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Indoor soundscapes at home during the COVID-19 lockdown in London – Part II: A structural equation model for comfort, content, and well-being

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ABSTRACT

The present work constitutes the sequel to the analysis of data from an online survey administered to 464 home workers in London in January 2021 during the COVID-19 lockdown. Perceived affective quality of indoor soundscapes has been assessed in the survey through a previously developed model, as the combination of two perceptual dimensions, one related to *comfort* (a comfortable – annoying continuum) and the other to *content* (a full of content – empty continuum). Part I of the study reported on differences in *comfort*, *content*, and soundscape appropriateness based on the activity performed at home during the lockdown, i.e. working from home (WFH) and relaxation. Moreover, associations between soundscape dimensions and psychological well-being have been highlighted. Part II of the study deals with the exploration of the influences of several acoustical, building, urban and person-related factors on soundscape dimensions and well-being. A mixed-method approach has been adopted by combining multivariate regression of questionnaire scores with the qualitative analysis of spontaneous descriptions given by respondents. Results showed that several sound sources, urban features, housing characteristics, working modes and demographic factors can influence (positively and negatively) soundscape dimensions differently depending on the task at hand. Notably, the perceived dominance of neighbours' noises during relaxation, moderated by noise sensitivity, and the number of people at home were common factors negatively affecting both *comfort* and well-being, that partially explained the association between comfortable indoor soundscapes and better mental health. The discussion points out the importance of considering the different impacts that acoustical factors (e.g. sound typology), building (e.g., house size), urban (e.g., availability of a quiet side), situational (e.g., number of people at home), and person-related factors (e.g., noise sensitivity) can provide on building occupants depending on the specific activity people are engaged with at home and the opportunities to foster people's well-being through building, urban and acoustic design.

1. Introduction

The work reports on the second part of the analysis of data gathered from an online survey conducted within the project 'Home as a place of rest and work: the ideal indoor soundscape during the Covid-19 pandemic and beyond'. The general objective of the project was to assess the acoustic environment in relation to two main activities performed at home during the pandemic, i.e. relaxing and working from home (WFH), and to link soundscape evaluation with the psychological well-being of participants and a number of acoustical, building, urban, and person-related factors that are known to potentially affect acoustic perception in residential buildings [1]. The study constituted a first application of the indoor soundscape model developed in a previous laboratory investigation [2] for the assessment of the acoustic environment in residential buildings. The model allows to represent the affective responses to the indoor acoustic environment in a two-dimensional model where the main dimension is related to how comfortable or annoying the environment was judged, and therefore noted as *comfort*. The second dimension is related to the

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saturation of the environment with sounds or events and is represented by how empty or full of content the acoustic environment is perceived to be, therefore noted as *content*.

Part I of the study [3] revealed a difference in soundscape evaluation according to the activity carried out at home. Environments were rated as more comfortable and more *content*-rich when considered for relaxation than for WFH. Moreover, acoustic environments perceived as more appropriate for WFH and for relaxation were characterized by higher *comfort* scores and lower *content* scores than those that were assessed as inappropriate. Soundscapes that are appropriate for relaxation were evaluated as comfortable and either full of content (i.e., engaging) or empty (i.e., private and under control), while spaces that are more appropriate to home working were comfortable but also poor in *content*, i.e., perceived as private and under control. Interestingly, the analysis showed an association between soundscapes and psychological well-being of respondents, evaluated through the WHO-5 well-being index [4]. Psychological well-being was positively associated with comfortable soundscapes both in relation to WFH and relaxation. As regards *content*, a weak negative correlation was found between *content* scores and psychological well-being in relation to WFH, but not for relaxation.

But what are the factors underlying psychological well-being and the two perceptual dimensions of indoor soundscapes? Part II of the study addresses this research question by assessing the influence of several acoustical, building, urban and person-related factors on the well-being of building occupants and on soundscape dimensions (i.e., *comfort* and *content*) evaluated according to two main activities performed at home during the COVID-19 lockdown. The information derived will allow to gain insights on factors to control through building and urban design for the creation of healthy and supportive acoustic environments at home [5].

2. Methods

An online survey was carried out in January 2021 via Prolific participant pool [6,7], targeting home workers living in UK (London) and Italy during the COVID-19 lockdown. The following analysis will focus on London as a first case study. The survey involved 464 Londoner respondents and was composed of five main sections addressing: (1) the WFH activity; (2) leisure activities performed at home; (3) housing features; (4) the urban context; and (5) person-related characteristics. The questionnaire included both closed and open-ended questions, that were analyzed through a mixed-method approach in order to increase result validity via methodological triangulation [8]. A detailed description of the study design and of the questions included in the survey (Q1 – Q29) is reported in Part I of the study [3].

In the following, details on quantitative analysis of data from closed-ended questions and qualitative analysis on verbal descriptions from open-ended questions are provided. Statistical analyses were run in IBM SPSS Statistics 26 [9] and in R [10], while qualitative analyses have been conducted in NVivo 12 software.

2.1. Quantitative analysis: Multivariate regression

Multivariate regression was employed as a special case of structural equation modelling (SEM) to investigate patterns of effects within a system of observed variables [11] and to visually display relationships in a path diagram. Please consider that the word "effect" is widely accepted in SEM but should not be taken to indicate claims of causality. We fitted two models, one for each of the two investigated uses (WFH and relaxation). The computation was performed with the *lavaan* package [12]. Models included the direct effect of acoustic, housing, urban context and person-related variables on *comfort* and *content* and on psychological well-being (cf. Fig. 1). Based on previous findings on the association between positive soundscapes and enhanced well-being [3,13–16], we hypothesize that the affective response to the acoustic environment, expressed by the *comfort* and *content* dimensions, and the psychological well-being have common predictors among the investigated variables. Moreover, we tested main and interaction effects between noise sensitivity and perceived dominance of sound sources on *comfort*, *content* and well-being. The hypothesis is that the relationship between how loud a sound source is heard and the investigated outcomes (*comfort*, *content* and well-being) is modulated by people's sensitivity to noise.

Variables included in the path models are described in Appendix A and in Fig. 1. All the regression paths between the exogenous variables (on the left in Fig. 1) and the three endogenous variables (on the right) have been tested. Variables expressed in Likert scales were considered as continuous. In order to reduce the model complexity, nominal variables were in general recoded to reduce the number of categories. Variables on house ownership, house size, and gender were reduced to dichotomous (cf. Appendix A). Two binary variables were derived by combining information on the rooms chosen respectively for WFH and relaxation (Q3, Q9, cf. Appendix A in Part I [3]), and the self-reported quietness of the urban areas outside those rooms (Q18). The variables describe whether the rooms overlooked a quiet or noisy urban area. Another binary variable was extracted from Q19 and is related to the presence of children at home. Due to the lockdown situation, we assume that children experiencing home schooling might have resulted into disrupting and comforting reactions respectively while working and relaxing at home. Variables related to the typology of building services at home were reduced into dichotomous variables specifying the presence of air systems for heating, cooling and ventilation (e.g. air conditioners, mechanical ventilation). While the extended data collected by those questions will be analyzed elsewhere, we included here only the information about air systems as they might provide new source of noise inside buildings. The variable describing the type of urban area (Q25) was dichotomized (0 = suburban, rural; 1 = urban), due to the few occurrences on the "rural" category (N = 1). Housing type variable, having more than two categories, was dummy coded (cf. Appendix A). Responses to "other" option were firstly inspected. When responses could not be included into existing or new categories, "other", "not applicable" and incongruent responses (e.g. participants giving conflicting information across different questions) were generally treated as missing values and deleted listwise. Exceptions are described in Appendix A. In questions related to the relevance of activities performed while WFH (Q1.1 – Q1.8), "not applicable" and "not at all" responses were collapsed. Similarly, "not applicable" answers to questions about sound dominance from other people at home and from neighbours were treated as "not at all" responses, as the information about people living alone and not having neighbours was already included elsewhere (Q20 and Q17).

