Investigating dependencies between indoor environmental parameters: thermal, air quality and acoustic perception

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Abstract: In buildings, occupants' interactions with systems and their behaviour is often influenced by environmental discomfort; thermal, visual, acoustic or air quality. Many studies have investigated the relationships between occupant behaviour and one of these discomforts, but very few studies have addressed multi-stressor effects. This paper reviews the results of a field study in two office buildings (N=1,420). Questions were applied to estimate the state of seven environmental controls and three environmental parameters; thermal perception, air quality and background noise level. As the data is ordinal, linear-by-linear association tests followed by Goodman Kruskal Gamma tests were undertaken to ascertain the significance and the strength of relationships between the three environmental parameters. Most results showed no relationship between the parameters; only a modest association between air quality and background noise level. Further analysis explored the relationships between the three parameters when environmental controls were at play, e.g. state of window opening or air-conditioning. In such cases, moderate to strong relationships were uncovered, notably between thermal perception and air quality. These new insights may inform the basis for drawing causal relationships between occupant behaviour and environmental parameters in a view to re-thinking and managing behaviours in affordable comfort for all.

Keywords: thermal comfort, air quality, acoustics, mixed-mode, office buildings

1. Introduction

In buildings, occupants often have to balance between environmental comforts. For example, switching on ventilation systems or opening a window to control air temperature may alleviate thermal discomfort, but at the same time this behaviour may increase the noise level, causing acoustic discomfort (Pellerin & Candas, 2003). Building standards and guidance typically consider each environmental parameter in silo (BS EN 16798), but in practice the occupants respond to many environmental parameters simultaneously, including thermal, acoustics and air quality. Few studies have explored this multi-parameter dependencies (Andargie & Azar, 2019; Fanger et al., 1977; Freihoefer et al., 2015; Geng et al., 2017; Pellerin & Candas, 2004; Ricciardi & Buratti, 2018; Yang & Moon, 2019). These studies have used measured and/or model variables as indicators of perception and assess those in controlled environments. Thermal perception relates to perceived warmth or coolness; measured variables include operative temperature (t_o) (^oC), activity levels (M) (met) and clothing (I_{cl}) (clo) levels (CIBSE, 2015, Table 1.5.). Acoustic perception relates to sounds or vibrations, preventing speech or music intelligibility and privacy. Measured variables used are sound frequency (Hz) and sound pressure level (N/m^2) or sound level (dB) (CIBSE, 2006). Perceived air quality relates to smell, sensitivity to irritants (pollen, smoke, other pollutants) and "fresh" air. There are no accepted measured variables for air quality, only a requirement to achieve a "healthy" air quality that is stipulated as a minimum level of air change rate is required for a given activity; e.g. 10 l/s/person in offices (CIBSE, 2015, Table 1.5.). The few studies, that have explored the multi-parameter aspect of perception, have focused on the relationships between measured variables and reported levels of perception or comforts.

On the relationship between thermal and acoustic perception, Yang & Moon (2019) have exposed participants (N=60) in a controlled environment to thirteen environmental settings; including combinations of five sound types, five sound levels and three temperature levels. For combinations of these environmental settings, surveys were undertaken to capture participants' thermal perception and noise perception. Then, relationships were drawn between physical environmental factors (i.e. sound type, sound level, temperature) and reported comfort (i.e. thermal perception and noise perception). Results showed that acoustic comfort increases at thermoneutrality and thermal comfort increases with a decrease in sound levels. Furthermore, in relation to indoor comfort the effect of acoustic factors was the greatest, followed by air temperature. Associations have been drawn between physical environmental parameters and the reported comfort levels, but not between the reported comfort levels themselves.

On the relationship between thermal and air quality perception, Zhang et al. (2011) have reviewed field studies' surveys from the ASHRAE database and undertook two controlled environment studies (N=36). Results showed that perceived air quality is associated with thermal comfort rather than temperature. Similar results were found in the study by Humphreys et al. (2002) reviewing field studies' surveys from the SCAT database. Besides, it was reported that when respondents were thermally uncomfortable then they rated air-quality more severely.

On the relationship between acoustic and air quality perception, Lee and Aletta (2019) found a significant and strong association between acoustic performance and olfactory comfort. It is suggested that olfactory comfort measure may be an indirect method for increasing acoustic performance in workspace.

