applied sciences

MDPI

Review

Sound Environments in Large Public Buildings for Crowd Transit: A Systematic Review

Tingting Yang, Francesco Aletta and Jian Kang *

UCL Institute for Environmental Design and Engineering, The Bartlett, University College London (UCL), Central House, 14 Upper Woburn Place, London WC1H 0NN, UK; tingting.yang.18@ucl.ac.uk (T.Y.); f.aletta@ucl.ac.uk (F.A.)
* Correspondence: j.kang@ucl.ac.uk; Tel.: +44-(0)20-3108-7338

Abstract: Sound environments in large public buildings are likely to be different from those of performance spaces, as well as those not specifically designed for acoustic "performance", but where sounds still play an important role because of the function they can promote (or disrupt). The aim of this study was identifying common strategies and empirical approaches researchers have been implementing for these acoustically complex enclosures and to provide some methodological indications for future studies on the topic. Studies conducted in three building types for crowd transit, such as museums/exhibition spaces, shopping malls, and transportation hubs/stations, which were collecting data about either physical outcomes or individual responses for such sound environments, were selected. The Scopus databases were searched for peer-reviewed journal papers published in English without time limitations. An additional manual search was performed on the reference lists of the retrieved items. The general consideration on inclusion was to meet the requirement that the case belonged to the three building types, and then the specific inclusion criteria were: (1) including at least an objective acoustic measure of the space; or (2) including at least a subjective measure of the space. The search returned 1060 results; after removing duplicates, two authors screened titles and abstracts and selected 117 papers for further analysis. Twenty-six studies were eventually included. Due to the limited number of items and differences in measures across studies, a quantitative meta-analysis could not be performed, and a qualitative approach was adopted instead. The most commonly used objective measures were SPL, and more specifically often considered as L_{Aeq}, and T. The intervals across studies were currently of inconsistency, and the selection is recommended to take space scale factor into account. The used subjective measures can be classified into four categories as annoyance, affective quality, room-acoustic quality, and acoustic spatiality. Four basic perceptual assessments concerning dynamic contents are accordingly suggested as "annoying-not annoying", "crowded-uncrowded", "long-short (reverberation)", and "far away-nearby". The other descriptors can be project-specific. The methodologies involve measurement, questionnaire/interview, listening test, and software simulation. It is necessary for the former two to consider temporal and spatial features of such spaces, and the adoption of the latter two will lead to better understanding of users' exposure in such spaces, e.g., acoustic sequences and user amount. The outputs of investigations inform that background noise level, e.g., 90 dB in museum/exhibition spaces, and sound reverberation, e.g., 4.0 to 5.0 s in shopping malls and transportation hubs/station, are of fundamental importance to the design of such spaces. Sufficient acoustic comfort can be achieved with integrated design of indoor soundscape.

Keywords: room acoustics; soundscape; museum; shopping mall; transportation station

check for updates

Citation: Yang, T.; Aletta, F.; Kang, J. Sound Environments in Large Public Buildings for Crowd Transit: A Systematic Review. *Appl. Sci.* **2021**, *11*, 3728. https://doi.org/10.3390/app11093728

Academic Editor: Kimihiro Sakagami

Received: 31 March 2021
Accepted: 19 April 2021
Published: 21 April 2021

1. Introduction

Characterizing the acoustic environment of performance spaces such as theatres, concert halls and auditoria has been one of the main topics in room acoustics studies during the past decades [1,2]. For spaces where the main function is sound-related (e.g., spaces for listening or performing) it is indeed crucial that clear criteria related to measurable parameters are in place to assess their acoustic quality and performance [3]. For this reason, international standards have been developed over time to harmonize measurement protocols and reporting requirements [4]. This gradually extended to spaces that are not specifically designed for acoustic "performance", but where sounds still play an important role because of the function they can promote (or disrupt), like libraries, open-plan offices, for which specific guidance has been produced [5,6], and restaurants, canteens [7–10] as well.

In parallel, researchers have approached the acoustic characterization of large indoor spaces also from a perceptual perspective, that is, investigating how users actually experience them aurally [11–13]. This applies to both spaces for acoustic performance and not, alike. There is indeed a growing interest around the emerging field of "indoor soundscape" for public buildings and methods to describe them [14–19], where soundscape is defined as the "acoustic environment as perceived and/or understood [. . .] in context" [20].

Yet, all the examples above imply a listener that is at a fixed position, while for many large public buildings, users experience the space dynamically. The focus of this review is on indoor spaces where listeners are likely to be exposed to the acoustic environment for crowd transit, such as museums and exhibition spaces, shopping malls, or transport stations and hubs. The safety of users and evacuation conditions, rather than acoustic comfort for perform or non-perform purpose, are the main concern in this context. It is mandatory to use public address and voice alarm systems [21,22], which requires specific values of several acoustic conditions necessary for the proper operation, e.g., reverberation time, signal-to-noise ratio, identification of the position of sound sources, and especially speech intelligibility. There is also extended guidance for acoustic retrofitting in such spaces [23]. However, less is known for these building types in terms of acoustic performance or soundscape (i.e., perceived) quality when they are in operation. In this context, soundscape assessment is not a quantitative parameter, but rather an approach to collect perceptual data from users of the space [20]. Thus, the underpinning research questions of this systematic review were: (1) what kind of objective parameters are used to characterize the acoustics of these spaces? (2) what kind of subjective measures (if any) are used to characterize the indoor soundscapes of these spaces? (3) What are the main methodologies used to characterize the acoustics and indoor soundscapes of these spaces? (4) How are the outputs of acoustic and/or indoor soundscapes investigations informing the design of such spaces?

The overarching goal is identifying common strategies and empirical approaches researchers have been implementing for these acoustically complex enclosures and provide some methodological indications for future studies on the topic.

2. Materials and Methods

Since this study is exploratory, no pre-defined protocol registration was considered for this review. The basic process and data extraction strategies were agreed upon at the beginning of the review work. The study was performed and reported in accordance with the PRISMA (Preferred Reporting Item for System Review and Meta-Analyses) guidelines for systematic reviews [24].

2.1. Search Strategy and Eligibility Criteria

Studies were selected if they collected data about the acoustics (or its perceptions) of large public buildings where users are expected to experience the space dynamically, i.e., users are not "static" (e.g., libraries, offices, etc.). For this reason, the definition of the search strategy was mostly driven by building types and functions, rather than specific geometrical features, and it was the outcome of brainstorming sessions and consultation among the authors. The general consideration on inclusion was to meet the requirement that the case belonged to the appropriate building type, for crowd transit (e.g., museums/exhibition spaces, shopping malls, and transportation hubs/stations). Then the specific inclusion criteria were: (1) including at least an objective acoustic measure of the space; or (2) including at least a subjective measure of the space. Only peer-reviewed journal articles published in English were considered.

Studies were identified by searching the Scopus database by manually scanning the reference lists of retrieved items and through consultation with experts in the field. The following query was submitted to the Scopus database: (TITLE-ABS-KEY (acoustic*) AND TITLE-ABS-KEY (museum*)) OR (TITLE-ABS-KEY (acoustic*) AND TITLE-ABS-KEY (transport* AND station*)) OR (TITLE-ABS-KEY (acoustic*) AND TITLE-ABS-KEY (shopping AND mall*)) OR (TITLE-ABS-KEY (acoustic*) AND TITLE-ABS-KEY (transit AND space*)) OR (TITLE-ABS-KEY (acoustic*) AND TITLE-ABS-KEY (sequential AND space*)) AND (LIMIT-TO (DOCTYPE, "ar")). No time limits for the search were applied. The last search was performed on 8 February 2021. While using two or three databases is a common approach in systematic reviews in medical and life sciences, the Scopus database alone was shown to be effective in covering the most relevant literature in built environment studies, and acoustics more specifically [25].

The assessment about the eligibility of the study was performed independently in a non-blinded standardized manner by two authors; a few disagreements between reviewers about inclusion/exclusion of some items were resolved by consensus and advice from the third author.

2.2. Data Extraction

Information was extracted from each included study on: (1) country where the study was conducted/designed; (2) building type, to describe the main function; (3) space type, to describe whether the study addressed a single space, multiple spaces, or sequential/adjacent spaces within the building of interest; (4) objective measure, to describe the investigated acoustic parameter(s); (5) subjective measure, to describe instruments used to collect individual responses about the acoustic perception of the space(s); (6) methodology, to report on whether the study was based on measurements, software simulations and/or surveys with users.

