Evaluation of healthy indoor acoustic environments in residential buildings by the occupants: a mixed-method approach

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Received 29 June 2023, Revised 14 October 2023, Accepted 16 October 2023. Available online 17 October 2023

Abstract

With the well-established importance of healthy indoor acoustic environments, this study aims to investigate how occupants evaluate, understand, and characterise healthy indoor acoustic environments in residential buildings. A mixed-method approach with both qualitative and quantitative study designs was used. For the qualitative study, interview transcripts from 35 respondents were coded using a grounded theory approach. In the subsequent quantitative study, a questionnaire was developed based on the interview data, and the answers of 720 participants were analysed using structural equation modelling. The results presented the elements, conceptual framework, and evaluation model of a healthy indoor acoustic environment in residential buildings from the occupant's perspective. Among all elements, *Attachment*, *Privacy*, *Autonomy*, and *Controllability* were identified as the four characteristics of a healthy indoor acoustic environment at home. *Controllability*, which is the most significant factor (total effect size = 0.475), had a positive influence on the evaluation of healthy indoor acoustic environments in residential buildings by reducing negative emotions, physical discomfort, and behavioural disturbances caused by noise. *Attachment* also contributed favourably to the evaluation, particularly in individuals aged 18 to 29. The evaluation model varied according to gender and age. Women exhibited more complex evaluation mechanisms and diverse understandings than men, both of which tended to become simpler with age. The results of this study provide a theoretical reference for designing acoustic environments for healthy housing.

Keywords

Healthy acoustic environment; Subjective evaluation; Indoor soundscape; Demographic factor; Healthy housing; Mixed-method approach

1 Introduction

A growing body of research [1] has provided evidence of the impacts of a built environment on the health of occupants. This evidence is crucial for creating an acoustic environment that supports health and well-being given the general inadequacy of buildings in providing satisfactory acoustic environments [2]. To investigate the health implications of acoustic environments, various studies have been conducted on different scenarios, such as open-plan offices [3], urban public open spaces [4], classrooms [5], and hospitals [6]. However, indoor residential environments should be prioritised because of the amount of time people spend in them [7].

Several standards, such as WHO housing and health guidelines [8], WELL [9], and Fitwel [10], have been developed to promote acoustical comfort and prevent noise annoyance and other negative health outcomes. However, the occupant's subjective evaluation and understanding of healthy indoor acoustic environments may not be consistent with what is described in these standards. Despite meeting the standards, the acoustic environments considered unhealthy by occupants may not provide adequate health benefits (particularly in terms of mental health [11]) or a good living experience. Additionally, research on indoor soundscapes revealed a recent shift from "avoiding annoyance and disease" to "adding value" [12], which was in line with the healthy housing framework. However, the characteristics of healthy indoor acoustic environments based on the occupant's subjective understanding are still unknown, and this knowledge gap has restricted the application of the indoor soundscape approach to the acoustic design of healthy housing.

To gain insights into how healthy acoustic environments in residential buildings are evaluated, understood, and characterised by the occupants, three main aspects should be highlighted. First, quietness is not necessarily healthy despite noise exposure levels being regarded as a crucial factor in creating indoor acoustic environments [13]. Noise reduction does not always improve acoustic comfort, and loudness can even be desirable in certain contexts [14,15]. Additionally, other dimensions besides quietness have been proposed for indoor soundscape evaluation

[16], some of which have been reported to be related to health or well-being, such as comfort [17,18], content [17], familiarity [19], and pleasantness [20]. Such efforts indicate that a healthy indoor acoustic environment may go beyond simply achieving quietness to prevent annoyance, just as people working on complex cognitive tasks believe that it should actively foster comfort [21]. Overall, it remains unclear which elements should be considered when creating a healthy acoustic environment at home and how these elements can be incorporated through a framework.

Second, the exact quantitative link between the elements and the evaluation of healthy indoor acoustic environments in residential buildings has yet to be established. Existing studies have mainly focused on the health impacts (either supportive or detrimental) of exposure to different acoustic environments [22]; however, the association between the characteristics and the health evaluation of acoustic environments is not explored. To date, only a few studies have indicated the possible evaluation mechanisms of healthy indoor acoustic environments. For instance, Chen et al. [23] introduced the demands of a healthy acoustic environment from a holistic perspective and revealed the relationship between demands and evaluation. However, it remains unknown how the acoustic environment is evaluated or understood in the residential context given its unique perceptual evaluations [24,25]. Torresin et al. [26] examined the characteristics of ideal residential indoor acoustic environments based on a qualitative analysis of verbal descriptions. Nevertheless, the magnitude of the impact of the different characteristics is still unclear, making it challenging to identify the most critical elements.

Third, despite the effects of gender and age on soundscape perception [27–29], it remains uncertain whether these demographic factors affect the evaluation of healthy indoor acoustic environments in residential buildings. The connection between noise and health impacts has been investigated in several single-population studies, such as those involving young [30,31] and older adults [32]; however, the differences between the various populations have been far less studied. Indeed, age and gender may lead to different acoustic requirements. For example, it has been reported that older adults prefer soundscapes that are quiet and natural [33,34], and females tend to incorporate their emotions into their preferences [33]. Age-related hearing loss [35] and auditory processing changes [36] may affect the evaluation and comprehension of acoustic environments. Overall, it is essential and urgent to explore the differences in the evaluation of healthy indoor acoustic environments in residential buildings to uphold health equity, particularly for vulnerable groups subjected to noise (e.g. the elderly) [37].

Therefore, this study aims to explore the elements, conceptual framework, and evaluation model of healthy indoor acoustic environments in residential buildings and the differences in the evaluation model across gender and age groups. Notably, the main motivation behind this study is to investigate the subjective evaluation of occupants for healthy acoustic environments instead of determining the precise definition or objective standard. The research questions for this study are as follows:

1) What are the elements and conceptual framework of healthy indoor acoustic environments in residential buildings from the occupant's perspective?

2) Based on the conceptual framework, what is the evaluation model (quantitative relationship among the elements) of healthy indoor acoustic environments in residential buildings?

3) Does the evaluation model differ with gender or age? If so, what are the differences?

2 Method

The study was divided into qualitative and quantitative parts and organised as follows: First, to explore the elements and conceptual framework of healthy indoor acoustic environments in residential buildings, in-depth interviews were conducted, and the interview transcripts were coded through grounded theory (GT). Second, to establish an evaluation model that describes the quantitative relationships among the elements, a questionnaire was developed based on the interview data, and the responses were analysed through structural equation modelling (SEM). Finally, differences in the evaluation models with respect to gender and age were analysed using SEM. A flowchart of the study is shown in Fig. 1.

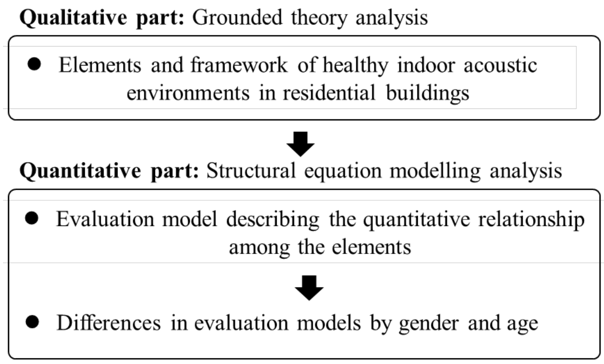

Fig. 1. Flowchart of the study.

2.1 Grounded theory (GT) analysis

2.1.1 Participants

In the GT approach, purposive sampling is typically used to obtain a research sample that provides the maximum amount of information [38]. In this study, the GT analysis (qualitative part) involved posting revelations on Chinese social media platforms to recruit participants who had rich experience of the acoustic environment in their homes. Thirty-five respondents (20 females, 15 males) aged 21 to 60 years (M = 39.7; SD = 11.5) from various professional backgrounds were recruited, and six of them had a medical background. The demographic information of each respondent can be found in Appendix A. Twenty-one of them were interviewed in-person in streets, residential areas, and parks in the Beijing, Tianjin, and Hebei regions of China, while the remainder were interviewed online. The interviews were conducted between March and May 2022, and the duration ranged from 30 to 50 minutes.

2.1.2 Interview procedure

As the primary data collection tool in the GT approach, in-depth interviews were conducted in this study. The interview mainly focused on three aspects, as shown in Table 1. The basic information of each respondent was first collected. Subsequently, the evaluation and understanding of healthy indoor acoustic environments in residential buildings were examined to identify the elements. Finally, the relationship between the elements was determined to construct a conceptual framework for healthy indoor acoustic environments in residential buildings. A definition of “acoustic environment” [39] was given before the interviews. If the interviewees requested it or the interviews were clearly off-topic, the concept of health as defined by the World Health Organization [40] was provided without further explanation. Ethical procedures were followed, and all participants provided informed consent.

Table 1. Interview outline.