Covariances between exogenous variables were modelled to account for correlations (e.g. between the type of urban area and the perceived dominance of certain sound sources). The covariance of residuals for the endogenous variables was included in the model (depicted with the double headed arrow in Fig. 1) and represent a correlation of unexplained variance from the two variables.

As endogenous variables (*comfort*, *content*, and well-being) failed to exhibit multivariate normality, a maximum likelihood estimation with robust standard errors and a Satorra-Bentler scaled test statistic (MLM) [17] was utilized for both parameter estimates and goodness-of-fit statistics. Model fit was evaluated

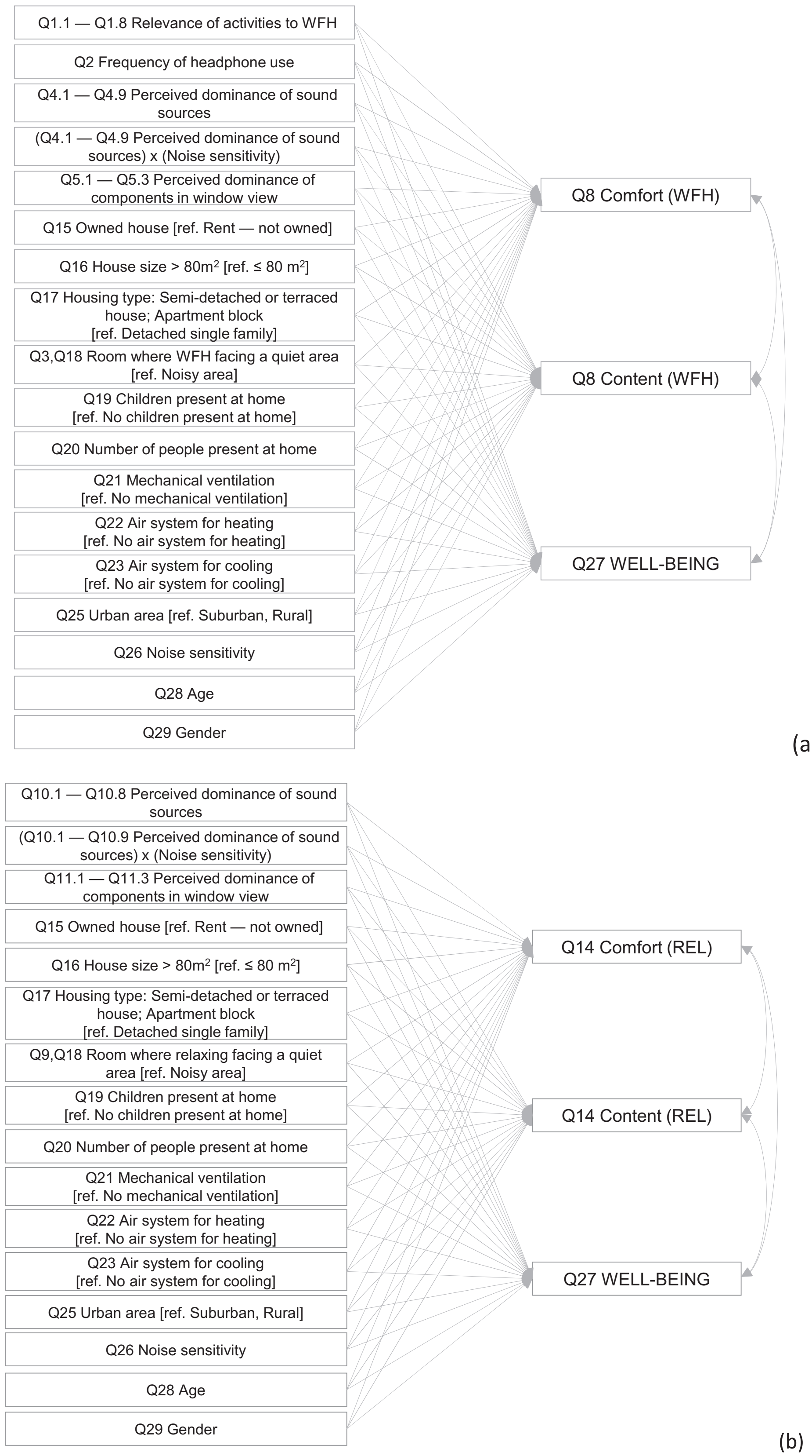

Fig. 1. Path diagrams depicting hypothesized pathways between variables in relation to working (a) and relaxing (b) at home. Rectangles represent measured variables. Single-headed arrows represent a direct effect of one variable on another. Double-headed arrows depict the covariance of residuals of the endogenous variables. Covariances between exogenous variables are not displayed to enhance readability.

through the Robust Comparative Fit Index CFI (≥0.95 for good fit [18]), the robust Root Mean Square Error of Approximation RMSEA (≤0.05 for good fit [18]), the Standardized Root Mean Square Residual SRMR (≤0.80 for good fit [18]), and the relative chi-square (a ratio χ^2/df between 2 and 3 is indicative of a good or acceptable fit [19]). The relative chi-square has been preferred, as chi-square is known to be sensitive to large sample sizes, generally above 200 [20]. The statistical significance threshold was set at 0.05.

2.2. Qualitative analysis

Participants' responses to open-ended questions were analyzed using the method of constant comparison of data [21]. Occurrences within each theme were summed across the participants, and then analyzed through descriptive statistics. Only codes with more than five occurrences have been retained.

The analysis was intended to assess the frequency of negative, neutral, and positive evaluations of specific sound sources that emerged from the analysis of free-format responses to questions Q6 ["*In your view, how is the sound environment currently (positively and negatively) affecting your working activity from home?* – e.g. *heard noises and sounds, building characteristics, urban environment*"] and Q12 ["*In your view, how is the sound environment currently (positively and negatively) affecting your leisure activities at home?* – e.g. *heard noises and sounds, building characteristics, urban environment*" *(While watching TV, reading, listening to music)*" – cf. Appendix A, Part I [3]]. While questions Q4 and Q10 showed the perceived dominance of specific sound sources specified by the researcher without an affective evaluation, the qualitative analysis of verbal data allowed to infer judgments for the sound sources that were spontaneously expressed by respondents, as previously done in the soundscape literature [22,23]. Furthermore, the frequency with which a sound source was mentioned can provide a first clue about potential factors that negatively and positively influence indoor soundscapes.

