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Acoustics for Supportive and Healthy Buildings: Emerging Themes on Indoor Soundscape Research

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Received: 1 July 2020; Accepted: 21 July 2020; Published: 28 July 2020

Abstract: The focus of the building industry and research is shifting from delivering satisfactory spaces to going beyond what is merely acceptable with a wave of new research and practice dedicated to exploring how the built environment can support task performance and enhance people's health and well-being. The present study addresses the role of acoustics in this paradigm shift. Indoor soundscape research has recently emerged as an approach that brings a perceptual perspective on building and room acoustics in order to shape built environments that "sound good" according to building occupants' preference and needs. This paper establishes an initial discussion over some of the open questions in this field of research that is still in an embryonic stage. A thematic analysis of structured interviews with a panel of experts offered a range of perspectives on the characterization, management, and design of indoor soundscapes and health-related outcomes. The discussion pointed out the importance of both perceptual and multisensory research and integrated participatory design practices to enable a holistic view regarding the complex building–user interrelations and the design of just cities. Soundscape methodologies tailored to the peculiarities of indoor soundscapes can help to measure and predict the human perceptual response to the acoustic stimuli in context, thus reducing the risk of mismatches between expected and real building experiences. This perceptual perspective is expected to widen the scientific evidence for the negative and positive impacts of the acoustic environment on human health, well-being, and quality of life. This will support prioritizing the role of acoustics in building design and challenge many current design practices that are based on a noise control approach.

Keywords: indoor soundscape; indoor environmental quality; acoustic design; salutogenesis; well-being; health; experience; people; environmental justice

1. Introduction

Indoor environmental quality (IEQ) has been defined by the ASHRAE Technical Committee 1.6 as "a perceived indoor experience of the building indoor environment that includes aspects of design, analysis, and operation of energy efficient, healthy, and comfortable buildings" [1].

A change in IEQ interpretation by the research community, policy makers, and the building industry has taken place over the past few decades. Perception was originally understood as a simple causal process involving building occupants as receptors passively responding to environmental stimuli [2–4]. Post-occupancy evaluations (POEs) have been designed to measure the satisfaction and self-reported productivity of occupants in order to diagnose issues [5]. Linear dose-response relationships have been studied for different environmental stimuli, mainly intended as negative stressors, in order to develop universally applicable predictive tools for the design of spaces acceptable for the "average" occupant. Evidence collected from objective and subjective measurements on the different domains of comfort (i.e., thermal, acoustic, visual, air quality) have been condensed into IEQ models expressing single rating scores for buildings [6]. This approach was based on a reductive physicalism, i.e., "the assumption that consciousness can be explained completely in terms of physical properties" [4], with no or limited consideration of psychological and behavioral factors. Building design aimed at optimizing discrete qualities of the indoor environment according to very narrow ranges, targeting the design of uniform, static, and neutral spaces, often resulted in occupational boredom [7,8]. This simplification of reality produced a mismatch between the predicted and the real experience of the built environment. This, in turn, resulted in the unintended behavior of building occupants, with a consequent building performance gap between the energy consumption in the design intent and in the actual operation.

In response, a user-centered theory of building design has been proposed [2,9] that acknowledges the active role of building occupants and incorporates their interactions with the built environment and advocates for more complex comfort models, addressing cultural, psychological, behavioral, social, and contextual dimensions [3] while taking into account the multi-sensory nature of human experience [10–12]. Given the complex and holistic nature of this framework, the use of qualitative methods is appropriate to collect in-depth data about user experiences in the built environment [2,4].

Furthermore, this research underpins a recent shift in the industry from producing minimally acceptable spaces to moving beyond occupants' lack of complaints and diseases with a new emphasis on how the built environment can actually support task performance and enhance people's health and well-being [10–15]. This focus on health and well-being is made evident from the rise of certification protocols that explicitly address these aspects, such as WELL [16], Fitwel [17], and the Living Buildings Challenge [18]. Design goals are becoming more and more challenging and comfort models, rating protocols and occupant surveys have to be refined accordingly. Spaces are required to not only reduce negative impacts on comfort, health, and productivity but also to support the activities of users and to produce enjoyment and health in their inhabitants. Occupant-centric [2,9], participatory [12,19], regenerative [20,21], salutogenic [12,22,23], and biophilic [24,25] design approaches represent substantial cornerstones of the search for a "flourishing" built environment [13]. The United Nations Sustainable Development Goals [26] require the sustainability debate to be elevated to include aspects related to social and environmental justice [27] alongside climate change and resource concerns [20]. Spatial and temporal sensory variability, together with opportunities for personal adaptation and control are encouraged for offering pleasure and delight [11,28–30]. New technologies from medical sciences (e.g., wearable sensors) are gradually being introduced to assess the health aspects of human responses to environmental stimuli or to improve comfort models on the basis of occupants' physiological response [31,32]. Examples of this continuous and ongoing evolution in IEQ research and practice include the development of personal comfort models [32,33] and personal comfort systems [34], the application of circadian lighting design [35], and the valuation of qualitative aspects affecting visual quality [36,37]; but what about acoustics in this "pursuit of wellbeing" [15]?

As far as acoustics is concerned, IEQ models have been traditionally based on the objective measurement of A-weighted (decibel) continuous sound pressure levels, and on surveys for the self-reported evaluation of noise levels and, sound privacy; eventually integrating the identification of annoying sources [5,6,38,39]. External sound has been typically considered as unwanted (i.e., noise) and eliciting annoyance, as such a "waste" to be reduced through sound insulation, regardless of the spectral and temporal composition of the outdoor acoustic environment and the meaning attributed to sound sources [40,41]. Wanted sounds or sounds of preference are not addressed either in IEQ models or in POE surveys, reflecting the general effort to minimize noise annoyance by reducing indoor sound levels.

However, the literature has already pointed out the inadequacy of decibel-based metrics to characterize perceived sound quality [42,43]. Reducing noise levels do not necessarily lead to improved comfort, as loudness can sometimes be "desirable" [44]. If noise exposure can severely affect human health and well-being [45], spaces that are too quiet can sometimes result in privacy issues (e.g., in open plan offices) and in feelings of anxiety [46]. Results from 20 years of the application of the Center for the Built Environment's (CBE at University of California, Berkeley, USA) occupant survey showed that the primary self-reported sources of dissatisfaction are the ones related to acoustics—sound privacy (54% dissatisfied), temperature (39%), and noise level (34%) [47]. Far from being designed for acoustic comfort, the data suggests that most buildings still face annoyance issues related to the sonic environment.

Understanding how noise can be annoying and sounds can be desirable to building occupants requires a perceptual characterization of the acoustic stimuli. To address this aim, soundscape research has evolved as a framework that integrates psychological, (psycho)acoustical, physiological, and social factors to explore how people perceive and experience the acoustic environment, in context [48]. Sound is managed and differentiated according to people's perception and employed as a design "resource" for shaping healthy and supportive acoustic environments, positively perceived by their users [41,49,50].

While standardized in 2014 [48], the soundscape concept dates back to the late 1960s with the work by Michael Southworth and the Canadian composer R. Murray Schafer and has evolved across different disciplines ever since [51]. The ISO soundscape standard series [48,52,53] was developed for use in the context of urban planning, and it has increasingly been applied in indoor environments to provide a perceptual perspective on building and room acoustics, often referred to as the "indoor soundscape" [43,54,55]. Notwithstanding the potential impact in terms of improving the living conditions of building occupants, indoor soundscape research and practice are still at an early stage and, as such, the underpinning science and practical guidance are still being developed. The purpose of this study is to contribute to this emerging field of research by establishing an initial discussion over some of the open questions that are still evolving. Moreover, this study aims to explore the link between acoustic design and practices that are currently under investigation in the field of health and well-being in the built environment (e.g., regenerative, salutogenic and biophilic design approaches).

