Investigating noise disturbance in open-plan offices using measurements of the room acoustics, and of the sound environment during occupancy

Manuj Yadav[1,2], Densil Cabrera[1], Jungsoo Kim[1], James Love[1], Jonathan Holmes[1], Janina Fels[2], Richard de Dear[1]

[1] Sydney School of Architecture, Design and Planning, The University of Sydney, Australia.
manuj.yadav@sydney.edu.au, densil.cabrera@sydney.edu.au, jungsoo.kim@sydney.edu.au, james.love@sydney.edu.au, jonothan.holmes@sydney.edu.au, richard.dedear@sydney.edu.au
[2] Institute for Hearing Technology and Acoustics, RWTH Aachen University, Germany.
mya@akustik.rwth-aachen.de, jfe@akustik.rwth-aachen.de

Abstract
Noise disturbance in open-plan offices (OPOs) has been a systemic issue throughout their history. This paper presents preliminary results from a study where an occupant survey (N = 366) was conducted in 30 office spaces within 9 buildings, along with measurements using the ISO 3382-3 method, and measurements of the sound environment during occupancy. Mixed-effects modeling shows that workplace satisfaction and noise disturbance vary as expected as a function of metrics based on occupied OPOs (e.g., psychoacoustic loudness), but present counterintuitive trends as a function of ISO 3382-3 metrics (e.g., distraction distance). However, these findings seem consistent when considered together within the context of room acoustics and within the multi-talker nature of OPOs, which underscores the need to consider measurements in both unoccupied and occupied states of OPOs in future studies.

Keywords: Open-plan offices, room acoustics, office acoustics, noise, psychoacoustics.

1 Introduction

Open-plan offices (OPOs) have been around for more than 50 years now, and so have the reports of noise disturbance by office occupants, which affects overall workplace satisfaction [1,2]. Changes in OPO design philosophies (e.g., landscaped, cubicle-based, activity-based, etc. offices) and modernisation of working conditions have resulted in changing office soundscapes, with generally quieter workstation equipment (e.g., computers rather than typewriters, card punching machines, etc.), quieter heating, ventilation, and air-conditioning (HVAC) systems, different telecommunication sounds, etc [1].

Unwanted noise due to speech-based communication, however, has remained a persistent feature throughout the OPO history and has consistently been listed as *the* major component of noise disturbance and annoyance in OPOs (e.g., [3–6]), within the scope of interaction with factors such as the type of work performed, workplace cultures, room and building acoustics, etc. Based on in-situ measurements and occupant surveys, several studies have attempted to characterise disturbance due to various noise components in OPOs using several objective metrics. $L_{A,eq,T}$ (A-weighted equivalent sound pressure level (SPL) over time T) has been the most common of these metrics in characterising noise disturbance and arguably the most consistent predictor across studies, although not always (e.g., [7]), starting from the earliest studies (e.g., [8]) to the more recent ones (e.g., [6]). Another popular approach has been to characterise the fluctuation/variability in the sound either as fluctuation strength, or as sound levels relative to the background noise level during working hours that is generally represented by L_{A90}, or a similar statistical measure. Examples of this concept include L_{A10} - L_{A90} (noise climate [9]) in some early studies, and $L_{A,eq}$ - L_{A90} (M_{eq} [10]) more recently. Other percentile levels (L_{A5}, L_{A10}, L_{A50}, L_{A90}, etc.) have also been considered with varying degree of success in characterising noise disturbance (cf. [11] and [7]). Some studies have explored variation in psychoacoustic parameters such as loudness as a function of the noisiness in offices (e.g., [11]). More simply, the effect of noise spectrum has also been investigated in the form of level of middle frequencies [11], balance between levels of lower and higher frequencies ([12]; a laboratory study), etc.