Most studies have used measured variables to report on building indoor environmental quality (Jain, 2019); only very few studies have explored the relationships between perceived indoor environmental parameters. Geng et al. (2017) have exposed participants (N=21) in a controlled environment to seven thermal conditions (air temperature varying from 16°C to 28°C) and studied their perceived thermal comfort and satisfaction with indoor air quality, lighting, acoustic and the overall environment. Their analysis introduced the notion of "comparative" impact caused by occupants' different comfort expectations. As the environment was perceived as too cold or too hot, thermal dissatisfaction was high, which lowered expectations on other environmental factors and therefore showed an increased satisfaction with air quality, lighting and acoustics. Besides, when thermal satisfaction was high, the expectations on other environmental factors increased, which resulted in a decrease in air quality, lighting and acoustic satisfaction.

To address the research gaps highlighted above, this paper reviews field studies' surveys of reported perceived indoor environmental parameters. The paper first explores relationships between thermal, air quality and acoustic perceptions. The prior hypothesis that interactions amongst these three parameters might be weak, as all are directly related to ventilation, heating and cooling strategies; e.g. opening a window will affect thermal, acoustic and air quality perception. The second part of the analysis explores relationships between thermal, air quality and acoustic perceptions while different indoor environmental controls were at play.

2. Study design

The study was undertaken in two office buildings (B1 and B2) in Southampton, UK, over a period of twelve months (from July 2017 to June 2018). 15% of the survey responses were completed during summer, 27% in autumn, 23% in winter and 34% in spring. According to Köppen-Geiger classification, the climate in Southampton is defined as oceanic, marine west coast (Cfb). Daily mean external temperatures in the Test Reference Year (TRY) weather file span across the range of -1.4°C to 22°C, with a mean of 10.5°C and standard deviation of 5.1°C (CIBSE, 2016). Both buildings are mixed-mode, providing heating in winter and peak cooling only when required in summer. Building B1 has an East/West orientation. Its East facade is runs along a service road; the road traffic noise levels, $L_{Aeq,16h}$ [1], is estimated below 55 dB at receptor's height of 4m above ground (Extrium, 2017). Building B2 has a North/South orientation. Its South facade is aligned with an A road; the road traffic noise levels, $L_{Aeq,16h}$ [1], is estimated between 60 and 65 dB at receptor height of 4m above ground (Extrium, 2017). Neither of the two buildings are in a Local Air Quality Management (LAQ) area. The study participants' characteristics are summarised in Table 1.

Table 1. Characteristics of the participants and individual control opportunities

Bdg.	No. of participants	No. of participants with perceived individual control						No. of participants per office type			Age (no.)			Sex (no.)	
		Door	Window	Blind	Heating	Cooling	Fan*	Single office	Small shared office **	Large shared office	<30	30 to 39	>39	F	M
B1	41	5	13	13	-	-	-	3	5	30	14	6	17	29	8
B2	28	10	16	16	6	8	-	16	10	2	12	7	6	11	14
ALL	69	15	29	29	6	8	-	19	15	32	26	13	23	40	24

* Ceiling, pedestal and/or desk fan ** Small shared office; i.e. 2 to 4-person office

The study applied a mixed method approach. Concurrently to environmental monitoring, three questionnaires were completed; an initial background survey, a weekly survey and a feedback survey. The weekly survey included three perceptual scales; thermal perception (ASHRAE 7-point scale), noise perception (7-point scale) and air quality perception (7-point scale) (see Table 2). These three scales originate from the SCAT survey (McCartney & Nicol, 2002). The number of completed weekly surveys was N=1,420; which is an average of 20 weekly surveys per participants (N=69). The weekly survey also recorded which environmental settings were used while completing the survey. The seven environmental settings are as follows: internal office door open, window open, blinds/curtains shut down, lights on, space air conditioning (AC) on, local heater on, local fan on.

[1] $L_{Aeq,16h}$ is defined as the annual average noise level (in dB) for the 16-hour period between 07:00-23:00.

Table 2. Questions from the weekly questionnaires

Thermal perception ***'How do you feel right now?' (TSV)***						
Cold *[coded: -3]*	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot *[coded: +3]*
Noise perception ***'How do you find the background noise level?'(NSV)***						
Very noisy *[coded: -3]*	Noisy	Slightly noisy	Neither noisy nor quiet	Slightly quiet	Quiet	Very quiet *[coded: +3]*
Air quality perception ***'How do you find the air quality?'(ASV)***						
Very bad *[coded: -3]*	Bad	Slightly bad	Neither bad nor good	Slightly good	Good	Excellent *[coded: +3]*

This study reviews the relationship between these three perceptual scales and associated three variables; thermal perception (TSV), acoustic perception (NSV) and air quality perception (ASV). As these three variables are ordinal, linear-by-linear association tests followed by Goodman Kruskal Gamma tests were undertaken to ascertain the significance and the strength of relationships between the three variables.