3. Results

3.1. Evaluation of sound sources from qualitative analysis

Fig. 2 shows the frequency of negative, neutral, and positive evaluations of specific sound sources in relation to the WFH (Fig. 2a) and relaxation (Fig. 2b) activities.

As regards WFH, results showed that the most frequent negative judgments were associated to noise from people at home, followed by traffic noise, neighbours, construction works, and noise generated by people outside. Positive judgments referred primarily to natural sounds, followed by sounds from music and TV controlled by the respondents themselves.

When assessing the impacts on relaxation, neighbours' noise featured as the most frequently mentioned source with a negative connotation, followed by traffic noise, and people at home. On the positive side, music and sounds from TV were most frequently reported, followed by natural sounds.

3.2. Path models: Influences of acoustical, building, urban and person-related factors on well-being and on soundscape dimensions

This section addresses the investigation of the influence of person-related variables, building features and variables related to the acoustic and urban contexts on soundscape assessment and well-being. The tested path model was described in Fig. 1.

We hypothesized that noise sensitivity would moderate the relationship between sound source dominance and the investigated outcomes (*comfort*, *content,* and well-being). However, as

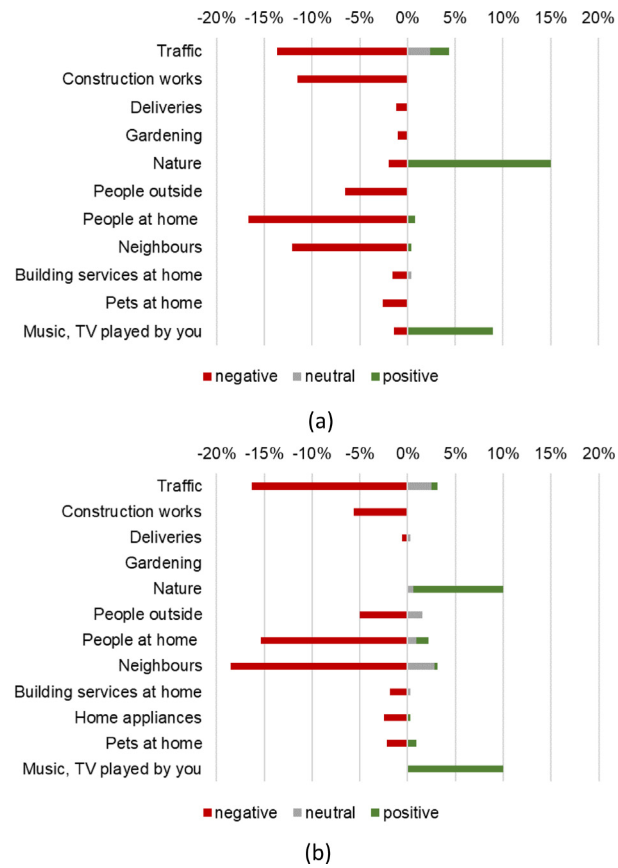

Fig. 2. Percentage of negative, neutral and positive evaluations of perceived sound sources that emerged from the analysis of free-format responses to Q6 and Q12, in relation to (a) WFH (N = 505) and (b) relaxation (N = 319).

the saliency of different sound sources was not derived by objective measures but by the appraisal made by respondents, we firstly tested whether perceived sound dominance was correlated to the noise sensitivity of respondents. The hypothesis was that people more sensitive to noise would report sound sources as more dominant. The only statistically significant relations were between noise sensitivity and the perceived dominance of sounds from neighbours both while working, $r_s = 0.186$, $p < .0005$, and relaxing, $r_s = 0.199$, $p < .0005$, and between noise sensitivity and the perceived dominance of sounds from people outside during relaxation, $r_s = 0.099$, $p = .033$. Those sound sources, and in particular neighbours' noise, were thus rated as more dominant by people more sensitive to noise. For other sound sources, the associations with noise sensitivity were not statistically significant.

3.2.1. Working from home model

The model exhibited a good fit, with robust CFI = 0.957, robust RMSEA = 0.047, SMRM = 0.077, and χ^2/df = 1.95. Significant regression paths are described in Table 1 and depicted in Fig. 3. The model explained 29% of the variance in *comfort* scores, 23% in *content*, and 24% in well-being.

Comfort was found to increase with natural sounds, and with music played by respondents themselves. The effect of noise from sirens, industry and construction works on *comfort* was less straightforward, as it was given by the simple main (negative) effect of the perceived noise and the (positive) interaction term with noise sensitivity. Notably, the impact of those outdoor sounds on *comfort* was moderated by noise sensitivity, with a higher *comfort* for people exhibiting high noise sensitivity. Noise sensitivity also moderated the effect of the perceived noise from neighbours

Table 1
Parameter estimates for significant regression paths in the WFH model. Single-headed arrows represent a direct effect of one variable on another. Double-headed arrows depict the covariance of residuals of the endogenous variables, as also indicated in Fig. 3.

Regression and covariance paths	Estimate	SE	p-value	St. estimate
Other noise from outside → Comfort	−0.199	0.064	0.002	−0.568
(Other noise from outside) × NS → Comfort	0.247	0.099	0.013	0.598
Natural sounds from outside → Comfort	0.128	0.063	0.041	0.361
Music or TV played by you → Comfort	0.073	0.034	0.033	0.280
Room where WFH facing a quiet area → Comfort	0.081	0.026	0.002	0.130
Age → Comfort	0.003	0.002	0.034	0.096
(Sounds from neighbors) × NS → Comfort	−0.230	0.097	0.018	−0.603
Frequency of headphone use → Comfort	−0.021	0.010	0.045	−0.081
Number of people present at home → Comfort	−0.042	0.013	0.002	−0.154
Frequency of headphone use → Content	0.028	0.009	0.003	0.132
Number of people present at home → Content	0.046	0.011	0.000	0.202
Online meetings → Content	−0.026	0.010	0.007	−0.121
Thinking/creative thinking → Content	0.025	0.011	0.028	0.108
Urban area → Content	0.059	0.027	0.029	0.105
Gender → Content	0.068	0.023	0.003	0.127
Gender → Well-being	−0.035	0.016	0.026	−0.091
Individual focused work away from your desk → Well-being	0.027	0.009	0.003	0.150
Sounds from other human beings present in your house → Well-being	−0.068	0.031	0.027	−0.364
Window view: vegetation → Well-being	0.021	0.008	0.007	0.124
Comfort ↔ Content	−0.017	0.003	0.000	−0.287
Comfort ↔ Well-being	0.012	0.002	0.000	0.269

on *comfort*. The higher the noise sensitivity, the more negative the effect of neighbours' noise on *comfort*. Higher *comfort* was associated with a less frequent use of headphones, working in a room facing a quiet area, the presence of fewer people at home, and older respondents.