Considering the differences in the metrics across the selected studies, a quality assessment and quantitative meta-analysis under the quality-effects model were not targeted [25]. Therefore, a qualitative approach to data synthesis was adopted to answer the review questions.

3. Results

The research through the databases and additional manual search returned 1060 results. After discussion among the authors, the abstracts of records were covered, and 943 items were excluded for the reason that the topic of the papers was irrelevant (e.g., different research field) and/or did not address the review research question. Consequently, the full texts of the remaining 117 papers were accessed and 91 of them were excluded because they did not meet the eligibility criteria (e.g., lack of either objective measurement or subjective survey, etc.). The remaining 26 papers were included and eventually considered in the review. Figure 1 summarizes the selection process of the review records.

Table 1 shows the data extracted from the 26 studies considered in this review, reported according to the chronological order of publication. It is important to notice that, due to the variance in country, building type, and space type, the investigated sites by each selected study varied in scales.

Ten studies were developed for museums/exhibition spaces; Nine studies were dealing with shopping malls; Six studies were focused on transportation hub/stations; One study covered all three selected building types, the results of which were presented in the section of museums/exhibition spaces. Among these, twelve studies have reported both physical outcomes and individual responses. One study was performed within large-scale environmental surveys (the acoustic aspects of which were not necessarily the main ones).

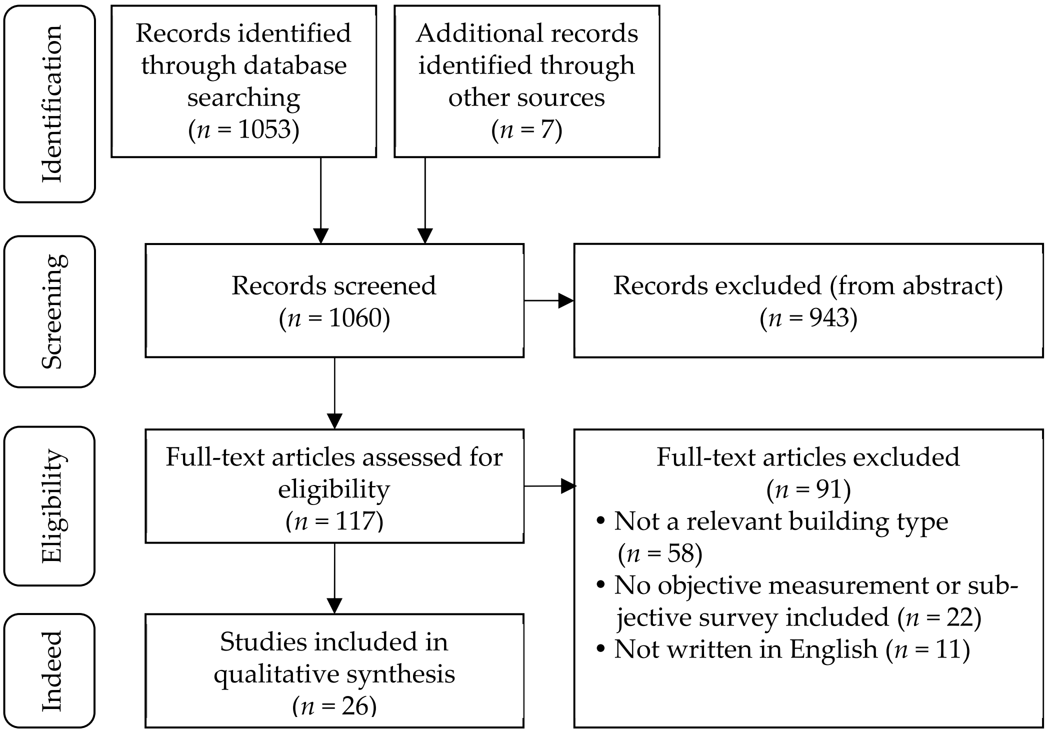


Figure 1. Flow of information through the different phases of the systematic review [24].

For the sake of reporting and discussion, the studies were grouped according to the selected building type of the abovementioned sample; methods and results are described in the following subsections, accordingly.

3.1. Museums/Exhibition Spaces

Orhan and Yilmazer [26] surveyed the courtyard of the Rahmi M. Koç Museum and its corridor, which was also an exhibition space, and one large exhibition space of the Erimtan Archaeology and Arts Museum in Ankara, Turkey to further generate a systematic categorization of museum content by exploring the visitor perception. The height of the investigated spaces of the former was 3.5 m for the first floor and 10.5 m for the courtyard, and that of the latter was 10.6 m. $L_{Aeq\text{-}20min}$ were measured on a weekend as 95.6 dB (L_{Amax}: 97.5 dB, L_{Amin}: 91.7 dB) in the former, and 94.4 dB (L_{Amax}: 96.5 dB, L_{Amin}: 93.1 dB) in the latter. It is worth mentioning that these sound levels in public buildings appear to be exceptionally high, but the authors do not provide further details. Following the guidance of ISO/TS 12913-2 about semi-structured interviews and five-point Likert scales for surveys, the investigated perceptual attributors were mainly "appropriate", "calm", "concentrating", "curious", "disturbing", "high", "positive", "uncomfortable", etc. It was concluded that visitor perceptions were mostly based on the sound contexts, rather than sound levels, even if measured sound levels were relatively high.

Sü Gül [27] conducted in situ tests in Hagia Sophia of Istanbul in Turkey and particularly simulated the exhibition states with a marble floor. The volume of each individual space ranged from 625 to 95,960 m^3. To determine the sound energy decays that occur in the different states of the space, the research considered several decay parameters and the degree of acoustical coupling. Among the many variables, the source-receiver distance and positioning within different sub-spaces appear to be the underlying determinant of multi-slope sound decay patterns. No subjective surveys were performed in this study.

D'Orazio et.al. [28] selected a highly attended exhibition space in the Archaeological Museum of Florence, Italy, assessing the reliability of a predictive dynamic model. The room was 28.0 in length, 9.30 in width, and 11.0 in height, and reverberation time-averaged over the octave band 500 to 1 kHz was 3.3 s. The objective measure included visitor flow,

$L_{\text{Aeq-1min}}$, and the number of people inside the spaces during a free-entrance day. The software simulation model involved the SPL attenuation among the visitors, Lombard slope and group size, communication quality related to SNR, and association between the number of visitors and acoustic condition. No subjective surveys were carried out in this study.

Yang and Kang [29] investigated two comparable sets of small box-shaped sequential exhibition spaces, of which one was equipped with a large-scale sound installation, in Tate Modern London, UK. The dimensions of small spaces were similar as 6.3 m in width, 6.3 m in length, and 4.9 m in height, with one exception of 13.0 m in length, 9.0 in width, and 9.8 in height. $L_{\text{Aeq-1min}}$ were measured between 66.8 to 39.7 dB in unoccupied condition, and from 68.3 to 58.8 dB in occupied condition on weekdays and weekends. To collect individual response of each space in sequence, the researchers conducted indoor soundwalks with two groups of subjects moving in opposite directions on the same path (i.e., towards/away from the primary source). Twelve perceptual attributes were extracted from both room acoustics and soundscape using five-point Likert scales, as "loudness", "clarity", "reverberance", "spaciousness", "listener envelopment", "intimacy", "warmth", and "stage support" for the former, and "directionality", "annoyance", "acoustic comfort" and "overall impression" for the latter. Perceptual loudness and listener envelopment were demonstrated to be statistically significant when users moved in two opposite directions to/from the primary source.

Mónica et al. [30] simulated the Archaeological Museum with transparent roof solutions in Lisbon, Portugal. The volumes of the investigated spaces were 19,600 and 38,145 m^3. The numerical software simulation was presented with selected objective parameters: The T range was between 1.0 and 4.3 s; C_{80} were between -8.2 and 2.6 dB; the EDT range was between 2.1 and 3.4 s; STI were between 0.25 and 0.41; D_{50} ranged between 0.04 and 0.18. No subjective surveys were found in this study.

Paxton et al. [31] investigated ultrasound in selected museums/galleries, shopping centres, and train stations. The difficulties of taking measurements with conventional equipment were highlighted. Tones were identified by SPL in the 20 kHz third-octave band. Five locations were measured in museum/gallery as 34, 43, and 46 dB, of which shopping centre at 1 location was not taken, and 2 locations in a railway station as 49 and 65 dB. The characteristics of the tones were consistent with the source being PA or VA system. Measured results did not exceed existing interim guidelines for public exposure to ultrasound, and existing research suggests that no significant undesirable effects would be anticipated following exposure to ultrasound of this nature for short periods. No subjective surveys were performed to the present.

