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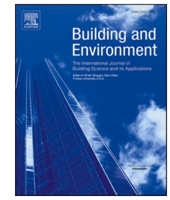

Towards developing a model of adaptive acoustic comfort in the built environment: A thematic analysis from an expert focus group

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ABSTRACT

The adaptive capacities of building occupants have so far been primarily investigated in relation to the thermal climate through the adaptive thermal comfort model. However, the concept of adaptation extends beyond thermal conditions and is relevant to other sensory modalities, such as acoustics. This is significant for both human health and well-being, as well as environmental considerations. The latter aspect is linked to potential variations in acoustic sensitivities between naturally ventilated and mechanically ventilated buildings, which, if identified and acknowledged, could lead to a greater applicability of passive ventilation strategies through tailored acoustic criteria. Drawing from thematic analysis of discussions held in a focus group comprising 8 experts in acoustics, soundscape, and adaptive thermal comfort, this study aims to 1) delineate the underlying assumptions of acoustic adaptation in built environments, and 2) establish a research agenda towards developing a framework for adaptive acoustic comfort. The identified themes include: the definition of adaptive acoustic comfort, potentially contributing acoustic and non-acoustic factors, differences and similarities with the adaptive thermal comfort model, and the methodology for collecting data. In terms of results, 1) adaptive acoustic comfort would be based on potential modifying effects of recent past acoustic exposure and other environmental factors (including multi-domain effects), contextual, and personal factors on people's acoustic expectations and preferences. 2) To test this concept, the very first step will have to be the construction of a comprehensive global acoustic comfort database.

1. Introduction

Adaptation is a key component in the context of analysis of vulnerability and sensitivity of buildings to climate change. Adaptive capacity is defined as "*the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences*" [1]. Similarly, the Intergovernmental Panel on Climate Change defines adaptation as "*the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities*" [2]. Adaptive capacities of humans have been studied so far mainly in relation to the thermal climate. Scholars like de Dear and Brager [3], and Nicol and Humphreys [4], have proposed adaptive thermal comfort models as appropriate tools for designing naturally ventilated spaces and quantifying their thermal comfort performance. This theme is of particular importance in the context of climate change as space cooling stands out as one of the major end uses of energy in the built environment, with significant responsibility for greenhouse gas emissions [5]. One of the most common architectural responses to these challenges is the passive and bioclimatic design of buildings [6], where natural ventilation partially or completely replaces mechanical conditioning to provide thermally comfortable indoor environments while simultaneously reducing energy demand for heating, ventilation, and air conditioning (HVAC). By challenging the conventional assumption that thermal comfort could only be achieved within a narrow range of internal temperatures, as in Fanger's model based on Predicted Mean Vote (PMV) [7], the adaptive thermal comfort model legitimized passive and low-energy design strategies focused on natural ventilation.

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The concept of adaptive capacities of building occupants in relation to the acoustic environment has been largely overlooked in literature until now. However, a model of "adaptive acoustic comfort" could be just as relevant as adaptive thermal comfort, both in terms of environmental and human health implications. Indeed, the implementation of passive ventilation and cooling strategies largely relies on the quality of the outdoor acoustic environment. Currently, acoustic criteria for buildings recommend background noise levels that do not consider the various contextual conditions in which people perceive sounds and any adaptive mechanisms that might be at play [8]. Increases in the admissible background noise levels for naturally ventilated environments compared to mechanically ventilated ones are included in some standards or guidelines [8] but are not supported by scientific evidence regarding differences in people's sensitivity according to the ventilation strategy. However, the recommended A-weighted noise level thresholds are often not achievable when window opening is considered for ventilation or ventilative cooling, making passive ventilation strategies difficult to implement unless the interdependence of ventilation requirements with acoustic ones is appropriately considered at the design and regulatory levels. Moreover, sound pressure levels can only explain the acoustic perception of individuals to a limited extent: at the same noise level, very different perceptual outcomes may occur based on various variables related to acoustic and non-acoustic factors (e.g., individual, environmental and contextual ones) [9–12]. Context is key to the definition of soundscape, defined within the ISO 12913-1 standard as the acoustic environment as perceived by humans *in context* [13].

Understanding the dynamics underlying adaptive acoustic comfort in naturally ventilated environments versus mechanically ventilated ones has the potential to facilitate a broader adoption of natural ventilation strategies by eventually relaxing acoustic criteria and defining new ones, based on context and adaptive opportunities (such as control over window opening and closing). Theorizing, empirically testing, and modelling of adaptive acoustic comfort would therefore have significant implications for energy consumption in the construction sector and, consequently, for the broader environment.

Furthermore, a deeper comprehension of individuals' acoustic comfort and their adaptive capabilities holds the potential for improving human health and well-being. Noise exposure stands as a prominent environmental health risk factor in Europe [14]. Noise annoyance is the most stringent critical health outcome in defining external recommended noise limits by the World Health Organization (WHO) [15,16] and noise is frequently cited as the primary source of dissatisfaction for building occupants [17]. Despite this, the severity of the phenomenon seems not to have been adequately addressed and comprehended [18]. Hence, understanding the factors contributing to acoustic comfort and the adaptive strategies occupants employ in challenging acoustic environments can play a pivotal role in gaining new knowledge on acoustic comfort principles and enhancing the health of individuals through a context-based acoustic design.

Drawing on decades of studies on adaptive thermal comfort (introduced in Section 1.1 to provide a reference for readers with different backgrounds from thermal comfort research), and preliminary hypotheses in the acoustic field (Section 1.2), this study aims to outline a discussion towards the theorization and testing of an adaptive acoustic comfort framework based on the research questions outlined in Section 1.3.

1.1. Overview of adaptive thermal comfort literature

Thermal comfort is usually defined as "*that condition of mind that expresses satisfaction with the thermal environment*" [19] and because of its obvious implications for the comfort industry, in particular the heating, ventilation and air conditioning (HVAC) sector, it has a long history of applied research particularly focused on specifications of the "comfort zone". Two main methods of research have been used to define the relationship between objective indoor thermal environmental conditions and this subjective state of mind, namely climate chamber experimentation with human participants and field studies inside real buildings occupied by real people going about their normal day-to-day lives [20–22]. The field study approach in particular has revealed a strong dependence of the temperatures that people find most comfortable (a.k.a. thermal neutrality) on their recent history of temperature exposures [23]. This relationship is most evident in naturally ventilated free-running buildings where thermal neutralities observed in field studies are strongly correlated with the outdoor thermal context of the building in question during the weeks immediately leading up to the field study, as showed in Fig. 1. Various climatological metrics have been proposed for the latter, but the most common are the mean monthly temperature, or a weighted, running mean outdoor temperature in which heavier weights are given to the most recent daily temperatures, and lightest weights for temperatures observed further back in the time series prior to the field study [24].