Therefore, the research questions for this study were designed to encompass the characterization, management and design of indoor (and indoor versus outdoor) soundscapes to potential health-related outcomes for occupants. The research questions being investigated were

- Q1. How can acoustic design contribute to shaping regenerative buildings?
- Q2. What differences and similarities exist between outdoor and indoor soundscape approaches?
- Q3. How can indoor soundscapes be measured?
- Q4. What is the potential of sound management for biophilic design?
- Q5. How are "wanted" sounds related to health outcomes?

These questions were explored via individual structured interviews conducted with a panel of experts. The answers to the interviews were analysed using qualitative methods. Knowledge gaps in indoor soundscape research are discussed, and a research agenda for future advancements in the field is proposed.

2. Methods

Because of the under-researched nature of the subject under investigation, the study relied on qualitative research methods and specifically on expert interviews for data gathering and on subsequent thematic analysis.

2.1. Expert Interviews

Talking to experts is a method very often employed in social research for preliminarily sounding out a subject under investigation. "Expert interviews can serve to establish an initial orientation in a field that is either substantively new or poorly defined, as a way of helping the researcher to develop a clearer idea of the problem or as a preliminary move in the identification of a final interview guide" [56]. As an exploratory tool, expert interviews are more effective than participatory observations or quantitative surveys in gathering high-value data while shortening the data collection process [57].

Interviews involved four experts that were "seen as 'crystallization points' for practical insider knowledge," interviewed "as surrogates for a wider circle of players" [57]. They were Jack Harvie-Clark, Jian Kang, Lisa Lavia, and Antonella Radicchi. The experts were selected based on their specific and complementary areas of expertise, cognitive diversity and roles as researchers or practitioners in the field of urban soundscape, indoor soundscape, acoustic design, and public health and well-being, thus addressing the area under investigation from different viewpoints.

Interview data were collected via structured interviews conducted through online meetings between April and May 2019. A list of eight open-ended questions employed for the data collection were distributed to the interviewees prior to the interview (cf. Appendix A). Each interview session lasted about one hour.

2.2. Data Analysis

The interviews were first recorded and then transcribed verbatim. The collected material was subjected to thematic analysis, a qualitative method that is often employed in the fields of psychological and social sciences to identify and analyse patterns of meaning in a dataset [58,59]. Transcripts have been coded around the five specific research questions underpinning the present study, thus mainly following a theoretical or deductive approach [58]. The analytic process started by breaking down the data into chunks, organizing the excerpts according to patterns of semantic content (i.e., semantic approach [58]) and then summarising and conceptualising data in "an attempt to theorise the significance of the patterns and their broader meanings and implications … often in relation to previous literature" [58]. As an example, a small section of the coding framework for the first research question (Q1) is reported in Table 1 to show the process that from code identification led to the theme generation and subsequent reporting, following the analytical path depicted in Figure 1. For the entire coding, please refer to the Supplementary Materials. Coding and theme formation were performed manually, and the analysis did not involve the interviewed authors. All participants consented to their names being listed and quotations being published in the present study. In the discussion section, the knowledge gaps that emerged from the analysis are highlighted and suggestions to set a future research agenda are provided, based on the authors' collective expertise.

Table 1. Example of the coding process for the first research question.

Codes	Example of Excerpt	Theme
Acoustics Underestimation	"Design at the moment is so visually driven"	
Need for Scientific Evidence	"We are living in a kind of transition phase and this is where we need a lot more evidence across soundscape"	
Perceptual Approach	"thinking about people's perception rather than just sound insulation, reverberation time . . . "	Dealing with complexity in user-building and building-city interaction
Multisensory Research	"There is a need to cover a much more accurate picture of the foundational importance of acoustics to the interaction of the acoustic sense with all of the other senses"	
Multidisciplinary Approach	"we need to talk also with psychologists, medical people . . . "	
. . .	. . .	

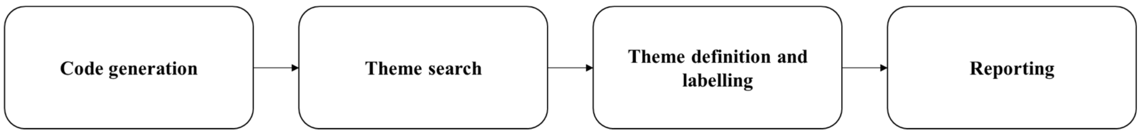

Figure 1. Stages of the thematic analysis.

3. Results

In the following sections, final themes resulting from the thematic analysis (based on the five research questions noted above in Section 1) are reported in relation to the different research questions.

3.1. How Can Acoustic Design Contribute to Shaping Regenerative Buildings?

Restorative and regenerative design are approaches that aim at shaping a built environment that is "ecologically sound, culturally rich, socially just and economically viable" [20,60]. Compared to traditional sustainability practices, the target is not only limiting the negative impact of the construction industry by reaching "the balance point where we give back as much as we take" [20], but it is providing positive impacts on the environment, on the health and quality of life of its inhabitants through appropriate community planning and building design [20,21,60]. The present research question seeks to contribute to the ongoing discussion on regenerative design conceptualization and application, by addressing the role of acoustics in such a paradigm shift towards "doing more good" for the society and environment [60].

One overarching theme which emerged around this question was the need to address the complexity of human-building interaction, as part of a broader urban context, in order to implement research approaches and design practices able to provide high-quality acoustic environments. High acoustic quality in the built environment was identified as a foundational element for restoring social and ecological systems to a healthy state. Nevertheless, its importance would be currently underestimated. Due to typical building design processes being primarily visually driven, the acoustic quality of buildings is often not prioritised at the project outset stage. Consequently, acoustic requirements are generally subjugated to visual ones.

> "I think there is the assumption within the design community and even in some cases in the traditional acoustics community that if we just improve the acoustics a bit but make sure that the visual is really, really good then we have accomplished something important. And my response to that is that you have made a step in the right direction, but we are still underselling the importance of acoustics if that's considered an accomplishment . . . It is better than nothing, but this is far from the whole picture because of the impact of

acoustics ... We haven't even begun to research the importance of acoustics to people in the built environment".

Consequently, acoustic-related issues rank first in post-occupancy evaluations [47,61]. By acknowledging and embracing the complexity of the acoustic experience in the built environment, further scientific evidence is needed to understand and value the impact of acoustic quality for policy makers and practitioners. This impact should be assessed from a perceptual perspective and through a multisensory approach [10,62], thus integrating disciplines related to acoustics, sociology, psychology, and physiology [63,64].

"There is a need to cover a much more accurate picture of the foundational importance of acoustics to the interaction of the acoustic sense with all of the other senses".

"It's a multidisciplinary scientific approach and the reason why we find it hard to find evidence from an acoustic perspective at the moment is because most acoustic research doesn't support that, because it's not measuring the human perceptual response".

"[The acoustic community] is attempting to measure the perceptual response through A-weighted dB units; without being too critical. ... the A-weighted dB unit is not anywhere near accurate enough to capture the human perceptual response".

Assessing the human perceptual response to the acoustic environment is the mission of soundscape research [48]. In soundscape practice, sounds and noise are assessed based on people's perception in context and valued as potential resources to be utilized in the design practice. This represents a step forward compared to the traditional noise control approach that aims at reducing noise annoyance by minimizing noise exposure, expressed by decibel-based metrics. This perceptual perspective could capture a holistic view of the negative and positive impacts of the acoustic environment on human health [49], well-being and quality of life [65]. This in turn can help reinforce the role of acoustics in building design and challenge many current design practices based on a noise control approach.

"I think there is a range of technologies ... , not just to consider sound as noise, or waste, but also as a resource ... Something we can think about is not only reducing the negative effects of noise but also promoting the positive effects of sound".

"I think there are two ways to get better acoustic design into green buildings and dwellings ... Much work has already been done, for example, by putting sound insulation, reverberation time requirements and noise level requirements in building and design practices. This is very positive but it's a more traditional approach ... But beyond that ... we can go further by introducing positive ways of using sounds, such as using sound masking systems inside of open plan offices and also creating some restorative spaces, for example in large shopping malls".