Martellotta and Pon [32] measured the absorption coefficients of the Barberini tapestries during a temporary exhibition held in the Cathedral of St. John the Divine in New York City, USA. The largest St. James chapel, connected by a large opening of 70 m^2 and a much smaller door, had a floor surface of 245 m^2 and a volume of about 3100 m^3. Another two St. Ambrose and St. Savior chapels have smaller surfaces of 100 and 120 m^2. The entire floor area of the site was 11,200 m^2, spanning a length of 180 m and height of 70 m at the crossing and 37 m at the main nave. T_{15} was used considering the SNR, and significant differences appeared in the high-frequency range, while at low frequencies T_{15} values with and without tapestries were more similar and (only at 125 Hz) values measured with tapestries inside were slightly longer than those measured without tapestries. No subjective surveys were reported in this study.

Thanh Vi et al. [33] presented a six-week multisensory display using mid-air haptic technology integrated with sound for the Full Stop painting by John Latham at the Tate Britain art gallery in London, UK. The dimensions of the exhibition unit were set up as 3.45 m in width and 5.1 in length. They used a questionnaire with five-point Likert scales and interviews to collect the individual response on the importance of auditory sense to the display, of which the mean value turned out to be 4.23. In addition, from the feedback of the interview, other perceptual attributes by the visitors were described as "meaningful", "distracting", "random", etc.

Pon et al. [34] also targeted the absorption coefficients of the Barberini tapestries and tested in a 17.7 m square gallery with a 5.38 m high ceiling in Meadow Museum in Dallas, USA. Following the guidance of ISO 3382-2 standard, similar results [32] were obtained: Signiant differences appeared at high frequencies, while at low frequencies, T_{20} values with and without tapestries were more similar. In an empty room, T_{20} was rather long, and application of the tapestries on the walls caused a dramatic drop in T_{20} at high frequencies, and determined a more even distribution of sound absorption, and an increased diffusion. No subjective surveys were reported in this study.

Zimmer and Lorenz [35] installed a listening system at the Kunst Museum in Bonn, Germany, in the context of an exhibition comprising artworks of the painter August Macke with user evaluations. The questionnaires covered closed questions mainly based on the selection among several predetermined statements and ratings, which was assessed by visitors through "yes", "no", and "partly", and the evaluation of the combination of artwork and auditory information used "coherent", "consulting", "irritating", "boring", "enriching", and "succeed".

Okubo et al. [36] took measurements in a multi-purpose hall. For concerts and conventions, it contains 2004 seats. It could be altered to exhibitions where most of the floor area is flattened. The volume ranged from 19,125 to 32,025 m^3, and the T range was between 1.2 to 1.7 s. Three parameters were measured as the lateral component, the front/back ratio, and left/right ratio, of which the difference in "early" components was larger than those in "late" components. No subjective surveys were performed in this study.

3.2. Shopping Malls

Kanev [37] surveyed two kinds of shopping mall spaces perceived as acoustically uncomfortable: one was the largest space in the centre containing restaurants and a sitting area for food stores, and the other was long corridors or galleries in which walls were glass facades containing boutiques, small cafes and local areas for short rest in Russia. The volume of five cases selected for the former ranged from 29,500 to 10,600 m^3, and the heights were between 9.2 to 18.2 m. The volume of three cases selected for the latter had ranged from 14,500 to 31,000 m^3, and the length was between 112 to 234 m. Results showed that at middle frequencies $L_{\text{Aeq-1min}}$ were 7 to 10 dB higher in occupied condition when compared to unoccupied one. Normal voice levels at a distance of 1 m were about 60 dB, raised voices created 65 to 70 dB. The largest measured T_{20} and T_{30} was found in the largest food court as 5.1 s, and the smallest one was obtained in the smallest gallery as 2.7 s. Two T thresholds and three ranges were proposed for assessments, and the necessities of the acoustic absorption materials were suggested for surfaces and volumes. No subjective surveys were performed to the present.

Mediastika et al. [38] surveyed three shopping malls, including the Tunjungan Plaza (retail area 160,000 m^2), Grand City Mall (retail area 45,000 m^2) in Surabaya, and Malioboro Mall (retail area 22,000 m^2) in Yogyakarta, Indonesia, with both sighted and visually impaired participants. The measurements were carried out with the indoor soundwalks on three Saturdays, either around lunch or dinner time. $L_{\text{Aeq-10min}}$ were reported to be around 70 dB (L_{AFmax}: 90.5 dB, L_{AFmin}: 60.3 dB). Both off-site and in-situ surveys were used: A focus group discussion method was assigned for off-site to collect attributes as perceived by the participants, and then constructed in a closed-ended questionnaire for in situ. The questionnaire used three-point Likert scales and was subject-based. With sighted people, three soundscape dimensions were labelled as (1) "pleasantness" including "good", "neat", "modest", "warm", "comfortable" and "like"; (2) "space" including "crowded", "messy", and "tight"; and (3) "facilities" including "complete" and "clear signage". With visually impaired people, five soundscape dimensions were abstracted as (1) "pleasantness" including "happy", "good", "luxurious", "modern", "comfortable", and "like"; (2) "space" including "spacious" and "large"; (3) "eventfulness" including "noisy", "loud", and "clamorous";

(4) "danger" including "dangerous"; and (4) "direction" including "know the position". It was concluded that pleasantness and space were the two most prominent factors for both participants. The visually impaired people perceived more favourably than the sighted, and they could perceive soundscape dimensions of danger and direction with the hearing sense alone. It is of interest to know the relationship between objective and perceptual attributes. The authors indicated that acoustic perceptions were more influenced by crowds compared to SPL. For sighted people, the more crowded the shopping mall, the higher SPL was perceived. For visually impaired people, the strongest correlation exists between Leq and "noisy".

Alnuman and Altaweel [39] studied a large shopping mall in the very centre of Amman, Jordan, and chose shopping areas, entrances, food courts, and playing areas to explore the sound environment and its correlation to the acoustic comfort of the workers. $L_{\text{Aeq-3min}}$ were collected between 10:30 and 12:30, between 13:30 and 15:30, between 16:30 and 18:30, between 19:30 and 21:30 during the entire seven-day period. The values were measured as a minimum of 58 dB in the shopping area in the early morning and a maximum of 83 dB in the playing area in the evening. An increase was observed when comparing the afternoon and evening with the early morning and midday time; similarly, sound levels for the weekends were higher than weekdays. T_{20} or T_{30} were separately measured in an unoccupied condition as 0.9 s in the food court and 1.4 s at the main entrance. The surveys used five-point Likert scales in the questionnaire with "comfortable-uncomfortable" as well as "quiet-noisy". L_{Aeq} were found to be correlated to acoustic comfort and loudness of staff working at these locations.

Urbán et al. [40] investigated a large vestibule of the Shopping Centre Palace in Bratislava, Slovakia. The main volume of the space was 5750 m^3 and the total surface area of interior surfaces was 1850 m^2. It had a round shape with a diameter of 24 m with a dome-shaped partly transparent roof at a maximal height of 14.5 m. T_{30} and flutter echo were measured, and the former turned out to be 4.3 s at 1 kHz. The software simulation with different solutions based on user feedbacks approached the issue of background noise level, reverberation, and speech intelligibility. Large halls with parallel walls or circular shape with a distance between walls ca 9 m (e.g., 50 ms) will cause audible flutter echoes. No subjective surveys were detailed.

Meng and Kang [41] studied six shopping malls, including Qiu Lin (31,000 m^2), Tong Ji (10,000 m^2), Man Ha Dun (28,700 m^2), Suo Fei Ya (32,000 m^2), Jin An (45,000 m^2), and Hui Zhan (30,000 m^2) in China. $L_{\text{Aeq-300to500s}}$ were averaged between 9 a.m. and noon, between noon and 3 p.m., between 3 p.m. and 6 p.m. across seasons as 71.3, 73.3, 71.4, 70.8, 68.3, and 69.4 dB. The questionnaire using five-point Likert scales exploring loudness "quiet-loud" and acoustic comfort "uncomfortable-comfortable". The ratings for the former were 3.36, 3.52, 3.48, 3.32, 3.20, and 3.30, and those of the latter were 3.08, 2.73, 2.96, 2.80, 3.41, and 3.27. Results showed that loudness was influenced by visiting reason, visiting frequency, and length of stay. Acoustic comfort was affected by the above factors in addition to the season of visit. The ratings of users waiting for someone were lower in acoustic comfort, whereas users who went to the shopping malls more than once a month rated higher. The influences of the period of visit and accompanying person were found insignificant.

