there are no mechanical sounds produced by facility activities listed in the ISO/TS 12913-2:2018 sound source taxonomy. However, among the non-mechanical sounds generated by facility activities, certain sounds associated with the city's historical functionality have been identified. These include construction sounds originating from manual excavation activities carried out over the years to meet the city's needs, ventilation sounds from air shafts, and sounds produced by the sliding stone lock system, a half-ton device used for defense. Additionally, sounds associated with fire for cooking, grinding with primitive tools (stone/metal/wood) during food preparation, and boiling in the kitchen area are present. Furthermore, the vocalizations of livestock, such as cattle, sheep, goats, and horses, have been observed within the underground stables (Figure 5).

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Due to its underground nature of Derinkuyu, certain environmental sounds listed in ISO/TS 12913-2:2018, such as wind and thunder, are absent. Furthermore, considering the historical context, amplified sounds and motorized transport sounds are also absent.

In summary, a new classification has been introduced in the taxonomy for non-mechanical sounds produced by facility activities that are not included in the standard. Accordingly, "sliding stone/lock," "grinding," and "cooking/boiling" have been added as sound source types. Additionally, within the category of domestic animal sounds, "horse" and "cattle" vocalizations have been incorporated, as they are not explicitly included in the standard.

There might be one more type of sound source; that is being communication sounds coming from small holes in each space. There is usually a small (estimate the diameter) hole in each room, which is taught to be used for ventilation but also for communication. Speech sounds or sometimes alarming sounds might be coming from them.