The awareness of sound and noise, and the potential for better acoustic design, would radically change current design practice, providing designers with a wider variety of technologies and approaches to be applied to the source–receiver path in order to shape regenerative buildings.

"Soundscape is also a framework because there are many potential routes to meet the minimum specification. That is good news for designers and practitioners because it provides a lot of flexibility".

"From the sound path viewpoint, differently from traditional technologies based on reducing noise, we also think about how to manipulate or adjust different kinds of sounds, so the treatment may be good for certain frequencies but not for other frequencies ... From the receiver viewpoint ... which is the most important perspective in soundscape practice ... we need to think of different people and different contexts ... so overall ... the design philosophy or technology would be quite different from [that used in] traditional noise control methods".

Participatory processes should be applied to engage users, public authorities and all the relevant stakeholders in the building design (or retrofit) process, as is already utilized in the context of urban planning [66,67]. This is central to the soundscape approach in order to ensure that the design meets people's preference.

> "This is the core of the soundscape approach. We are interested in how people perceive and experience the acoustic environment in context ... If you apply this definition to indoor soundscape design, you understand that it's mandatory to involve people not only in the evaluation but also in the design of buildings".

The design process should address the complexity of user-building and building-city interactions through integrated design practices both at urban and building scales.

> "To me the best way to address good acoustic quality is to implement integrated urban design and planning approaches, thus taking into account not only the acoustical dimension of the places but also the spatial ones and other environmental characteristics of spaces".

> "If you really want to get great quality of indoor places you need to take into account that your buildings are placed in neighbourhood, you have to take into account what kind of mobility is going on in the neighbourhood".

> "Integrated assessment of acoustics and overheating and ventilation ... Traditionally in the UK they have been considered separately, so you do the noise assessment assuming the window is closed and if you do an overheating assessment you assume the window is open".

Acoustic design needs to be integrated with other disciplines from the very first stages of urban and building design. Unintended consequences occurring as a result of a fragmented approach very often jeopardize the success of design actions. For example, the lack of integrated design in addressing the topics of acoustics and overheating currently result in building occupants having to decide whether to give priority to acoustic or thermal comfort [40,68]. Perceptual and multisensory research on the one side and integrated participatory design practices on the other would enable a holistic view of the complex building–user interrelations and reduce the risk of mismatches between expected and real building experiences [4].

3.2. What Differences and Similarities Exist between Outdoor and Indoor Soundscape Approaches?

According to the definition provided by ISO 12913-1:2014 [48], soundscape is the "acoustic environment as perceived or experienced and/or understood by a person or people, in context" [48]. The soundscape framework is thus valid both in indoor and outdoor contexts, wherever the perception of acoustics affects a person or people.

> "I think that [soundscape] methods are equally valid for any environment whether it's indoor or outdoor because we don't turn off our acoustic sense. The response, according to the soundscape model theory, is modulated by the context and our expectations. Our expectations outdoor might be different from our expectations indoor but we are still having a response to the acoustic environment".

Three main themes were extracted, dealing with (1) contextual differences that may result in different expectations, (2) differences in the objective acoustic environment, and in (3) consequent soundscape strategies to apply in indoor contexts compared to outdoor ones.

People may only spend a limited amount of time in outdoor urban spaces, for example while relaxing or moving through the city; they may often be provided with the opportunity to choose their preferred place to walk and relax. By contrast, people may tend to spend more time indoors, performing a variety of tasks, often without being able to move to better places or to choose where to stay.

> "In outdoor spaces people may not stay as long and there may be much more choices where to stay. In a hotel atrium or in a museum for example, you often don't have many spaces to choose. Also, in indoor spaces people may have longer exposure to sound, such as in open plan offices ... There are many differences and also people's tasks are different".

As regards the acoustic environment, enclosed spaces are characterized by a reverberant sound field that can amplify both sounds and noise.

> "Indoor spaces have reverberation associated, so the sound disturbance between sources can be stronger than outdoors".

Indoor spaces can be affected by a combination of outdoor-generated and indoor-generated sounds. Thus, sounds affecting the user may originate from the same space where the user is located and from adjacent indoor and outdoor environments. Sounds can be airborne or structure-borne and transmitted through or originated from façades, ventilation openings, building structures, or building services.

Urban soundscape research has developed and investigated strategies to enhance soundscape quality. Unwanted sounds are reduced or eliminated through noise control measures, noises are made less noticeable by adjusting their temporal and spectral characteristics, and wanted sounds are enhanced to exploit energetic and attentional masking [41]. When designing masking strategies in indoor spaces, those should be based on the appropriate combination of indoor and outdoor sounds according to people's perception (i.e., wanted versus unwanted sounds). While urban soundscape approaches currently typically employ natural sounds (e.g., water sounds) to mask man-made sounds, their use in indoor spaces is more challenging, as natural elements are typically found in outdoor contexts (cf. Section 3.4). Masking opportunities may be provided by allowing a certain level of ingress of outdoor urban sounds through building façades and windows to balance against unwanted indoor sounds.

> "The risk of having high insulation to the outside is that you might hear your neighbours more; and the sounds of your neighbours can sometimes be much more annoying than the sounds from outside. So, it can be useful to have some external desired sound from outside to mask unwanted sound from your neighbours otherwise you may need higher indoor sound insulation".

As a consequence, façades and ventilation systems might be reinterpreted as filters able to transmit, block, or modify outdoor sounds in order to provide a connection with the outdoor environment, reduce unwanted sounds, and enhance the wanted ones, as proposed in Torresin et al. [40].

In addition to the desire to hear natural or, sometimes, urban sounds, music is typically played indoors by people. This may often be through headphones, thus providing building users with the possibility to isolate themselves and curate their own acoustic environment. Equally, wearing headphones may be a way to compensate for sub-optimal acoustic conditions, in which case representing a failure of acoustic design.

> "Music is a popular masking sound. Ideally, people like to hear their own music rather than other sources of sound. Maybe it's more important to provide the opportunity for people to shape their own sound environment with the sound they prefer".

> "I have started to use headphones and I am surprised by the extent to which I feel unconnected to the rest of the office when I do that. It increases my personal space, to not be disturbed and interrupted ... But is it [wearing headphones] a failure of the acoustic environment or is it a good way to manage it?"

However, natural features (e.g., fountains) and active systems playing sounds should not be relied upon as a substitute for good acoustic design. Added sounds can be very controversial. If used, they must fit the intended purpose of the space in order to create supportive environments suited to the tasks to be performed and peoples' personal preferences. Nevertheless, the acoustic quality of the space should not strictly rely on these types of sounds, as also stressed in the field of urban soundscape management [41].

> "Nothing replaces having good acoustics. Having good acoustics in the design of a building is the foundational element . . . Like a concert hall that is designed to be able to play a range of types of music, if you have really good acoustics principles in the design of the building then you can put many kinds of music in there, it is fit for purpose for a multitude of uses".

To help ensure that added sounds are "wanted" by the majority of users, their adoption should follow participatory processes directly involving the building users.

> "I would avoid superimposing supposed positive sounds into an environment because something that is good for you, might be not good for me . . . There might be the possibility to add some wanted sounds, but still I think that these kinds of design measures should be negotiated with people living in the places, in the buildings".

3.3. How Can Indoor Soundscapes Be Measured?

Two main themes emerged with reference to data collection methods, in relation to (1) how to assess people's perceptual response in indoor acoustic contexts and (2) how to measure the objective acoustic environment, in comparison to methods available from soundscape literature and standards for outdoor urban contexts [52,69]. Survey methods currently used in post-occupancy evaluations should integrate soundscape methodologies (cf. ISO/TS 12913-2 [52]) able to better describe the human perceptual response to the acoustic environment.

> "A better application of questionnaires and surveys methods [is needed] to gain information from people about their environment . . . the soundscape theory has information about the type of survey methods that can be used".

Rating scales, questionnaires, and interviews can be used to gather self-reported views from building users. However, open interviews allow people to more freely express their feelings and thoughts without the limitations of rating schemes pre-determined by researchers.