Twenty years ago the American Society of Heating, Refrigerating and Air-conditioning Engineers incorporated an adaptive comfort model [3] into their thermal comfort standard ASHRAE Std-55-2004 [25]. Its scope of application was explicitly circumscribed to just naturally ventilated buildings that had no mechanical cooling capabilities, based on the extensive field study evidence showing that the statistical association between indoor thermal neutrality and outdoor climate was strongest and most statistically significant in naturally ventilated buildings. However, a recent re-analysis of the original ASHRAE adaptive comfort model [26] using a much larger field study database [27] than was available to the original model's team two decades ago, revealed an even stronger statistical association between indoor comfort temperatures and indoor mean temperature at the time of the field study. Moreover, this statistical relationship was observed across all building types in the expanded database, regardless of their ventilation strategy i.e. naturally ventilated, mixed-mode, and fully sealed air-conditioned buildings alike. It's generally accepted that we spend upwards of 90 % of our daily lives inside built environments, so in hindsight it seems logical that our comfort expectations are most closely adapted to the indoor climate prevailing in our buildings. In light of this new understanding, the most recent version of the adaptive comfort section in ASHRAE Std-55 [24] has enlarged its scope of application to include mixed-mode buildings, regardless of whether they are operating in their naturally ventilated or air-conditioned modes. But the evidence doesn't stop at mixed-mode buildings, and so pressure is beginning to build for the adaptive comfort standard's scope to be expanded even further to include permanently air-conditioned buildings. If that were to happen the implications for the building sector's demand for cooling energy and its associated greenhouse gas emissions would be profound [28].

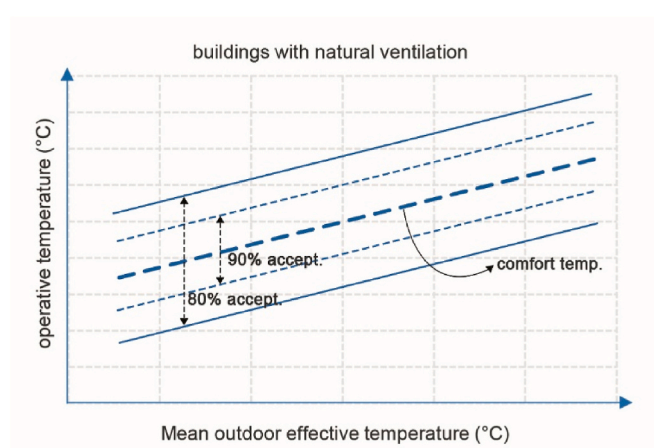

Fig. 1. – *Adaptive model for predicting optimum and acceptable comfort temperature ranges in buildings with natural ventilation (modified from* Ref. [3]).

1.2. Overview of adaptive acoustic comfort literature

The concept of “adaptive acoustic comfort”, understood as the counterpart of adaptive thermal comfort, is described by Field first [29–31] (though not explicitly mentioning the term) and later by Harvie Clark et al. [32]. Building upon the concept of adaptive thermal comfort, Field hypothesizes that people’s sensitivity to noise may change in naturally ventilated buildings based on factors such as different expectations of low ambient noise, appreciation of non-acoustic benefits provided by natural ventilation, and socio-cultural background, as people in countries where windows are typically open for most of the year would tend to be more tolerant of noise [30]. Therefore, Field advocates for a differentiation of building acoustic criteria based on the ventilation strategy, akin to what occurs in the realm of thermal comfort [30]. In explaining the rationale behind the acoustic criteria proposed in the Acoustics Ventilation and Overheating Residential Design Guide (AVO guide) by the Association of Noise Consultants in the UK [33], Harvie Clark et al. explicitly refer to the term “adaptive acoustic comfort” [32] to suggest an increased tolerance for the ingress of environmental noise (compared to annual average values) when occupants utilize open windows to mitigate overheating for a short time. Finally, the concept is taken up by Torresin et al. within the framework of indoor soundscape [8]. The significance of a soundscape approach becomes apparent when considering the adaptive hypothesis, which, rooted in the definition by de Dear and Brager [3], posits that contextual factors and past experiences shape the (thermal) expectations and preferences of building occupants [3]. This underscores the importance of a soundscape approach due to its emphasis on context when evaluating the perception of the acoustic phenomenon. Challenging the traditional focus on the conflict between noise ingress and natural ventilation and adopting a soundscape perspective, Torresin et al. suggest that acoustic comfort could even be a co-benefit of natural ventilation in specific contexts [8]. This could include fostering a connection with the external environment (e.g., in natural contexts), creating a sense of place, and offering opportunities for privacy and masking against annoying indoor sources [34].

1.3. Research aims

In light of the potential impacts on the environment and humans and the lack of scientific exploration on the topic of adaptive acoustic comfort, the main objectives for this paper are:

1. Preliminarily defining adaptive acoustic comfort based on expert interviews;
2. Outlining a research agenda to validate the formulated concept.

The focus of this discussion is not specific to a particular category of buildings, but extends to both commercial office buildings and residential ones.

2. Materials and methods

Due to the explorative nature of the research, a qualitative approach was adopted. Qualitative research methods are commonly utilized to uncover new phenomena and areas of research and to provide insight into experiences that are challenging to quantify, such as those found in people-environment relationships [35]. An expert focus group was chosen as a suitable approach for generating ideas related to the development of a specific concept, as well as for gathering data and conducting subsequent thematic analysis [36]. Informed consent was obtained from all subjects. The study complied with regulations for the protection of personal data and ethics at the University of Trento.

2.1. Expert focus group

Focus groups serve to both generate innovative ideas and assess potential concepts, offering valuable insights into diverse opinions within specific groups and allowing for generating of a significant amount of data in a relatively short period [37]. These discussions offer direct insights into the similarities and differences among participants’ opinions and experiences, allowing for evaluation from various perspectives. In this study, a workshop-like session was conducted with experts, to preliminarily discuss and define the concept of adaptive acoustic comfort. A collegial discussion among internationally recognized experts in diverse fields such as thermal and acoustic comfort facilitates the emergence of new theories through a transdisciplinary approach. The approach generates “*knowledge that goes over and above disciplinary boundaries following a process that assembles disciplines and recombines information*” [38]. This methodological choice aimed to not only maintain an open perspective towards emerging data but also to extract meaningful insights through a thematic lens, thereby contributing to a comprehensive understanding of the link between adaptive thermal and adaptive acoustic comfort.

2.1.1. Participants

In this study, experts were selected through purposive sampling based on their specialized expertise in the fields of acoustics and adaptive thermal comfort. In qualitative research, purposive selections are made to align the sample with the specific context and goals of the study rather than using random sampling [39]. Purposive selections are made in expert workshops to focus on specific areas of interest and enhance the robustness of the data collected by relying on opinions of experts. Without assuming the goal of encompassing the various viewpoints within the scientific community, the study sought to rather initiate a preliminary discussion on the topic. For the acoustic domain, we chose to include experts with knowledge of acoustic comfort in the built environment, as well as a general understanding of physiology and environmental psychology. These combined competencies have been instrumental in developing the theory of adaptive thermal comfort. Therefore, the workshop involved eight researchers with main expertise in adaptive thermal comfort (Richard de Dear, Thomas Parkinson), acoustics and psychoacoustics (Densil Cabrera, Yoshimi Hasegawa), outdoor and indoor soundscape (Jian Kang, Francesco Aletta, Simone Torresin), as well as sustainable building design (Rossano Albatici). In particular, the workshop involved researchers from the IEQ Lab at the School of Architecture, Design, and Planning at the University of Sydney, to draw lessons from the study of adaptive behaviours in thermal environments, highlight potential analogies between the two domains (acoustic and thermal), and identify challenges in the definition of a framework for adaptive acoustic comfort.