3. Results

3.1 Descriptive analysis

As shown in Figure 1, most surveys reported neutrality; TSV was reported 'neutral' in 39% of all surveys, NSV 'Neither noisy nor quiet' in 34% of all surveys, and ASV 'Neither bad nor good' in 48% of all surveys. For TSV, cold perception accounted for 28% of all surveys, while warm perception accounted for 32% of all surveys. The odds of a participant feeling warm were 1.16 times higher than a participant feeling cold; although only 15% of the surveys were completed in summer. For NSV, noisy perception accounted for 46% of all surveys, while quiet perception accounted for 23% of all surveys. The odds of a participant perceiving the environment being noisy were 2 times higher than perceiving the environment being quiet. For ASV, bad air quality perception accounted for 36% of all surveys, while good air quality perception accounted for 16% of all surveys. The odds of a participant perceiving the air quality being bag were 2.2 times higher than perceiving the air quality being good.

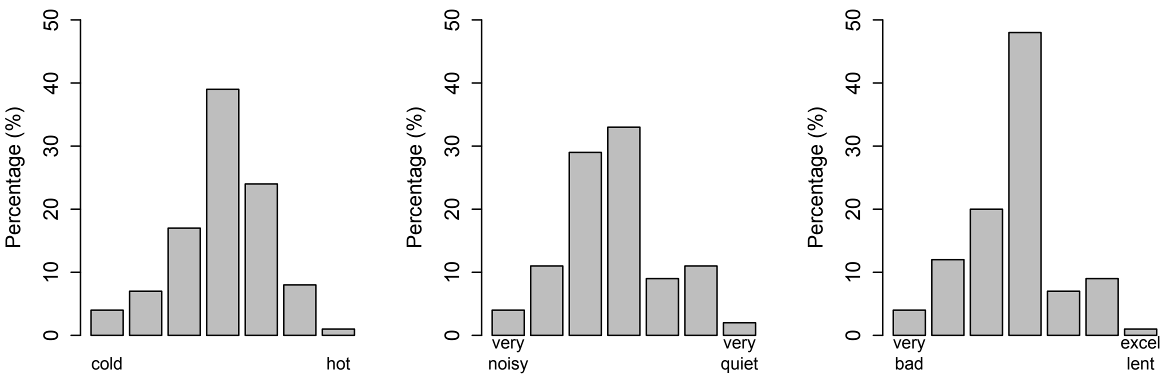

Figure 1. Distributions of thermal perception (TSV, left), acoustic perception (NSV, middle) and air quality perception (ASV, right) survey results.

3.2 Inferential analysis dataset level

The first part of the inferential analysis reviews the relationships of amongst the three variables (TSV, NSV and ASV) for the entire dataset (see Figure 2).