> "When I answer the questionnaires about my sound environment, I always feel that the questions are not quite the way in which I think about it or I would describe it. Interviews would be the best way to collect soundscape data".

Such methods are often integrated within soundwalks [52], a participatory group walk in an area with a focus on listening to the acoustic environment and on reporting the perceptual response (Figure 2). The area can be real or virtual, in the latter case referring to "virtual soundwalks" [70]. Soundwalks are useful to collect feedback from people, while inviting participants to re-connect to the acoustic environment in which they are immersed.

> "Usually when I lead soundwalks I have discussions with the participants. So, you not only collect feedback from the single participant, but you can also get feedback or patterns emerging from the group discussion, from the exchange that participants have among them after the soundwalk".

> "If you lead soundwalks with people you somehow invite them to reconnect with their sensorial experience of the places, you invite them to retune to their environment and this is something we are not so used to [because] we always wear headphones, we tend to stay detached somehow from the environment".

Figure 2. Example of a soundwalk performed inside of a public library (from Xiao and Aletta [71]).

Soundwalks have typically been applied in outdoor urban contexts, with limited examples in the literature reporting indoor soundwalks [42,71–73]. However, the adoption of soundwalks in indoor built environments is not unusual in the field of soundscape studies or sound art. According to Westerkamp [74], for instance,

> "A soundwalk is any excursion whose main purpose is listening to the environment. It is exposing our ears to every sound around us no matter where we are. We may be at home, we may be walking across a downtown street, through a park, along the beach; we may be sitting in a doctor's office, in a hotel lobby, in a bank ... we may be standing at the airport, the train station, the bus-stop. Wherever we go we will give our ears priority".

According to the interview results, there does not seem to be a unanimous view on soundwalk applicability in indoor built environments. Soundwalks might be directly applied indoor or adapted and modified to address the peculiarities of indoor contexts (e.g., sedentary activities), under the framework described by the ISO 12913 soundscape standard series [48,52,53].

> "I think that soundwalks could be also led indoors".

> "When you apply these kinds of methods indoors, there should be a ... specific translation of those methods. For example, soundwalks may not be appropriate in indoor spaces. For example, you don't normally walk [i.e., while performing the main task] in open plan offices or in restaurants ... So maybe using the same principle you can design new survey methods, but the principle is the same, just finding out what is people's perception when they are using the space. So, once you keep that in mind, I think even consultants could design something along with the ISO standard way".

Further research would be needed to explore soundwalk applicability in different indoor contexts. Guidance should be given on implementation modalities, for instance with reference to the length of the exposure to the acoustic environment in order to account for habituation effects.

> "What is not obvious when you do [a soundwalk] is how you might feel if you were there for a longer period of time, how much habituation you need in one place in order to get the sense as if you were there for a longer period of time".

Beside soundwalks, mobile applications (apps) can be used to gather feedback from building users about the perceived acoustic environment, as already experienced in the case of urban soundscape apps [67,75,76]. The use of mobile apps as a soundscape data collection tool allows people to provide their feedback when they want to and independently from the researcher.

> "Through the use of mobile apps people can collect data; can give their feedbacks on the quality of the indoor places independently from the researchers. People can work autonomously, they are not influenced by the researchers and mostly they can collect the data when they feel they need to share and they want to provide feedback".

One consequence of self-report methods is that responses may be biased due to the attentive listening mode participants assume when they are asked to perform a soundscape evaluation.

> "If you are listening actively or passively to the environment, this changes the perception of the environment. As soon as you ask somebody about how they feel about the sound, they start listening actively, in a different way than before you asked them".

Non-participatory methods can help overcome this bias as the impact of sounds is inferred by observing the behaviour of participants while they are not aware of the observations taking place [77].

> "With non-participatory methods you can better understand what people are going to be like in their environment".

The characterization of the physical acoustic environment should combine traditional methods including noise control engineering, room and building acoustics with psychoacoustic methodologies to determine the basic auditory sensations elicited by sounds in context [78]. Binaural recordings enable aurally accurate data collection for analyses and reproduction of the acoustic environment.

> "Collecting psychoacoustic data helps to really broaden out the picture of the acoustic assessment of the environment and helps to explain the human perceptual response in context. So, better use of psychoacoustic data integrated with traditional methods is one very important thing".

> "Better instrumentation [is needed] to measure and to collect better acoustic data based on psychoacoustics".

Given the complexity of the perception process and the multitude of factors involved, the combination of different soundscape methods related to the human perception, the acoustic environment, and the context is highly encouraged, as it allows data validation through triangulation [53].

> "My preference, my preferred method, is to use a combinational method because I think if you use a combination you can cross validate your findings and also more robustly support findings that you have".

By triangulating physical and perceptual data, new soundscape indices may be developed in order to represent the way building users perceive the acoustic environment.

> "We are at the beginning of investigating how to synthesize or harmonize different forms of measurements to fully assess the human perceptual response".

Similarly to the ongoing research for urban soundscape indices [79,80], indoor soundscape indices would allow designers to be able to predict the perceived acoustic comfort inside buildings during the design stage, thus overcoming current soundscape prediction limits.

> "It would be difficult for buildings that don't exist because soundscape only exists in the minds of people in the context. So, it is very difficult to do simulations to ask and understand 'how do you feel in this building?' Usually, in current practice, you can only get into an existing building [e.g., post-occupancy] and ask how they feel".

In the meantime, virtual reality technologies can help address this problem [81]; soundscape assessments can be performed on artificial virtual environments before the building realization. Accurate auralization and playback procedures can render future acoustic environments, thus enabling potential building users to experience the soundscape in advance, as by default, with visual rendering of buildings.

> "Auralization and visualization techniques can be used to support decision making and planning and help people to better assess the human perceptual response in context before things are completed. However, the auralization demo could be very different than [what users may experience] when having to live in the environment 24/7. It is not a panacea, but a step forward from what we have today where people just see visual models of things".

3.4. What Is the Potential of Sound Management for Biophilic Design?

Within the design approaches suggested for restorative and regenerative buildings, biophilic practices are encouraged to connect building users with nature, and with "the natural cycle of day and night, change of seasons, wind, temperature or fauna and flora" [60]. What is the role of sound stimuli in providing such a connection?

Natural sounds can be brought indoor through façade ventilation openings, where natural outdoor contexts are available. In urban scenarios, this is often not the case and research has investigated the use of natural features (e.g., indoor fountains) and active systems to generate or reproduce natural sounds masking unwanted ones (e.g., traffic noise) [82,83]. A further solution worth investigation would be the use of natural materials (e.g., wood or gravel) in creating, for instance, floor coverings.

> "You could somehow enhance the sonic stimuli coming from nature indoors if you work with different materials for pavements. You can use wood or gravel".

The main theme that emerged around this question was related to biophilic strategies based on playing natural sounds indoor. Some of the interviewees declared themselves skeptical of this solution, as added sounds may be perceived as "fake".

> "Personally, I don't like being played fake birdsong rather than real birds. I find recorded birdsong a bit fake".

> "I am skeptical that you can get some good sonic stimuli from nature indoors unless you use augmented technology to do that. But I am not so much a fan of artificial soundscapes".

In playing natural sounds indoors, it is important to provide a coherent combination of visual and audio stimuli related to natural elements. Visual scenes may be provided through pictures or window views. Both components (audio and visual) enhance each other and can determine people's appreciation of the environment.

> "Sometimes, if we cannot connect to nature outside 100% visually, but we use sound, we can enhance it. Then the overall effect can be greater. And, vice versa. If you want people to appreciate outdoor sounds like water … if people can't see it, then it can sound like white noise and people may be not happy … A window would be good, otherwise you can have pictures of natural scenes".

Interestingly, previous literature reported that natural scenes could provide enhanced physiological stress recovery in combination with audio-visual stimuli related to nature but not in a visual-only scenario [84]. This supports the importance of establishing coherence between sound stimuli and natural scenes to enhance the potential benefits available from using these design techniques.