Besides the above parameters that focus on more global or room averaged sound metrics during occupied hours, more recent studies have focussed on the decay of sound level and speech intelligibility along workstations in unoccupied OPOs, as described in ISO 3382-3 [13]. These include objective metrics (called single number quantities in ISO 3382-3) based on spatial decay of speech SPL in unoccupied offices: the spatial decay rate of speech ($D_{2,S}$) and A-weighted SPL of speech at 4 m ($L_{p,A,S,4m}$), along with the background noise due to HVAC and machinery sounds ($L_{p,A,B}$). Spatial decay of speech transmission index (STI) in unoccupied offices is primarily addressed using the parameter distraction distance, r_D (in m). For a wide range of room acoustic conditions across 21 offices that were measured within several studies, Haapakangas et al. [14] reported r_D to be the most consistent predictor of noise-and speech-based disturbance out of the ISO 3382-3 metrics. The authors, however, commented on inconsistencies, and some sources of uncertainty, in measurements across the various constituent studies [14]. This was further highlighted in Cabrera et al. where it was shown that the r_D values [15] can vary by 2.3 m or more due to the different STI measurement methods used across the studies comprising the data in Haapakangas et al.[14]. Park et al. [6] reported a linear relationship between $L_{A,eq,8h}$ and noise disturbance, which is consistent with several previous studies including some of the earliest studies about noise in offices (e.g., [8]), but no relationship with r_D. The latter finding is inconsistent with Haapakangas et al. [14], presumably since the room acoustic sample in Park et al. was smaller (7 OPOs; 12 in total but 6 OPO with the same room acoustics), although other workplace factors cannot be ruled out. This finding is relevant for ISO 22955 [16], which is a more recent standard, has a broader scope than ISO 3382-3 while using a subset of its metrics ($D_{2,S}$ and $L_{p,A,S,4m}$), and additionally considers workstation noise level during occupation characterised as $L_{A,eq,T}$, room reverberation time (T in s), and some other level and sound insulation metrics.

Overall, studies of noise disturbance in OPOs are characterised by variability in the methods and results across previous studies, small sample sizes, diversity in workplace factors, etc. While a case can be made for $L_{A,eq,T}$, r_D, etc. based on individual studies and standards, more work is needed to establish robust level-based or psychoacoustic parameter(s) to characterise noise disturbance in occupied OPOs that are consistent across studies, countries, and workplace parameters. This undoubtedly represents a mammoth and potentially long-term undertaking. This paper is an attempt towards such an investigation, wherein a relatively large sample of OPOs representing a wide range of room acoustic conditions (larger than [6] and similar to [14]) was measured using the ISO 3382-3 method [15,17], along with extensive in-situ measurements [1] that meets most of the ISO 22955 [16] criteria, and an occupant survey. The occupant survey, adapted from the one described in [5] and which was subsequently integrated within ISO 22955 [16], has questions relating to various indoor environmental quality (IEQ) aspects and job satisfaction, along with a range of questions dealing specifically with assessment of the noise environment, occupants' sensitivity to noise, and their general health. In this paper, the aim is primarily to investigate the relationship of certain survey items about noise disturbance and workplace satisfaction with various acoustic and psychoacoustic parameters.

2 Methods

2.1 General information about the OPOs

The OPOs sampled in this study were located within 9 buildings in metropolitan areas of Australia, and all the measurements were conducted within a two-year period (2017-2018). All the measurements, survey and communication with building managers were approved by The University of Sydney Human Research Ethics Committee (Project: 2017/285). The number of offices where the measurements took place, and the rest of the details are presented in sections 2.2 – 2.4.

Two out of the nine buildings had non-academic university offices, while the rest were commercial offices. Key workplace factors in these offices are summarised in Table 1. These offices were broadly divided into five categories based on the primary work activities (Table 1). However, all the offices were mixed function to an extent, e.g., engineering offices had some management staff, and vice-versa. It was not possible to determine the exact roles per staff member to ensure anonymity (see section 2.3). Several offices were measured per building, which are either separate units over different floors or non-contiguous units on the same floor but with sufficiently different workplace and/or room acoustic environments. All offices had centralised HVAC systems, and none had sound masking systems. The surface area in Table 1 represents the portion of the entire floor plate consisting of OPOs only and not the areas for building services (elevator lobbies, plant rooms), kitchens, enclosed rooms for meetings, personnel, etc., which may partly account for smaller office areas in Table 1 compared to some previous studies, e.g., [3,6]. Most offices had flat ceilings with some sound absorption treatment, although some offices had complicated ceiling designs. Most office were carpeted with carpet tiles, and most office did not have any partition between workstations other than a computer screen in most cases. The offices with partitions included 1, 2, or 3-sided (i.e., cubicle) partitions that ranged in height from 1.1 – 1.6 m. Two buildings include offices with no pre-allocated seating, although certain teams usually occupied a certain portion of the offices. Such offices are labelled activity-based workplaces (ABW) or related terms, where employees can choose a workspace to suit their activity. Both the ABW buildings had several areas that allowed working away from workstations (e.g., meeting rooms, collaboration areas), although holding conversations at and between workstations within the open-plan areas was still quite common.