2.1.2. Online workshop setting and procedure

A workshop was conducted in December 2023 in a hybrid format (i.e., both online and on-site, at the University of Sydney). The duration of the workshop was approximately 1 h. The session was moderated by a researcher (Simone Torresin), and the schedule is presented in Fig. 3. The workshop was supported by an online whiteboard containing fundamental content related to adaptive thermal comfort and adaptive acoustic comfort (see Fig. 2). The left side of the whiteboard featured a circle containing excerpts from documents that defined adaptive thermal comfort (as outlined in Section 1.1), while the outer area displayed excerpts from literature related to adaptive acoustic comfort (Section 1.2). On the right side, the circles intersected to encourage participants to consider the differences and intersections between the two domains. The original Fig. 1 from Ref. [3] was also presented as a reference.

The workshop was guided by two research questions: defining adaptive acoustic comfort and identifying its differences from adaptive thermal comfort. After a round of introductions, the moderator outlined the content presented on the whiteboard. Participants then assessed the

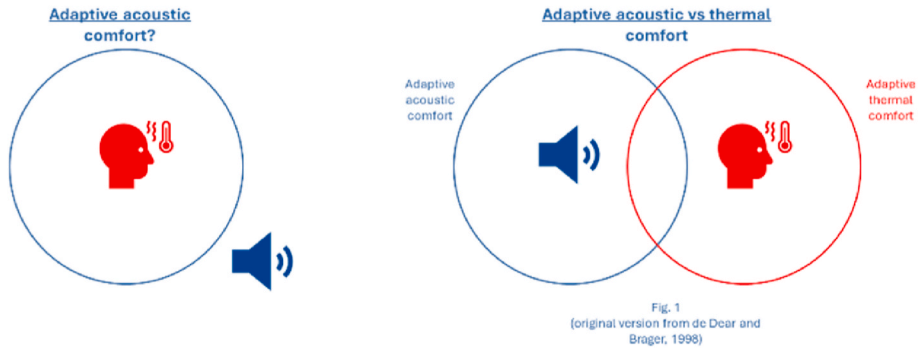

Fig. 2. – Schematic representation of the whiteboard content presented at the workshop.

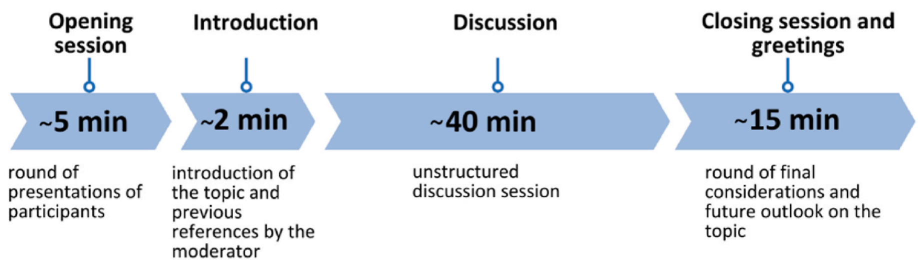

Fig. 3. – Schedule of the workshop.

topic based on their respective areas of expertise. The interventions were spontaneous, allowing participants to choose if and when to speak, with the online participants (F.A., J.K., S.D., R.A.) raising their hands to contribute. They provided mutual responses to questions posed by participants regarding acoustic adaptation as well as similarities and differences between thermal and acoustic domains. In the final part of the workshop, all participants were asked about their general opinions, comments on the understanding of adaptive acoustic comfort, and anticipated challenges. The session concluded with every participant having expressed at least one opinion on the topic, without any interruptions or restrictions on ongoing discussions due to time constraints.

2.2. Data analysis

The workshop content was recorded and transcribed verbatim. Thematic analysis was applied to identify, analyse, and present patterns of meaning in the data for a detailed organization and explanation of the collected expert opinions [40]. The analytical process commenced with data segmentation (or coding), organizing excerpts based on patterns of semantic content (or themes) using a semantic approach [40]. Since the workshop unfolded in an unstructured manner and through a sort of brainstorming, the analysis was conducted using an inductive (or data-driven, or bottom-up [40]) approach, without referring to a pre-existing coding frame [40,41]. Coding was performed in NVivo 12 software (QSR International). Coding, theme formation, and labelling were done manually and did not involve the focus group expert participants. The coding was then reviewed by a second researcher, and any conflicts were resolved through discussion. All experts participated in the current study by offering comments on the research gaps identified through the thematic analysis and outlining challenges and steps for a future research agenda in the discussion section, drawing on their collective expertise. An example of the process leading from coding to theme formation is provided in Table 1, while the extended coding exported from NVivo is available as supplementary material. Themes identified by the researchers are not necessarily aligned with the research questions that guided the workshop. Instead, they depended on what emerged during the discussion, as is often the case [42]. The

Table 1
– Example of the coding process for the second theme.

Example of excerpt	Code	Theme
"You're not adapting to the acoustic environment, you're adapting to the whole environment"	Environment, context	Factors potentially influencing acoustic adaptation
"We are not even bringing in, you know, personal factors or opportunities or the idea of you know, sense of control like … Am I able to actually open or close the window or switch on, switch off the mechanical ventilation or things like that."	Availability of control	
"It depends on several factors and I was thinking … another aspect when doing studies on acoustic comfort … we always assess individual noise sensitivity."	Individual traits	
"we can suppose a different noise sensitivity from mechanically ventilated buildings because we have a different expectation of low noise levels [compared to naturally ventilated buildings]*. We have different benefits like the sense of fresh air and the contact with the outside."*	Multi-domain and multisensory factors	
…	…	

interpretative analysis of data is followed by a reporting phase, where the thematic description is substantiated by data extracts in the analytic narrative [42]. This is key in semantic approaches, where themes stem from the explicit meaning of the data, and in expert interviews where words inherently convey valuable opinions based on their expertise.

3. Results

Through the process of thematic analysis of the material collected during the expert focus group, four main themes have been identified, the first concerning the definition of adaptive acoustic comfort itself, the second related to the factors that may potentially underlie adaptive acoustic opportunities, the hypothesized differences and analogies between acoustic and thermal adaptive comfort, and finally, a discussion of the open fronts regarding the definition of a model of adaptive acoustic comfort. Themes and sub-themes are represented in Fig. 4. Below a detailed description of each of the four themes is reported.

3.1. The concept of acoustic adaptation

At the core of adaptive comfort lies the concept of "adaptive opportunity", according to which the ability to exert control over a particular condition would change the perceptual outcome of experiencing that condition.

> "*We have a term that is: "adaptive opportunities", and that's exactly what you were referring to. If you can do something about it, it becomes less obnoxious. If you've got no adaptive opportunities at your disposal, the slightest irritation gets amplified into intolerable.*"

According to the adaptive acoustic comfort hypothesis, comfort conditions are not universal but rather influenced by various personal and contextual factors (outlined in the following theme). This suggests varying sensitivity to the acoustic environment and noise tolerance, thus potentially enabling the introduction of diverse acoustic criteria and noise level thresholds based on the context.