Part	Questions
1. Basic information	age, gender, occupation, and education background
2. Elements	2.1 How is the acoustic environment in your home? Is it healthy? Why? 2.2 What do you consider healthy indoor acoustic environments at home? Why?
3. Conceptual framework	3.1 Does the acoustic environment in your home have a positive/negative effect on your health? Why? 3.2 If the acoustic environment in your home has a positive/negative effect on your health, how is it manifested?

2.1.3 Data analysis

The analysis began when the data were collected and ended when the obtained information reached theoretical saturation [38]. According to previous practices [23,41,42], interview transcripts were analysed using qualitative analysis software through semantic coding using open, axial, and selective coding [38]. First, in open coding, the interview transcripts were segmented and labelled by searching for key phrases and subsequently conceptualised by comparing their associations and similarities. The thematic categories employed to organise the emerging theoretical constructs were redefined by constantly comparing new codes with those already identified. The codes with a total occurrence of less than ten times have not been retained. Second, the identification of categories led to axial coding, in which the relationships between categories were explored, and the embryonic form of the conceptual framework was developed using the coding paradigm [38]. Finally, selective coding was performed, in which categories central to the phenomenon were selected as core categories, and all categories linked to the core category were incorporated to construct a conceptual framework.

2.2 Structural equation modelling (SEM) analysis

2.2.1 Participants

Different groups of subjects participated in the qualitative and quantitative analyses. In the SEM analysis (quantitative part), a questionnaire survey entitled "Survey of Acoustic Environment Quality at Home" was conducted from September 2022 to October 2022 via online and in-person approaches. A total of 882 participants participated in the survey: 237 completed the paper questionnaires in the streets, residential areas, and parks of Tianjin, China, and the remainder finished the questionnaires online. Of the 882 responses, 162 were considered invalid (non-urban population, participants who have not lived at home in the past 30 days or have not passed an attention check). Therefore, the remaining 720 responses were used for data analysis, with the demographic information provided in Table 2.

Table 2. Demographic information from the questionnaire survey (N=720).

Variables	Description	Proportion (%)
Age	18~24	17.9
	25~29	19.9
	30~34	17.6
	35~39	10.1
	40~44	10.4
	45~49	6.1
	50~54	11.3
	55~59	2.4
	⩾60	4.4
Gender	Male as the base category	46.0
Education background	High school or lower	12.5
	Higher	87.5
Total monthly household income (RMB)	⩽10000	26.3
	10000~20000	43.5
	⩾20000	30.3
Household population	1	13.5
	2~8	86.5
Occupation	Employed	70.3
	Students, homemakers, retired, and unemployed	29.7

RMB = renminbi, the official Chinese currency.

2.2.2 Questionnaire design

The questionnaire consisted of ten sections. The first section covered the respondents' demographic information (Table 2). The remaining nine sections were associated with the nine elements (categories) of healthy indoor acoustic environments in residential buildings. The elements were identified with GT analysis, and further details will be presented in the section titled “Elements”. After reviewing the critical issues from the interview transcriptions and previous literature, the measuring items for each element were determined and briefly listed as *Attachment*, *Privacy*, *Autonomy*, *Controllability*, *Comfort*, *Annoyance*, *Pathogenicity*, *Disturbance*, and *Health Evaluation*, as shown in Table 3. All responses, except those concerning *Health Evaluation*, were recorded on a five-point Likert scale, where 1= strongly disagree and 5= strongly agree.

Health Evaluation, which refers to the effect of indoor acoustic environments in residential buildings on occupants' health, was measured using an adaptation of the Short Form Health Survey (SF-8). SF-8 has been widely used in noise-related health surveys [43–45] and has shown good internal consistency and validity in the Chinese population [46]. Given that the negative associations with the word "noise" might have introduced a response bias, the items measuring *Health Evaluation* were rated by participants on a 7-point bipolar scale to allow them to express a negative, neutral, or positive impact of the acoustic environment at home (-3 = very significantly limited or impaired, 0 = no effect, 3 = very significantly improved or promoted).

Table 3. Measuring items for each element.

Element & code	Item	Reference
Attachment		[47,48]
Att1	Intimacy	
Att2	Companionship	

Att3	Affective connection	
Privacy		[49]
Pri1	Frequency of hearing neighbours' speech	
Pri2	Degree of understanding neighbours' speech	
Pri3	Ability to identify by sounds if neighbours are home	
Autonomy		[26]
Aut1	Restriction on playing music	
Aut2	Various options for altering acoustic environments	
Aut3	Ability to adjust acoustic environments according to preferences	
Controllability		[50]
Con1	At the mercy of the noise	
Con2	Protect against noise	
Con3	No more disturbance when windows are closed	
Comfort		[51,52]
Com1	Comfort	
Com2	Pleasantness	
Com3	Relaxation	
Com4	Safety	
Annoyance		[51–53]
Ann1	Discomfort	
Ann2	Annoyance	
Ann3	Anger	
Ann4	Anxiety	
Ann5	Unsafety	
Pathogenicity		[54–56]
Pat1	Headache	
Pat2	Earache	
Pat3	Elevated blood pressure	
Pat4	Cardiac discomfort	
Disturbance		[50]
Dis1	Disturb talk/phone	
Dis2	Disturb radio/TV	
Dis3	Disturb concentration	
Health Evaluation		[46]
Hea1	Effect on general health	
Hea2	Effect on physical functioning	
Hea3	Effect on role-physical	
Hea4	Effect on bodily pain	
Hea5	Effect on vitality	
Hea6	Effect on social functioning	
Hea7	Effect on mental health	
Hea8	Effect on role-emotional	

2.2.3 Data analysis

SEM typically begins with an exploratory factor analysis (EFA) and validation factor analysis (CFA) [57,58]. In this study, EFA was used to identify the main factors and evaluate the validity of the research data, whereas CFA was used to validate the hypotheses regarding the observed and latent variables. EFA was conducted using SPSS 26.0, and CFA and SEM were conducted using Mplus 7.0. A maximum likelihood estimation with robust standard errors and a Satorra-Bentler scaled test statistic (MLM) was used for both parameter estimations and goodness-of-fit statistics, as some variables failed to exhibit multivariate normality [59].

3 Results

3.1 Elements and conceptual framework of healthy indoor acoustic environments

An example of the open coding process is presented in Table 4. Using a similar coding process, nine categories that refer to the elements of healthy indoor acoustic environments in residential buildings were identified as follows: *Attachment, Privacy, Autonomy, Controllability, Comfort* (positive emotions), *Annoyance* (negative emotions), *Pathogenicity* (physiological discomfort), *Disturbance* (behavioural disturbance), and *Health Evaluation*. In axial coding, the coding paradigm was used to develop relationships among categories. This was followed by selective coding, during which a conceptual framework was created.

Table 4. Example of the open coding process.

Memos	Labels	Conceptualizing data	Conceptualizing data	Categories
P (17): *The sound of the coffee machine working is intimate and makes me comfortable and relaxed; it is a healthy sound because it brings me positive emotions.* ***P (12):*** *Argument is a privacy issue and should not be overheard by my neighbours; I do not want to hear my neighbours' arguments either because it would not only disturb my work but also annoy me. … An acoustic environment that disturbs me or causes negative emotions is definitely not healthy.* ***P (19):*** *Music makes me feel good, and I hope to play it whenever I want to without worrying about whether it will disturb others; In addition, the sounds of freely playing music can also mask annoying noises.* ***P (31)****: I can regulate the volume of the appliances and switch them off when I get annoyed; however, my neighbour drags a chair around and generates a sudden noise that I cannot anticipate, giving me a headache and a racing heart. This kind of sound environment is definitely harmful to my health.*	**a1**: Sound source **a2**: Intimate sound **a3**: Comfortable **a4**: Relaxed **a5**: Healthy sounds **a6**: Positive emotions **a7**: Privacy **a8**: Avoid being overheard **a9**: Not hearing neighbours' arguments **a10**: Work interference **a11**: Annoyance **a12**: Disturbance **a13**: Negative emotions **a14**: Healthy acoustic environments **a15**: Pleasant **a16**: Freely playing music **a17**: Not disturbing others **a18**: Relieving annoyance **a19**: Regulating volume **a20**: Avoid annoyance **a21**: Unpredictable sounds **a22**: Headache **a23**: Racing heart **a24**: Harmful to health	**aa1**: Intimate sounds bring comfort and relaxation. (a1, a2, a3, a4) **aa2**: Acoustic environments that bring positive emotions are healthy. (a5, a6) **aa3**: Preventing neighbours from hearing arguments and not hearing theirs. (a8, a9) **aa4:** A lack of privacy causes annoyance and work interference. (a7, a10, a11) **aa5**: An acoustic environment that leads to negative emotions and disturbance is unhealthy. (a12 a13, a14) **aa6**: An acoustic environment where music can be played freely results in pleasantness. (a15, a16, a17) **aa7**: Freely playing music relieves annoyance. (a18) **aa8**: Regulating the volume can avoid annoyance. (a19, a20) **aa9**: Unpredictable sounds lead to physical discomfort. (a21, a22, a23) **aa10**: An acoustic environment that causes physical discomfort is unhealthy. (a24)	**Aa1**: A sense of attachment brings positive emotions and contributes to healthy acoustic environments. (aa1, aa2) **Aa2**: Lack of privacy leads to negative emotions and behavioural disturbance and has a negative impact on health evaluation. (aa3, aa4, aa5) **Aa3**: A sense of autonomy brings positive emotions and alleviates noise annoyance. (aa6, aa7) **Aa4**: Controllability relieves noise annoyance, and a lack of control will lead to physical discomfort. (aa8, aa9) **Aa5**: The acoustic environment leading to physiological illness is unhealthy. (aa10)	**A1**: Attachment **A2**: Privacy **A3**: Autonomy **A4**: Controllability **A5**: Comfort (Positive emotions) **A6**: Annoyance (Negative emotions) **A7**: Pathogenicity (Physiological discomfort) **A8**: Disturbance (Behavioral disturbance) **A9**: Health Evaluation