An increase in *content* scores was correlated to a more frequent use of headphones, a higher number of people living at home, to living in an urban area (compared to a suburban or rural area), to a lower relevance of online meetings and to a higher importance of creative thinking in daily work. As regards gender, women were more likely to report higher *content* and lower psychological well-being than men.

Being more engaged with individual focused work away from the desk and seeing vegetation from windows was associated with higher well-being, while hearing more sounds from other people at home provided a negative effect. A residual negative correlation resulted between *comfort* and *content*, while a residual positive correlation resulted between *comfort* and well-being, due to unspecified factors.

3.2.2. Relaxing at home model

The model for relaxation had a good fit, with robust CFI = 0.972, robust RMSEA = 0.057, SMRM = 0.071, and χ^2/df = 2.42. Significant regression paths are reported in Table 2 and shown in Fig. 4. The model explained 32% of the variance in *comfort*, 22% in *content* and 21% in well-being. Higher *comfort* was associated with rooms overlooking quiet areas, with bigger houses (>80 m^2), and fewer people present at home. The effect of noise from neighbours on *comfort* was given by the simple main (positive) effect of the perceived noise and by the negative interaction term with noise sensitivity. Noise sensitivity thus moderated the relationship between perceived neighbourś noise and *comfort*: the higher the noise sensitivity, the more negative the effect of neighbours' noise on *comfort*.

Higher *content* scores were correlated to rooms facing noisy areas, to smaller houses (<80 m^2), apartments (compared to detached houses), absence of mechanical ventilation, presence of more people at home, and female respondents. Noise sensitivity moderated the effect of sounds from neighbours on *content*: the higher the noise sensitivity, the higher the *content* scores at increasing dominance of neighbours' noises.

Results showed that lower psychological well-being was associated with the presence of more people at home, female respondents, TV sounds and music played by the respondents themselves. The effect of sounds from people outside on well-being was given by the simple main (negative) effect of the perceived noise and the (positive) interaction term with noise sensitivity: the higher the noise sensitivity, the more positive the effect of outdoor human sounds on well-being. Noise sensitivity also moderated the relationship between the perceived dominance of neighbours' noise and well-being, with a more negative effect on well-being for people highly sensitive to noise. A residual negative correlation resulted between *comfort* and *content*, while a residual positive correlation resulted between *comfort* and well-being, likely due to factors not included in the model.

4. Discussion

The study presented the results of an online survey conducted in London with the purpose of exploring the relationships between a number of contextual, building, urban, and person-related variables on psychological well-being and indoor soundscapes, when evaluated according to working and relaxation activities at home. In the following, the effects on soundscape dimensions and well-being are discussed by triangulating the results from rating scales with those from the qualitative analysis of free format responses, also with reference to previous literature and findings from Part I of the study [3].

4.1. Comfort

Higher comfort was associated with working and relaxing in a room overlooking a quiet urban area. Findings are consistent with the existing literature on the beneficial effects of the availability of a quiet side of the dwelling in terms of reduced annoyance, increased health and quality of life [24–27]. Notably, the present study suggests that people who have access to a quiet side perceive the acoustic environment as more comfortable in relation to both relaxing and working at home, thus extending the previous findings.

As regards the contribution of specific sound sources, listening to natural sounds resulted in improved comfort conditions while

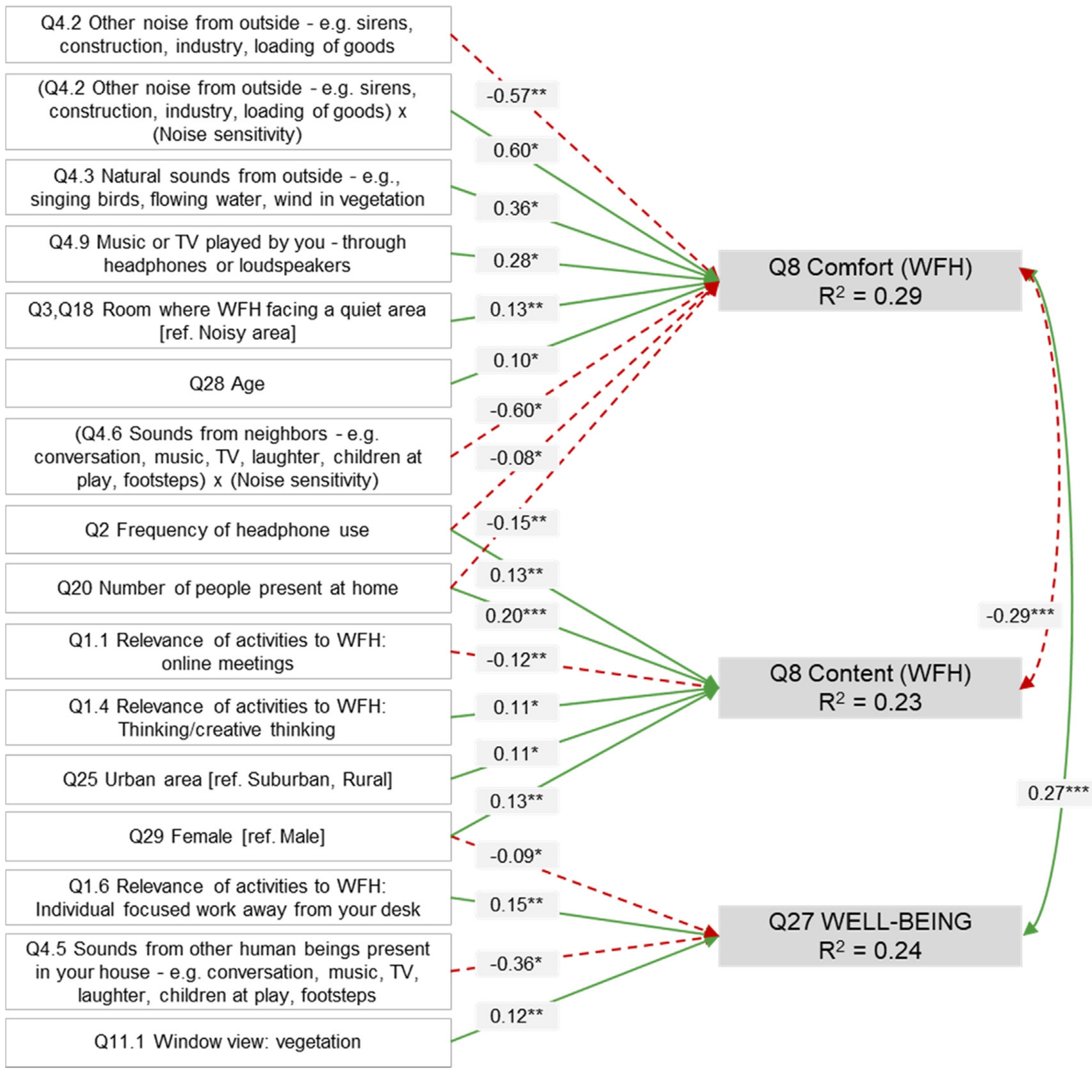

Fig. 3. Path diagram depicting significant pathways between variables in relation to working at home. Single-headed arrows represent a direct effect of one variable on another. Standardized regression estimates with their significance level are given for each path. Positive associations are depicted by continuous green, while negative associations are given by red dotted arrows. R^2 represents the proportion of variance explained in endogenous variables. Double-headed arrows depict the covariance of residuals of the endogenous variables. Covariances between exogenous variables are not displayed to enhance readability. $^*p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

WFH (cf. Fig. 3), while the direct effect on *comfort* during relaxation was not statistically significant (cf. Fig. 4). This was also confirmed by the analysis of open-ended questions, as natural sounds were most often mentioned among the positively perceived sounds in relation to remote working (cf. Fig. 2). If the literature has repeatedly reported on the positive perception of natural sounds and their enhancing effect towards comfort and pleasantness [2,28], the present study suggests a prevailing effect in relation to WFH compared to relaxation, that might be worth investigating in future research.