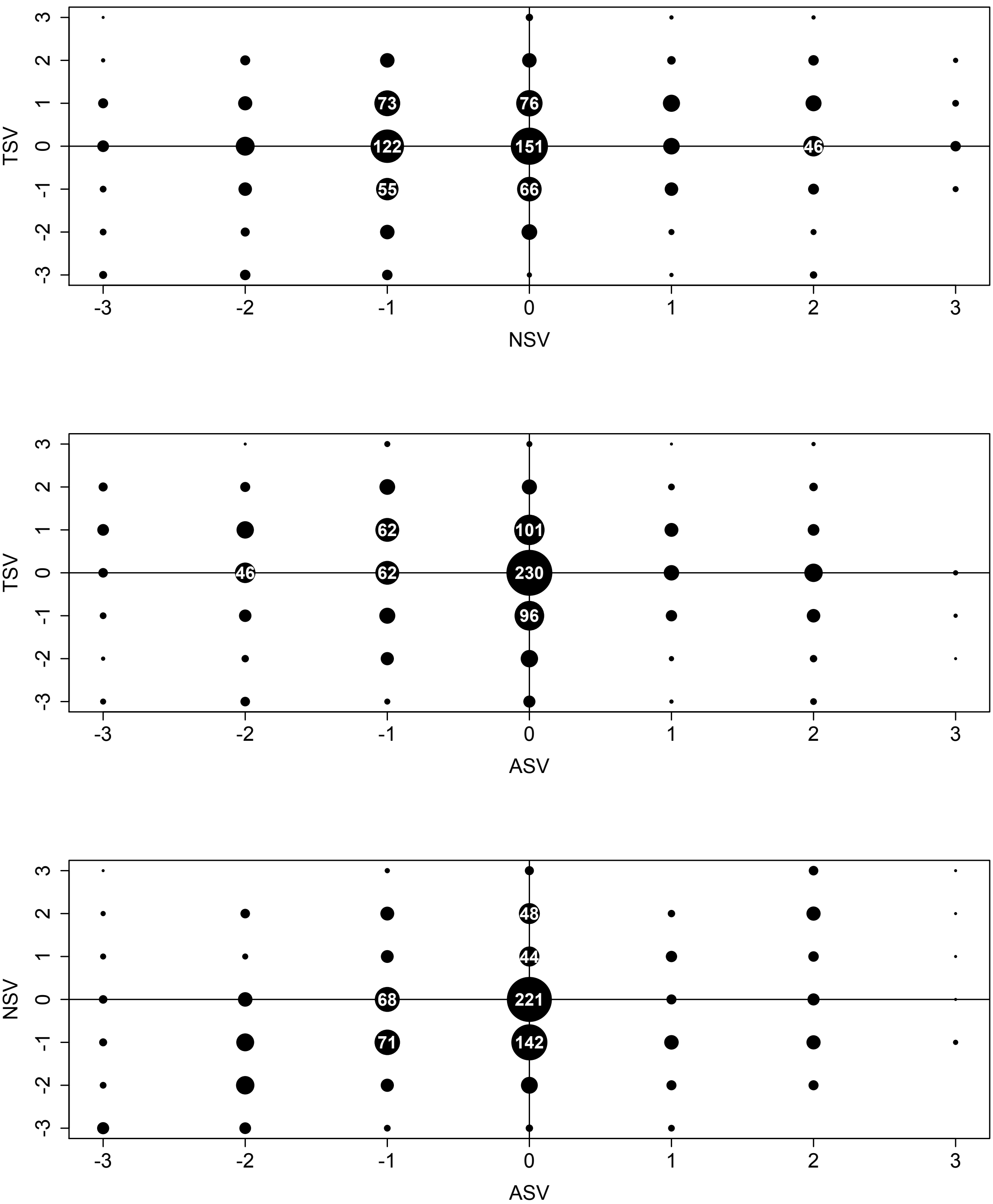

Figure 2. Comparison of agreement between the three variables from the individual surveys (number of responses shown within circles and proportional to the area of circles).

There was a significant but negligible positive correlation between TSV and NSV (G=0.11, p<0.05). There was a significant but negligible negative correlation between TSV and ASV (G=-0.11, p<0.05). There was a significant, moderate and positive correlation between NSV and ASV (G=-0.25, p<0.05). The findings indicate that a noisy environment is associated with poor air quality, while a quiet environment is associated with good air quality; e.i. occupants in noisy environments are likely to perceive bad air quality.

3.3 Inferential analysis subset level

The second part of the inferential analysis reviews the relationships of between the three variables (TSV, NSV and ASV) while the different environmental controls were at play. The results shown in Table 3 indicate moderate to very strong relationships. There were significant, moderate and positive correlations between TSV and NSV, when windows were open (G=0.22, p<0.05), when blinds/curtains were down (G=0.23, p<0.05), or when space air conditioning (AC) was on (G=0.31, p<0.05). Noisy environment was associated with cold thermal perception, while a quiet environment was associated with warm thermal perception. As participants felt warm and there is little external noise, they may have opened windows. There was a significant, negative and very strong correlation between TSV and ASV, when local fans were on (G=0.76, p<0.05). A warm environment was associated with poor air quality, while a cool environment was associated with good air quality. Participants may have switched on local fans to increase cooling sensation; this would have consequently increased convection and might explain the “good” perceived air quality. There were significant, positive and moderate to strong correlations between NSV and ASV, when blinds/curtains were shut down (G=0.2, p<0.05), space air conditioning (AC) was on (G=0.19, p<0.05), or local heaters were on (G=0.25, p<0.05). Quiet environments were associated with good air quality, while noisy environments were associated with poor air quality. Participants may have switched on the AC to improve the perception of fresh air; this action will have increased the internal noise level.