> "*So, I think there's a lot of space there for this kind of idea of, you know, relaxing some thresholds or different thresholds in different contexts, basically.*"

> "*But the idea of adaptive acoustic comfort is that, again, if on average noise levels are always higher, then people — in natural ventilated buildings and so on — are willing to accept higher indoor levels.*"

3.2. Factors potentially influencing acoustic adaptation

The environment in which individuals find themselves is the primary determinant of their adaptation and response. In the context of adaptive acoustic comfort, the environment is primarily defined as the acoustic environment. The occupant's perceptual response would depend not only on its energetic attributes (loudness, frequency content, temporal patterns) but also on the types of sources that make up the soundscape.

> "*... different outdoor urban soundscapes or contexts, because having an outdoor natural park or a fountain can be very loud but the perceptual effect is not the same as in the case of having loud traffic noise*"

> "*But the underlying idea that, you know, we adapt and react to different environmental conditions is very much there.*"

However, it is emphasized that it is the environment in its entirety that determines the occupant's adaptation and their varying sensitivity to sounds and noises, thereby acknowledging the multisensory nature of the person-environment relationship.

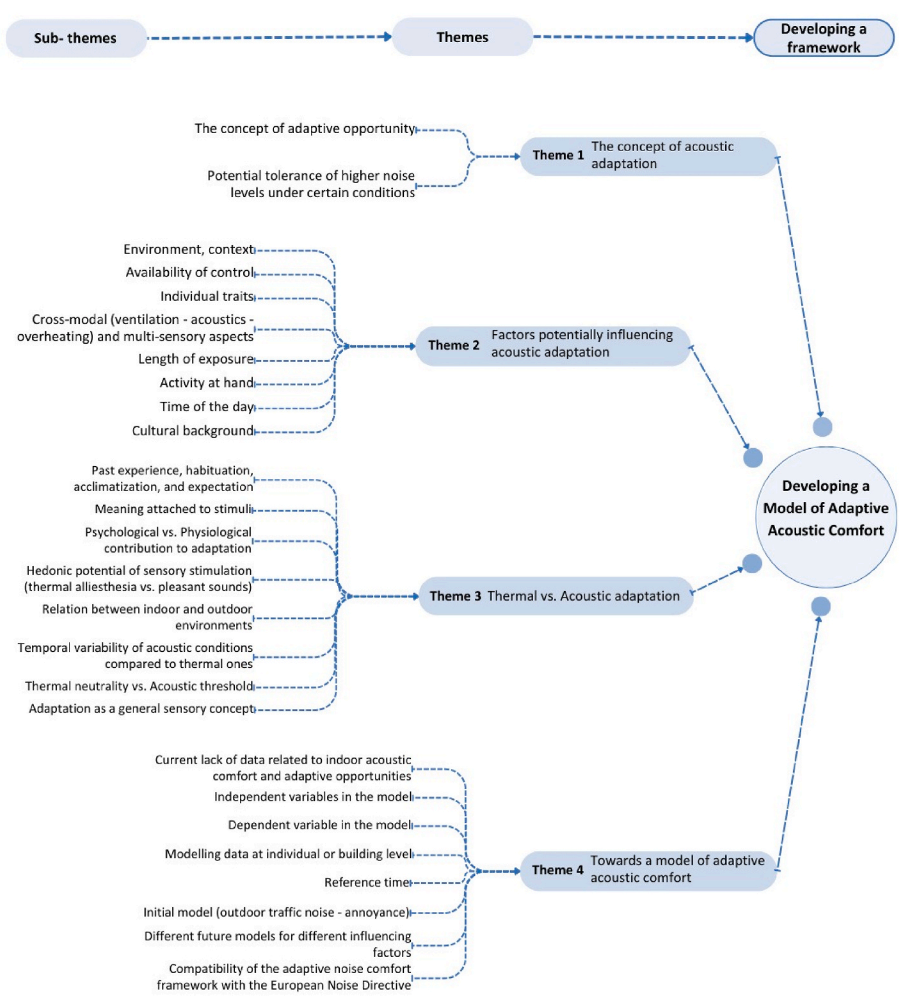

Fig. 4. – Sub-themes and themes.

"*You're not adapting to the acoustic environment, you're adapting to the whole environment*"

Reference is made to the Acoustics Ventilation and Overheating Guide and Field's description of opportunities for acoustic adaptation in relation to ventilation types, already introduced in section 1.2. The theme of adaptive comfort thus intertwines with that of multisensory response, considering, for example, combined exposure to acoustic environmental conditions and overheating, or a different acoustic tolerance based on airflow, air freshness, and contact with the outside provided in naturally ventilated buildings upon opening windows. Moreover, the theme is inherently multi-domain, as it evaluates the combined effects related to the acoustic, thermal, and ventilation domains.

"*the adaptation in the adaptive acoustic concept is kind of more like a trade-off*"

"*Does the sense of fresh air that you have when you open a window and the co-benefits of opening the windows allow you to appreciate higher noise levels?*"

"*my feeling is that in the context of acoustics literature, adaptive acoustic comfort has been used mostly as a buzzword and somehow as a proxy for this kind of multi-sensory interactions and* [...] *the idea is that more environmental domains come into play when it comes to assessing the acoustic comfort and the acoustic quality.*"

As anticipated, at the core of the concept of adaptive opportunity is the level of control individuals have over their environment through their actions. Having control over the acoustic environment, such as the ability to open and close windows in naturally ventilated buildings, might result in a different tolerance for acoustic conditions compared to sealed buildings with mechanical ventilation.

"*the idea of, you know, the sense of control like ... Am I able to actually open or close the window or switch on, switch off the mechanical ventilation? or things like that.*"

"*It's part of having control. So, you can close and open the window. So that's like you have control of your acoustic environment.*"

The ability to adapt to the acoustic environment would depend on the activity being performed and the time of the day in which they are performed, with different activities and day or night exposures involving different acoustic needs, and this is inherently tied to the building use.

"*... noise can be pleasant or not and it also depends or it's mainly related to the activity you are doing.*"

"*And then there is this difference between day and night, because* [...] *some loudness during the day, just to feel the sense of place, connection outside* [could be wanted]*, while, sometimes, a completely silent environment would be sometimes an issue.*"

The duration of exposure is another factor that could determine people's adaptive capacity to the acoustic environment. On one hand, this may involve habituation dynamics, which will be addressed in the next theme. On the other hand, brief exposures to suboptimal environmental conditions could lead to tolerating different acoustic conditions (e.g., increased background noise levels) if compensated by other benefits (e.g., mitigating overheating through window opening), in a sort of trade-off, which is the basis of the AVO guide.

"*They have talked about this* [adaptive acoustic comfort] *in the context of the Acoustics, Ventilation and Overheating ventilation design guide by the Association of Noise Consultants in the UK in which they assume basically the proposed higher requirements in indoor acoustic levels when for limited amount of time you have to open windows for mitigating overheating risk.*"

The individual's adaptive capacity would then depend on a series of personal traits, such as noise sensitivity or the cultural background. Personal factors would play a crucial role in adaptive acoustic comfort, given its predominantly psychological rather than physiological nature, as elaborated in the subsequent theme.