3.1.1 Elements

In this study, the phenomenon (central idea) can be described as the evaluation of healthy indoor acoustic environments in residential buildings. According to the data analysis, the four categories of *Attachment, Privacy, Autonomy,* and *Controllability* were considered the characteristics of healthy indoor acoustic environments in residential buildings. As necessary conditions to motivate the evaluation, these four characteristics could be referred to as the causal conditions that gave rise to the phenomenon.

The category *Attachment*, with sub-categories of intimacy, belongingness, companionship, familiarity, and security, indicated that healthy indoor acoustic environments in residential buildings should enable occupants to feel connected and provide opportunities to be comforted by sounds. *Privacy*, which is determined by the extent to which speech was heard and understood by unintended neighbours, was directly related to the voices of neighbours, as hearing someone was considered synonymous with being heard. According to the interviews, *Autonomy* was characterised by both free expression and free choice of sounds. More precisely, healthy indoor acoustic environments at home were considered as having the freedom to produce noise without disturbing others and choose desirable sounds according to individual preferences. *Controllability* was ascertained by comparing noise-induced stress with the individual's ability to cope with it. According to the interviewees, the acoustic environment remains healthy as long as the stress can be managed behaviourally or cognitively.

The categories of *Comfort* (positive emotions)*, Annoyance* (negative emotions)*, Pathogenicity* (physiological discomfort)*, and Disturbance* (behavioural disturbance) could be referred to as the action/interactional strategies by which the evaluation of healthy indoor acoustic environments in residential buildings was conducted. Moreover, *Health Evaluation* could be considered as the final consequence of evaluating healthy indoor acoustic environments in residential buildings.

In the interviews, *Attachment* and *Autonomy* were frequently correlated with *Comfort*. For example, as described by p05 and p16, a sense of attachment inspired by sounds promoted positive emotions, and restrictions on the freedom of expression of sound would reduce acoustic comfort.

P13: *The sound of my mom's cooking brings me a sense of security, reminding me that I am not at school but at home.*

p19: *You can't enjoy the pleasure of music if you have to worry about disturbing your partner.*

Notably, a possible relationship between *Attachment* (or *Autonomy*) and *Annoyance* exists. The sounds of family members would divert the attention from the annoying noise, and the adjustment of music volume would provide more opportunities to mask the noise. These were captured in the following statements of some participants:

P2: *I like to hear the sounds of family members to keep the room from becoming too silent; otherwise, I will notice the annoying sound of the computer fan running.*

P17: *I wish I could turn up the volume of the music at will to mask the sounds that annoy me.*

Additionally, complaints about *Privacy* and *Controllability* were often mentioned alongside *Annoyance* and *Disturbance*, and a lack of *Controllability* may be related to *Pathogenicity*, as shown in the following excerpt:

P23: *The sound of the neighbours talking leads to a lack of acoustic privacy; these sounds not only annoyed me but also disturbed my work… These sounds do not bother me if I can control them; however, if I cannot, even modest sounds make me anxious and distracted.*

P5: *Traffic noise can be heard even with the windows closed, which leads to insomnia and subsequent headaches*.

3.1.2 Conceptual framework

A conceptual framework of healthy indoor acoustic environments in residential buildings was created to explain the relationships among the elements, as shown in Fig. 2. According to the interpretation in Section "Elements", the phenomenon of this research could be described as the evaluation of healthy indoor acoustic environments in residential buildings; *Attachment*, *Privacy*, *Autonomy*, and *Controllability* were the causal conditions of the phenomenon, whereas *Comfort*, *Annoyance*, *Pathogenicity*, and *Disturbance* were the action/interactional strategies that affected *Health Evaluation* (consequence of the phenomenon). Based on the specific relationship between the elements described in Section "Elements", the conceptual framework was eventually identified as follows:

1) *Attachment* indirectly affects *Health Evaluation* by its direct impact on *Comfort* and *Annoyance*;

2) *Privacy* indirectly affects *Health Evaluation* by its direct impact on *Annoyance* and *Disturbance*;

3) *Autonomy* indirectly affects *Health Evaluation* by its direct impact on *Comfort* and *Annoyance*;

4) *Controllability* indirectly affects *Health Evaluation* by its direct impact on *Annoyance*, *Pathogenicity*, and *Disturbance*.

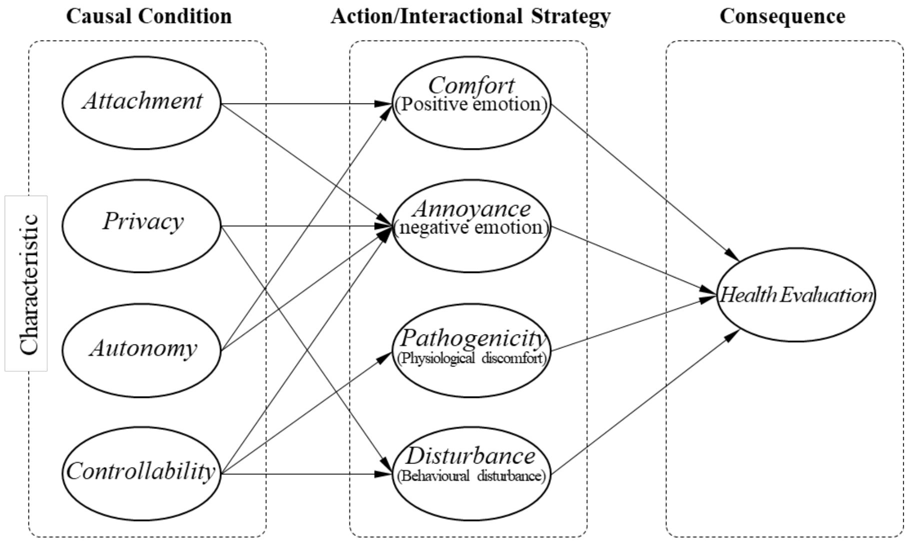

Fig. 2. Conceptual framework of healthy indoor acoustic environments in residential buildings.

3.2 Evaluation model

In Section 3.1, the qualitative relationships among the elements were revealed through a conceptual framework. In this section, the quantitative relationships are explored using SEM. Bartlett's Test of Sphericity ($p < 0.001$) and the KMO value (KMO > 0.60) were first used to analyse the validity of the dataset for factor analysis, and the test results ($p = 0.000$, KMO = 0.933) confirmed the possibility of SEM.

3.2.1 Exploratory factor analysis (EFA)

The principal factors affecting the evaluation of healthy indoor acoustic environments in residential buildings were extracted by EFA, in which varimax rotation was employed to determine the orthogonal factors. Eight factors had an eigenvalue greater than one; however, the ninth factor was retained according to the trend of the scree plot, location of the inflexion point, and simplicity of the theoretical interpretation. Consistent with the presets in the questionnaire design, the nine factors explained 74.8% of the variance, as shown in Table 5.

Table 5. Principle factors extracted by the EFA.

Principal factors & code	Factor loading	Variance explained (%)
Health Evaluation		15.8
Hea1	0.70	
Hea2	0.78	
Hea3	0.78	
Hea4	0.78	
Hea5	0.77	
Hea6	0.78	
Hea7	0.76	
Hea8	0.77	
Comfort		9.6
Com1	0.89	
Com2	0.87	
Com3	0.88	
Com4	0.85	
Annoyance		9.6
Ann1	0.72	
Ann2	0.75	
Ann3	0.73	
Ann4	0.73	
Ann5	0.67	
Pathogenicity		8.6
Pat1	0.73	
Pat2	0.73	
Pat3	0.81	
Pat4	0.76	
Attachment		7.0
Att1	0.82	
Att2	0.82	
Att3	0.82	
Disturbance		6.2
Dis1	0.84	
Dis2	0.84	
Dis3	0.69	
Privacy		6.2
Pri1	0.83	
Pri2	0.85	
Pri3	0.77	
Autonomy		5.9
Aut1	0.74	
Aut2	0.80	
Aut3	0.80	
Controllability		5.9
Con1	0.61	
Con2	0.73	
Con3	0.70	

3.2.2 Confirmatory factor analysis (CFA)

The reliability and validity of the variables were tested using CFA, as shown in Table 6. The reliability analysis was based on Cronbach's alpha coefficients of the variables; all potential variables had Cronbach's alpha values above 0.70, indicating good reliability. The construct validity was checked using the same methods as previous studies [57,58], and the results showed that all observable variables had good convergent validity (standardised factor loadings ≥0.5, AVE ≥ 0.5, CR ≥ 0.7) and that the overall construct had good discriminant validity (MSV < AVE, ASV < AVE).