Higher comfort while working was correlated to listening to sounds from TV and to music played by the people themselves (cf. Fig. 3). Music and TV sounds have been mentioned most often as pleasant sounds in relation to relaxation and among the most beneficial for working, behind natural sounds (cf. Fig. 4). According to the findings reported in Part I of the study [3], listening to music, watching TV, and wearing noise cancelling headphones allowed occupants to take control over the acoustic environment and to shape their wanted soundscapes against the available ones, thus resulting in improved comfort conditions.

While positively perceived sounds (e.g., natural sounds, music) had a direct effect on *comfort*, the effect of more disrupting sounds (e.g., construction works, neighbours' noise, cf. Fig. 2) was generally moderated by noise sensitivity. In the literature, higher annoyance to indoor and outdoor noise sources is generally reported by individuals that are more sensitive to noise [29–31]. In the present study, an association between noise sensitivity and the perceived dominance of sounds from neighbours and from people outside was observed. Building occupants exhibiting higher noise sensitivity reported neighbours' noise, both while working and relaxing, and sounds from people outside during relaxation as more dominant. No significant direct effect of noise sensitivity on *comfort* was observed.

Traffic noise has been frequently mentioned as a disturbing noise source both in relation to home working, behind the effect of other people present in the dwelling, and in relation to relaxation, behind neighbours (cf. Fig. 2). Nevertheless, *comfort* was not directly affected by the perceived dominance of traffic noise neither in relation to working or relaxation. This is likely due to a drop in traffic flow and related noise levels in London [32,33], that resulted in a reduction of noise annoyance from outdoor

Table 2
Parameter estimates for significant regression paths in the relaxation model. Single-headed arrows represent a direct effect of one variable on another. Double-headed arrows depict the covariance of residuals of the endogenous variables, as also indicated in Fig. 4.

Regression and covariance paths	Estimate	SE	p-value	St. estimate
Room where relaxing facing a quiet area → Comfort	0.059	0.028	0.035	0.097
House size > 80 m^2 → Comfort	0.084	0.027	0.002	0.131
Sounds from neighbors → Comfort	0.151	0.068	0.026	0.404
(Sounds from neighbors) × NS → Comfort	−0.290	0.099	0.003	−0.727
Number of people present at home → Comfort	−0.035	0.014	0.014	−0.127
Room where relaxing facing a quiet area → Comfort	−0.053	0.021	0.012	−0.117
House size > 80 m^2 → Content	−0.043	0.022	0.050	−0.091
(Sounds from neighbors) × NS → Content	0.170	0.077	0.028	0.578
Number of people present at home → Content	0.045	0.011	0.000	0.223
Mechanical ventilation → Content	−0.064	0.032	0.049	−0.095
Housing type: Apartment block → Content	0.074	0.033	0.025	0.155
Gender → Content	0.080	0.020	0.000	0.171
(Sounds from neighbours) × NS → Well-being	−0.137	0.059	0.021	−0.561
Number of people present at home → Well-being	−0.018	0.009	0.036	−0.108
Gender → Well-being	−0.044	0.016	0.007	−0.112
Sounds from human beings from outside →Well-being	−0.120	0.039	0.002	−0.512
(Sounds from human beings from outside) × NS	0.153	0.061	0.012	0.607
Music or TV played by you	−0.074	0.027	0.007	−0.405
Comfort ↔ Content	−0.006	0.003	0.020	−0.116
Comfort ↔ Well-being	0.011	0.002	0.000	0.253