"*I was thinking ... another aspect* [that might be relevant in the context of adaptive acoustic comfort] *... when doing studies on acoustic comfort, we always assess individual noise sensitivity.*"

3.3. Thermal vs. acoustic adaptation

Since the focus group involved experts in the field thermal adaptation, an interesting theme that emerged during the workshop was to highlight possible differences and analogies between the model of adaptive thermal comfort, already well-established in literature and included in standards, and a potential model of adaptive acoustic comfort.

Keywordsin the narrative of adaptive thermal comfort include acclimatization, habituation, and expectation.

"*Acclimatization, which is a physiological process in which the thermo-physiological systems of our body kind of get more efficient at handling heat or cold ......, heat acclimatization is mostly about sweating ... sweating earlier and sweating more freely and acclimatization is mostly about sweating more effectively ....ensuring that core temperature doesn't rise, ...all of that happens automatically. We don't need to turn on acclimatization, it just happens as a result of exposure. So that's the physiological process or concept.*"

"*Habituate is another term that you might use. We kind of just get used to the average level of thermal exposure in our recent history ...*"

"*People have psychologically adjusted their thermal expectations up or down to the levels that they're generally exposed to. The point is this that we kind of adapt to what we're exposed to and in terms of thermal comfort.*"

By analogy, at the foundation of the hypothesis of adaptive acoustic comfort, there would therefore be the fact that noise sensitivity and expectations adjust based on previous exposure, within certain limits. Satisfaction or discomfort towards environmental conditions would then hinge on whether expectations are met or not.

"*People who live in an extremely quiet environment would find living under the flight path in Marrickville intolerable (expensive house, right under the flight path* [in Sydney]*)*"

"*Things become objectionable when they exceed our expectations. But if everything sits within what we expected, I think people adjust a little bit, it's no problem.*"

The adaptive phenomena would therefore not be exclusive to the thermal sensory domain, but rather general, albeit underpinned by different psychological and physiological mechanisms.

"*I'm not a physician, but I would assume that mechanisms at central nervous systems are probably quite different. But the underlying idea that, you know, we adapt and react to different environmental conditions is very much there.* [...] *So again, I think probably we have been using different semantics and terminology, but more or less I see a lot of things running in parallel* [between the thermal and acoustic domains].*"

"*Whether we are talking about residential or non-residential buildings, if the place is where the airplane goes over your head many times, you can expect you know this is where we are living. So yeah, this is what we have to adapt to.*"

"*I think this adaptation concept is applicable to all senses. It's not just acoustics. It's everything.*"

The processes driving thermal adaptation involve both physiological factors, which relate to the body's heat regulation and acclimatization, and psychological factors, which involve adjusting individual expectations based on past experiences. The hypothesis formulated during the focus group suggests that acoustic adaptation would be primarily psychological in nature. This assumption is rooted in the fact that sound stimuli carry meaning, such as related to the source producing it or the informational content of the sound itself, unlike thermal stimuli.

> "*Fundamentally, I think the difference between sound and thermal stimuli is that sound has more meaning. It carries positive or negative information. But maybe temperature has less meaning, so … I'm just wondering, for the adaptive process, what's the proportion of physiological side and the perception side? Maybe* […] *for the acoustic side perception is the most dominant.*"

> "*We don't really know what the balance is between physiological and sensory in the thermal context. It's a black box.*"

The connection between indoor and outdoor environments plays a key role in shaping the thermal and acoustic exposure within buildings, where we spend most of our time. This correlation is particularly pronounced in naturally ventilated buildings, where air exchange occurs through window openings.

> "*We're indoor animals. We live in buildings most of our lives and it's the indoor thermal environment that we're adapting to. Why did we get such a strong correlation with outdoor temperature? The answer is very simple, because we're talking about naturally ventilated buildings, so indoor temperatures are very closely related to outdoor temperatures.*"

> "[you have the] *same issue* [in the acoustic case] *if you keep the windows open. Basically, whenever there is noise outside, you get to feel it* [indoor] … *you will still get the filtering* [from outside, to inside, provided by] *the building facade and whatever diffraction is happening at the edges* [of the] *the windows or any other ventilation point. But yeah, the gaps* [between outdoor and indoor noise levels] *immediately reduce when you are in naturally ventilated buildings.*"

A factor to consider, especially in data collection supporting the construction of a model of comfort, as discussed in the next theme, is the different temporal variability of thermal and acoustic stimuli. While thermal stimuli typically exhibit a slow temporal variation, acoustic stimuli vary more rapidly, depending on the context, and can even have an impulsive character.

> "*… I open the window, I have the trucks on the roads, the helicopter in the sky. So you have several sounds coming inside the building, they change quite rapidly, while temperature usually doesn't change that quickly.*"

Both scenarios, however, involve the sensory stimulus potentially triggering pleasure. Specifically in the thermal context, the phenomenon is referred to as thermal alliesthesia [43], recalling a term coined by Cabanac in 1971 [44].

> "*the gist of it was this that … let putting it into a thermal context, but it was equally applicable to the other sensory modes as well …* […] *if the body's heat content is displaced away from some mutual value or thermoneutral zone, any external or peripheral stimulation that has the promise of restoring back to neutrality will be perceived as pleasant as not only neutral, but more than neutral actually, positively pleasant and conversely, any external stimulus that will exacerbate the displacement from that thermoneutral zone will be perceived as obnoxious or unpleasant. So hot summer's day, standing in the sunshine, it's unpleasant. Cold winters day, standing in the same sunshine, will be very pleasant. Same stimulus, different meaning, because the internal state of the body is different.*"

> "*if you are reading some sounds can be pleasant or not …*"

The boundary between pleasure and annoyance would be marked in the thermal context by thermal neutrality. However, in the acoustic domain, neutrality would be differently defined: there would be a threshold beyond which the stimulus causes discomfort. The difference between a range of thermal comfort around thermal neutrality and a threshold of acoustic tolerance towards noise levels is conceptually represented in Figs. 1 and 5, respectively, for the thermal and acoustic domains.

> "*But the point of that the analysis was to define a comfort temperature, which translates to neither warm nor cool, or not too warm, not too cool. Neutral is another word you might use. But I'm thinking …* […] *there's nothing like that in noise there … it's not symmetrical around the midpoint. I think what you're talking about is the point where the noise becomes, you know, objectionable. It's fundamentally a different perception, perceptual concept, it's not a neutrality at all.*"

3.4. Towards a model of adaptive acoustic comfort

The hypotheses advanced regarding the adaptation mechanisms underlying acoustic comfort are not currently substantiated by data. Hence, the third theme revolves around gathering data and testing the hypothesis of adaptive acoustic comfort, mirroring the approach used in investigating adaptive thermal comfort, as depicted in Fig. 1.