Table 6. Reliability and construct validity of the variables.

Construct & code	Cronbach's alpha	Std. factor loading	CR	AVE	MSV	ASV
Health Evaluation	0.93		0.93	0.63	0.38	0.23
Hea1		0.74				
Hea2		0.71				
Hea3		0.75				
Hea4		0.74				
Hea5		0.86				
Hea6		0.86				
Hea7		0.87				
Hea8		0.81				
Comfort	0.93		0.93	0.78	0.19	0.10
Com1		0.90				
Com2		0.89				
Com3		0.90				
Com4		0.84				
Annoyance	0.92		0.92	0.70	0.48	0.29
Ann1		0.80				
Ann2		0.87				
Ann3		0.85				
Ann4		0.86				
Ann5		0.80				
Pathogenicity	0.85		0.86	0.60	0.48	0.19
Pat1		0.68				
Pat2		0.74				
Pat3		0.83				
Pat4		0.84				
Attachment	0.93		0.93	0.82	0.42	0.21
Att1		0.90				
Att2		0.92				
Att3		0.89				
Disturbance	0.82		0.84	0.63	0.30	0.17
Dis1		0.76				
Dis2		0.85				
Dis3		0.77				
Privacy	0.79		0.80	0.57	0.10	0.07
Pri1		0.80				
Pri2		0.79				
Pri3		0.66				
Autonomy	0.77		0.80	0.59	0.29	0.15
Aut1		0.49				
Aut2		0.85				
Aut3		0.89				
Controllability	0.76		0.77	0.53	0.46	0.27
Con1		0.62				

Con2	0.77
Con3	0.79

3.2.3 Structural equation model (SEM)

The SEM was conducted after the EFA and CFA. The variance inflation factor (VIF) was first used to test for multicollinearity in the structural model, and the results showed that the VIF estimates for all variables were less than 5.0, indicating no multicollinearity in the model [60]. Based on previous studies [18,57,58], the goodness-of-fit indices and recommended values for this model are listed in Table 7 with no modifications. The R^2 value of 0.43 (> 0.33) for *Health Evaluation* represents a medium level of explanation for this latent variable.

Table 7. Goodness-of-fit indices of the model and recommended values (N = 720).

Model fit index	x^2/df	CFI	RMSEA	SRMR
Obtained values	2.81	0.932	0.050	0.056
Recommended values	＜5.0	＞0.90	＜0.08	＜0.08

The evaluation model is illustrated in Fig. 3, and the regression coefficients of the pathways in the model are listed in Table 8, which shows the quantitative relationships between the different elements. The results showed that 10 out of the 13 pathways were statistically significant, indicating that most of the qualitative relationships created through GT are supported by the quantitative analysis. Specifically, both *Attachment* and *Autonomy* showed significant positive effects on *Comfort* (β = 0.378, p = 0.000; β = 0.152, $p < 0.01$) but no significant effects on *Annoyance*. Similarly, although there was a negative relationship between *Privacy* and *Disturbance* (β = -0.103, $p \leq 0.05$), *Privacy* showed no significant effects on *Annoyance*, indicating that a lack of acoustic privacy would not cause increased negative emotions (explained by discomfort, annoyance, anger, anxiety, and unsafety).

Controllability had a significant negative association with *Annoyance* (β = -0.796, p = 0.000), *Pathogenicity* (β = -0.611, p = 0.000), and *Disturbance* (β = -0.582, p = 0.000), highlighting the importance of *Controllability* for protecting against the adverse impacts of noise. Additionally, all characteristics had a significant positive correlation with each other.

Comfort, *Annoyance*, *Pathogenicity*, and *Disturbance* were all significantly associated with *Health Evaluation*. *Annoyance* showed more significant effects (β = -0.457, p = 0.000); however, there was a weak negative relationship between *Pathogenicity* and *Health Evaluation* (β = -0.075, $p < 0.05$), indicating that the evaluation of a healthy indoor acoustic environment in residential buildings should not be based on whether it causes disease or other physiological discomforts.

Table 8. Quantitative relationships between the different elements in the model.

Pathways	Estimate	S.E.	P-value	St. Estimate
Attachment → Comfort	0.426	0.050	0.000	0.378
Attachment → Annoyance	-0.056	0.081	0.484	-0.033
Privacy → Annoyance	-0.062	0.058	0.286	-0.036
Privacy → Disturbance	-0.132	0.055	0.016	-0.103
Autonomy → Comfort	0.171	0.051	0.001	0.152
Autonomy → Annoyance	0.046	0.070	0.511	0.026
Controllability → Annoyance	-1.380	0.152	0.000	-0.796
Controllability→ Pathogenicity	-0.771	0.060	0.000	-0.611
Controllability → Disturbance	-0.747	0.071	0.000	-0.582
Comfort → Health Evaluation	0.264	0.043	0.000	0.224
Annoyance → Health Evaluation	-0.350	0.031	0.000	-0.457
Pathogenicity → Health Evaluation	-0.079	0.037	0.032	-0.075
Disturbance → Health Evaluation	-0.103	0.043	0.018	-0.100

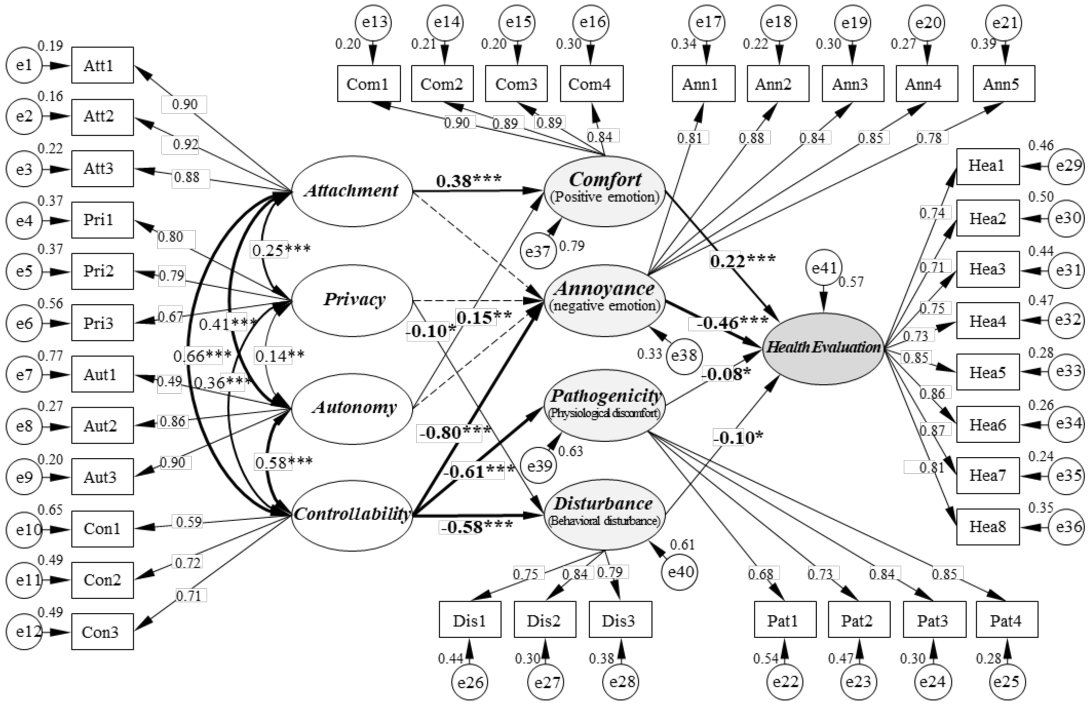

Fig. 3. SEM results of the evaluation model. Statistically significant pathways are annotated with standardized coefficients (*p≤0.05, **p≤0.01, ***p≤0.000), and the magnitude of the standardized pathways coefficient is expressed using lines of different widths. Non-significant paths are marked with dashed lines.

The total effect of each characteristic on *Health Evaluation* is shown in Fig. 4. According to Cohen's guidelines, effect sizes are classified as small (0.1), medium (0.3), or large (0.5) [61]. Overall, *Controllability* had a large effect size on *Health Evaluation* (effect size = 0.475), which worked primarily by alleviating *Annoyance*. The effect size of *Attachment* was 0.084, indicating a small but positive contribution to *Health Evaluation*. However, the effect sizes of both *Privacy* and *Autonomy* were significantly limited.