However, added sounds should in any case be "wanted" by building users, suitable for the tasks to be performed, designed and evaluated according to soundscape methods (see Section 3.3) and following participatory processes.

> "Any biophilic element needs to have the right sort of acoustic profile that is going to support the work or the usage of the space. And again, this can be done by measuring and assessing, using psychoacoustic principles and, where possible, non-participatory observation … "

Artificial biophilic sounds might contribute towards enhancing indoor soundscape quality by providing contact with nature. However, the acoustic quality of a space should not entirely rely on them. As building users or individual preference might change over time, the space should be acoustically suitable even without the presence of those added sounds.

> "One of the potential challenges of biophilic design is that, what happens if you have different tenants? What happens if you go to rent the building to someone else and maybe they don't want waterfalls, they want something totally different?"

> "The biophilic elements are more like interior design features, they can be used if that suits the environment and people who are working there. But also, if they are taken out, people can still have a good quality acoustic environment ... ".

> "Biophilic design is a tool, it is not the solution".

3.5. How Are "Wanted" Sounds Related to Health Outcomes?

Environmental noise exposure at certain levels has been proven to be a risk for human health and well-being [85]. Noise can induce both auditory and non-auditory health effects [85,86]. The former includes noise-induced hearing loss and tinnitus [87]. The latter includes annoyance [88], sleep disturbance [89], hypertension and cardiovascular diseases [90], and cognitive impairment [91].

Therefore, the question is to what extent "wanted" sounds may be used without compromising building user's health. The World Health Organization (WHO) Environmental Noise Guidelines for the European Region recommended outdoor noise limits based on source-specific exposure–response relationships between environmental noise (expressed in terms of L_{den} and L_{night}) from transportation sources (i.e., road traffic, railway and aircraft), wind turbines and leisure events and the proportion of people adversely affected [45]. From the analysis of expert interviews in this study one main theme which emerged was the need to review such limits from a holistic perspective, including nonacoustical factors, using soundscape methods. It should be noted that limits provided by the Environmental Noise Guidelines for the European Region are bounded by the significance of annoyance rather than of other physical or mental diseases (e.g., increased risk of ischemic heart disease, hypertension, mental health) [45]. Indeed, the prevalence of highly annoyed people (set at 10% absolute risk) is the factor presenting the lowest exposure levels (in L_{den}) based on the relative risks of adverse health effects from road traffic, railway, and aircraft sources.

> "The limiting factor in every case for the environmental noise limits [in WHO Environmental Noise Guidelines for the European Region guidelines] was annoyance. So, the [WHO] guideline levels, which are external noise levels, are based on annoyance rather than other health impacts of noise".

This suggests that the recommended noise limits could potentially be relaxed in the case of sounds that lower or lessen annoyance or are desired (e.g., pleasant or calming), at least within levels that impede the onset of annoyance or other critical or important health outcomes identified by the WHO.

Thus, complementary threshold levels could be identified, below which the soundscape quality is determined by the type and character of desired sounds (versus unwanted sounds) rather than only by weighted decibel-based metrics. Importantly, soundscape metrics should be linked to health and well-being indicators to avoid the emergence of health risks caused by annoyance and unsafe sound exposure. This is conceptually represented in Figure 3.

> "I think the principle is, below a certain level the type of sound is more important, if it's positive or negative. But above a certain level you need to be careful. Although sometimes with positive sounds people are happy, but it is not good for their health. For example, in a very loud disco people are happy, they are not annoyed, but that is not necessarily good for their ears and heart".

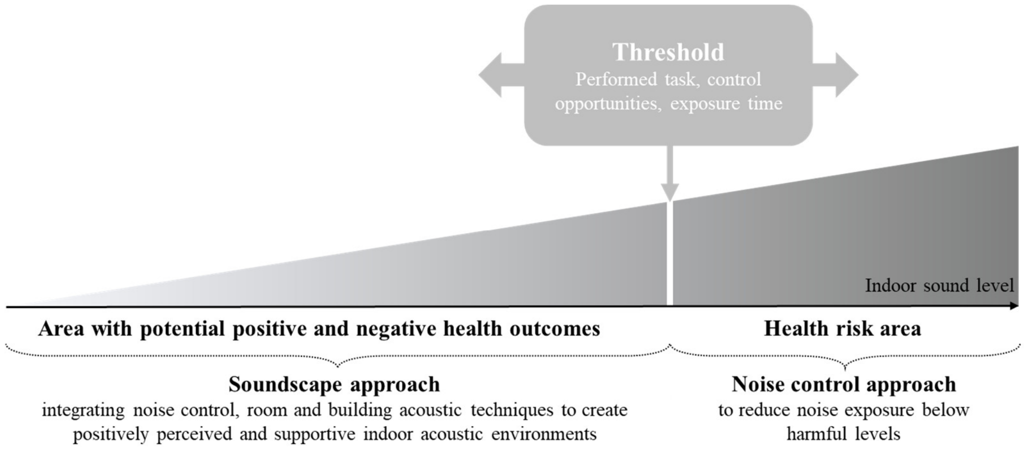

Figure 3. Soundscape and noise control approaches in relation to health outcomes. The horizontal axis conceptually depicts increasing indoor sound levels. A threshold level demarcates an upper area in which a noise control approach must be applied to lower sound and noise exposure below harmful levels (i.e., health risk area). Below the threshold level, a soundscape approach should be applied in order to enhance wanted sounds over unwanted ones, reducing the negative health outcomes and fostering the positive ones. Threshold levels depend on the space use, control opportunities, and exposure time.

Below this threshold, soundscape quality based on the presence of sounds of preference according to people's perceptual response would be more important than the sound level itself.

> "People may want a calm environment, but they don't want a monotonous or boring environment, they might want an exciting environment, they don't want a chaotic environment. Acoustic boredom, being in a monotonous acoustic environment is just as frustrating as being in a chaotic environment because they are both unwanted. It is not a function of the decibel level, it's a function of the perceptual response in context".

The threshold level might depend on several factors, including the availability of control over the environment, the performed task and the length of the exposure.

> "There is a kind of threshold, but this threshold may be different from space to space. For example, in outdoor spaces we found 65–70 dB LAeq in urban public spaces. But if you are sleeping, this threshold would be much lower. So, it really depends on what the task is and on what you do, and how long you have been exposed to sound. For example, if you are exposed to a fountain for five minutes, that's fine, but if there is one fountain next to your desk, even if it is 30 dB, you may still feel annoyed after certain time".

This threshold should account for the availability of control opportunities by building occupants. The literature has already pointed out how giving control to occupants can result in high levels of satisfaction [30]. According to cognitive stress theory [92,93], when the indoor environment is perceived as threatening and coping strategies are available, people may react with resignation or active behaviors. Thus, the reaction of resignation resulting from indoor environments that do not meet people's expectations and needs can trigger stress reactions that are detrimental to their health and the quality of life. Likewise, active behaviors (e.g., opening windows in overheating conditions) can decrease building occupants' psychological stress [93] and, if adaptive opportunities can be applied successfully, turning dissatisfaction into pleasure [30,94].

> "From a pure soundscape perspective we would say, if I am choosing, I have control over my environment, I know if I am going to open this window I am going to hear some unwanted sounds but I may prefer that than this monotonous environment that is driving me crazy …

> Seen radically from a soundscape perspective we would say that because I have control over that situation, I am choosing it, therefore I am moderating my own cognitive response to this and . . . you may then not have the stress response that you have when you feel angry about the noise and no control to stop it".
>
> "The key thing is about occupant control of the environment because when the occupants have control over their environment, they feel differently about it so they may rate it differently . . . That concept of having control over the environment changing your response to certain environmental conditions is embedded in the adaptive thermal comfort model".