Dökmeci Yorukoglu and Yılmazer [42] selected an atrium (30,000 m^3) as food court area of the CEPA shopping centre in Ankara, Turkey, exploring associations between measured noise levels and users' responses. $L_{\text{Aeq-2hr}}$ were obtained between 10 a.m. and noon, between noon and 2 p.m., between 4 p.m., and 6 p.m., between 8 p.m. and 10 p.m. during the weekdays and weekends. Results reveal that the average value in unoccupied condition was 44 dB, and those in occupied condition were 63.5 and 68.3 dB for weekdays and weekends. The peak occurred between noon and 2 p.m., between 6 and 8 p.m. during weekdays, and the highest value was delivered between 4 p.m. and 6 p.m. at weekends. Opening and closing of visiting time displayed as lowest of a day. The questionnaire used five-point Likert scales investigating noisiness with "quiet-noisy". The subjective ratings of sound levels were demonstrated to correlate well with the measured ones, and noise level above 67 dBA led to a sudden increase in ratings.

Chen and Kang [43] chose three atriums in Sheffield's Meadowhall, one of the largest shopping malls in the UK. $L_{\text{Aeq-5min}}$ were obtained with an interval of one hour for weekdays and weekends. Unsurprisingly the former was systematically lower than the latter. The values were around 65 to 80 dB, and reached 72.5 to 76.3 dB because of music, 70.0 to 78.7 dB, and 67.8 to 72.0 dB because of public address systems. The highest one was delivered as 82.6 dBA at 12:30 a.m. because of a show. Although sound levels were rather different, the shapes of six spectra were similar with a peak at middle frequencies, and a considerably dropped at high frequencies. The investigated spaces generally featured long reverberation at all frequencies. The longest one was for a large space, or at middle frequencies, and the shortest one was for a long and narrow space, or at low frequencies. The questionnaire used five-point Likert scales investigating "annoying-favourable", "uncomfortable-comfortable", "loud-quiet", "noisy-quiet, "echoing-dead". The authors concluded associations between objective and subjective measures, e.g., level and acoustic comfort, EDT, and communication quality.

Skarlatos [44] measured the noise levels in the commercial centres of Patras, Greece, which covered 10 measuring sites 5 days per week and 2 h per day (10:30 a.m. to 12:30 p.m.) with an interval of 10 min to examine whether the noise energy emitted by the source and the measured noise level was normally distributed. The $L_{\text{Aeq-3min}}$ corresponding to the whole sample was 80.24 dB and the 95% confidence interval was between 79.89 and 80.55 dB. No subjective surveys were reported.

Hopkins [45] surveyed the corridors of the West Edmonton mega-mall in Canada. The measurements were taken between 10 a.m. and noon, between 2 p.m. and 5 p.m., and between 7 p.m. and 9 p.m. during the entire seven-day period, and sound levels ranged between 58 to 89 dBA. The weekdays mornings and afternoons exhibited the lowest and highest modes, paralleling the daily troughs and peaks in visiting time. The same held true for the patron visitation and sound level peaks on Saturday and Sunday afternoons and their throughs on Saturday morning and Sunday night. To ascertain the attributes ascribed to the mega-mall, three off-site surveys using a written questionnaire were conducted. Words elicited by participants were more likely to be positive as "fun", "fantastic", "exciting" than negative ones as "overcrowded", "confusing", "glitzy" in addition to spatial as "big", "huge", and "large". Among the 576 negative words used, the term with the greatest frequency of occurrence was "noisy".

3.3. Transport Hubs/Stations

Wang et al. [46] took the recordings in 9 airports, 14 railway stations, 4 bus stations, and 7 subway stations (a total of 34) to explore the acoustic sequences on noise acceptance, that is, when the users were staying or walking in a transport hub, sequential sounds form sequence sounds sessions. The listening-test surveys, as an aspect of indoor soundscape research, extracted 209 sections of 30 s acoustic units. The acoustic units were divided into strong, medium, and weak levels, and compiled into 37 pieces of acoustic sequences, which were then subjected to four tests for acceptance evaluations using a 0-to-10 opinion scale. The effects of the acoustic sequence were demonstrated to improve the sound experience in such spaces.

Wu et al. [47] investigated acoustic comfort of six spaces, including seating area (11,100 m^3), security check (180 m^3), ticket check, ticket lobby (864 m^3), restaurant (172 m^3), and shop (288 m^3) of Harbin railway station in China. $L_{\text{Aeq-5min}}$ were obtained between 8 a.m. and 6 p.m. with a one-hour interval. The questionnaire used five-point Likert scales surveying "uncomfortable-comfortable", "noisy-quiet", "loud-soft", "low-high", "long-short", and "clear-unclear". Results revealed that the comfort and communication level decreased with increasing SPL, which were all below 70 dB in the seating area, ticket lobby, and shops. The restaurants were noisiest at 75.1 dB, and comfort was rated higher than those in ticket check. The mean value of comfort in the railway station was acceptable as 3.65. However, comfort in the seating area and shop were higher as 3.81 and 3.91, respectively, and those in the restaurant were lower as 3.28. The seating area, shop area, and ticket lobby were quieter, and the areas with high concentrations of users were "noisy". T was related to space scale: the larger the space is, the longer it is. As it increased, comfort and communication level increased. Participants felt reverberation in space when it exceeded 4.5 s.

Yilmazer and Bora [48] selected the park, station entrance, and underground platform of Akköprü metro station in Turkey. The station was 895 m in length and 216 m in width. The height of the entrance level was 3.19 m and the height of the platform level was 3.36 m from the base to the suspended aluminium ceiling, and 7.33 m from the metro rails to the top of the metro tunnel. The methodologies involved the measurements of $L_{\mathrm{Aeq\text{-}15min}}$, soundwalks with noise annoyance and $L_{\mathrm{Aeq\text{-}30s}}$, and listening tests on the relationships between space recognition and sound marks. The in-situ measurements were conducted on Saturday afternoon. Results show that noise levels were similar between 55 to 60 dB in the park and station entrance, while annoyance was higher in the station entrance. On the underground platform, L_{Aeq} were lower than those at the station entrance, yet annoyance was close. The listening test asked the participants to describe the recorded space from 17 perceptual adjective pairs and define the sound sources. Only half of the participants were able to correctly determine the function of the spaces; for indoor spaces, they chose words most frequently as "unpleasant", "stressing", and "artificial".

Han et al. [49] investigated six subway stations across seasons in Seoul, South Korea, to explore thermal, air, light, acoustic, and passengers' overall comfort. The results concerning the acoustic comfort were only reported with two cases, of which the depths of the concourse were 6.0 and 8.0 m, and those of platform (two-platform form) were 10.2 and 23.1 m, respectively. In summer, noise levels were 67.9 and 63.3 dB in the concourses, and 65.3 and 62.9 dB on the platforms. In Fall, noise levels were reported to be 64.8 and 63.3 dB in the concourses, and 64.2 and 61.7 dB on the platforms. In winter, noise levels were measured to be 65.5 and 61.3 dB in the concourses, and 64.3 and 61.1 dB on the platforms. The questionnaire surveys were conducted between 8 a.m. and 10 p.m. for two days in each season. Five-point Likert scales were used to approach "comfortable-uncomfortable". As a result, "uncomfortable" was selected more than "comfortable" compared to other physical aspects in all three seasons. Since the associations between objective measure and subjective response turned out to be very low, the authors suggested rethinking of methodologies of surveying comfort in such spaces with a short visiting time.

Tardieu et al. [50] sampled six train stations, including Avignon TGV, Bordeaux St Jean, Lille Flandres, Nantes, Paris Gare de l'Est and Rennes in France. The level of each sample was between 65 and 70 dBA. The listening tests composed of several steps, and the first experiment employed a free-categorization task with free verbalizations revealing three main types of acoustical information as sound sources, human activities, and room effects. The perceptual attributes referred to room effects including "close", "confused", "large", "small", "external", "closed", "isolated", "echoes", "resonances", and those concerning the personal judgments including "quiet", "noisy", "rhythmic", "intimate", and "pleasant". The results showed that people were able to recognize the type of space (platform, hall, etc.) just by listening to its soundscape.