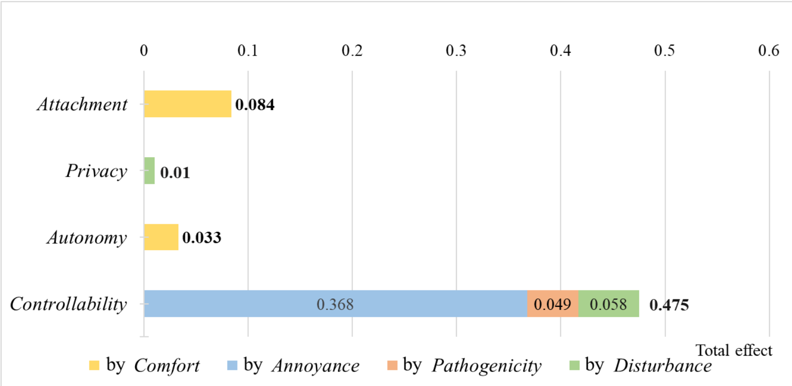

Fig. 4 Total effect of each characteristic on the evaluation of healthy indoor acoustic environments.

3.3 Differences in the evaluation model by gender and age

3.3.1 Model differences by gender

To examine the differences between the elements for males (N = 331) and females (N = 389), a two-sample Mann-Whitney U test was conducted based on the EFA factor scores. The results indicate that females have higher *Autonomy* and lower *Controllability* than males, with no significant differences between genders in the other elements, as shown in Table 9.

Table 9. Median scores for the elements by gender. The numbers in parentheses represent the quartiles.

Elements	Male	Female	Z	P
Attachment	-0.05 (-0.66, 0.75)	0.06 (-0.70, 0.67)	-0.364	0.716
Privacy	0.03 (-0.69, 0.71)	-0.08 (-0.76, 0.67)	-0.866	0.387
Autonomy	-0.13 (-0.86, 0.63)	0.22 (-0.54, 0.74)	-3.444	0.001
Controllability	0.27(-0.47, 0.81)	-0.12 (-0.89, 0.59)	-4.043	0.000
Comfort	0.01 (-0.70, 0.56)	0.10 (-0.49, 0.79)	-1.897	0.058
Annoyance	-0.05 (-0.70, 0.56)	0.12 (-0.57, 0.65)	-1.400	0.162
Pathogenicity	-0.24 (-0.78, 0.65)	-0.23 (-0.71, 0.60)	-0.219	0.827
Disturbance	-0.07 (-0.69, 0.51)	-0.15 (-0.76, 0.39)	-1.750	0.080
Health Evaluation	-0.03 (-0.44, 0.33)	-0.12 (-0.47, 0.26)	-1.771	0.077

Parameter estimation and goodness-of-fit statistics were conducted separately for the male and female samples. Both groups had good goodness-of-fit indices, indicating that the model can be used to explain the differences across genders, as shown in Table 10.

Table 10. Goodness-of-fit indices of the model for different genders and recommended values.

Model fit index	X^2/df	CFI	RMSEA	SRMR
Male (N = 331)	1.863	0.931	0.051	0.068
Female (N = 389)	2.038	0.929	0.052	0.057
Recommended values	<5.0	>0.90	<0.08	<0.08

The SEM results showing the model differences by gender are illustrated in Fig. 5, and more path hypotheses were accepted for females. Specifically, there was a significant negative correlation between *Attachment* and *Annoyance* in females (β = -0.11, $p < 0.05$), indicating that a sense of attachment evoked by sounds can alleviate women's noise annoyance. *Privacy* was more important for women because a lack of acoustic privacy would lead to *Annoyance* and *Disturbance*. *Autonomy* showed a significant positive effect on *Comfort* in females (β = 0.21, p = 0.000), indicating that women's freedom to make noise is related to improved acoustic comfort. Moreover, *Health Evaluation* in females was significantly affected by *Pathogenicity* and *Disturbance*, but males failed to show such associations.

Fig. 6 shows the total effect of each characteristic on *Health Evaluation* for different genders. The most influential element, *Controllability*, had large effect sizes for both females (effect size = 0.485) and males (effect size = 0.401). *Attachment* had small effect sizes on *Health Evaluation* in both genders, with a slightly larger effect in females. In addition, it is worth noting that only *Health Evaluation* in women was influenced by *Privacy* and *Autonomy*.

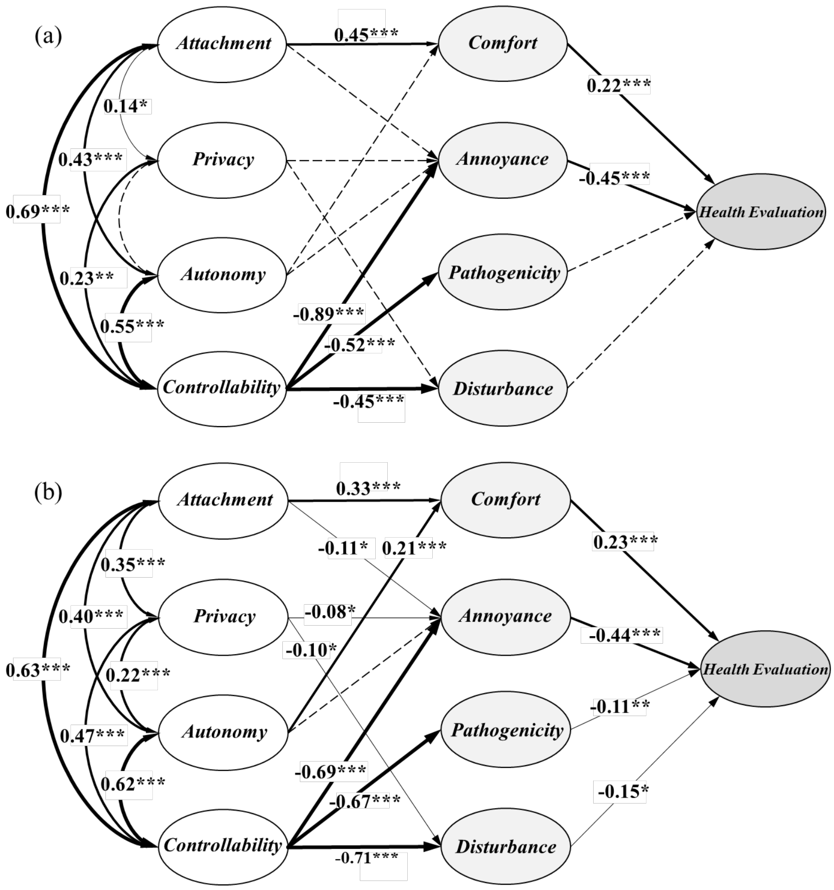

Fig. 5. SEM results for different genders: (a) male and (b) female. Statistically significant paths are annotated with standardized coefficients (*p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.000), and the magnitude of the standardized path coefficient is expressed using lines of different widths. Non-significant paths are marked with dashed lines.

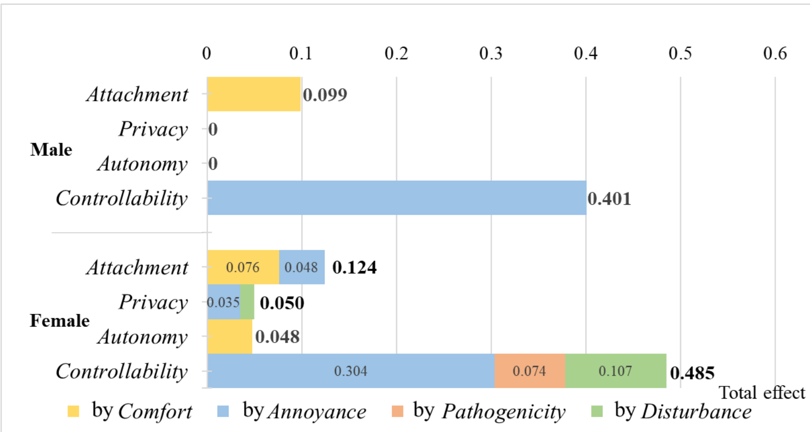

Fig. 6. Total effect of each characteristic on the evaluation of healthy indoor acoustic environments for different genders.

3.3.2 Model differences by age

All samples were divided into three groups based on age: younger adults (18-29 years, N = 272), middle-aged adults (30-49 years, N = 318), and older adults (≥50 years, N = 130). A multisampling Kruskal-Wallis H test was performed based on the factor scores of the EFA to examine the differences between the elements in different age groups, as shown in Table 11. The results showed that participants of various ages had significant differences. Younger adults exhibited higher levels of both *Attachment* and *Autonomy* but the lowest level of *Controllability*. Older adults appeared to be less emotionally responsive to acoustic environments at home, as they reported the lowest levels of *Comfort* and *Annoyance*. Moreover, although younger adults reported the least *Pathogenicity*, they rated the level of *Health Evaluation* significantly lower than older adults.

