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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.

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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
saturation of the environment with sounds or events and is repre-
sented 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 eval-
uation according to the activity carried out at home. Environ-
ments were rated as more comfortable and more content-rich when con-
sidered for relaxation than for WFH. Moreover, acoustic environ-
ments 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. Sound-
scapes that are appropriate for relaxation were evaluated as com-
fortable 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 relax-
ation. 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 (Lon-
don) and Italy during the COVID-19 lockdown. The following ana-
lysis 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 method-
ological 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 descrip-
tions from open-ended questions are provided. Statistical analyses
were run in IBM SPSS Statistics 26 [9] and in R [10], while qualita-
tive analyses have been conducted in NVivo 12 software.

2.1. Quantitative analysis: Multivariate regression

Multivariate regression was employed as a special case of struc-
tural 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 “ef-
fect” 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 per-
formed with the lavaan package [12]. Models included the direct
effect of acoustic, housing, urban context and person-related vari-
able 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 environ-
ment, 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 Appen-
dix 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 com-
plexity, 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 pres-
ence 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 typol-
ogy 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 ana-
lyzed elsewhere, we included here only the information about air
systems as they might provide new source of noise inside build-
ings. 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. partici-
pants 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. Simi-
larly, “not applicable” answers to questions about sound domi-
nance 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 else-
where (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 rep-
resent 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 $\chi^2$/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 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 $\chi^2$/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.
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 outdoor human sounds 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 $\chi^2$/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 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

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.

4.1. 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
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
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 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.
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 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 been shown to correlate to reduced comfort. 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 m²) 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, soundscape 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, soundscape 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 conducive 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-
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

![Conceptual representation of acoustical, building and urban-related variables contributing to privacy, control and engagement dimensions in relation to (a) WFH and (b) relaxation.](image)
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 m²). 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 Q4.1 – Q4.9      | Frequency of headphone use 9 variables on the perceived dominance of different sound sources | Continuous       | None “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 Q10.1 – Q10.9 | Comfort and content scores 9 variables on the perceived dominance of different sound sources | Continuous       | None “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       | None “Not applicable” responses removed listwise | REL   |
| Q14.1 – Q14.8 Q15  | Comfort and content scores House ownership | Dichotomous (0 = Rent – not owned, 1 = Owned) | None “Other” responses removed listwise | REL   |
| Q16 Q17             | House size Housing type | Dichotomous (0 = ≤ 80 m²; 1 = > 80 m²) Dummy coded: Semi-detached or terraced house; Apartment block [ref. Detached single family] | None | 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 removed listwise | REL |

(continued on next page)
Appendix A – Variables (continued)

| Reference questions | Variable description | Type of variable | Missing values, “other”, “not applicable responses | Model |
|---------------------|----------------------|-----------------|-------------------------------------------------|-------|
| Q19                 | room where WFH       | Dichotomous (0 = no mechanical ventilation; 1 = mechanical ventilation) | None | WFH / REL |
| Q20                 | Number of people present at home | Continuous | None | WFH / REL |
| Q21                 | Mechanical ventilation | Dichotomous (0 = no air system; 1 = air system for heating) | None | WFH / REL |
| Q22                 | Air system for heating | Dichotomous (0 = no air system; 1 = air system for cooling) | None | WFH / REL |
| Q23                 | Air system for cooling | Dichotomous (0 = suburban, rural; 1 = urban) | None | WFH / REL |
| Q24                 | Noise sensitivity    | Continuous      | None | WFH / REL |
| Q25                 | Age                  | Continuous      | None | WFH / REL |
| Q26                 | Gender               | Dichotomous (0 = male; 1 = female) | None | WFH / REL |