Nowicka [51] measured three underground stations, including Metro Politechnika, Metro Wierzbno, and Metro Stoklosy in Warsaw, Poland. The enclosures were one-platform stations of 10.0 to 11.0 m in width. The heights and widths (at platform level) were the same as 6.0 m and 20.0 m, respectively. Measured EDT increased with the source distance in Metro Stoklosy, while those of the other two stations were independent of source distance at 500 Hz. RASTI was better in Metro Stoklosy confirming better reverberation condition with absorptive materials on ceilings. It was found that rectangular cross-section led to better RASTI. No subjective survey was related in this research.

Table 1. List of studies included in the systematic review in chronological order of publication. The country, building type, space type, objective measure, perceptual attribute, and methodologies were reported. The studies often included several experimental conditions and sound levels. Therefore, for more specific information, it is possible to refer to the original studies.

Reference	Country	Building Type	Space Type	Objective Measure	Perceptual Attribute	Methodologies
Kanev [37]	Russia	Shopping Mall	Multiple	$L_{\text{Aeq-1min}}$, T_{20}, T_{30}	-	Measurement
Mediastika et al. [38]	Indonesia	Shopping Mall	Multiple	$L_{\text{Aeq-10min}}$, L_{Amin}, L_{Amax}	Annoyance: *Comfortable-Uncomfortable, Good-Bad;* Affective Quality: *Clamorous-Quiet, Clear Signage-Unclear, Crowded-Empty, Noisy-Clam, Complete-Incomplete, Cool-Warm, Happy-Unhappy, Like-Dislike, Luxurious-Modest, Modern-Ancient, Mute-Loud, Neat-Messy, Safe-Dangerous;* Acoustic Spatiality: *Large-Small, Tight-Loose, Spacious-Narrow, Know the position-don't*	Measurement, Soundwalk
Orhan and Yilmazer [26]	Turkey	Museum /Exhibition space	Multiple	$L_{\text{Aeq-20min}}$, L_{Amin}, L_{Amax}	Annoyance: *Disturbing, Positive, Uncomfortable;* Affective Quality: *Appropriate, Calm, Concentrating, Curious, High*	Measurement, Questionnaire
Sü Gül [27]	Turkey	Museum /Exhibition space	Multiple	SPL, T_{30}	-	Measurement, Simulation
D'Orazio et al. [28]	Italy	Museum /Exhibition space	Single	$L_{\text{Aeq-1min}}$, SNR	-	Measurement, Simulation
Yang and Kang [29]	UK	Museum /Exhibition space	Sequential	$L_{\text{Aeq-1min}}$	Annoyance: *Acoustic Comfort, Annoyance;* Affective Quality: *Overall Impression;* Room-Acoustic Quality: *Clarity, Intimacy, Listener Envelopment, Loudness, Reverberation, Spaciousness, Stage Support, Warmth;* Acoustic Spatiality: *Directionality*	Measurement, Soundwalk
Wu et al. [47]	China	Transportation hub/station	Multiple	$L_{\text{Aeq-5min}}$, T_{20}	Annoyance: *Uncomfortable-Comfortable;* Affective Quality: *Noisy-Quiet, Loud-Soft;* Room-Acoustic Quality: *Clear-Unclear (Intelligibility), Low-High (Loudness), Long-Short (Reverberation)*	Measurement, Questionnaire
Alnuman and Altaweel [39]	Jordan	Shopping Mall	Multiple	$L_{\text{Aeq-3min}}$, T_{20}, T_{30}	Annoyance: *Comfortable-Uncomfortable;* Room-Acoustic Quality: *Quiet-Noisy*	Measurement, Questionnaire
Mónica et al. [30]	Portugal	Museum /Exhibition space	Multiple	T, C_{50}, EDT, STI, D_{80}	-	Simulation
Wang et al. [46]	-	Transportation hub/station	Multiple	-	Annoyance: *Acceptance*	Listening test, Questionnaire
Paxton et al. [31]	-	Museum /Exhibition space, Shopping Mall, Transportation hub/station	Multiple	SPL in the 20 kHz third-octave band	-	Measurement
Martellotta and Pon [32]	USA	Museum /Exhibition space	Multiple	SNR, T_{15}	-	Measurement, Simulation
Yilmazer and Bora [48]	Turkey	Transportation hub/station	Multiple	$L_{\text{Aeq-15min}}$, $L_{\text{Aeq-30s}}$	Annoyance: *Annoying-Not annoying, Disturbing-Comfortable;* Affective Quality: *Agitating-Calming, Crowded-Uncrowded, Discordant-Harmonic, Dark-Light, Empty-Joyful, Exciting-Gloomy, Hard-Soft, Heavy-light, Loud-Quiet, Loud-Soft, Rough-Smooth, Stressing-Relaxing, Sharp-not sharp, Strange-Common, Unsteady-Steady, Unpleasant-Pleasant;* Acoustic Spatiality: *Far Away-Nearby*	Listening test Measurement, Questionnaire,
Thanh Vi et al. [33]	UK	Museum /Exhibition space	Multiple	-	Annoyance: *Important;* Affective Quality: *Distracting, Meaningful, Random*	Interview, Listening test, Questionnaire

Table 1. *Cont.*

Reference	Country	Building Type	Space Type	Objective Measure	Perceptual Attribute	Methodologies
Pon et al. [34]	USA	Museum /Exhibition space	Single	T_{20}	-	Measurement, Simulation
Urbán et al. [40]	Slovakia	Shopping Mall	Multiple	T_{30}, flutter echo	-	Measurement, Simulation
Han et al. [49]	South Korean	Transportation hub/station	Multiple	L_{Aeq}	Annoyance: *Uncomfortable-Comfortable*	Measurement, Questionnaire
Meng and Kang [41]	China	Shopping Mall	Multiple	$L_{\text{Aeq-300-500s}}$	Annoyance: *Comfortable-Uncomfortable;* Room-acoustic Quality: *Quiet-Loud*	Measurement, Questionnaire
Dökmeci Yorukoglu and Yilmazer [42]	Turkey	Shopping Mall	Multiple	$L_{\text{Aeq-2hr}}$	Annoyance: *Quiet-Noisy*	Measurement, Questionnaire
Zimmermann and Lorenz [35]	Germany	Museum /Exhibition space	Multiple	-	Annoyance: *Irritating*; Affective Quality: *Coherent, Boring, Enriching, Succeed*	Listening test, Questionnaire
Tardieu et al. [50]	France	Transportation hub/station	Multiple	$L_{\text{Aeq-10s}}$	Affective Quality: *Intimate, Noisy, Pleasant, Quiet, Rhythmic;* Acoustic Spatiality: *Closed Space, Confused, Large (Reverberation), Echoes, External, Isolated, Resonances, Small (Reverberation)*	Listening test, Questionnaire
Nowicka [51]	Poland	Transportation hub/station	Single	EDT, RASTI	-	Measurement, Simulation
Chen and Kang [43]	UK	Shopping Mall	Multiple	EDT, T, $L_{\text{Aeq-5min}}$	Annoyance: *Annoying-Favourable, Uncomfortable-Comfortable;* Affective Quality: *Noisy-Quiet;* Room-acoustic Quality: *Echoing-Dead (Reverberation), Loud-Quiet (Loudness)*	Measurement, Questionnaire
Skarlatos [44]	Greece	Shopping Mall	Multiple	$L_{\text{Aeq-3min}}$	-	Measurement
Okubo et al. [36]	-	Museum /Exhibition space	Single	LC, FBR, LRR	-	Measurement
Hopkins [45]	Canada	Shopping Mall	Multiple	$L_{\text{Aeq-10s}}$	Affective Quality: *Confusing, Exciting, Fun, Fantastic, Glitzy, Overcrowded;* Room-acoustic Quality: *Loud; Noisy;* Acoustic Spatiality: *Big, Huge, Large*	Measurement, Questionnaire

4. Discussion

4.1. Objective Measures

The most commonly used acoustic measures in the investigated spaces were sound pressure levels (SPL), and more specifically often considered as A-weighted equivalent sound levels (L_{Aeq}) (the sound level in decibels having the same total sound energy as the fluctuating level measured, with A-weighting system on frequency domain, which generally reflects human response more precisely than other weightings), and reverberation time (T). The former was mainly reported as the averaged noise level during visiting time, and the latter was majorly approached by reverberation time measured under the condition without users.