However, active coping behaviors "if wrongly targeted may also increase the risk of adverse health effects by creating unwanted or unexpected side-effects" [93], thus creating a secondary adverse exposure (e.g., harmful noise exposure when opening windows in overheating conditions) and further coping reactions. Hence, control opportunities should not be relied upon as a substitute for well-planned integrated design of the indoor built environment. Trade-offs between different design needs (e.g., energy savings, air quality, thermal and acoustic comfort) should be resolved during the design stage, without leaving the building occupants with the burden of choosing which comfort domain to prioritize (e.g., thermal comfort) at the expense of others (e.g., acoustic comfort), thus inadvertently forcing trade-offs which may lead to potential health risks.

> "It is not ideal. Ideal would be that people would not have to make a choice between thermal and acoustic comfort and noise pollution".

Control and adaptive environmental comfort opportunities can be positively employed to allow building occupants to personalize their environment according to their intra and inter-individual changing needs and to experience acoustic delight from temporal and spatial sensorial variability [11,28,40]. At the same time, these considerations can provide designers with a wider variety of indoor environmental design parameters. This type of holistic design can also maximize the benefits to be achieved from building energy performance capabilities [11,40].

The threshold indicated in Figure 3 should be defined from new scientific evidence, based on the application of soundscape methods, in order to investigate both positive and negative health outcomes by measuring the human perceptual response to sound in context.

> "Because the way in which noise is measured and assessed [in WHO guidelines], it has not incorporated soundscape techniques . . . Because they are only considering dose-response evidence based on decibel levels, it is already incomplete evidence because we know that there is a greater ability to get more accurate evidence using augmented methods [i.e., from nonacoustical factors and psychoacoustic metrics] other than the dB units alone".

Below such threshold values, soundscape methodologies should be integrated into traditional room and building acoustic noise control approaches to design positively perceived indoor environments, in order to exploit the hedonic potential of sounds, support optimal task performance, and generate positive health and well-being outcomes [49,95].

4. Discussion

The emerging themes resulting from the analysis of expert interviews helped to frame an initial picture of the indoor soundscape research, pointing to some of the knowledge gaps that need to be considered as drivers of the future research agenda, as discussed in the following sections. Figure 4 depicts the process that led from research question formulation to the definition of core themes through thematic analysis, to the identification of knowledge gaps. Colour coding identifies core themes underpinning each research gap.

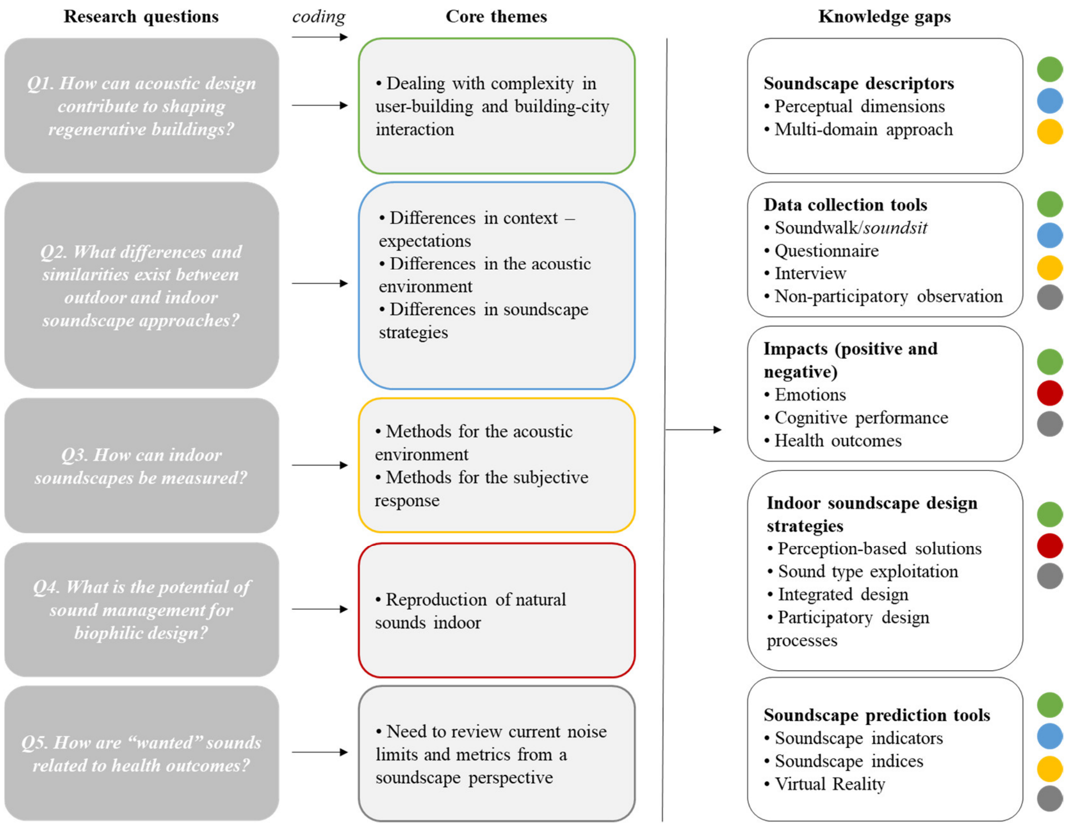

Figure 4. Flow-chart depicting the process from (i) research questions, which led to (ii) core themes coded around the research questions, which led to the identification of (iii) knowledge gaps and areas of interest for future research in indoor soundscapes. Color coding show core themes underpinning each research gap.

4.1. Defining Indoor Soundscape Descriptors under a Multi-Domain Perspective

As outlined in Section 3.1, the foundation of sound exploitation to generate supportive and healthy built environments is the assessment of the human perceptual response to the acoustic environment in context. Similarly to what has been done in the field of outdoor urban soundscapes [96], perceptual dimensions underlying the affective response to the indoor acoustic environment should be identified, accounting for (1) the peculiarities of indoor soundscapes compared to outdoor ones (cf. Section 3.2) and (2) the differences in people's expectations and needs depending on the different building type and space use (e.g., living room, classroom, open-space office).

The identification of such perceptual dimensions would result in soundscape descriptors to be used to describe the perception of the indoor acoustic environment [97]. Thus, a reference system for indoor soundscape measurement could be defined in line with the pleasantness—eventfulness space proposed by Axelsson et al. [96] and recently included in ISO/TS 12913-3:2019 [53]. This would allow the visualization of indoor soundscapes in a *n*-dimensional perceptual space, thus enabling building designers to set targets for their design actions and to assess the effectiveness of the interventions in terms of perceptual outcomes, as suggested in case of urban planning by Cain et al. [98].

In order to address the complexity of human-building interactions, the multifactorial nature of human experience in the built environment should be acknowledged and gradually integrated into soundscape models. Moving beyond single-domain perspectives where each environmental stimulus is studied in isolation, multi-domain approaches are highly encouraged [10,99]. As people experience the thermal, visual, acoustical, and olfactory environments simultaneously, multi-domain research allows for the investigation of interaction effects between multiple environmental factors on building occupants' perception and cognitive performance [62]. Besides environmental conditions, many other factors can determine the perception of the indoor acoustic environment and should be further considered in future studies, such as the urban context and building characteristics, personality traits, socioeconomic factors, and situational circumstances [43,54]. Embracing an experiential and multifactorial perspective in the assessment of the indoor acoustic environment, encompassing intra and inter-individual variability of building occupants, and dealing with temporal and spatial variability, is certainly an extremely complex task but it is the required route to get a realistic picture of the impacts of the built environment on its occupants.

4.2. Developing Soundscape Data Collection Tools

The definition of a reference system for indoor soundscape measurement would suggest which perceptual dimensions to measure and how to measure them through a set of rating scales to be employed in soundscape evaluations. As highlighted in Section 3.3, further research is needed to explore the applicability of (urban) outdoor soundscape data collection methods to indoor environments; and to tailor existing methodologies to indoor soundscape features under the general framework provided by the ISO 12913 soundscape standard series [48,52,53]. Questionnaires and interviews can be integrated into soundwalks or into corresponding methods for the assessment of indoor built environments (for example, a "soundsit"). Mobile apps could be employed to gather feedback from building users when it is convenient for them to do so. Rating scales could be combined with qualitative methods derived from psychological and social studies such as grounded theory to systematically extract information from qualitative data gathered during questionnaires or interviews [100–102]. Moreover, non-participatory methods [77] can provide valuable information about people's response to the acoustic environment under highly ecologically valid conditions; however, further research would be needed to inform guidance and standardization.