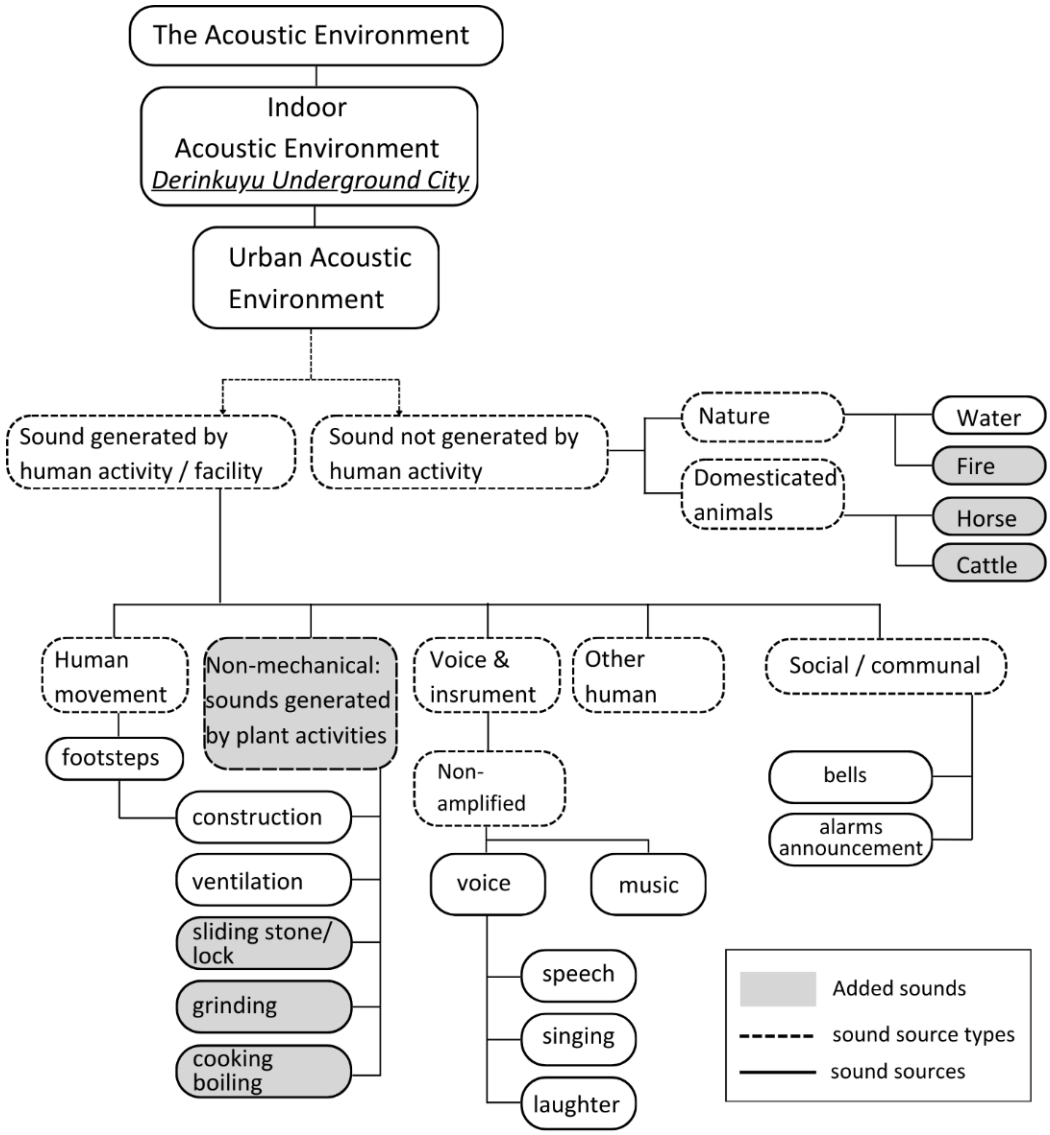


Figure 5. Taxonomy of the acoustic environment for soundscape of Derinkuyu Underground City.

C. ACOUSTIC ENVIRONMENT

Through on-site surveys and architectural studies conducted in the selected spaces within the scope of this study, the spatial dimensions were determined, and these spaces were modelled in 3D. Reverberation times are measured by recording sweep signals, converting them to impulse responses and deriving reverberation time

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values from these impulse responses in ODEON. and sound absorption coefficients in these spaces were estimated from the measured reverberation time values. The measured reverberation times for the church, kitchen, and resting area are as follows: 2.02 RT (T20mid) for the church, 0.52 RT (T20mid) for the living area, and 0.62 RT (T20mid) for the kitchen. The frequency distribution of reverberation time values is presented in the table below (Table 1).

Table 1. Measurement results of the 3 rooms in Derinkuyu Underground City.

RT (T20ave.)	Volume	125	250	500	1000	2000	4000	8000	RT(mid)
Church	159 m^3	4,79	3,30	2,20	1,50	1,10	0,80	0,57	2,02
Living Room	23 m^3	0,80	0,79	0,55	0,42	0,34	0,29	0,26	0,52
Kitchen	92 m^3	1,30	0,91	0,65	0,49	0,43	0,37	0,29	0,62

In Architectural Acoustics, M. David Egan recommends a reverberation time (RT) of 2.0 to 3.0 seconds for worship spaces such as churches. This range is considered optimal for preserving the richness of musical performances while supporting speech intelligibility. Egan suggests an RT of 1.2 to 1.8 seconds for speech-focused worship spaces and 2.0 to 3.0 seconds for music and choir-oriented spaces [11]. In Derinkuyu Underground City, the RTmid value was measured as 2.02 seconds, which is within the recommended range. This reverberation time is considered to be functionally appropriate for the space. for the space.

Similarly, In the Regulation on the Protection of Buildings Against Noise, published in 2017 in Turkey [12], the acoustic performance criteria of buildings are defined in detail. According to the regulation, the maximum reverberation time (RT) for living areas classified under C-D performance class is specified as 0.8 seconds.

Furthermore, DIN 18041:2016, Acoustic Quality in Rooms – Requirements, Recommendations, and Guidelines for Planning [13], emphasize that kitchens generally feature hard surfaces and materials that tend to increase reverberation. The recommended reverberation time for such spaces ranges between 0.4 and 0.8 seconds, with larger commercial kitchens approaching the upper limit. In Derinkuyu Underground City, the RTmid value for the kitchen was measured as 0.62 seconds. Considering its function as a public space, this value falls within the standard-recommended range and is deemed appropriate for its intended use.

All these results show that church, living room and kitchen have reverberation time values within the modern recommended limits. It should be also taken into account that especially when living room and kitchen were occupied, there must be soft materials which might even reduce reverberation time values.

The sound absorption coefficient of tuff stone estimated for 3 three different spaces are shown as below. Accordingly, it was found that the sound absorption coefficients were similar in the kitchen and living area, but a lower sound absorption coefficient was found in the church (Table 2).

Table 2. Estimated absorption coefficients for the tuff stones rooms in Derinkuyu Underground City.