The L_{Aeq} across buildings types turned out to be equivalent, while the intervals across studies were sometimes inconsistent: the average value was normally around 60 to 70 dB. It reached approximately 90 dB in the case of PA system, music, and higher attendance, and was lower than 55 dB when the space was not busy even during visiting time.

Concerning the different intervals selected for L_{Aeq} (e.g., 1 min, 3 min, 5 min, 10 min, 15 min, 2 h, etc.), it is found that there was currently nothing to connect the selection to space scale, space type as well as sound source. Most studies failed to thoroughly explain their reasons. Some studies [41] may choose the measuring duration in accordance with the goal of the users, expecting the selected interval to cover users' visiting time, which could be highly dependent on the usage and preference of the space. The intervals for museums/exhibition spaces and transportation hubs/stations are in general shorter than those for shopping malls: the former could be within 10 min, and the latter could be last up to 2 h.

On the other hand, the measured T-values in museums/exhibition spaces and shopping malls across locations were between 1.0 and 3.0 s, and those in transportation hubs/stations could be larger than 4.0 s. The larger the spaces are, in general, the larger the values are. Concerning the dynamic ranges for measuring T-values (e.g., T_{15}, T_{20}, T_{30}, etc.), T_{20} was more frequently to be adopted because in some cases the radiated source power is not sufficient to rely on T_{30}.

In clarifying the research question as objective items to characterize the acoustics of such space, it is known that shopping malls exhibited regular sound-level modes daily and weekly, which are considered to be consistent with the users' attendance, and the results obtained in different locations with various functions were rich for references. The L_{Aeq} range in transportation hubs/stations could be the largest, since some spaces were semi-open or open. However, the specific data focusing on the users' content to approach the dynamic aspects, such as visitors' amount in the spaces, in museums/exhibition spaces and transportation hubs/stations are rather hard to find. Yet, it is not known which interval is most suitable for L_{Aeq} for each building type. The variety of the current state may also show that having a consistent measure is not a perfect solution. Influence of space scale and space type should be taken into account together when selecting the intervals in future works, for example, a larger space may be encountered with more users to hold more events, and therefore the selected interval for L_{Aeq} is required to be longer.

4.2. Perceptual Attributes

The used subjective measures for perceptual attributes were found to be abundant. Most studies collected individual responses through surveys, which assessed six aspects, including the overall acoustic evaluation, sound noticeability, sound preference, soundscape descriptors, sound descriptors, and control, covering topics in both room acoustics and soundscape. The subjective items characterizing the acoustics of spaces could be classified into four categories as below:

- Annoyance: "annoying" or "comfortable", etc., demonstrating the positive/negative effects of the sound environments
- Affective Quality: "cool" or "warm", etc., which is associated with the emotional fluctuations of individuals caused by the sound or acoustic activities
- Room-Acoustic Quality: "loudness" or "reverberation", etc., which neutrally (i.e., no valence-related scales) describes the auditory perceptions of the space
- Acoustic Spatiality: "directionality", "large", etc., which is a subjective impression rather than a measure related to the spatial localization or recognition of sound source or sound environment.

The former two categories, that is, annoyance and affective quality, were focusing on the individual-related changes, and the latter two, that is, room-acoustic quality and acoustic spatiality, were treated objectively. As it can be seen, perceptual attributes as annoying, comfortable, and loudness could be the basic descriptors which have been most frequently surveyed at present and used to measure the levels subjectively in the spaces. The selections of other measures and their results were highly project-specific, and it is reasonable to believe that the comparisons across building types could be unsuitable at this stage.

In terms of special considerations on users' dynamics of subjective perception, some attributes appeared to be concerned with a number of users, such as "crowded-uncrowded", "crowded-empty", and "unsteady-steady". Meanwhile, some attributes were applied with the source noticeability, such as "directionality", "far away-nearby", and "know the position-don't". However, detailed results of these descriptors were limited, comparing to the reports of loudness and comfort.

Regarding the spatial features of sound environment of such large public, some attributes looking at the space scale, such as "large-small", "tight-loose", "spacious-narrow", were also found to be of interests to be known in one or two surveys, especially for the visually impaired people, besides the "reverberation" or "intelligibility".

Most studies have confirmed certain associations between objective and subjective measures, although they were discussing sound levels and annoyance, or loudness. Some studies [29,46] started to consider user-related factors together, such as acoustic sequence in sound levels and users' directions. Some studies [26] pointed out that the effects of sound source content were more dominant than those of sound levels in perceptions of such spaces. Overall, the present deficiencies were somehow similar to those of objective measures, that is, overlooking the effects of space scale and type, as well as sound source. Given the current application of these subjective measures are not standardized with building types, four basic perceptual assessments belonging to each category are recommended: (1) "annoying-not annoying"; (2) "crowded-uncrowded"; (3) "long-short" (reverberation), and (4) "far away-nearby". In addition, other attributes related to building type affecting the crowd are suggested, such as "concentrating" for museums/exhibition spaces, "exciting" for shopping malls, and "clear" for transportation hubs/stations. These main four perceptual constructs should be the core around which developing assessment scales, rather than proposing long lists of items for users to assess.

4.3. Methodologies

The methodologies involved in this review are mainly four approaches: (1) measurement; (2) questionnaire/interview; (3) listening test; (4) software simulation. The former two were in general applied to collect in-situ data, and the latter two were mainly adopted to interpret or solve the issues that were considered to be unreasonable to reach by the former. This review did not find any experiment using listening test for shopping malls, all of which were developed as in situ measurements, or questionnaire, or interviews. However, for transportation hubs/stations, in collecting the subjective data, the method of listening test was more frequently to be adopted rather than in-situ survey. In terms of museums/exhibition spaces, there were more experiments dependent on software simulation [52]. Some sites were functioning as performing spaces and simulated for exhibition configurations.

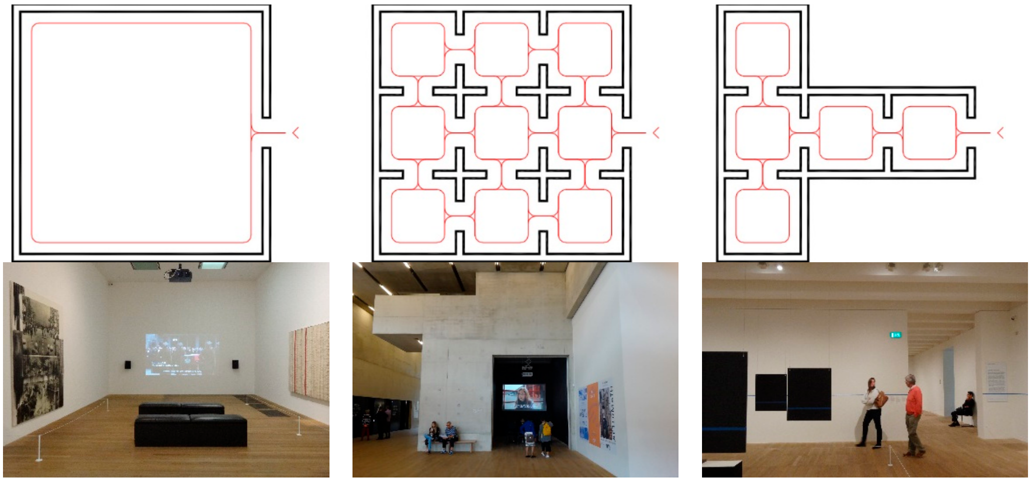
Normally, the methodologies of in situ investigation on such a large public environment would inevitably consider survey time and locations. The measurements, in obtaining the physical outcomes of the site, were conducted in three or four blocks, as morning, midday, and evening, and take the entire seven-day period in order to cover weekends and weekdays, especially for shopping malls. Some studies [41,49] lasted four seasons. The selection of measuring locations was to cover a representative sample of the case, otherwise, it was intended for the specific research questions, such as space types, or practical problems. The questionnaire and interviews usually use five-point Likert scales, with either open or close end questions, probably associated with indoor soundwalk (a soundscape method that implies a walk in an indoor area with a focus on listening to the acoustic environment [14]). Aside from this feature, the divisions between the three selected building types and the other ones which were not targeted in this review of the methodologies were in general subtle to spot at present.