Table 11. Median scores for the elements by age. The quartiles are represented by the numbers in parentheses, and the statistical significance is shown by different letters. An identical letter between two groups indicates no significant difference, whereas the absence of an identical letter indicates a significant difference.

Elements	Younger adults (18-29)	Middle-aged adults (30-49)	older adults (≥50)	H	P
Attachment	0.09 (-0.66, 0.90) a	-0.16 (-0.84, 0.60) b	0.07 (-0.52, 0.72) ab	7.069	0.029
Privacy	-0.01 (-0.73, 0.76) a	-0.14 (-0.80, 0.60) a	0.09 (-0.69, 0.78) a	3.747	0.154
Autonomy	0.27 (-0.43, 0.81) a	-0.15 (-0.77, 0.54) b	-0.03 (-0.93, 0.70) ab	14.336	0.001
Controllability	-0.27 (-1.04, 0.48) a	0.12 (-0.62, 0.70) b	0.45 (-0.09, 1.01) c	43.773	0.000
Comfort	0.09 (-0.47, 0.77) a	0.10 (-0.50, 0.67) a	-0.18 (-1.02, 0.58) b	11.484	0.003
Annoyance	0.15 (-0.50, 0.64) a	0.06 (-0.62, 0.61) a	-0.19 (-1.09, 0.51) b	10.464	0.005
Pathogenicity	-0.43 (-0.87, 0.23) a	-0.17 (-0.75, 0.80) b	-0.03 (-0.60, 0.92) b	22.812	0.000
Disturbance	-0.07 (-0.74, 0.51) a	-0.12 (-0.71, 0.50) a	-0.23 (-0.74, 0.32) a	1.109	0.574
Health Evaluation	-0.21 (-0.47, 0.20) a	-0.02 (-0.50, 0.34) ab	0.15 (-0.31, 0.37) b	13.271	0.001

Parameter estimation and goodness-of-fit statistics were performed for each age group; however, the goodness-of-fit indices for older adults did not meet the recommended values. After releasing the covariance between the two sets of measurement errors (Hea3 with Hea2; Con3 with Con2), the goodness-of-fit indices for all groups reached acceptable values, as shown in Table 12.

Table 12. Goodness-of-fit indices of the model for each age group and recommended values.

Model fit index		X^2/df	CFI	RMSEA	SRMR
Younger adults (18-29, N = 272)		1.490	0.940	0.042	0.059
Middle-aged adults (30-49, N = 318)		1.907	0.936	0.053	0.062
Older adults (≥50, N = 130)	Values of the unmodified model	1.752	0.881	0.076	0.090
	Values of the modified model	1.611	0.904	0.069	0.088
Recommended values		＜5.0	＞0.90	＜0.08	＜0.08

Fig. 7 shows the differences in the model according to age. Overall, fewer path hypotheses were confirmed by the quantitative analysis as people aged, indicating that older individuals tend to evaluate healthy indoor acoustic environments in residential buildings in a less complex manner. Specifically, *Attachment* showed a significant negative effect on *Annoyance* (β = -0.19, p < 0.01) in younger adults; however, no such effect was observed in the other two groups. *Privacy* had no effect on *Disturbance* in middle-aged adults, and *Autonomy* had no positive effect on *Comfort* in older adults, both of which differed from the other age groups. *Pathogenicity* revealed a significant negative effect on *Health Evaluation* (β = -0.17, p ⩽ 0.000) in middle-aged adults; however, other age groups failed to show this association. *Disturbance* had a critical effect (β = -0.19, p ⩽ 0.01) on *Health Evaluation* in younger adults, but this effect diminished with increasing age.

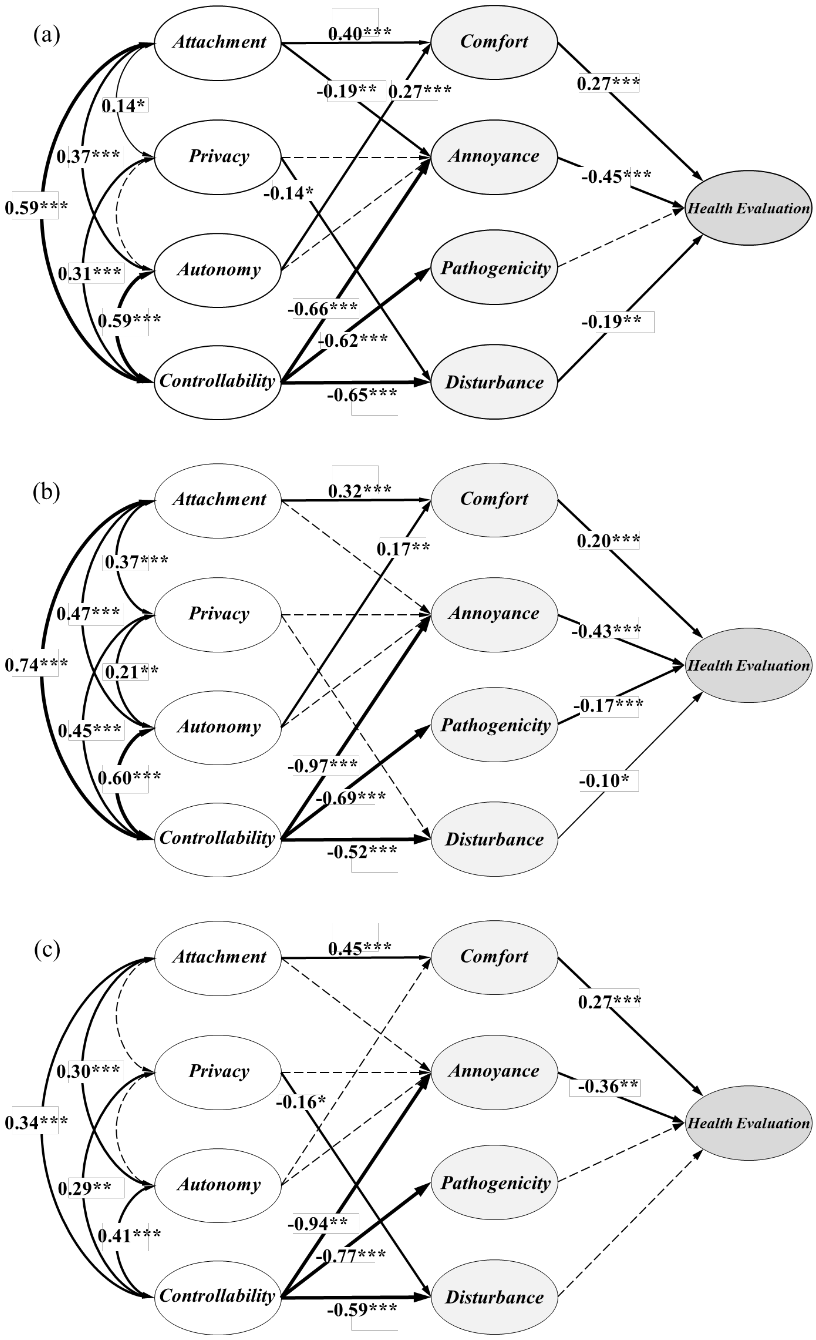

Fig. 7. SEM results for different age groups: (a) younger adults: 18-29, (b) middle-aged adults: 30-49, and (c) older adults: ≥50. Statistically significant paths are annotated with standardized coefficients (*p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.000), and the magnitude of the standardized path coefficient is expressed using lines of different widths. Non-significant paths are marked with dashed lines.

The total effect of each characteristic for different age groups is shown in Fig. 8. Generally, *Health Evaluation* was influenced by fewer characteristics with age. *Controllability* remained the most influential factor in all age groups, particularly for middle-aged adults (total effect size = 0.585). *Attachment* showed a medium effect size (total effect size = 0.194) on *Health Evaluation* in younger adults, suggesting that the sense of attachment is another crucial factor in constructing healthy indoor acoustic environments for those aged 18-29 years.

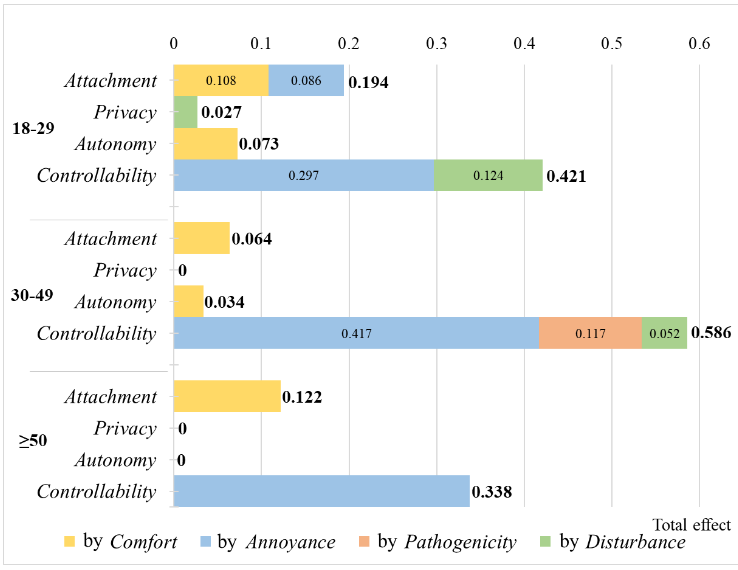

Fig. 8 Total effect of each characteristic on the evaluation of healthy indoor acoustic environments for different age groups.