Material	125	250	500	1000	2000	4000	8000
Church	0,01	0,02	0,04	0,06	0,08	0,10	0,10
Living Room	0,08	0,08	0,11	0,14	0,17	0,20	0,20
Kitchen	0,06	0,09	0,12	0,16	0,18	0,20	0,22

In Derinkuyu underground city, a virtual indoor acoustic environment has been defined in 3 different typologies. Accordingly, sound scenarios were developed according to the number of people and actions in the church, kitchen and living area. Below is a demonstration of the sound scenarios to be developed and auralized with 1 receiver/listener and multiple sources (resources in the scenario consist of footsteps, bells, fire, human speech sound, grinding and human speech sound according to typologies) in each space. In the next part of the study, listening tests and VR tour from these auralizations will be used (Figure 5).

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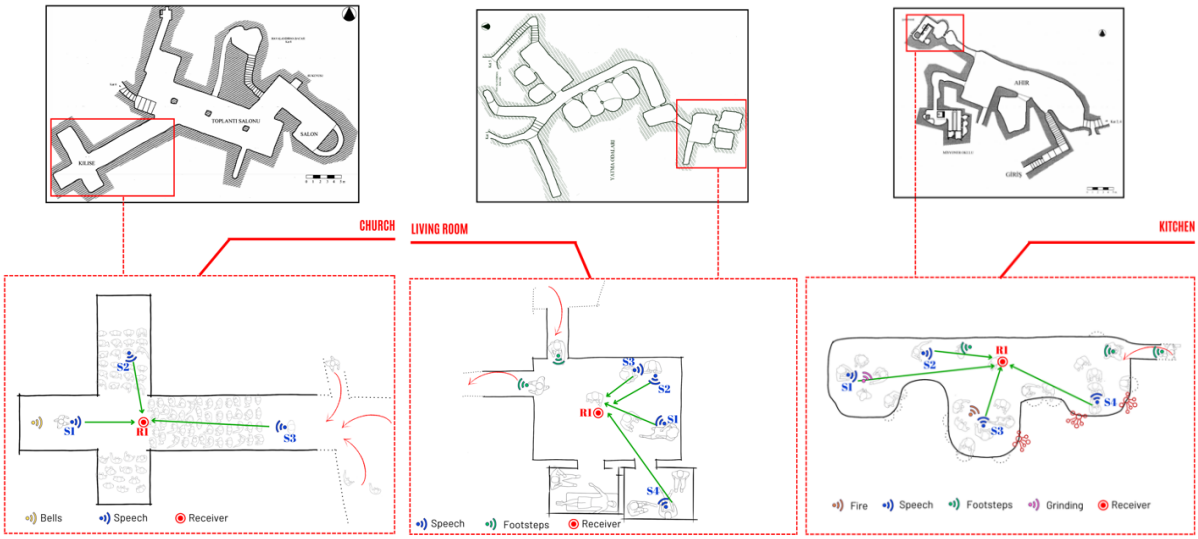


Figure 6. Sound scenario in the church, in the living room and in the kitchen.

4. CONCLUSION

In this study, the context, a component of the soundscape, was defined, and sound sources were identified and categorized based on literature reviews and assumptions. Following the identification of the context and sound sources, also acoustic measurements of reverberation time, the acoustic environment was defined.

However, limitations arise in defining the temporal aspect required for the context due to a lack of literature and historical records. The Derinkuyu Underground City, which has hosted numerous civilizations over thousands of years, was expanded and transformed over time to meet evolving needs. As a result, projections about its past do not encompass clearly defined temporal boundaries. Additionally, the absence of any connections to the surface apart from entrances and exits likely altered the inhabitants' perception of day and night, rendering the underground city a timeless, temporally independent space.

Due to the architectural and structural features of the Derinkuyu Underground City, the delineation between private and public spaces is ambiguous, and spatial boundaries remain undefined. This lack of spatial clarity complicates the formulation of definitive conclusions and limits within the area. The undefined and interconnected nature of spatial units in the city also influences auditory perception. Compared to well-defined and independent units, the spaces in the Derinkuyu Underground City are acoustically more dynamic and livelier. Consequently, individuals who constantly hear sounds from other areas might feel safer.

Moreover, the structural characteristics of the Derinkuyu Underground City—such as the absence of doors and windows—mean that all spaces are, in essence, public and exposed to noise from adjacent areas. This may have heightened the auditory sensitivity of its inhabitants. For reasons of defense and security, the individuals living in this environment were likely more attuned to sounds as part of their survival and safety strategies.

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