Table 1: Summary statistics of 30 offices in 9 buildings where both in-situ and ISO 3382-3 measurements were conducted

Parameter	**Summary**
Number of workstations	Mean (Standard deviation (SD)), Range: 43 (19), 16 – 78
Workstation Density (per 100 m^2)	Mean (SD) Range: 12.1 (5.6), 4 – 24
Ceiling height (m)	Mean (SD) Range: 3.1 (0.9), 2.7 – 7.6
Surface area (m^2)	Mean (SD) Range: 249 (192), 69 – 719
Ceiling type	Absorptive = 22 (73.3%), Hard = 8 (26.7%)
Carpet	Yes = 23 (76.7%), No = 7 (23.3%)
Activity-based workplace	Yes = 14 (53.3%), No = 16 (46.7%)
Partition	Yes = 10 (33.3%), No = 20 (66.7%)
Work activities	Architecture, Design = 4 (13.3%), Policy = 7 (23.3%), Engineering = 4 (13.3%), Management = 14 (46.7%), Customer Service = 1 (3.3%)

2.2 Sound measurements during occupied hours

In-situ measurements of the sound environment during occupied hours were conducted in 43 OPOs (more details in [1]), out of which 30 were selected in the current study (Table 1). The measurements included omnidirectional and binaural transducers placed at a seated listener's height of 1.2 m at several workstations per office for at least 4 hours (some offices were measured for up to a week), to approximate the representative listening conditions for the occupants.

2.3 Room acoustic measurements

Room acoustic measurements in unoccupied offices with normal HVAC operation were conducted in 36 offices according to the ISO 3382-3 method [13], out of which 30 offices were included in the current study, in which the in-situ measurements were also conducted. More detailed description of the 36 offices with room acoustic measurements is provided in [17], and the description of all 43 offices is provided in [1].

2.4 Occupant survey and participants

An online survey, which was hosted on a secure server by the University of Sydney, was conducted in 43 offices, out of which responses from 30 offices were selected (see sections 2.2 – 2.3). The participants were asked to base their responses on long-term opinions about the workplace, and for participants in activity-based workplaces (ABW) to base their responses about the open-plan areas only that they most frequented. The latter was considered reasonable in the two ABW in the sample, after discussions with the building managers and by the researchers experience during site visits. The survey was divided into five main sections:

(1) General information about the participant (e.g., age, gender, roles, etc.) and their workstation (e.g., whether fixed desk or not, etc.).
(2) Questions on the level of agreement about satisfaction with various indoor environmental quality factors (IEQ) and overall job satisfaction, which were answered on a continuous semantic differential scale (SDS) each with "Not at all" and "Totally" at the extremes of the scale.
(3) Questions about various aspects of the noise at the workstation. There were three types of questions: level of agreement with disturbance due to various noise components (e.g., overall, speech, machinery, etc.) that were answered on an SDS each with "Not at all" and "Totally" at the scale extremes; selecting one or more options to answer a question (e.g., approaches to concentrate when bothered by noise); and open-ended answers to questions (e.g., effect of a certain type of noise).
(4) Statements about the relationship of the participant with noise in general at home, at night, and at work. The participant indicated the level of agreement with each statement on an SDS with "Completely disagree" and "Completely agree" at the extremes of the scale.
(5) Statements about general health, where the participant answered on an SDS with either "Very poor" and "Very good" (e.g., Overall, my health is …), or "Never" and "Constantly" (e.g., I have back or neck pains) at the extremes of the scale.

Each questionnaire item based on the SDS had an underlying continuous scale of 0-100, which was not visible to the participant; response was made by moving a horizontal slider to the desired location between the extremes. The survey was adapted from the one presented in [5] and [16].

The researchers did not have any direct contact with the occupants. Instead, they liaised with the respective office managers, who then distributed the survey link and handled further communication with the office occupants. Participation was voluntary and personal information was anonymised from the researchers and the managers. Participants were allowed to access the survey and change their responses for approximately two weeks.

425 participants completed the survey; however, a reduced data set from **366** participants (*Age*: Mean (SD) = 38.4 (10.5), Range = 21 – 80; *Females* = 55.6%; *Fixed desk* = 53.8%) was used for further analyses. This data set included offices where both in-situ and room acoustic measurements were conducted.