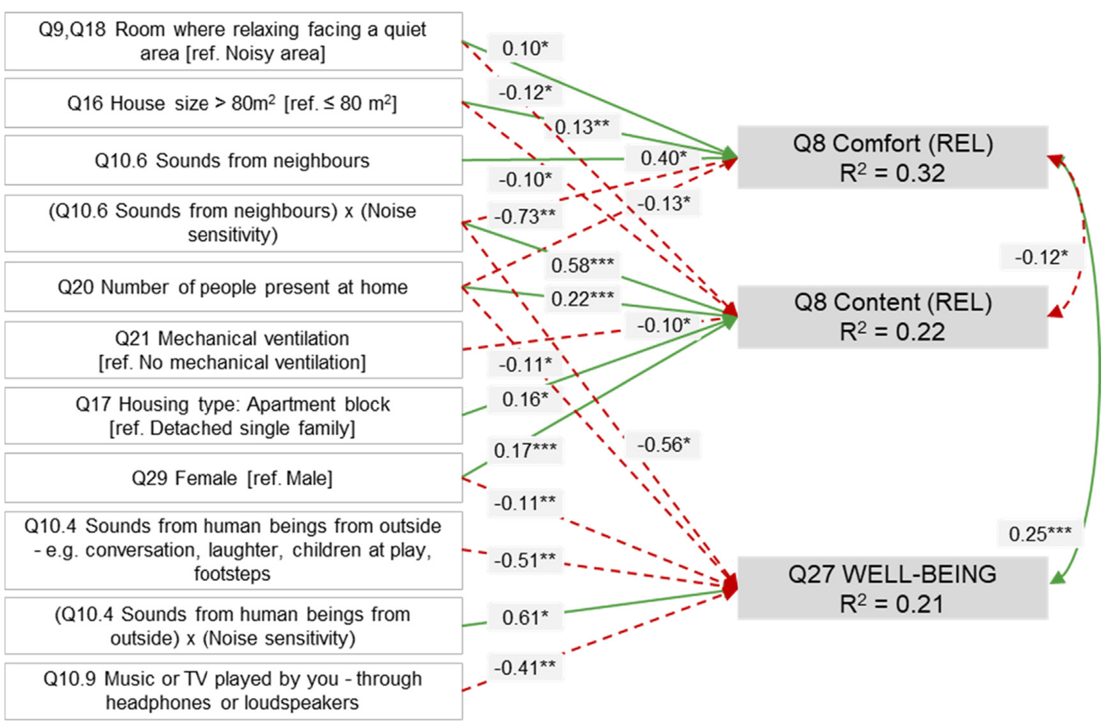

Fig. 4. Path diagram depicting significant pathways between variables in relation to relaxation activities. Single-headed arrows represent a direct effect of one variable on another. Standardized regression estimates with their significance level are given for each path. Positive associations are depicted by continuous green, while negative associations are given by red dotted arrows. R^2 represents the proportion of variance explained in endogenous variables. Double-headed arrows depict the covariance of residuals of the endogenous variables. Covariances between exogenous variables are not displayed to enhance readability. *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sources during the COVID-19 lockdown compared to the pre-pandemic period [33]. Differently, construction works were still allowed during the lockdown and the noise generated could stand out louder due to the reduced traffic flows [33]. As a result, an increased number of tweets and noise complaints related to construction and building works was revealed in London during the period of confinement [33,34]. In the present study construction works were mentioned among the sound sources negatively impacting working activities (cf. Fig. 2). From the multivariate model, construction works, industry and sirens had an impact on *comfort* while WFH through the direct (negative) effect of perceived noise dominance and the (positive) interaction effect with noise sensitivity (cf. Fig. 3). Counterintuitively, all else equal, the negative impact of those noises on *comfort* was reduced in people exhibiting high noise sensitivity. The effect was not significant in relation to leisure activities, as those are often performed at times when construction and industrial works have ceased, and traffic and sirens are reduced [3].

As regards neighbours' noise, noise sensitivity was found to moderate the effect of the perceived noise from neighbours on *comfort* both in relation to WFH and relaxation: the higher the noise sensitivity, the more negative the effect of neighbours' noise on *comfort*. Depending on the studies and investigated contexts, neighbours' noises are reported to be sources of annoyance in residential settings that can be more [35] or less disruptive [36] than outdoor sounds. In a pre-COVID study in London, neighbours' and outdoor noises perceived inside dwellings were found to be equally annoying [37]. During the lockdown in London, the perceived neighbours' noise level, the related annoyance and noise complaints significantly increased [33,34]. The present study provides complementary information on the perceived comfort in relation to the performed activity at home. Noises from neighbours featured as the third most frequently mentioned disruptive sound sources in relation to WFH and the most frequently mentioned when considering relaxation (cf. Fig. 2).

The number of people at home was found to be negatively correlated to *comfort* both in relation to working and relaxing at home (Fig. 3 and Fig. 4). Notably, people at home were the most frequently mentioned source of disturbance in relation to WFH (cf. Fig. 2). Similarly, a Canadian study reported that noise generated by occupants in the same suite (e.g., roommates and family) was the biggest issue for those working from home [38].

Increased use of headphones while working from home has been shown to correlate to reduced *comfort*. More frequent use of headphones can be considered as a proxy for poor acoustic conditions. While this variable was included in the survey only in the WFH section, the analysis of open-ended questions revealed that headphones (including noise-cancelling headphones) were often employed to cope with unfavourable acoustic conditions both while working and relaxing at home [3].

House size resulted a relevant variable in defining comfort during relaxation. Living in larger dwellings (>80 m^2) was associated with greater comfort during relaxation, whereas the effect was not statistically significant when considered for working at home.

As regards age, in the present study higher *comfort* scores were associated with older respondents but only in relation to WFH. Other studies reported higher annoyance by older people (e.g. [36]) and it must be noticed that no clear trend can be found in the literature regarding the effect of socio-demographic parameters, such as age, on comfort and noise annoyance [30].

4.2. Content

Studies on urban soundscapes have been recently investigating the impact of several acoustical and non-acoustical factors on the two main perceptual dimensions that define the affective response to the outdoor acoustic environment, i.e. *pleasantness* and *eventfulness* [28,39]. Differently, previous research in indoor built environments has traditionally dealt with the impact of several factors on valence-related constructs only (i.e., acoustic comfort, satisfaction, and noise annoyance). The present study constitutes the first attempt to explore factors associated with *content*, that is the *eventfulness*-equivalent dimension for indoor residential settings [2].

Relaxing in rooms overlooking a quiet urban area was related to lower *content* (cf. Fig. 4), while the effect was not significant in relation to home working (cf. Fig. 3). As regards the sound source typology, the effect of neighbours' noise on *content* during relaxation was moderated by noise sensitivity, with higher dominance of neighbours' noises resulting in higher *content* for respondents that were more sensitive to noise.

More frequent use of headphones while working was correlated to increased *content* scores. This is likely due to a coping mechanism in presence of soundscapes rich in *content* that were generally judged inappropriate to WFH [3]. Interestingly, the type of task at hand influenced the perceived soundscape *content*. Being more engaged in online meetings was associated with a lower perceived *content*, whereas creative thinking was correlated to increased *content*. The lower sensitivity to *content* during online meetings and the higher sensitivity to *content* during creative thinking might be linked to different cognitive functions and listening modes involved. Given the exploratory nature of the study, future research might help provide further groundwork.

The higher the number of people in the dwelling, the higher the *content* due to the increased amount of human activities at home. Moreover, *content* was explained by several building and urban-related features. Living in larger houses (>80 m^2) resulted in reduced *content* scores during relaxation (cf. Fig. 4), likely because activities are "diluted" over a larger space. Compared to detached houses, flats were associated with higher *content* during relaxation (cf. Fig. 4), and dwellings in urban areas were associated with increased *content* when WFH compared to suburban and rural areas (cf. Fig. 3). This might be due to the fact that in apartments and urban contexts dwellings are more saturated with outdoor and neighbours' sounds, thus resulting in increased *content* values. Moreover, houses equipped with mechanical ventilation were related to lower *content* during relaxation. In the absence of mechanical ventilation, opening windows to ventilate the dwellings (i.e., natural ventilation) can result in increased *content* values due to the access of outdoor sounds.

As regards demographic parameters, only gender was associated with *content*, with higher values reported by female respondents both in relation to home working and relaxation.

4.3. Connecting comfort and content results: privacy, control, and engagement

By intersecting the factors that influence the two main perceptual dimensions, *comfort* and *content*, it was possible to derive the variables that contribute to describe the alternative dimensions related to privacy, control and engagement [2]. The result is conceptually depicted in Fig. 5, where acoustical, building, and urban-related features are reported in relation to soundscape evaluation during working and relaxation. Variables involving both main and interaction effects have not been included as their interpretation would not be straightforward and suitable to this simplified representation.

By way of example, soundscapes perceived as private and under control, corresponding to high *comfort* and low *content* scores, were perceived as more appropriate to home working [3]. As depicted in Fig. 5 a, soundscapes characterized by increased privacy and perceived control can be thought as a combination of the following factors generating either greater comfort or lower content: the presence of more natural sounds, music and sounds from TV played by the respondents themselves, lower neighbours' noise and/or by people less sensitive to noise, less frequent use of headphones, fewer people present in the dwelling, houses mainly located in a suburban or rural area and facing a quiet area outdoor.

When evaluated in relation to leisure activities, a private and controlled soundscape was more likely found in spaces facing a quiet outdoor area, having lower neighbours' noise and/or people less sensitive to noise, and could be more frequently found in larger, detached houses, equipped with mechanical ventilation and with a lower number of people at home (Fig. 5 b).