> "*eventually we need to substantiate this* [the hypothesis of an adaptive acoustic comfort] *with data from people.*"

> "*The idea of model as in a prediction thing, like all those graphs that you have, you know with indoor temperature as a function of outdoor temperature …* [reference to Fig. 1] *There's nothing like that in the in acoustic literature as far as I know.*"

The adaptive thermal comfort model predicts the ranges of acceptable and optimal temperatures as a function of the running mean outdoor temperature (*X*-axis) and the indoor operative temperature (*Y*-axis) based on correlations from survey data in which occupants have expressed their thermal sensation, as already introduced in Section 1.1. Dose-response relationships are derived for different types of ventilated strategies (i.e., buildings with natural ventilation, mechanical ventilation or mixed-mode ventilation). The first step towards testing an adaptive acoustic comfort model is therefore to identify the corresponding variables that define, on one hand, the exposure to the acoustic environment (*X* and *Y* axes), and on the other, the perceptual response of the occupants.

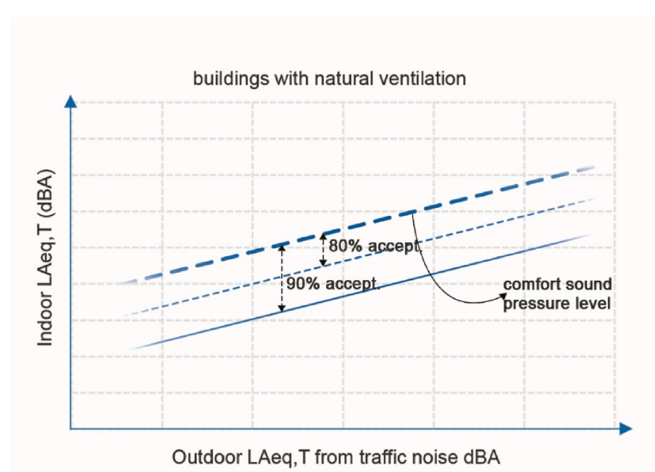

Fig. 5. – Concept of adaptive model for predicting optimum and acceptable comfort sound pressure levels ranges in buildings with natural ventilation exposed to outdoor traffic noise. Lower acceptability is assumed at higher sound levels.

"*You're gonna have to come up with some characterization of exposure and I guess that's the challenge.*"

"The challenge in my mind is how you operationalize the X and the Y variables [with reference to Fig. 1, if it were developed for the acoustic domain]*."*

An initial model could explore the relationship between outdoor road traffic noise (as a starting point for a specific sound source typically perceived as annoying) and indoor background sound levels in naturally ventilated buildings, and occupants' responses in terms of annoyance, as conceptually depicted in Fig. 5.

This proposal stems from the availability of data from noise maps that have been created in Europe following the implementation of the European Environmental Noise Directive (DEN) [45], with the mapping of the L_{den} parameter (day-evening-night noise level), which represents a weighted average of the yearly individual noise levels during the day, evening, and night. Drawing again from the metrics currently most commonly used and accessible, the internal level could be expressed in terms of A-weighted equivalent sound pressure level ($L_{\text{A,eq}}$), while the occupants' response could be initially assessed in terms of annoyance, potentially measured via ISO/TS 15666 [46], thus adhering to the traditionally pursued focus between traffic noise and disturbance [15], potentially relying on data already collected in previous studies and available in the literature.

"*And again, road traffic noise and you know, social surveys, for instance on annoyance are much easier to get and gather or potentially collate from different sources. So my feeling is that if we are to start this, the first point should be outdoor traffic noise levels in a way that, at least in Europe, because, for instance, we have the huge, you know, noise mapping exercise in the context of the Environmental Noise directive as a first pilot or in a way to explore this, we could even rely on, you know, not measured but rather modelled outdoor traffic noise levels via the Environmental Noise directive because we have data basically in that case for every European city with more than 100,000 residents. And then that's the starting point for the data outside. Then we should see if we have data inside and so on and that's the other big point I wanted to ask about.*"

This naturally gives rise to numerous open questions regarding the choice of parameters for characterizing indoor and outdoor exposure, as well as occupants' responses, beyond those typically utilized.

"*You know, first of all here as a suggestion, we have put a A-weighted equivalent sound level. We don't know whether that's the right indicator to start thinking about such a model.*"

Moreover, the discussion has underscored two aspects regarding data processing and aggregation concerning spatial and temporal dimensions. In the context of building the adaptive thermal comfort model, the collected data were indeed aggregated at the building level.

"The data was aggregated to the building level. And that's another kind of, you know, twist, [another] *story ... you're gonna have to weight that one too into your context, because for us, you know, Tom said 20,000 questionnaires and that's right. But at the end of the day, it all got reduced down to about 160 different buildings around the world, and those buildings, or the neutral temperature that each of those buildings had, became the data on the Y axis.* [...] *The analysis was done at the building scale first, and then the results from that analysis become the input to the graph that we see on the whiteboard* [Fig. 1]*."*

"*It's hard to do the modelling on at the individual level for one person, because what you're trying to, what we were trying to do is trying to define a temperature, a comfort temperature. That would be a group average, a group of people exposed to the same conditions. There are some warm there is some cool, but on average, what's the what's the most comfortable temperature? What's the temperature that will satisfy most of the occupants of that building exposed to those conditions?*"

In the acoustic domain, however, aggregating data at the building level may conceal significant differences between the acoustic conditions to which different floors or different facades of the building are exposed, potentially resulting in different perceptual responses.

"*Maybe for acoustics it's different because of ... like the distance from the streets. If you consider the highest floors of a high rise building you cannot average data with lower floors ...*"

Regarding the temporal weighting of data inputted to the adaptive thermal comfort model, the reference period of the outdoor running mean temperature is the month preceding the moment when the thermal comfort assessment is made. However, greater weight is given to the recent history of thermal exposure in the last week and, particularly, in the last 24 h.

"*Monthly. If on the X axis we simply got the most accessible meteorological metric available, and that's the main monthly temperature, so 30 days. But more recently, we've kind of established that it's probably 90% the last week and you know that the other three weeks might have a bit of an impact, but it's really just the last week that has the most impact. It's yesterday. That's the most significant thing. You know what? What do people wear when they look out their window in the morning? Their instinct as to wear what they wore yesterday, so yesterday's exposure has a big impact on their adaptation to today's weather.*"

Similarly, aspects related to time weighting will be crucial when processing acoustic data for developing the adaptive acoustic comfort model. Initially, the collected data may focus on establishing the dose-response relationship between road traffic noise and annoyance in naturally ventilated buildings. However, future models could be designed to capture the potential impacts of diverse environmental and contextual factors outlined in Theme two. These models might include factors such as the outdoor soundscape, day and night periods, different climatic conditions (e.g., during overheating), or specific population groups (e.g., children, adults, neuroatypical individuals).

"*In the long run we will get to the point where, depending on what kind of sound source is dominant outside, then you may have linear model, linear fits which are slightly different, maybe with an offset or different slope depending on what's outside in terms of context and semantics, like is it pleasant or unpleasant? and so on.*"

The framework for adaptive acoustic comfort would align well with the current structure of the Environmental Noise Directive (END) as it does not set limit or target values for environmental noise at the European level, but rather leaves this decision to the competent Member State authorities. Therefore, aspects such as differences in climate and culture, which would differently influence adaptive capacities depending on the various national contexts, could be implemented at the individual state level.