2.5 Data processing and analysis

2.5.1 Objective metrics

Block *A* in Table 2 presents key metrics derived from in-situ measurements (section 2.2; details in [1]) and Block *B* presents room acoustics metrics derived from measurements in unoccupied rooms (section 2.3; details in [17]). Briefly, L refers to various types of statistical SPL parameters that were calculated using 4 hour recordings; $NCl = L_{A10} - L_{A90}$; $M_{A,eq} = L_{A,eq} - L_{A90}$; *ONI* is defined in [3]; *Lo – Hi* is the difference between A-weighted averages of *Lo*w (16-63 Hz) and *Hi*gh (1000-4000 Hz) one-third octave bands levels[12]; N refers to short-term psychoacoustic loudness; S refers to psychoacoustic sharpness; R refers to psychoacoustic roughness; T_{30} refers to reverberation time; r_D to $L_{p,A,B}$ are the ISO 3382-3 [13] metrics that were introduced in section 1; and r_C refers to comfort distance, which combines $L_{p,A,S,4\,m}$ and $D_{2,s}$, and refers to the distance from an omnidirectional loudspeaker where the A-weighted SPL of speech falls under 45 dB [18]. r_C is likely to be included in the revised version of ISO 3382-3:2012 [18].

Table 2: Summary statistics of some metrics from measurements in (*A*) occupied and (*B*) unoccupied OPOs.

Metric (*A*)	Unit	Mean, SD, Range	Metric (*B*)	Unit	Mean, SD, Range
$L_{A,eq,\,4h}$	decibel (dB)	53.88 (2.86), 48.28 – 58.48	T_{30}	seconds	0.57 (0.25), 0.30 – 1.20
$L_{A10,\,4h}$	decibel (dB)	57.39 (3.07), 51.58 – 62.46	r_D	meter	10.43 (2.542), 4.43 – 17.00
$L_{A50,\,4h}$	decibel (dB)	47.51 (3.39), 42.38 – 53.29	$D_{2,s}$	decibel (dB)	5.09 (1.03), 2.68 – 7.40
$L_{A90,\,4h}$	decibel (dB)	32.58 (3.45), 27.62 – 38.67	$L_{p,A,S,\,4\,m}$	decibel (dB)	52.05 (2.34), 46.10 – 54.90
NCl	decibel (dB)	24.80 (1.52), 22.61 – 30.20	$L_{p,A,B}$	decibel (dB)	42.49 (4.17), 35.56 – 51.00
$M_{A,eq}$	decibel (dB)	21.29 (1.84), 18.38 – 27.61	r_C	meter	12.13 (5.05), 4.62 – 30.15
ONI	decibel (dB)	92.12 (3.72), 85.14 – 101.97			
Lo - Hi	decibel (dB)	-18.95 (3.75), -26.10, -11.17			
N_{mean}	sone	6.22 (1.15), 4.59 – 8.80			
N_5	sone	9.48 (1.83), 6.44 – 14.63			
N_{90}	sone	4.59 (0.90), 3.17 – 6.27			
S_{mean}	acum	1.17 (0.10), 1.03 – 1.36			
FS	vacil	0.34 (0.12), 0.07 – 0.57			
R_{mean}	asper	0.08 (0.03), 0.05 – 0.16			
R_{max}	asper	0.02 (0.00), 0.01 – 0.02			
R_{90}	asper	4.08 (1.60), 1.24 – 7.13			

2.5.2 Survey responses for noise disturbance

This paper considers a subset of survey responses that were rated on an underlying scale of 0-100 (section 2.4). However, each item was recoded based on a median split, with responses > 50 coded as 1 and ≤ 50 as 0 and using these binary scales as the response variables. This method is based on Haapakangas et al., who used median splitting to recode their 5-point scale (valued 1 – 5), with response ≤ 3 as 0 and responses > 3 coded as 1 [14]. The latter group was labelled as 'highly disturbed' or HD, and %HD per office due to total noise or speech was used for reporting some results in [14]. The HD label is adopted here just for convenience; the use of other labels/adjectives such as 'disturbed', 'bothered' or 'annoyed' is possible too. Park et al. [6] also recoded their 7-point scale following [14], but chose a 75% cut-off point of 5, i.e., recoding 6 and 7 responses as 1 (i.e., HD), instead. This study focuses on the following survey responses:

(i) Satisfaction with the *overall noise environment* (Sat_{ne}), the *possibility to concentrate* (Sat_{conc}), *speech privacy* (Sat_{priv}), and *overall comfort* (Sat_{comf}) in the workplace. After recoding, 0 represents dissatisfied and 1 represents satisfied occupants. Sat_{priv} was split based on its own median value, i.e., 29, since it was considerably lower than 50.