While some methods can be more suitable for laboratory or field research purposes, others, less time-consuming, could be coherently integrated into post-occupancy evaluation (POE) practices [103] and building certification protocols. Current occupant surveys reflect the aim to design buildings that are acceptable enough to prevent complains. This is exemplified in the study by Kim and de Dear in which, by applying Kano's satisfaction model to the building context, they investigated CBE's occupant survey database and categorized indoor environmental quality (IEQ) factors into basic, proportional, and bonus factors [104]. "Noise level" was found to be a basic factor, that is a minimum requirement that can cause dissatisfaction when under-performing, without contributing to the occupant satisfaction. Differently, "sound privacy" was classified as a proportional factor, as occupant's satisfaction was found to vary proportionally to the performance of this factor, both on the negative and positive side. Interestingly, among the factors investigated using the CBE occupant survey, none could be classified as a "bonus factor"; that is, a factor that goes beyond the minimum expectations of the occupants, so that when a building "performs very well on bonus factors, there is a strong positive effect on occupant's satisfaction" [104]. Results reflect the survey orientation towards diagnosing issues rather than to opportunities for improvement. Aspects related for instance to the quality of window view or to the semantic meaning of heard sounds were not investigated by the POE survey, despite the likelihood of identifying bonus factors relevant for people's enjoyment of their experience indoors.

Nevertheless, the current focus on healthy buildings presents an opportunity to revise current POE practices to collect evidence not only about failures but also successes, in order to inform the design of better-than-neutral indoor environments [11,47]. A number of factors that are currently lacking in current POE surveys should be included, such as positive (e.g., functional, cognitive, emotional) impacts of space design on building users, perceived control and personalization opportunities, personality traits, and users' expectations. The integration of soundscape data collection tools can help provide a more detailed picture of the complex building–user interaction, thus providing useful feedback for the design of healthy and supportive indoor soundscapes.

4.3. Providing Scientific Evidence of Sound Benefits on Emotion, Cognitive Performance and Health Outcomes through Soundscape-Based Research

The recent pursuit of health and well-being outcomes in the building sector has called for a shift in the way people think about the built environment and conduct research over the impacts on people's emotion, cognitive response and health. Acoustic environments perceived as pleasant require more than just the absence of annoyance; supportive acoustic environments are not only non-detrimental for task performance; and the absence of disease does not necessarily result in healthy environments. In line with recent trends in other IEQ domains, soundscape research is striving to define new ways to do "more good" for the lives of building occupants by "advancing positive stimuli and making their minds and affects flourish and thrive" [11].

Based on soundscape perceptual models and data collection tools to be developed, a better understanding should be gained on the relationship between tasks building users are called to accomplish and the cognitive and emotional states they must achieve to perform at their best. Research should further investigate how wanted sounds and intelligibility conditions can impair or support relationships between performance and cognitive and emotional states. For instance, enjoyable soundscapes where found to induce positive emotions and enhanced levels of arousal, that in turn could improve task performance (as in the case of the so-called Mozart effect [105]).

By shifting the focus from a pathogenic (i.e., absence of disease) to a salutogenic (i.e., health promotion) model of building design [12,22,23], new scientific evidence will inform regarding the positive and negative outcomes of soundscapes on people's health and well-being. Going beyond mere cause–effect relationships between decibel noise exposure and resulting annoyance, new exposure thresholds can be identified below which to apply soundscape methodologies for improving the conditions of people inhabiting the built environment. Such knowledge would provide new noise exposure limits for building protocols, design guidelines, and standards that vary with the space use, the availability of control, and exposure time (cf. Section 3.5 and Figure 3).

4.4. Designing Indoor Soundscape Strategies

Indoor soundscape design aims at implementing strategies to improve the quality of indoor soundscapes by enhancing wanted sounds and masking and reducing unwanted sound, according to people's perception in context. As highlighted in Section 3.1, the soundscape framework would provide practitioners with a greater design flexibility and a wider range of design options. This can lead to the development of new technologies or to rethinking existing ones according to new perception-based knowledge (e.g., building automation systems, active noise control, ventilation systems [40]), in keeping with an occupant-centric design and operation of buildings [9].

Solutions allowing building occupants to adapt and tailor their personal acoustic environment should be further investigated in order to quantify the potential benefit resulting from the availability of control over their environment. Such solutions could range from very basic ones, such as manual window opening, to more advanced ones, such as individual masking systems and sensor-driven controls combining user feedback, the Internet of Things (IoT), and machine learning techniques.

Strategies should be adapted for the purpose of the space and the extent of specified control over the environment. Different strategies might be applied in mixed use spaces (e.g., public shared spaces such as libraries, museums, train stations), in single use spaces for multiple users (e.g., classrooms, shops, music halls, meeting rooms) and single use spaces for single users (e.g., residential spaces, private offices).

Moving beyond mere noise level reduction, further research should be oriented to the investigation of sound type exploitation. Scientific evidence is needed to "measure" the benefits associated with the availability of natural sounds and to guide the reproduction of natural sounds indoors for biophilic purposes. In addition to natural sounds, attention should be paid to the exploitation of commonly available urban sounds for providing a contact with the outdoor environment and a sense of place, depending on the specific building use and available urban context. The implementation of soundscape strategies negotiated with the building users and the development of solutions capable of self-learning and updating to suit the single occupant with a data-driven approach would enable the creation of suitable spaces for specific users rather than just the "average person".

Participatory processes in building design and urban redevelopment allow for a bottom-up production of datasets of the way people perceive and experience everyday soundscapes and their concerns and expectations [67,106]. The active involvement of people in the identification and evaluation of real and ideal soundscapes can provide a positive impact on environmental and social justice issues in relation to noise pollution and acoustical well-being [67] by (i) informing about an unequal access to healthy living environments across different populations [107–111], (ii) encouraging the adoption of fair procedures in noise management [112,113], and (iii) identifying "opportunities for enhancing degraded living environments by creating and improving soundscapes that align with residents' values and preferences" [106].

To be effective, soundscape strategies need to be implemented first at an urban scale, through integrated urban design and planning approaches, and then at a building scale, by harmonizing requirements from the different disciplines involved in building design. Positive indoor soundscapes depend first of all on access to favourable urban contexts. The availability of quiet sides in people's dwellings, of green parks or vibrant public spaces is possible only through careful planning and re-design of urban areas and mobility plans and the quality of landscapes and soundscapes. At a building level, a fragmented approach to building design can lead to unintended consequences in occupant's behaviour (e.g., turning off the ventilation system for noise disturbance or opening the window to get a contact with the outdoor environment), with consequences on people's health (e.g., poor air quality) or energy performance (e.g., energy waste). Therefore, integrated design approaches are needed at design stage to solve the multifaceted requirements of the different disciplines, which otherwise need to be faced by the final user with a gap in building performance or in people's health and well-being.

4.5. Developing Soundscape Prediction Tools

One of the main limits in current soundscape research is the gap between soundscape descriptors, that are used in "measurement by persons", and soundscape indicators, to be used in the "measurement by instruments" to predict the impact of environment sounds according to people's perception [52]. Following the conceptual framework by Aletta et al. [97], soundscape indicators and new prediction models can be developed by triangulating physical data coming from monoaural and binaural measurements with perceptual data gathered through soundscape data collection tools. Indoor soundscape indices will provide a perceptual perspective into metrics coming from room and building acoustics, integrating, for example, perceived properties of the acoustic environment (e.g., sound type and meaning) with psychoacoustic parameters in new metrics yet to be developed.