4 Discussion

4.1 Elements and conceptual framework

Understanding healthy acoustic environments in residential buildings is the foundation for filling the gap between the intended goal of acoustic design in healthy housing and the actual performance of acoustic environments at home. *Attachment*, *Privacy*, *Autonomy*, and *Controllability*, which are the four characteristics suggested in this study, are largely consistent with the description of an ideal residential indoor soundscape in a previous study conducted in London [26], implying that residents from different cultural backgrounds share a strong similarity in the pursuit of their home's acoustic environment.

The characteristics of healthy indoor acoustic environments and the indoor affective response model [16] were compared to facilitate the use of the soundscape approach in the acoustic design of healthy housing. During the comparison process, *Attachment* was not linked to the *engaging-detached* axis as they had different connotations. According to the results of the GT analysis, *Attachment* incorporated the sub-concepts of intimacy, belonging, companionship, familiarity, and security and referred to an affective connection provoked by sounds between occupants and home environments. However, Torresin et al. [16] reported that the *engaging-detached* axis, explained with attributes such as “Exciting” “Interesting, interest-arousing” and “Banal, insignificant, meaningless, without interest”, aligns well with the *Vibrancy* or *Excitement* perceptual construct that has already emerged from previous soundscape literature [15,62,63].

As shown in Fig. 9, an ellipse containing *Attachment* (expressed by the attributes "familiar, intimate, personal" and "safe"), *Privacy* (expressed by the attribute "private"), and *Controllability* (expressed by the attribute "under control") is regarded as the area where a healthy indoor acoustic environment is located, without finding precise descriptors corresponding to *Autonomy*. The comparison showed that the evaluation of healthy indoor acoustic environments by the occupants was determined more by the “comfortable – annoying” continuum, which was similar to the findings reported by Torresin et al. [16], in which *Comfort* explained more of the variance than *Content* in indoor soundscape evaluation. Furthermore, a healthy acoustic environment was found to be lower in *Content*, strengthening the idea that *Empty* has a positive value [16,17].

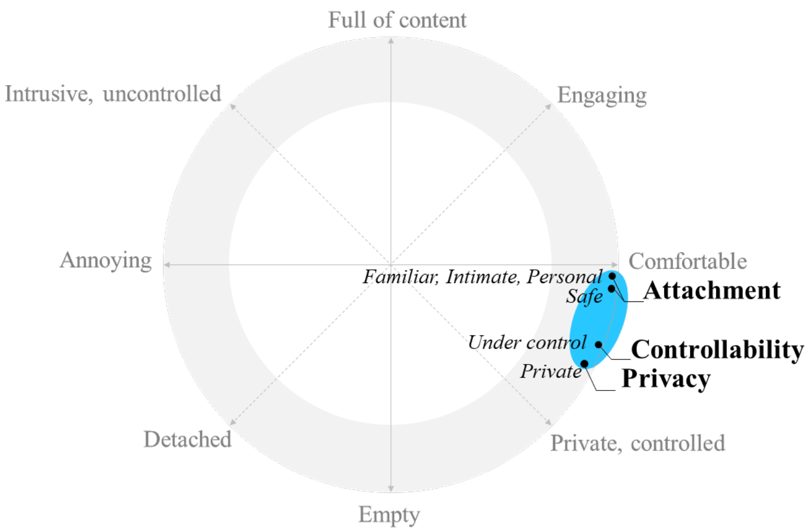

Fig. 9. Area (elliptical coverage area) where a healthy indoor acoustic environment is located in the indoor affective response model.

A holistic conceptual framework of healthy acoustic environments, with wide applicability in various contexts, has been previously developed [23]. As an extension, the present study focused on the residential context and explored how healthy acoustic environments are evaluated, understood, and characterised by the occupants. Notably, the GT analysis and subsequent CFA in the present study confirmed that the positive and negative psychological responses provoked by noise were two different dimensions and should be assessed individually, which is not consistent with the results of the previous study [23]. However, it is consistent with that of Yang et al. [64], who demonstrated that the increase of pleasantness of noise does not necessarily result in the reduction of its antonym.

According to a visual inspection of the coding matrix of the interview transcripts (Fig. B.1 in Appendix B), the differences in the evaluation between the six respondents with a medical background and the others were compared. The results indicated that the medical background appeared to influence the evaluation of healthy indoor acoustic environments in residential buildings. Respondents with a medical background provided more comprehensive and evidence-based views, as well as more insights into the impacts of indoor acoustic environments on physiological states. Further details on the comparison results are provided in Appendix B.

4.2 Effects of *Controllability* and *Attachment* on the evaluation

As a core concept in evaluating the quality of an interior environment, controllability was referred to as an explanatory mechanism that demonstrates adverse health effects due to noise exposure [65,66]. This concept is fundamentally based on an individual's belief that they can successfully manage the noise issue and that health may be less negatively affected even when exposed to more noise, as long as the person perceives themselves as having sufficient resources to cope with it [50]. In contrast to the dimensions of outdoor soundscape perception [62], the secondary axis of the "controlled - uncontrolled" continuum is unique to the indoor one [16], indicating that *Controllability* appears to be peculiar to indoor residential acoustic environments. As reported by Riedel et al. [65], "*home is meant to be a place where residents ideally should be in control of their immediate environment, to pursue any activity without constraints from external stressors and uncontrollable circumstances, to feel comfortable, safe, and at ease*".

According to Stallen [67], annoyance is a psychological stress reaction to noise, with the primary and secondary assessments being the degree of perceived disturbances and the perception of resources available to deal with the noise, respectively. The present study confirmed the significance of *Controllability* in determining noise-induced negative emotions, which is consistent with the findings of previous studies [65,68]. Significant effects of *Controllability* on both self-reported physiological discomfort and behavioural disturbances were also observed. These findings imply that exposure to even low levels of noise has the potential to elicit adverse physiological responses if individuals perceive a lack of coping strategies; furthermore, it is possible to achieve better work performance at home by increasing indirect coping capacity (e.g. exact knowledge of the time schedule of the noise source) when exposure levels cannot be directly reduced.

It has been remarked that place attachment promotes relaxation, comfort, and security [69]. Although room acoustics are rarely considered when place attachment is investigated, the present study revealed that the attachment evoked by sounds at home is closely related to improved acoustic comfort. This finding is in good agreement with that derived from the indoor affective response model [16], where the attributes describing *Attachment* are located significantly close to the attribute “comfortable”. Previous research [26] highlighted the necessity of feeling in contact with the external environment and being comforted by the sounds created by family members; similarly, the study confirmed that *Attachment* had a significant positive influence on the evaluation of healthy indoor acoustic environments in residential buildings, suggesting that the evaluation went beyond simply preventing noise annoyance. Notably, this study failed to demonstrate the mitigating effect of *Attachment* on noise annoyance. One possibility is that the sounds facilitating attachment (e.g. sounds created by family members) may also lead to annoyance [70].

4.3 Gender and age influencing the evaluation model

Despite having the greatest impact regardless of gender or age, the effect size of *Controllability* was larger for women and middle-aged adults. These findings support the notion that the association between perceived control and health was stronger in women than men [71]. However, Michael reported that perceived control was more strongly associated with self-rated health in older than younger individuals [72], which is slightly inconsistent with the results of the present study. One explanation for this difference may be the insufficient sample size for those aged 70 years or older in the present study. Hence, future research specifically on older adults is required to better reveal the influence of *Controllability* on evaluating the acoustic environment.

With respect to *Attachment*, a negative association with *Annoyance* was confirmed only in women and younger adults, strengthening the idea that its psychological benefits are influenced by age and gender [48,69]. The total effect size of *Attachment* on *Health Evaluation* was larger in people aged 18 to 29 years, indicating that acoustic strategies aimed at promoting attachment [73] are more likely to improve young adults' assessments of the home acoustic environment.

Privacy had no effect on the evaluation of either males or middle-aged adults, possibly because of their shorter stay at home, as the quantity of time spent at home was found to be a contextual factor influencing indoor soundscape evaluation [28,74]. Moreover, a statistically significant effect of *Autonomy* on the evaluation was not observed in either males or older adults, suggesting that they had a lower expectation of freely making noise at home.