(ii) Noise disturbance due to *overall noise environment* (HD_{noise}) and *intelligible speech* (HD_{speech}). After the recoding, 0 represents undisturbed and 1 represents disturbed occupants (or highly disturbed as per [14]). The overall *noise level* (NL) at the workstation is also considered.

Median splitting is generally termed dichotomization of a scale. The methodological legitimacy of dichotomization has been hotly debated, with a long list of publications either supporting or deriding it (e.g., [19]). The latter group generally advocate using the underlying values of a continuous scale, like the one used in the current survey, as the dependent/response variable in statistical models, which arguably allows for a simpler interpretation of results without resorting to arbitrary splitting. The latter method was also used for the current data, just for comparisons with the median-split data and is not presented in detail.

2.5.3 Statistical modelling

Logistic regression models were fitted with the recoded survey items as dependent variables, which are presented in section 2.5.2, in separate models. The independent variables in each model were the metrics presented in Table 2, with one metric per dependent variable and per model. Since there are interdependencies in the data due to the participants being clustered within offices and buildings, these random-effects were modelled by allowing independently varying intercepts in mixed-effects models where necessary, i.e., when the log-likelihood of models without (i.e., generalised linear models) and with the random effects (i.e., generalised linear mixed-effects models) was significant ($p < .05$). To reduce the effect of outlying values, robust regression methods were used where necessary. The effects of gender and age were not significant across the models. The effect of other personal and workplace factors is planned for future studies. For brevity, detailed modelling steps are not presented, and only the significant models are described in the following. The analysis was performed within the software R using packages *tidyverse* [20], *robustbase* [21], and *lme4* [22].

3 Results

3.1 General findings

Table 3: Pearson correlation coefficient (r) matrix of some IEQ and noise disturbance item responses (scaled 0 – 100; see section 2.4). Large effect sizes ($r > 0.5$) highlighted in bold.

	Conc.	SP	OC	NL	ND_{total}	ND_{speech}
Noise environment	**0.78**	0.48	**0.63**	**-0.62**	**-0.74**	**-0.57**
Concentration (Conc.)	–	0.48	**0.64**	**-0.57**	**-0.72**	**-0.55**
Speech privacy (SP)	0.48	–	0.46	-0.43	-0.42	-0.47
Overall comfort (OC)	**0.64**	0.46	–	-0.47	**-0.55**	-0.44
Level of noise (NL)	**-0.58**	-0.43	-0.47	–	**0.73**	**0.51**
Noise disturbance (ND_{total})	**-0.68**	-0.42	**-0.54**	**0.73**	–	**0.66**
Speech disturbance (ND_{speech})	**-0.54**	-0.47	-0.44	**0.51**	**0.66**	–

Based on a median split, 71.8% of the participants reported the level of noise at their workstation as high, which is a higher proportion than that in a previous study (56% in [5]); 66.3% of the participants were sensitive to noise in general (average of noise sensitivity responses; section 2.4). While advanced analyses that consider intercorrelations between survey items will be presented in future publications, Table 3 allows a simple overview of the relationships between satisfaction with selected IEQ items and noise disturbance items. The IEQ items including satisfaction with the overall workplace comfort, overall noise environment, and possibility to concentrate are highly and positively correlated, and are negatively correlated with the overall noise disturbance (large effect size) and speech disturbance (medium effect size). The latter two are, as expected, also highly correlated, with a lower effect size than [14], where it was $r = 0.77$. Satisfaction with speech privacy showed medium sized effect sizes throughout.

When asked about their approach(es) to concentrate when bothered by workplace noise (multiple responses were allowed), 55.1% of the participants reported 'listening to music on headphones', 40.5% reported 'taking a break to refresh', 34.1% reported 'relocating somewhere else to work' (47% in ABW), 6.8% reported using other strategies such as 'working from home', 'attempt to ignore/block-out the noise', 'asking colleagues to stop talking', etc.