References

[1] Torresin S, Albatici R, Aletta F, Babich F, Kang J. Assessment methods and factors determining positive indoor soundscapes in residential buildings: a systematic review. Sustain 2019;11:5290. https://doi.org/10.3390/s111105290.
[2] Torresin S, Albatici R, Aletta F, Babich F, Oberman T, Siboni S, et al. Indoor soundscapes assessment: a principal components model of acoustic perception in residential buildings. Build Environ 2020;182:107152. https://doi.org/10.1016/j.buildenv.2020.107152.
[3] Torresin S, Albatici R, Aletta F, Babich F, Oberman T, Stawinoga AE, et al. Exploring associations between the perception of the acoustic environment, occupants’ activity and well-being. Appl Acoust 2021;203. https://doi.org/10.1016/j.apacoust.2021.108305.
[4] Topp CW, Østergaard SD, Søndergaard S, Bech P. The WHO-5 well-being index: a systematic review of the literature. Psychother Psychosom 2015;84(3):167–76. https://doi.org/10.1159/000367585.
[5] Torresin S, Aletta F, Babich F, Bourdeau E. Acoustics for supportive and healthy buildings: emerging themes on indoor sustainability. Sustain 2020:6054. https://doi.org/10.3390/s12116054.
[6] Peer E, Brandimarte L, Samat S, Acquisti A. Beyond the Turk: Alternative platforms for crowd sourcing behavioral research. J Exp Soc Psychol 2017;70:153–63. https://doi.org/10.1016/j.jesp.2017.01.008.
[7] Palan S, Schitter C, Prolific.ac—A subject pool for online experiments. J Behav Exp Finance 2018;17:22–7. https://doi.org/10.1016/j.jbef.2017.12.004.
[8] Fiebig A. Soundscape standardization dare the impossible – Case studies valuing current soundscape standards. ICA, 23rd Int Congr Acoust 2019:8p.
[9] IBM Corp. IBM SPSS Statistics for Windows, Version 26.0 2019.
[10] Duncan OD. Path analysis: Sociological examples. Causal Model Soc Sci 1972:55–80. https://doi.org/10.4324/9781315081663.
[11] Rosseel Y. lavaan: An R Package for Structural Equation Modeling. J Stat Softw 2012:48:1–36.
[12] Aletta F, Oberman T, Kang J, et al. Associations between positive health-related factors determining positive indoor soundscapes in residential buildings: a systematic review. Sustain 2019;11:5290. https://doi.org/10.3390/s111105290.
[13] Aletta F, Oberman T, Mitchell A, Erfanian M, Lionello M, Kachlicka M, et al. Associations between positive health-related factors determining positive indoor soundscapes in residential buildings: a systematic review. Sustain 2019;11:5290. https://doi.org/10.3390/s111105290.
[14] Aletta F, Molinero L, Astolfi A, Di Blasio S, Shitrepi L, Oberman T, et al. Exploring associations between soundscape experience and self-reported wellbeing in open public urban spaces: a field study. Lancet 2019;394:517. https://doi.org/10.1016/S0140-6736(19)32814-4.
[15] Aletta F, Oberman T, Kang J. Associations between positive health-related effects and soundscapes perceptual constructs: a systematic review. Int J Environ Res Public Health 2018;15:2392. https://doi.org/10.3390/ijerph15112392.
[16] Erdan M, Mitchell AJ, Kang J, Aletta F. The psychophysiological implications of soundscapes: a systematic review of empirical literature and a research agenda. Int J Environ Res Public Health 2019;16(19):3533. https://doi.org/10.3390/ijerph16193533.
[17] Satorra A, Bentler PM. Corrections to test statistics and standard errors in covariance structure analysis. 1994.
[18] Kline RB. Principles and Practices of Structural Equation Modelling. Fourth. New York: Guilford Press; 2015.
[19] Schermelleh-Engel K, Moosbrugger H, Müller H. Evaluating the fit of structural equation models: Tests of significance and descriptive goodness-of-fit measures. MPR-Online 2003;8:23–74.
[20] Schumacker RE, Lomax RG. A Beginner’s Guide to Structural Equation Modeling. psychological press; 2004.
[21] Hallberg I-M. The “core category” of grounded theory: Making constant comparisons. Int J Qual Stud Health Well-Being 2006;1(3):141–8. https://doi.org/10.3390/ijerph16193533.
[22] Guastavino C. The ideal urban soundscape: Investigating the sound quality of French cities. Acta Acust United with Acust 2006;92:945–51.
[23] Topp CW, Østergaard SD, Søndergaard S, Bech P. The WHO-5 well-being index: a systematic review of the literature. Psychother Psychosom 2015;84(3):167–76. https://doi.org/10.1159/000367585.
[24] Torresin S, Albatici R, Aletta F, Babich F, Oberman T, Stawinoga AE, et al. Indoor soundscapes at home during the COVID-19 lockdown in London – Part I: associations between the perception of the acoustic environment, occupants’ activity and well-being. Appl Acoust 2021;203. https://doi.org/10.1016/j.apacoust.2021.108305.
[25] Fiebig A. Soundscape standardization dare the impossible – Case studies valuing current soundscape standards. ICA, 23rd Int Congr Acoust 2019:8p.
[26] Team RC, others. R: A language and environment for statistical computing. 2013.
[27] Duscan OD. Path analysis: Sociological examples. Causal Model Soc Sci 2017:72:55–80. https://doi.org/10.4324/9781315081663.
[28] Rosseel Y. lavaan: An R Package for Structural Equation Modeling. J Stat Softw 2012:48:1–36.
[29] Aletta F, Oberman T, Mitchell A, Erfanian M, Lionello M, Kachlicka M, et al. Associations between soundscape experience and self-reported wellbeing in open public urban spaces: a field study. Lancet 2019;394:517. https://doi.org/10.1016/S0140-6736(19)32814-4.
[30] Aletta F, Oberman T, Kang J. Associations between positive health-related effects and soundscapes perceptual constructs: a systematic review. Int J Environ Res Public Health 2018;15:2392. https://doi.org/10.3390/ijerph15112392.
[31] Aletta F, Oberman T, Mitchell A, Hong J, Kang J. Assessing the changing urban sound environment during the COVID-19 lockdown period using short-term acoustic measurements. Noise Mapp 2020;7:1–12. https://doi.org/10.1515/np-2020-0011.
[32] Satorra A, Bentler PM. Corrections to test statistics and standard errors in covariance structure analysis. 1994.
[33] Kline RB. Principles and Practices of Structural Equation Modelling. Fourth. New York: Guilford Press; 2015.
[34] Schermelleh-Engel K, Moosbrugger H, Müller H. Evaluating the fit of structural equation models: Tests of significance and descriptive goodness-of-fit measures. MPR-Online 2003;8:23–74.
[35] Schumacker RE, Lomax RG. A Beginner’s Guide to Structural Equation Modeling. psychological press; 2004.
[36] Hallberg I-M. The “core category” of grounded theory: Making constant comparisons. Int J Qual Stud Health Well-Being 2006;1(3):141–8. https://doi.org/10.3390/ijerph16193533.