Comparatively, the methodologies of listening test and software simulation were found to be less focused on the temporal and spatial features of the site in this context. Most studies were addressing the prediction accuracy of theoretical solutions in such spaces through software simulation exploring the potentials in using decay and attenuation of objective parameters. Furthermore, listening tests were aimed to find the exploratory factors related and unrelated to the dynamics of acoustic environment, such as acoustic sequence and users' attendance. These attempts were gradually filling the vacancy in this area.

Overall, these methods have potential advancements, and they are supposed to develop with the theoretical advances, technique innovations, or social changes, such as the issues with Covid-19.

4.4. Effects on Design

The investigated studies included in this review of large public buildings were sorted into three space types: single, multiple, and sequential ones. Figure 2 illustrates, for example, the configurations of these three space types by museums/exhibition spaces (take Tate Modern, UK, as an example). After an overview of space type and space scale across studies, it is concluded that the investigated spaces of museums/exhibition spaces could be single and multiple, which were smaller and more unified with units. Those of shopping malls and transportation hubs/stations, either corridors, atriums, or platforms, were much larger in scales and more complex as multiple spaces. However, although most studies reported their case selection with volumes or areas, the effects of these space factors were not always being reflected with results.



(**a**) (**b**) (**c**)

Figure 2. Configurations of space type. (**a**) single; (**b**) multiple; (**c**) sequential.

The outputs of acoustic and/or indoor soundscapes investigations in such spaces are growing. Overall, the sound environments of these large public buildings were perceived to be uncomfortable to some extent. Currently, they inform that the design of such spaces should focus the performance of background noise level, and sound reverberation. Based on the physical outcomes obtained by measurements and software simulation, some studies [28] for museums/exhibition spaces suggested users' control, or presented conditional results, e.g., with/without the investigated exhibits, to avoid detrimental effects of noise level. Some studies [37] for shopping malls and transportation hubs/stations [51] put forward advice on the selections of space scale, shape with different acoustic absorption solutions. Feedbacks from the users certainly helped those seeking sufficient acoustic comfort besides loudness and speech intelligibility, for example, the results of some studies [40] indicated that the differences between large and small space scales were obvious. On balance, even a good objective led to bad subjective sometimes. The research on objective measure and perceptual attributes are not comparable at this moment. Objective parameters are less than subjective parameters, and therefore they are still basic in application. In looking for objective parameters or creating a new one in this context, it could be possible to take the direction to/from the source factor into account. The integration design of indoor soundscape will also promote the sound environment of such large public buildings in tune with specific functions of such space.

4.5. Limitations

Given the exploratory nature of the review, this study could be limited since it eliminated the ones without peer review (e.g., conference papers, book chapters, etc,) and not in English. Furthermore, the search strategies to cover the targeted public spaces would meet limitations, although the authors have done their best to avoid missing studies using other definitions on such spaces. Extensive discussion among the authors, with input from other experts in the field was aimed at compensating for the abovementioned limitations.

5. Conclusions

This paper reported on the sound environments in large public spaces for crowd transit. For this purpose, a systematic review in accordance with the PRISMA guidelines was performed. After the screening process, the dataset resulted in twenty-six items that were sorted into three groups, depending on the building types, that is: museums/exhibition spaces, shopping malls, and transposition hubs/stations, of the investigation. Having substantially different methodological approaches, the studies were qualitatively analysed. The review presented obvious significances in sound environments between such spaces and other ones. The main conclusions are:

- The most commonly used objective measures were SPL, and more specifically often considered as L_{Aeq}, and T. The intervals across studies are currently inconsistent, and the selection is recommended to take the space scale factor into account.
- The used subjective measures can be classified into four categories, including annoyance, affective quality, room-acoustic quality, and acoustic spatiality. Four basic perceptual assessments for special consideration on dynamic content are accordingly suggested as "annoying-not annoying", "crowed-uncrowded", "long-short (reverberation)", and "far away-nearby". The other measures can be project-specific.
- The adopted methodologies involve measurement, questionnaire/interview, listening test and software simulation. It is necessary for the former two to consider temporal and spatial features of such spaces, and the latter two will lead to a better understanding of users' exposure in such spaces, e.g., acoustic sequence and user amount.
- The outputs of acoustic and/or indoor soundscapes investigations inform that improvement of background noise level, e.g., 90 dB in museum/exhibition spaces, and sound reverberation, e.g., over 4.0 to 5.0 s in shopping malls and transportation hubs/station are of fundamental importance. Sufficient acoustic comfort for building types can be achieved with integrated design of indoor soundscape.

The review qualitatively showed an increasing interest on sound to enhance users' health and well-being in such large public spaces. Apart from the further work on association between objective and subjective measures, the supplement of dynamic content will hopefully renew the users' experience and improve the indoor environmental quality.