"[We] *already have an "adaptive noise" approach, like the EU* [environmental noise] *directive says. We have this common index* [L_{den}]*, but every country could have its own requirements for noise* [based on that index]*. This, of course, is based on many factors, like economical and other factors, but I think adaptation from human could be part of it .... cultural differences, etc...*"

4. Discussion

In this section, the two research questions underlying the study are discussed based on the four themes identified from the thematic analysis presented in the previous section.

4.1. A preliminary definition of adaptive acoustic comfort

The discussions held in the expert focus group have led to envisioning the dynamics that could underlie adaptive acoustic comfort in building occupants, starting from an analogy with the concept of adaptive thermal comfort. The general definition of adaptive acoustic comfort, emerged in Theme 1, is:

a model that relates indoor acoustic conditions to outdoor ones, moderated by other environmental, contextual, and personal factors.

This principle is probably common to multiple senses, as argued in Theme 3. The proposed framework moves away from an idea of universal noise level thresholds linked to absolute acoustic comfort and embraces the complexity of acoustic perception and personal adaptation capacities.

The link between a number of acoustic and non-acoustic factors, highlighted in Theme 2, and the perception, interpretation, and response to acoustic conditions has indeed long been investigated in the literature and is currently subject to standardization [9]. It ranges from the long tradition of studies on dose-effect relationships between exposure to noise levels (mainly outdoor and negatively perceived) and annoyance [10,47], to the more recent literature on the soundscape that values the type of sound source composing the acoustic environment in relation to potential negative and positive impacts the sound environment can have on humans, in terms of, for example, restorative effects, support for activities, and improvement of quality of life [13,16,48]. Not least, considering the wide variation in individuals' experiences of sounds (i.e., aural diversity) and other environmental stimuli (e.g., lighting, temperature) while ensuring inclusion and fairness to all remains a subject of ongoing debate [49,50].

However, the adaptive perspective of acoustic comfort further highlights the multifactorial nature of acoustic perception and adds some fundamental elements compared to the current narrative of acoustic comfort, of which ventilation strategy is a key parameter. Acoustic tolerance would indeed be linked to expectations that may depend on recent past exposure. This is inherently different depending on the whether the building is mechanically or naturally ventilated. In naturally ventilated buildings, acoustic exposure is linked to the external acoustic environment through ventilation openings and, as proposed by Field [29], the expectation of low ambient noise is inherently lower than in presence of mechanical ventilation. It's important to highlight that the literature examining the relationship between noise annoyance and outdoor noise levels has not yet found evidence of acoustic habituation, by comparing noise annoyance at two points in time [10,51,52]. On the contrary, in certain cases, there might be a cumulative impact over time of the disturbance that could result in an increased sensitivity to noise. Nonetheless, this phenomenon warrants further investigation, especially when considering factors like differences in ventilation strategy, which can alter exposure in the immediate past and related expectations—an aspect that hasn't been addressed thus far.

In addition to aspects related to various characteristics of the acoustic environment and past acoustic exposure, other non-acoustic factors can contribute to modifying occupants' expectations and therefore their tolerance. Beyond factors traditionally addressed in acoustic literature, such as demographic variables, personal traits (noise sensitivity), and situational factors (ongoing activities), important aspects are also multi-sensory and multi-domain in nature [53–55], once again dependent on the type of acoustic ventilation strategy. Opening windows in naturally ventilated buildings is indeed linked to a series of co-benefits involving other senses (cooling in case of indoor overheating, air movement, contact with external odours, etc.) that could lead to different acoustic tolerance depending, for example, on trade-off mechanisms or sensory interaction phenomena (e.g., combined exposure to noise and heat). Finally, the availability of control over the acoustic environment, through, for example, control of window opening and closing, could favour a different acoustic sensitivity compared to sealed buildings with mechanical ventilation.

The availability of adaptive opportunities makes us more tolerant of the environment when we can control it, while their absence would make the environment increasingly unbearable as already theorized in the literature on thermal comfort [56]. As interestingly highlighted in the third theme, one of the differences, however, compared to thermal adaptation mechanisms would be linked to the fact that, while adaptive thermal comfort involves mechanisms of both physiological (related to acclimatization) and psychological nature (related to adjustment of thermal expectations based on recent past exposure), acoustic adaptation would be more psychological in nature. This would be first of all related to different psycho-physiological mechanisms involved. Consider, for example, the process of acclimatization, which in the case of thermal conditions requires significantly longer periods compared to the acoustic case, whereas the response to a new sound scenario is almost immediate. Secondly, the nature of the sensory stimulus itself is different. As highlighted in Theme 3, while sound can provide information and communicate safety, thermal stimuli do not have such a "meaning". In both cases, however, the variation of the sensory stimulus could trigger pleasure in the occupant through mechanisms of thermal alliesthesia [43], thanks to the meaning attached to the sound itself [34,57], or when various sound conditions alternate, enabling individuals to appreciate their qualities through contrast [58], as exemplified by the concept of "tranquility induced by contrast" [59]. The threshold between pleasure and annoyance would be marked in the thermal case by a zone of physiological thermal neutrality (see Fig. 1) and in the acoustic case by a threshold, a point beyond which adaptation capacities are no longer sufficient, and acoustic conditions would become unsustainable (see Fig. 5).

What has been formulated so far is the result of empirical evidence in the acoustic field and hypotheses based on observations in other sensory areas, as in the case of adaptive thermal comfort. However, the framework on adaptive acoustic comfort needs to be substantiated with data collected from people and the built environments in which they work and live. In the next section, the steps in future research towards the definition and population of a database for testing adaptive acoustic comfort are outlined.

4.2. Research agenda towards a model of adaptive acoustic comfort

Given the multitude of factors potentially underpinning acoustic adaptation, the availability of a large amount of data on acoustic comfort from individuals and their exposure to indoor and outdoor acoustic environments, as well as potential confounders, is crucial for verifying and testing the hypotheses presented in this study. In the field of thermal comfort, a key tool in the development and understanding of adaptive thermal comfort has been the formation of a large harmonized open access database from field campaigns through a coordinated effort of researchers from around the world, namely the ASHRAE Global Thermal Comfort Database [60]. As reported in de Dear and Brager, "*although chamber studies have the advantage of careful control, field research is best for assessing the potential impacts of behavioral or psychological adaptations as they occur in realistic settings*" [3]. Nothing similar to the ASHRAE Global Thermal Comfort Database currently exists in the acoustic field, where most of the available data concern relationships between annoyance and acoustic levels (outdoor) under the influence of the END directive. Dose-response relationships have been developed and have led to the establishment of thresholds by the WHO for outdoor exposure to environmental noise from road traffic, railway traffic, aircraft, and wind turbines in Europe [61]. Many of the factors highlighted by the thematic analysis of the focus group outcomes and which can potentially influence adaptive dynamics of acoustic comfort (e.g., personal traits, environmental conditions, ventilation strategy) have been addressed mostly in small pilot studies [62] or laboratory studies that do not involve relevant population samples or do not capture adaptation phenomena based on previous exposure [53,55,63,64]. Additionally, data available from outdoor noise mapping should be integrated with data on indoor noise exposure, where people actually spend most of their time.