Table 3. Value of Gamma

	Door	**Window**	**Blinds/curtains**	**Light**	**AC**	**Heater**	**Fan**
Sample Size	**272**	**86**	**154**	**774**	**259**	**16**	**41**
TSV vs. NSV	-	0.22 *	0.23 *	-	0.31 *	0.41	-
TSV vs. ASV	-	-0.22	-	-	-	-	-0.76 *
NSV vs. ASV	-	-	0.2 *	-	0.19 *	0.62 *	-

* p<0.05

4. Discussion and conclusions

The results of the dataset analysis showed no relationship between variables; only a modest positive association between air quality and background noise level. Further analysis explored the relationships between the three different perceptions when environmental controls were at play. In such cases, moderate to very strong relationships were uncovered; these are summarised as follows:

- Noisy environments were associated with cold thermal perception, while quiet environments were associated with warm thermal perception.
- Warm environments were associated with poor air quality, while cool environments were associated with good air quality.
- Quiet environments were associated with poor air quality, while noisy environments were associated with good air quality.

These results show that in general there was no association between the studied environmental factors, i.e. thermal, acoustic and air quality perceptions. Correlations were evident only when heating, cooling and/or ventilation systems (HVAC) were in use. For example, when a window is open, the occupants will have to balance among their different environmental preferences of thermal, acoustic and air quality. This may often be challenging to achieve. In the case of window opening or local fan being used, these comfort adaptation driven behaviours will have to balance between indoor and outdoor heat, pollutants and noises, as summarised in Table 4.

Table 4. Non-exhaustive list of heat, pollutants, noises in buildings

	Thermal	**Air-Quality**	**Acoustic**
Indoor	Internal heat gains Temperature gradients Air flows	Odours Carbon dioxide (CO_2) Particulates (PM) Volatile organic compounds (VOC) Sulfur dioxide (SO_2) Nitrogen oxide (NO_x)	Airborne sounds (speech, equipment, building mechanical systems) Structure-borne sounds (foot fall, equipment)
Outdoor	External heat sources (equipment, etc.) Solar gains (direct / indirect) External weather conditions	Odours Nitrogen oxide (NO_x) Particulates (PM) Volatile organic compounds (VOC)	Airborne sounds (speech, road, rail, aviation, etc.) Structure-borne sounds (road work, etc.)

Occupants perceive their environment and may act upon discomfort through behavioural adaption by changing the HVAC system settings. In this study, discomfort may be thermal, acoustic and/or related to air quality. As described by CIBSE (2006), discomfort occurs when (1) environmental “changes are too fast for adaptation to take place”, (2) environmental changes “are outside individual control”, or/and (3) perception is beyond personal comfort boundaries. To address the second point, perceived occupant control over the environment is key to achieve higher tolerance of less than ideal conditions, which will certainly occur while balancing between different environmental preferences. Therefore, it is recommended that HVAC control strategies are at the core of building design and management. To address the third point, thermal or acoustic perceptions vary widely from person to person (Gauthier et al., 2020; CIBSE - Section 1.10.1, 2015). Moreover, environmental perceptions will depend on the situation and activity undertaken in the space (e.g. lone working, meeting, video call, etc.) Therefore, it is recommended that a wide range of different environmental conditions are design within office buildings. A popular design may follow the concept of ‘hot-desking’. A desk may not be allocated to a specific person, but to a group of individuals with similar environmental preferences and activities. However, other spaces may require to be designed with flexibility and may adopt personal environmental control systems.

In this paper, a multi-domain approach was applied to study the interactions amongst three environmental perceptions (thermal, acoustic, air quality) based on questionnaire surveys in two office buildings; no measured variables were reviewed. This addresses a gap in research, as very few studies have reviewed reported perception and have been undertaken in ‘free-living’ environments. Indeed, most studies have used measured or modelled variables as substitutes for perception. However, human perception does not depend entirely on physiological and physical mechanisms, but also depends on thermal experiences, expectations, social norms, efficacy of control, etc. (Brager & de Dear, 1998). As online survey tools have developed in recent years, making data collection more affordable, future research should and can now gather reported environmental perceptions. Furthermore, research should adopt a holistic approach as associations amongst indoor environmental parameters may be have an important role in behavioural adaptation.

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