Author Contributions: Conceptualization, T.Y., F.A. and J.K.; methodology, T.Y., F.A. and J.K.; formal analysis, T.Y. and F.A.; investigation, T.Y.; resources, J.K.; data curation, T.Y.; writing—original draft preparation, T.Y. and F.A.; writing—review and editing, T.Y., F.A. and J.K.; supervision, F.A. and J.K.; project administration, J.K.; funding acquisition, J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research programme (grant agreement No. 740696).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No datasets were generated or analyzed during the current study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Barron, M.B. Using the standard on objective measures for concert auditoria, ISO 3382, to give reliable results. *Acoust. Sci. Technol.* **2005**, *26*, 162–169. [CrossRef]
2. Kuttruff, H. *Room Acoust*; Spon Press: London, UK, 2000.
3. Pelorson, X.; Vian, J.-P.; Polack, J.-D. On the variability or Room Acoust. Parameters: Reprod. and Stat. Validity. *Appl. Sci.* **1992**, *37*, 175–198.
4. *ISO 3382–1:2009 Acoustics—Measurement of Room Acoustic Parameters—Part 1: Performance Spaces*; International Organization for Standardization: Geneva, Switzerland, 2009.
5. *ISO 3382-2:2008 Acoustics—Measurement of Room Acoustic Parameters—Part 2: Reverberation Time in Ordinary Rooms*; International Organization for Standardization: Geneva, Switzerland, 2008.
6. *ISO 3382-3:2012 Acoustics—Measurement of room Acoustic Parameters—Part 3: Open Plan Offices*; International Organization for Standardization: Geneva, Switzerland, 2012.
7. Tang, S.K.; Chan, D.W.T.; Chan, K.C. Prediction of sound-pressure level in an occupied enclosure. *J. Acoust. Soc. Am.* **1997**, *101*, 2990–2993. [CrossRef]
8. Holger Rindel, J. Verbal communication and noise in eating establishments. *Appl. Sci.* **2010**, *71*, 1156–1161.
9. Hodgson, M.; Steininger, G.; Razavi, Z. Measurement and prediction of speech and noise levels and the Lombard effect in eating establishments. *J. Acoust. Soc. Am.* **2007**, *121*, 2023–2033. [CrossRef] [PubMed]
10. Devos, P.; Aletta, F.; Thomas, P.; Vander Mynsbrugge, T.; Petrovic, M.; Van de Velde, D.; De Vriendt, P.; Botteldooren, D. Application of a Prediction Model for Ambient Noise Levels and Acoustical Capacity for Living Rooms in Nursing Homes Hosting Older People with Dementia. *Appl. Sci.* **2020**, *10*, 4205. [CrossRef]
11. Aletta, F.; Astolfi, A. Soundscapes of buildings and built environments. *Build. Acoust.* **2018**, *25*, 195–197. [CrossRef]
12. Kang, J. Acoustic comfort in non-acoustic buildings: A review of recent work in Sheffield. *Proc. Inst. Acoust.* **2003**, *25*, 125–132.
13. Kang, J. Acoustic quality in non-acoustic public buildings. *Tech. Acoust.* **2006**, *25*, 513–522.
14. Xiao, J.; Aletta, F. A soundscape approach to exploring design strategies for acoustic comfort in modern public libraries: A case study of the Library of Birmingham. *Noise Mapp.* **2016**, *3*, 264–273. [CrossRef]
15. Dökmeci Yorukoglu, P.N.; Kang, J. Analysing Sound Environment and Architectural Characteristics of Libraries through Indoor Soundscape Framework. *Arch. Acoust.* **2016**, *41*, 203–212. [CrossRef]
16. Dökmeci Yorukoglu, P.N.; Kang, J. Development and testing of Indoor Soundscape Questionnaire for evaluating contextual experience in public spaces. *Build. Acoust.* **2017**, *24*, 307–324. [CrossRef]
17. Yilmazer, S.; Acun, V. A grounded theory approach to assess indoor soundscape in historic religious spaces of Anatolian culture: A case study on Hacı Bayram Mosque. *Build. Acoust.* **2018**, *25*, 137–150. [CrossRef]
18. Torresin, S.; Aletta, F.; Babich, F.; Bourdeau, E.; Harvie-Clark, J.; Kang, J.; Albatici, R. Acoustics for Supportive and Healthy Buildings: Emerging Themes on Indoor Soundscape Research. *Sustainability* **2020**, *12*, 6054. [CrossRef]
19. Torresin, S.; Albatici, R.; Aletta, F.; Babich, F.; Oberman, T.; Siboni, S.; Kang, J. Indoor soundscape assessment: A principal components model of acoustic perception in residential buildings. *Build Environ.* **2020**, *182*, 107152. [CrossRef]
20. *ISO 12913-1:2014 Acoust.—Soundscape—Part 1: Definition and Conceptual Framework*; International Organization for Standardization: Geneva, Switzerland, 2014.
21. *BS 5839-1:2017 Fire Detection and Fire Alarm Systems for Buildings.—Part 1: Code of Practice for Design, Installation, Commissioning and Maintenance of Systems in Non-Domestic Premises*; British Standards Institute: London, UK, 2017.
22. *BS 5839-6:2019 Fire Detection and Fire Alarm Systems for Buildings.—Part 6: Code of Practice for the Design, Installation, Commissioning and Maintenance of Fire Detection and Fire alarm Systems in Domestic Premises*; British Standards Institute: London, UK, 2019.
23. Everest, F.A.; Pohlmann, K. *Master Handbook of Acoustics*; McGraw-Hill/TAB Electronics: New York, NY, USA, 2009.
24. Liberati, A.; Altman, D.G.; Tetzlaff, J.; Mulrow, C.; Gøtzsche, P.C.; Ioannidis, J.P.; Moher, D. The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration. *PLoS Med.* **2009**, *6*, e1000100. [CrossRef]
25. Aletta, F.; Oberman, T.; Kang, J. Associations between Positive Health-Related Effects and Soundscapes Perceptual Constructs: A Systematic Review. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2392. [CrossRef]
26. Orhan, C.; Yilmazer, S. Harmony of context and the built environment: Soundscapes in museum. *Appl. Acoust.* **2020**, *173*, 107709. [CrossRef]
27. Sü Gül, Z. Exploration of room acoustics coupling in Hagia Sophia of Istanbul for its different states. *J. Acoust. Soc. Am.* **2020**, *149*, 320–339. [CrossRef]
28. D'Orazio, D.; Montoschi, F.; Garai, M. Acoustic comfort in highly attended museums: A dynamical model. *Build Environ.* **2020**, *183*, 107176. [CrossRef]
29. Yang, T.; Kang, J. Subjective evaluation of sequential spaces. *Appl. Acoust.* **2020**, *161*, 107139. [CrossRef]
30. Mónica, M.; Mendonça, P.; Guedes, J.; Carvalho, A. Roof Replacement of a Heritage Building Using Transparent Solutions: Room Acoustic Performance Comparison. *Int. J. Archit. Herit.* **2020**, 1777593. [CrossRef]
31. Paxton, B.; Harvie-Clark, J.; Albert, M. Measurements of ultrasound from public address and voice alarm systems in public places. *J. Acoust. Soc. Am.* **2018**, *144*, 2548–2553. [CrossRef]

32. Martellotta, F.; Pon, L. On-site acoustical characterization of Baroque tapestries: The Barberini collection at St. John the Divine Cathedral. *J. Acoust. Soc. Am.* **2018**, *144*, 1615–1626. [CrossRef]
33. Thanh Vi, C.; Ablart, D.; Gatti, E.; Velasco, C.; Obrist, M. Not just seeing, but also feeling art Mid-air haptic experiences integrated in a multisensory art exhibition. *Int. J. Hum.-Comput. Int.* **2017**, *108*, 1–14.
34. Pon, L.; Douglas, S.; Martellotta, F. Sound absorption measurements under strongly non-diffuse conditions: The case of the Pastrana tapestries at Meadows Museum in Dallas. *Acta Acust. United Acust.* **2016**, *102*, 955–962. [CrossRef]
35. Zimmermann, A.; Lorenz, A. LISTEN: A user-adaptive audio-augmented museum guide. *User Model User-Adapt Interact* **2008**, *18*, 389–416. [CrossRef]
36. Okubo, H.; Otani, M.; Ikezawa, R.; Komiyama, S.; Nakabayashi, K. A system for measuring the directional room acoustical parameters. *Appl. Acoust.* **2001**, *62*, 203–215. [CrossRef]
37. Kanev, N. Study and improvement of acoustic conditions in public spaces of shopping malls. *Acoustics* **2021**, *3*, 137–155. [CrossRef]
38. Mediastika, C.; Sudarsono, A.; Kristanto, L. Indonesian shopping malls: A soundscape appraisal by sighted and visually impaired people. *Archit. Eng. Des. Manag.* **2020**. [CrossRef]
39. Alnuman, N.; Altaweel, M.Z. Investigation of the Acoustical Environment in A Shopping Mall and Its Correlation to the Acoustic Comfort of the Workers. *Appl. Sci.* **2020**, *10*, 1170. [CrossRef]
40. Urbán, D.; Zrneková, J.; Zat'ko, P.; Maywal, C.; Rychtáriková, M. Acoustic comfort in atria covered by novel structural skins. *Procedia Eng.* **2016**, *155*, 361–368. [CrossRef]
41. Meng, Q.; Kang, J. Influence of Social and Behavioural Characteristics of Users on Their Evaluation of Subjective Loudness and Acoustic Comfort in Shopping Malls. *PLoS ONE* **2013**, *8*. [CrossRef] [PubMed]
42. Dökmeci Yorukoglu, P.N.; Yılmazer, S. Relationships between Measured Levels and Subjective Ratings: A Case Study of the Food-Court Area in CEPA Shopping Center, Ankara. *Build. Acoust.* **2012**, *19*, 57–73. [CrossRef]
43. Chen, B.; Kang, J. Acoustic Comfort in Shopping Mall Atrium Spaces—A Case Study in Sheffield Meadowhall. *Archit. Sci. Rev.* **2004**, *47*, 107–114. [CrossRef]
44. Skarlatos, D. Confidence intervals of Leq in the case of stationary random noise measurements. *Environ. Monit. Assess.* **2003**, *85*, 55–67. [CrossRef] [PubMed]
45. Hopkins, J. Orchestrating an Indoor City: Ambient Noise Inside a Mega-Mall. *Environ. Behav.* **1994**, *26*, 785–812. [CrossRef]
46. Wang, B.; Kang, J.; Zhao, W. Noise acceptance of acoustic sequences for indoor soundscape in transport hubs. *J. Acoust. Soc. Am.* **2019**, *147*, 206–217. [CrossRef] [PubMed]
47. Wu, Y.; Kang, J.; Zheng, W.; Wu, Y. Acoustic comfort in large railway stations. *Appl. Acoust.* **2019**, *160*, 107137. [CrossRef]
48. Yilmazer, S.; Bora, Z. Understanding the indoor soundscape in public transport spaces A case study in Akköprü metro station, Ankara. *Build. Acoust.* **2017**, *24*, 325–339. [CrossRef]
49. Han, J.; Kwon, S.; Chun, C. Indoor environment and passengers' comfort in subway stations in Seoul. *Build. Environ.* **2016**, *104*, 221–231. [CrossRef]
50. Tardieu, J.; Susini, P.; Poisson, F.; Lazareff, P.; McAdams, S. Perceptual study of soundscapes in train stations. *Appl. Sci.* **2008**, *69*, 1224–1239. [CrossRef]
51. Nowicka, E. Assessing the Acoustical Climate of Underground Stations. *Int. J. Occup. Saf. Ergon.* **2007**, *13*, 427–431. [CrossRef]
52. Vorländer, M. Computer simulations in room acoustics: Concepts and uncertainties. *J. Acoust. Soc. Am.* **2013**, *133*, 1203–1213. [CrossRef] [PubMed]