Overall, this study demonstrated that the evaluation in females and younger adults was influenced by more characteristics; in other words, both had more diverse understandings of healthy indoor acoustic environments at home. Despite the largely inconclusive or inconsistent relationship between gender and soundscape evaluation [14,27], the results of this study support the idea that women are generally more emotionally sensitive to seemingly minute changes in the acoustic environment [33]. The finding that ageing tends to simplify the evaluation mechanisms can be interpreted in light of previous studies, which showed that the loss of function of the peripheral auditory system [35] and contextual factors, such as experience and memory [27], might lead to changes in soundscape evaluation.

4.4 Practical implications and limitations

This study has three potential practical implications. First, the characteristics of healthy indoor acoustic environments in residential buildings were revealed, providing a specific acoustic goal closer to the real understanding of occupants in the design of healthy housing. Second, the evaluation model has proposed implementation strategies for constructing a healthy indoor acoustic environment at home and can help architects determine the most effective method. Third, the findings provide empirical grounds for advancing theories on the influence of demographic characteristics on evaluating healthy indoor acoustic environments, which is beneficial for health equity, as architects can prioritise the more crucial aspects when designing acoustic environments for vulnerable groups.

This study has several limitations. First, the conceptual framework was based on a general concept of stress and described the links between elements as unidirectional; therefore, it did not adequately capture the bio-psycho-social complexity. Second, the sample size of individuals over 70 years of age was limited, which may have made the estimations for older adults insufficiently precise. Third, sleep problems caused by noise were not included in the questionnaire, which might have resulted in an underestimation of the impact of *Behavioral Disturbance*. Finally, as extensive household measurements are not practical, this study did not investigate objective exposure parameters, thereby limiting the applicability of the findings. These parameters may be integrated into the model in future studies.

5 Conclusion

Following a mixed-method approach, this study investigated the evaluation of healthy indoor acoustic environments in residential buildings by the occupants. The following conclusions can be drawn from the three research questions:

1) Nine elements of healthy indoor acoustic environments in residential buildings were identified, and a conceptual framework was established based on their relationships. The phenomenon/central idea of this framework is the evaluation of healthy indoor acoustic environments in residential buildings. The characteristics of healthy residential indoor acoustic environments, namely, *Attachment*, *Privacy*, *Autonomy*, and *Controllability,* were the causal conditions of the phenomenon;

Comfort, *Annoyance*, *Pathogenicity*, and *Disturbance* were the action/interactional strategies where the phenomenon was performed; and *Health Evaluation* was the consequence of the phenomenon.

2) *Controllability* and *Attachment* both showed a significant positive impact on the evaluation. *Controllability*, which had the largest effect size (total effect size = 0.475) of the four characteristics, significantly improved the evaluation by reducing negative emotions, physical discomfort, and behavioural disturbances caused by noise. The impact of *Attachment* was achieved through a favourable contribution to acoustic comfort. The effects of both *Privacy* and *Autonomy* on the evaluation were significantly limited.

3) Regardless of gender or age, *Controllability* always had the greatest impact on the evaluation of healthy indoor acoustic environments in residential buildings; however, the positive effect of *Attachment* was mainly observed in younger adults aged 18 to 29 years. Women exhibited more complex evaluation mechanisms and more diverse understandings than men, both of which tended to become simpler as people aged.

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.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (grant number 51978454). Sincere thanks to Yue Fu for the help during the data collection.

Appendix

Appendix A. Demographic information of each respondent in the grounded theory analysis

Table A.1. Demographic information of each respondent in the grounded theory analysis. Six respondents with a medical background were defined as "medical group", and the others were defined as "non-medical group". H: high school degree or lower; U: university degree; P: post-graduate degree; D: doctoral degree

Medical group	**Respondent**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**									
	Age	25	29	32	36	48	50									
	Gender	female	male	female	male	female	female									
	Occupation	audiologist	orthopedist	internist	researcher	internist	psychologist									
	Education level	U	D	D	D	U	U									
Non-medical group	**Respondent**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	**P14**	**P15**	**P16**	**P17**	**P18**	**P19**	**P20**	**P21**
	Age	21	23	26	28	28	29	29	30	31	31	31	33	35	38	42
	Gender	male	male	male	female	female	female	female	male	male	male	female	female	male	female	female
	Occupation	undergraduate student	undergraduate student	PhD student	human resource	accountant	PhD student	architect	engineer	university lecturer	architect	administrator	engineer	actor	salesperson	cafeteria attendant
	Education level	U	U	D	P	P	D	P	P	P	P	U	P	U	H	H
	Respondent	**P22**	**P23**	**P24**	**P25**	**P26**	**P27**	**P28**	**P29**	**P30**	**P31**	**P32**	**P33**	**P34**	**P35**	
	Age	42	43	44	48	49	49	52	52	53	54	54	57	58	60	
	Gender	female	male	female	female	male	female	male	female	male	female	male	female	male	male	
	Occupation	engineer	bank clerk	homemaker	salesperson	university professor	human resource	teacher	engineer	engineer	property manager	administrator	retired	retired	property manager	
	Education level	U	U	U	H	P	U	U	U	U	H	P	H	U	H	

Appendix B. Comparison in the evaluation of healthy indoor acoustic environments between the respondents with a medical background and the others

Given that the comparison of the evaluation of healthy indoor acoustic environments between laypersons and medical personnel may bring useful discussions, the thirty-five respondents interviewed were divided into two sub-groups: six respondents with a medical background were defined as “medical group”, and the others were defined as “non-medical group”.

Some differences in the evaluation of healthy indoor acoustic environments in residential buildings between the two sub-groups appeared to exist. The medical group tended to express more comprehensive and evidence-based views; however, the non-medical group was more inclined to provide specific and experience-based understandings. Specifically, the coding distribution was more evenly distributed in the coding matrix of the medical group than that of the non-medical group based on a visual inspection (Fig. B.1), indicating that the evaluation from the former seemed to be more complete and comprehensive. Respondents in the medical group provided more insights into the impacts of indoor acoustic environments on *Pathogenicity* (Fig. B.1), possibly due to their professional background and work experience. The non-medical group was more willing to elaborate on their understandings based on the specific negative effects of self-experienced noise events, mainly negative emotions and behaviour disturbances (Fig. B.1). These differences can be directly captured in the following statements:

P3 (Medical group): *Short-term exposure to housing renovation noise may trigger only a transient increase in blood pressure, while long-term exposure may be associated with hypertension.*

P15 (Non-medical group): *The sounds of dragging chairs upstairs are particularly annoying, and these sounds make it impossible for me to work from home*.

However, given the limited sample size of the medical group and their general lack of acoustic knowledge, more thorough research is necessary to further explore the differences in the evaluation between laypersons and medical personnel, both directly and scientifically.

Medical group (P1–P6) | Non-medical group (P7–P35)

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18
Causal condition																		
Attachment	7	3	3	1		11	2		2	7	1	5	4	11	2	5	12	
Privacy	1		2	2	2	1				6	1	4	12	4		3		1
Autonomy		2	1	7	2	1	6	6	5	9		5				4	4	4
Controllability	3	10	4	6	3	9	7	3	5	2	3	8	2	4	6	5	7	3
Action/interactional strategies																		
Comfort (positive emotions)	4	5	2	1	2	7		1	3	5	3		13	4	1		2	7
Annoyance (negative emotions)	5	8	8	9	7	4	3	10	8	3	4	4	7	10	12	5	5	8
Pathogenicity (physiological discomfort)	6	3	11	5	9				1		2		3					2
Disturbance (behavioural disturbance)	2	8	9	8	5	4	8	14	13	1	6	6		3	5	4	4	11
Sum	28	39	40	39	30	37	26	34	37	33	20	32	41	36	26	26	34	36

	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31	P32	P33	P34	P35	Sum
Causal condition																		
Attachment	8		2	2	2			2	2	3		2	3	1		5	2	110
Privacy			1		4						1		2	1				48
Autonomy	4	2	2	1	1				2	1	2	6	3			1	7	88
Controllability		4	1		7	3	2	1	6	7	10	10	8	6	5	7	9	176
Action/interactional strategies																		
Comfort (positive emotions)	6		3					1	1		1	2					2	76
Annoyance (negative emotions)	9	3	5	8	9	13	8	12	8	5	8	9	5	8	10	5	11	256
Pathogenicity (physiological discomfort)	1		4	2		3	2	4	3		1		3					65
Disturbance (behavioural disturbance)	1	15	2	6	14	10	4	5	2	6	2		12	1	4	1	10	206
Sum	29	24	20	19	37	29	16	25	24	22	25	29	36	17	19	19	41	1025

Fig. B.1. Coding matrix of the medical group (P1 – P6) and the non-medical group (P7 – P35). The numerical value in each square represents the occurrence frequency of the corresponding category; the redder the color, the higher the frequency. The sum of the occurrence frequency of all categories based on each respondent is listed at the bottom, and the sum of the occurrence frequency of each category based on all the respondents is listed on the right side.

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