For speech distraction, 53.5% participants reported being distracted *more* by multi-talker speech, 28.2% by single-talker speech, and 18.3% by both single-and multi-talker speech equally. This is rather strong subjective evidence for the multi-talker nature of speech distraction, where undesired 'glimpsing' into intelligible, and perhaps irrelevant, content from more than one talker may lead to more distraction and concentration decline, than listening to a solitary talker (posited, e.g., in [23]). Further, this finding highlights the limitations of traditional room acoustic treatment, which, even in exorbitant amounts, would be ineffective against speech from nearby workstations (also mentioned in [14]).

3.2 Statistical models

Table 4 presents the statistically significant models for selected survey items (section 2.5.2) as a function of objective acoustic and psychoacoustic metrics. Statistical significance is determined by the 95% confidence interval (CI) of the predictors' odds ratio (OR) not crossing 1. OR for all predictors can be interpreted based on 1 unit increment, except for S_{mean}, which is based on a 0.1 acum increment.

Table 4: Relationship between key survey items and objective metrics.

Dependent variable	Predictor	Odds ratio [95% CI]
Satisfaction with the possibility to concentrate (Sat_{conc})	$L_{p,A,S,\,4\,m}$	1.16 [1.02,1.32]
	$L_{A90,\,4h}$	0.92 [0.86,0.99]
Satisfaction with speech privacy, (Sat_{priv})	$L_{p,A,S,\,4\,m}$	1.20 [1.05,1.37]
	r_C	1.09 [1.03,1.15]
	R_{max}	0.84 [0.72,0.98]
	N_{90}	1.37 [1.04,1.82]
Satisfaction with the overall comfort in the workplace, (Sat_{comf})	$L_{p,A,S,\,4\,m}$	1.19 [1.06,1.35]
	$L_{A,eq}$, L_{A10}, L_{A90}	0.90 [0.83,0.98]
	Lo - Hi	1.11 [1.04,1.2]
	N_{mean}	0.79 [0.64,0.98]
	N_5	0.80 [0.69,0.93]
	ONI	0.92 [0.86,0.99]
Noise level at the workstation, (NL)	N_{mean}	1.30 [1.01,1.67]
	N_5	1.22 [1.03,1.45]
Noise disturbance, (HD_{noise})	R_{max}	1.22 [1.04,1.42]
Speech disturbance, (HD_{speech})	$L_{p,A,B}$	1.07 [1.01,1.14]
	r_D	0.87 [0.77,0.99]
	S_{mean}	0.75 [0.63,0.95]

3.2.1 Models of workplace satisfaction

In Table 4, for the first three dependent variables, OR > 1 indicates increasing odds of satisfaction with an increase in the predictor's value, and OR < 0 indicates decreasing odds of satisfaction. Hence, the odds of satisfaction with the possibility to concentrate is predicted to increase by 16% with 1 dB increase in $L_{p,A,S,\,4\,m}$ value and predicted to decrease by 8% with 1 dB increase in the occupied OPO background noise (L_{A90}). The odds of satisfaction with speech privacy and overall comfort in the workplace can be similarly interpreted. None of the predictors were statistically significant in predicting the satisfaction with the overall noise environment at the workplace, although it showed similar trends as the other satisfaction variables.

3.2.2 Models of noise disturbance

The odds of increasing noise level at the workstation being reported increased by 30% and 22% with 1 sone of increase in the mean psychoacoustic loudness (N_{mean}) and the 5th percentile loudness (N_5), respectively. The odds of increasing disturbance by speech noise is predicted to increase by 7% with 1 dB increase in the unoccupied OPO background noise ($L_{p,A,B}$), predicted to decrease by 13% with 1 m increase in distraction distance values (r_D), and predicted to decrease by 15% with 0.1 acum decrease in the values of psychoacoustic sharpness. The odds of increasing disturbance by total noise is predicted to increase by 22% with 1 asper change in the maximum value of psychoacoustic roughness.

4 Discussion

In explaining workplace satisfaction and noise disturbance ratings, the metrics based on measurements in unoccupied and occupied OPOs show consistent and opposite trends in the models presented in section 3.2. Improving room acoustic conditions over OPOs as quantified by ISO 3382-3 metrics is associated with decreasing satisfaction with the three IEQ performance parameters considered (possibility to concentrate, speech privacy and overall comfort within the workplace), and increasing dissatisfaction with the total noise and speech noise. These findings seem counterintuitive where better room acoustic conditions are being perceived as detrimental, and also go against the findings of Haapakangas et al. [14], where the reported odds ratios for the noise disturbance items had opposite signs to what is reported here. For instance, in their study, increasing r_D values were associated with decreasing odds of noise and speech disturbance [14], while Park et al. reported no such relationship [6], albeit based on a much smaller range of room acoustics conditions than [14] and the current sample.