Differently, acoustic environments characterized by a combination of natural sounds, music and TV sounds, with lower neighbours' noise and/or by people less sensitive to noise, within rooms located in urban areas and having a quiet side were conductive to engaging soundscapes for WFH. Flats (compared to detached houses) and rooms in which windows are opened for ventilation are highly associated with higher *content*. If coupled with factors providing higher *comfort* this can result in sound-

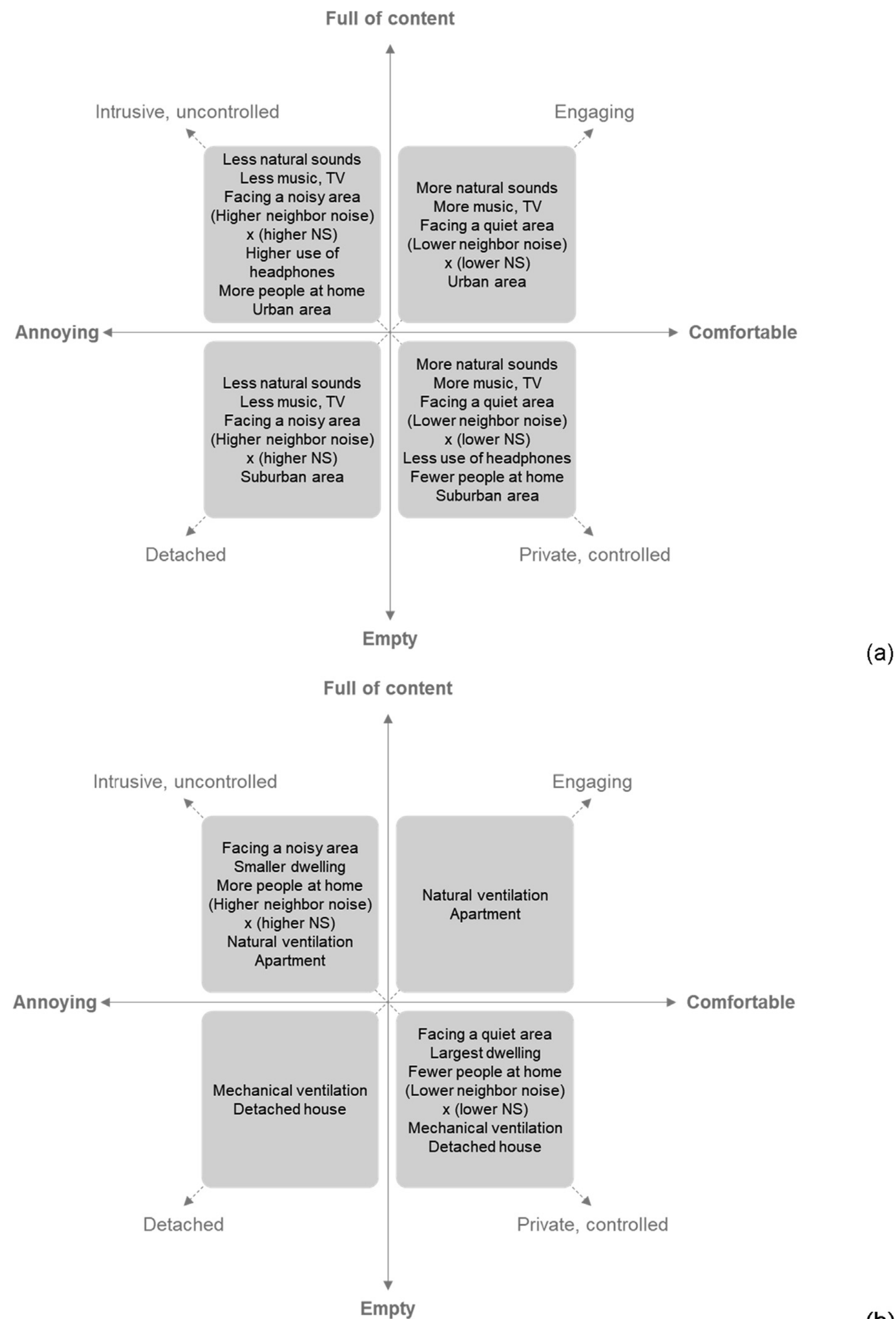

Fig. 5. Conceptual representation of acoustical, building and urban-related variables contributing to privacy, control and engagement dimensions in relation to (a) WFH and (b) relaxation.

scapes that are engaging during relaxation, thus confirming the potential effect of natural ventilation to provide positive soundscapes as previously suggested [40].

4.4. Well-being

The results showed an association between the perceived dominance of sounds from specific sources and building occupants' psychological well-being. Noise sensitivity was found to moderate the relationship between well-being and the perceived dominance of outdoor human sounds and neighbours' noises during relaxation (cf. Fig. 4). The effect of outdoor human sounds on well-being was given by the sum of the simple main negative effect of the perceived sounds and the positive interaction effect with noise sensitivity, meaning a more positive effect of outdoor human sounds on well-being for people that were more sensitive to noise. Outdoor sounds might contribute in some cases to an enhanced well-being by creating a connection with the outdoor environment and alleviating the sense of loneliness, especially during the confinement period, as reported by participants [3]. As regards neighbours' noises during relaxation, a more negative effect on well-being was observed in people that were more sensitive to noise. The exposure to neighbours' noise can result in annoyance and in a lack of privacy, with a detrimental effects on health and well-being of building occupants [41–44]. The perceived dominance of TV sounds and music played by the respondents themselves during relaxation were found to be negatively correlated with well-being. This might be a proxy for an excessively noisy acoustic environment, as people in some cases reported about the need to turn up the volume of TV or playback devices in order to overpower the existing background noise. Previous literature reported some evidence on the relationship between the exposure to indoor noise pollution in living environments and depressive moods [45]. Lower well-being was correlated to higher dominance of sounds from other human beings present at home while WFH. The intrusion of noises from other people at home while working could induce negative mental states, such as reduced *comfort*, that might increase the risks of mental health issues. In relation to relaxation, the number of people present in the dwelling was negatively associated with participants' well-being. The effect of crowding on depression, poor mental health and social well-being has been frequently reported in the literature [46,47], and a study on children suggested that the noise generated at home might be one of the mechanisms underpinning the impact of crowding on well-being [48]. The number of people at home and the dominance of neighbours' noises while relaxing, moderated by noise sensitivity, were common factors negatively affecting both *comfort* and well-being and this can partially explain the association between uncomfortable conditions and poor well-being.

Among the investigated working modes, performing individual focused work away from the desk was associated with improved well-being. This might be explained by reduced cognitive loads or by a higher flexibility provided by those activities (e.g. allowing to choose a more appropriate space where to work), but dedicated investigations would be needed before conclusions could be drawn.

The view of vegetation from a window where WFH was positively correlated to the mental well-being of respondents (cf. Fig. 3). This is in line with the findings of previous literature, showing an impact of poor-quality views on depressive symptoms during the COVID-19 lockdown [49]. On the contrary, windows with access to nature can elicit positive emotions, recover from stressful experiences, restore attentional capacity after cognitive fatigue, and improve well-being [50–52].