As summarized in Theme 3, an initial model could capitalize on data on external road traffic noise levels available from the implementation of the END directive on agglomerations with more than 100,000 inhabitants, integrating them with data on indoor exposure and occupants' perceptual feedback in terms of annoyance for naturally and mechanically ventilated buildings (see Fig. 5).

Subsequently, a more extensive database could be populated and lead to testing the effects of acoustic adaptation based on different environmental and contextual factors, such as types of outdoor soundscapes (e.g., rural areas, densely trafficked urbanized areas, pedestrian areas, …), prevailing building use (e.g., residential, commercial, …), day and night periods, and climatic conditions (e.g., overheating). Perceptual response could be more articulated and take into account dimensions underlying the affective response to the acoustic environment, as highlighted in the literature on soundscapes [57,65], and this could lead to *ad hoc* allowances or penalties in terms of thresholds levels. This could highlight potential effects given by environmental conditions in the built environment that go beyond the reduction of annoyance, in order to inform the acoustic design of living and working environments that leverage the hedonic potential of sensory stimuli and the adaptive capacities of humans.

The main steps for the research agenda are.

1. Definition of the most suitable (psycho)acoustic metrics for characterizing indoor and outdoor exposure and occupants' response, their temporal and spatial resolution, as well as the non-acoustic factors assumed to potentially influence acoustic comfort (e.g., ventilation strategy, noise sensitivity, data on the thermal and visual environment, …)
2. Collection of data in a global acoustic comfort database
3. Testing the factors influencing adaptive comfort dynamics through the analysis of collected data.

This would potentially lead to different models of adaptive acoustic comfort depending on the relevant factors that will be considered from time to time, as conceptually depicted in Fig. 6. Drawing on the analogy of the adaptive thermal comfort model, which operates within specific ranges of outdoor mean temperature, the adaptive acoustic comfort models depicted in Figs. 1 and 6 would similarly function within a spectrum of sound levels. While comfort adaptation above certain noise thresholds might not occur [66] or be advisable for the occupants' health [16], at lower sound levels, acoustic comfort could exhibit greater variability and be influenced by various factors beyond sound pressure levels alone, potentially allowing for phenomena of acoustic adaptation. The three steps should involve, among others, built environment scientists, environmental psychologists, audiologists, sociologists, physiologists, and cognitive scientists. This transdisciplinary approach supports the definition of potential variables of interest and the formulation and testing of hypotheses of acoustic adaptation.

The availability of large-scale data on indoor acoustic comfort presents significant potential in terms of revolutionizing the understanding of acoustic comfort, with impacts on:

- Improving people's health and well-being, given the impacts of noise exposure on health and building occupants' dissatisfaction already highlighted in the Introduction
- Environmental emissions, by potentially defining areas of acoustic comfort tailored to the different ventilation strategies, with the potential to relax acoustic limits that currently hinder the widespread application of passive ventilation solutions.

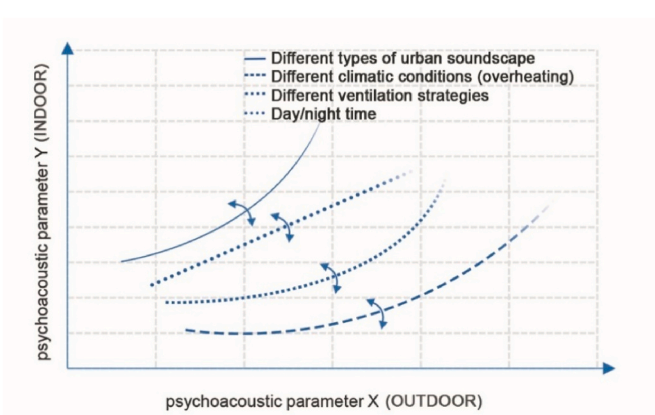

Fig. 6. – Conceptual representation of possible models of adaptive acoustic comfort as a function of different contextual variables.

5. Limitations

The use of qualitative research methods (identifying and describing patterns from the analysis of collected data) may potentially be influenced by researchers' personal opinions and background [42]. However, the inclusion of two researchers in the coding phase and the subsequent involvement of all workshop participants in manuscript development ensured that the statements were analysed, synthesized and reported coherently to the participants' intentions.

Moreover, the study was limited by the selection of a small number of experts with backgrounds in acoustic and thermal comfort, psychoacoustics, and general knowledge in physiology and environmental psychology. In the future, input from fields such as physiology, psychology, cognitive sciences, and audiology, as well as from other members of the indoor environmental quality research community, will be highly beneficial. We did not choose interviewees to comprehensively cover all possible viewpoints in the scientific community, but to provide initial expert opinions to attract international interest and initiate global data collection on indoor acoustic comfort in buildings. This aligns with the purpose of using expert interviews as an exploratory tool [67]. The exploratory focus group with experts facilitated the emergence of a theory from discussions between two otherwise distant communities, structured hypotheses for future testing, and identified knowledge gaps and challenges to address in subsequent quantitative and/or qualitative research projects.

6. Conclusions

The current study initiates a discussion on adaptive acoustic comfort, drawing parallels with adaptive thermal comfort. It is based on thematic analysis of data gathered from a focus group comprising experts in both thermal and acoustic domains. The key findings, pertaining to 1) the formulation of a preliminary definition of adaptive acoustic comfort and 2) the delineation of a roadmap for validating the hypotheses proposed, are as follows.

1. Adaptive acoustic comfort is defined as a model that relates indoor acoustic conditions to outdoor ones, moderated by other environmental, contextual, and personal factors. The discussion has hypothesized differences between the mechanisms of thermal and acoustic adaptation, linked on one hand to the nature of the stimuli and on the other to how these stimuli are processed at a psychological and physiological level. Among the environmental, personal, and contextual factors relevant to adaptive acoustic comfort, there would be past acoustic exposure, also dependent on the available ventilation strategy, the availability of control over the environment, multi-domain interactions with non-acoustic environmental stimuli, individual noise sensitivity, and ongoing activities, depending on the building's use and the time of day.
2. There is a need for research to gather global indoor/outdoor acoustic exposure data in buildings, coupled with various contextual information, in a manner akin to the ASHRAE thermal comfort database. This will enable testing of the adaptive acoustic comfort hypothesis and development of models for relevant factors (e.g., types of soundscapes, ventilation strategies, etc.).

This holds significant potential for both human health impacts, leading to new understanding of acoustic comfort based on currently unavailable data, and environmental impacts, promoting tailored acoustic requirements based on ventilation strategies, potentially enabling wider adoption of passive ventilation strategies.

CRediT authorship contribution statement

S. Torresin: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **F. Aletta:** Writing – review & editing, Supervision, Methodology, Conceptualization. **S. Dicle:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **R. Albatici:** Writing – review & editing. **R. de Dear:** Writing – review & editing, Writing – original draft. **Y. Hasegawa:** Writing – review & editing. **J. Kang:** Writing – review & editing, Supervision. **T. Parkinson:** Writing – review & editing, Writing – original draft. **D. Cabrera:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is available in the supplementary material.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.112074.

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