For the metrics based on measurements in occupied OPOs, however, the trends reported are more in line with expectations. Since the survey responses are based on perception of both room acoustics and the OPO sound environment, the latter needs to be considered in some detail to contextualise the trends with the room acoustics metrics. Increasing psychoacoustic loudness values, for instance, are associated with increasing noise level reported at workstations, and increasing maximum roughness (perception of amplitude modulations between 15 – 300 Hz), which may be referring to increasing sound fluctuations in the sound environment, is associated with increasing noise disturbance. Similarly, reducing SPLs and loudness values are associated with increasing satisfaction with the overall comfort, and the possibility to concentrate. For speech privacy, which refers here to the satisfaction with the possibility to have private conversations, the required conditions may be represented by higher level of ambient noise (up to a reasonable limit) that has lower fluctuation characteristics, to provide conditions with both adequate speech masking for one's own speech, and low distraction due to surrounding speech and other fluctuating sounds. This may partly explain the speech privacy responses, associated here with reducing roughness and increasing background loudness.

Roughness has previously been used in studies to predict annoyance due to HVAC, etc. sounds (e.g., [24]), but has not been directly used in the OPO context before. In general, however, amplitude modulations have been postulated to be useful in characterising noise disturbance, in the form of level-based metrics (summarised in [1]) in several studies and fluctuation strength (quantifying slower amplitude modulations up to 20 Hz) in laboratory studies [25]. Hence, the current findings further support the sound fluctuation-based investigations of the OPO noise environment. Sharpness has also been associated with sensory unpleasantness due to greater proportion of high-frequency energy in sounds. A decrease in sharpness in simple terms indicates decreasing high-frequency noise, which can be hypothesised as a likely decrease in frequencies that are important for speech intelligibility, especially around the 2 kHz octave band. Indeed, OPO sound environments have been shown to have higher proportion of high-frequency sounds, indicating the presence of speech among other sounds, with steeper one-third octave band slopes compared to typical HVAC noise alone (-4 dB/octave and -5 dB/octave slopes, respectively) [1]. Hence, speech masking effects are likely to increase and speech distraction likely to decrease with a decrease in frequencies important for speech intelligibility, quantified here as decreasing mean sharpness.

Improvements in the room acoustic conditions as quantified in ISO 3382-3 has been hypothesised (supported by findings in [14]) to improve subjective perceptions. The corresponding physical effect involves increased sound absorption, mainly for higher frequencies with the typical acoustic treatments used in OPOs, which cannot be very effective in reducing detrimental sound from nearby workstations. The current results based on occupied measurements seem to indicate that there might be reduced sound/speech masking due to such global sound absorption, which may in fact increase noise and multi-talker speech distraction, especially due to nearby workstations. In other words, while noisy offices with limited sound absorption are problematic, they may be providing beneficial masking sound, which diminishes by increasing absorptive treatments, and leads to increasing workplace dissatisfaction and disturbance due to noise. This is suggested as a likely explanation of the current results. However, other psychophysical and multisensory effects are not ruled out, as several factors, including indoor environmental quality and personal factors, etc., are not considered here, and are proposed for future studies. Overall, the current results can be explained, and further point towards a more complex assessment, of the noise environment and satisfaction within OPOs.

5 Conclusions

While room acoustic metrics such as distraction distance (r_D) and the ones characterising SPL decay in unoccupied conditions present a practical approach in designing offices, the present results show that 'good' physical acoustics conditions based primarily on room acoustic criteria (as in ISO 3382-3, ISO 22955, etc.) may not necessarily lead to better experience for the occupants. Changes in loudness and fluctuations in the multi-source and multi-speech sound environment during occupancy allow a more intuitive characterisation of occupants' perception but are harder to control in the design process. The current findings show that occupants may prefer quieter offices overall while rating the performance of workplace satisfaction and noise disturbance criteria, but this may not be achieved through simply better room acoustic characterisation based on standards. Instead, the complexity of occupants' perception in OPOs may need a comprehensive assessment of both room acoustics and psychoacoustics metrics derived from in-situ measurements.

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