As regards gender effect, lower psychological well-being was associated with female participants.

5. Conclusions

In this second part of the study, results of an online survey conducted on 464 home workers in London in January 2021 during the COVID-19 lockdown have been analyzed in order to explore the influences of several acoustical, building, urban and person-related factors on occupants' well-being and on soundscape dimensions (i.e., *comfort* and *content*), according to two activities performed at home during the pandemic, i.e., working and relaxing.

The analysis of data collected from open-ended questions revealed that, as regards WFH, the most frequent negative judgments were associated to noise from people at home, whereas positive judgments referred primarily to natural sounds. When considering relaxation, neighbours' noise featured as the most frequently mentioned source with a negative connotation, while, on the positive side, music and sounds from TV were most frequently reported. Higher *comfort* scores while WFH were related to a higher dominance of natural sounds, music and TV sounds, lower neighbours' noises and/or low sensitivity to noise, working in a room overlooking a quiet area, a less frequent use of headphones, a lower number of people at home, and being older. With reference to relaxation, increased *comfort* was correlated to the availability of a quiet side, a lower number of people at home, and a larger dwelling (>80 m^2). Higher *content* while WFH was associated with a more frequent use of headphones, a lower relevance of online meetings and a higher relevance of creative thinking, a higher number of people at home, being female, and living in an urban area. As regards relaxation, higher perceived dominance of neighbours' noises and/or high sensitivity to noise, sharing the house with more people, the absence of mechanical ventilation, living in a flat and being female was associated with higher *content* scores. Finally, increased well-being resulted in those performing individual focused work away from the desk, male respondents, people less exposed to sounds from other people at home while working, having access to vegetation through the window while WFH, lower dominance of neighbours' noises while relaxing and/or lower noise sensitivity, a lower dominance of music and TV sounds while relaxing, and a lower number of people at home. The dominance of neighbours' noises during relaxation, moderated by noise sensitivity, and the number of people at home were common factors negatively affecting both *comfort* and well-being, and this might partially explain the association between acoustic comfort and positive mental states.

Results pointed out the importance of the availability of a quiet side of the dwelling and the detrimental effect of crowding and neighbours' noise on *comfort*. *Content* was related to the saturation of the environment with indoor (e.g., people at home, neighbours) and outdoor sounds, and on space availability depending on housing features. Different sound typologies were found to influence *comfort* and *content*, and such relation was often moderated by building occupants' noise sensitivity.

Overall, the study confirmed the importance of considering the different impacts that acoustical, building, urban and person-related factors can provide on building occupants depending on the specific activity people are engaged with at home. The lack of data in the pre-pandemic period does not allow to determine at this stage the impacts, if any, in the observed associations due to the psychological status of participants in this emergency period. Therefore, the associations highlighted in the present study might be further assessed in future longitudinal studies. The study highlighted an association between positively perceived soundscapes and psychological well-being that could only be partially explained by the variables included in the present study but that reinforce the role of building, urban and acoustic design to promote healthy conditions for their occupants. Future investigations might help to explain the direction and the mechanisms linking comfort to psychological well-being (or vice versa). Lastly, the future analysis of the Italian dataset will help generalize the results presented in the present paper also considering possible cultural differences [53], thus informing about actions to be applied at a broad scale in the post-pandemic design of healthy buildings.

CRediT authorship contribution statement

Simone Torresin: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Writing - review & editing. **Rossano Albatici:** Conceptualization, Writing - review & editing. **Francesco Aletta:** Conceptualization, Methodology, Writing - review & editing. **Francesco Babich:** Conceptualization, Writing - review & editing. **Tin Oberman:** Conceptualization, Writing - review & editing. **Agnieszka Elzbieta Stawinoga:** Formal analysis, Writing - review & editing. **Jian Kang:** Conceptualization, Supervision, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jian Kang reports financial support was provided by Chartered Institution of Building Services Engineers.

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Appendix A – Variables

Summary of variables included in the path models. The table presents reference questions for the variables (cf. Part I of the study), a short description, variable treatment in *lavaan*, missing values treatment, and the model in which the variables are included (WFH stands for working from home, REL stands for relaxation).

Reference questions	Variable description	Type of variable	Missing values, “other”, “not applicable” responses	Model
Q1.1 – Q1.8	9 variables on the relevance of different activities to WFH	Continuous	“Not applicable” responses treated as “not at all”	WFH
Q2	Frequency of headphone use	Continuous	None	WFH
Q4.1 – Q4.9	9 variables on the perceived dominance of different sound sources	Continuous	“Not applicable” responses removed listwise. Only for Q4.5 – Q4.6: “Not applicable” responses treated as “not at all”	WFH
Q5.1 – Q5.3	3 variables on the perceived dominance of components in window view	Continuous	“Not applicable” responses removed listwise	WFH
Q8.1 – Q8.8	Comfort and content scores	Continuous	None	WFH
Q10.1 – Q10.9	9 variables on the perceived dominance of different sound sources	Continuous	“Not applicable” responses removed listwise. Only for Q10.5 – Q10.6: “Not applicable” responses treated as “not at all”	REL
Q11.1 – Q11.3	3 variables on the perceived dominance of components in window view	Continuous	“Not applicable” responses removed listwise	REL
Q14.1 – Q14.8	Comfort and content scores	Continuous	None	REL
Q15	House ownership	Dichotomous (0 = Rent – not owned, 1 = Owned)	“Other” responses removed listwise	WFH / REL
Q16	House size	Dichotomous (0 = $\leq$ 80 m^2; 1 = > 80 m^2)	None	WFH / REL
Q17	Housing type	Dummy coded: Semi-detached or terraced house; Apartment block [ref. Detached single family]	None	WFH / REL
Q3, Q18	Quietness of area outside the room where WFH	Dichotomous (0 = noisy; 1 = quiet)	Missing values removed listwise	WFH
Q9, Q18	Quietness of area outside the	Dichotomous (0 = noisy; 1 = quiet)	Missing values	REL

(*continued on next page*)

Appendix A – Variables (*continued*)

Reference questions	Variable description	Type of variable	Missing values, "other", "not applicable" responses	Model
	room where WFH		removed listwise	
Q19	Children presence at home	Dichotomous (0 = no children present; 1 = children present)	None	WFH / REL
Q20	Number of people present at home	Continuous	None	WFH / REL
Q21	Mechanical ventilation	Dichotomous (0 = no mechanical ventilation; 1 = mechanical ventilation)	None	WFH / REL
Q22	Air system for heating	Dichotomous (0 = no air system; 1 = air system for heating)	None	WFH / REL
Q23	Air system for cooling	Dichotomous (0 = no air system; 1 = air system for cooling)	None	WFH / REL
Q25	Type of urban area	Dichotomous (0 = suburban, rural; 1 = urban)	None	WFH / REL
Q26	Noise sensitivity	Continuous	None	WFH / REL
Q27	Well-being	Continuous	None	WFH / REL
Q28	Age	Continuous	None	WFH / REL
Q29	Gender	Dichotomous (0 = male; 1 = female)	"Other" responses removed listwise	WFH / REL

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