As outlined in Section 3.3, the use of virtual reality technologies can be used to perform visual and aural assessments of indoor virtual environments before building construction or retrofit, in order to increase the probability of meeting the preferences and needs of final users. While current modelling, auralization and playback capabilities seem to be mature enough to realistically render future acoustic environments, such practice is still mainly limited to research studies and selected "real-world" projects; they are not, as yet, widely used in the process of building design and sales, as is the case with visual renderings. Therefore, further research is needed to improve the ecological validity of such auralization and reproduction techniques and make them accessible to practitioners.

5. Limitations

This study was limited by the selection of a restricted number of experts with a background in acoustic research, public health and well-being, building design and urban planning. Future research should involve acousticians, architects and urban planners in conjunction with medical experts and social scientists. Cognisant of the explorative nature of the study, interviewees were not chosen to comprehensively cover the many possible viewpoints that can be found in the scientific community but to provide initial expert opinions for establishing a preliminary discussion in the field of indoor soundscape research. This approach is in line with the purpose of using expert interviews as an exploratory tool [56]. Exploratory interviews helped to structure the subject under investigation, to highlight knowledge gaps and to generate hypotheses to be further analyzed and reviewed in future quantitative and/or qualitative oriented research projects.

6. Conclusions

The present study established an initial discussion regarding some of the open questions in the emerging field of indoor soundscape research. The questions and answers were based on the thematic analysis of structured interviews with a panel of experts, which led to the following conclusions related to the investigated research questions:

- The soundscape framework, integrated into multisensory research, can help improve understanding of the human perceptual response to the indoor built environment in context, providing scientific evidence for the negative and positive impacts of soundscapes on human health, well-being and quality of life. Such evidence can potentially reinforce the role of acoustics in building design, foster socially and environmentally just urban and building design processes and challenge many current design practices based predominantly on a noise control approach. Indoor soundscape design solutions need to be implemented through participatory and integrated design approaches in order to shape indoor spaces able to provide acoustic delight, support for cognitive functions and enhanced well-being.
- Soundscape research needs to address the peculiarities of indoor soundscapes compared to outdoor ones. Differences are related to the physical acoustic environment, to contextual features that may result in different expectations (e.g., space use, time of permanence) and to consequent soundscape strategies to apply. Notably, in indoor spaces, masking strategies are based on the appropriate combination of indoor-generated and outdoor-generated sounds according to people's perception (i.e., wanted vs. unwanted sounds).
- Research should explore the applicability of urban soundscape data collection methods to indoor environments and tailor existing methodologies to indoor soundscape features under the general framework provided by the ISO 12913 soundscape standard series [48,52,53]. Questionnaires and interviews integrated into soundwalks (or "soundsits") and non-participatory observational methods [77] can provide valuable information on the human response to the acoustic environment. If integrated into current occupant-survey methods this could inform the design of better-than-neutral indoor acoustic environments.
- Sound can contribute to providing contact with nature according to biophilic design approaches. When outdoor natural contexts are not available, artificial natural sounds might be played if appropriate. However, added sounds should only be used if "wanted" by building users, coherently combined with visual stimuli; suitable for the tasks to be performed and the intended use of the building, designed and evaluated according to soundscape methods, and developed following participatory processes. Besides natural sounds, attention should be paid to the exploitation of commonly available urban sounds for providing contact with the outdoor environment and a sense of place, depending on the specific building use and available urban context.
- Moving beyond cause–effect relationships between decibel levels and resulting noise annoyance, new scientific evidence might be provided on the health, mental-health, and well-being effects of noise exposure and soundscape perceptual indicators. Such knowledge would provide new sound quality metrics and levels for building protocols, design guidelines, and standards that are a function of the space use, the availability of control, and exposure time. Below such thresholds,

soundscape methodologies should be applied for improving the conditions of people inhabiting the built environment, in terms of emotion, cognitive performance, and health outcomes.

Interestingly, many of the challenges for indoor soundscape research align with similar priorities already identified for urban outdoor soundscape research and practice [114], while others are specific to the indoor built environments (e.g., integration with building-related disciplines, and impact on cognitive performance). Taken together, acoustic comfort research seems to be close to a paradigm shift similar to those already experienced in other IEQ research domains. By providing a perceptual perspective on building and room acoustics, indoor soundscape science can deliver satisfactory spaces that go beyond what is merely acceptable and harmless, thereby contributing to the ongoing pursuit of health and well-being in building research and practice.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/15/6054/s1, Table S1: Coding.

Author Contributions: Conceptualization, S.T., F.A., F.B., E.B., and R.A.; methodology, S.T., F.A., F.B., and R.A.; interview, S.T.; thematic analysis, S.T. and F.A.; writing—original draft preparation, S.T.; writing—review and editing, S.T., F.A., F.B., E.B., J.H.-C., J.K., L.L., A.R., and R.A.; supervision, F.A., F.B., J.K., and R.A.; funding acquisition, F.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the COST Action CA16114 'RESTORE: Rethinking Sustainability towards a Regenerative Economy' and by the "Programma di cooperazione Interreg V-A Italia-Svizzera 2014–2020", project "QAES" ID no. 613474. F.A., and J.K. received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 740696).

Acknowledgments: Expert interviews were conducted by Simone Torresin within the framework of a Short-Term Scientific Mission at the International WELL Building Institute, supported by the COST Action RESTORE. We gratefully acknowledge Angela Loder and the International WELL Building Institute for having hosted the STSM.

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

Appendix A. Questionnaire

1. Restorative buildings are defined as buildings able to restore social and ecological systems to a healthy state through their impact on the environment, health, quality of life, and productivity of their inhabitants. Moreover, scientific literature provides strong evidence about the impact of acoustic conditions on health and well-being of building users. How do you think acoustic design can contribute in creating restorative buildings? Could you provide some examples of approaches and technologies that should be adopted for restorative purposes?
2. During the last few decades, research and design criteria for the indoor environment have been oriented to a more and more human-centred perspective, by putting the focus on building users' perception as a basis for the environmental characterization. As far as acoustics is concerned, the soundscape approach, originally developed for outdoor urban studies, has been introduced in the context of the indoor built environment to consider how the acoustic environment is perceived, experienced and understood by building users. Do you think that that such approach—namely, the "indoor soundscaping" approach—could be integrated into building assessment protocols, such as WELL? In case, how?
3. Research on urban soundscape has stressed the need to go beyond the traditional approach based on sound level reduction, by considering the way in which the sound environment is perceived, in context, by people. This has provided the opportunity to exploit the potential of positive wanted sounds, besides the need to limit the unwanted ones (i.e., noise). What differences and similarities may exist between the outdoor and the indoor soundscape approaches in sound and noise management?
4. Soundwalks, questionnaires, guided interviews, and non-participatory observations are some of the main methods used to collect soundscape data. What methodology do you think would be most effective to capture individual's subjective perception of the indoor environment?

5. Let's think about naturally ventilated buildings (i.e., buildings in which ventilation is performed without mechanical systems, e.g., through windows opening) or mixed-mode ventilated buildings (i.e., a hybrid approach that combines natural and mechanical ventilation). Research has seen, during the last decade, a revival of natural ventilation as a passive low-energy option to provide—in some cases and conditions—fresh air and indoor environments thermally more stimulating and pleasurable compared to the static indoor climates achievable in centralized mechanically controlled buildings. One of the main limitations in the use of natural ventilation lies in the conflict between ventilation needs and access of external noise through ventilation openings, that connect the indoor soundscape with the outdoor soundscape. How do you think this conflict could be overcome?
6. Biophilic design aims at increasing building users' contact with nature, usually through visual natural scenes. What is the potential of sound stimuli to provide a contact with nature in indoor environments?
7. The adverse health effects of environmental noise on people are widely recognized. To what extent wanted sounds can be accepted without compromising building user's health?
8. Imagine to be in a living or working indoor built space. In general, which qualitative attributes would you use to describe how you perceive the indoor acoustic environment? Please provide a list of adjectives that come to your mind.

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