Acoustical planning for workplace health and well-being: a case study in four open-plan offices

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Abstract: Noise is the most frequent reason for complaints about environmental conditions in the workplace and is associated with individual health and well-being issues, decrease of productivity and performance. This study identified a set of acoustic strategies for open-plan workplaces and examined a case study that included them in four open-plan offices in the United States. The set of measures was defined based on a literature review and a focus group interview with 17 experts. A total of four topics were identified as key performance indicators (KPIs) of proper acoustic environments in the open-plan workplaces. A total of 19 items were then developed within these four topics as the protocols for planning acoustic strategies for workplace health and well-being. In the case study, the level of acoustic performance for workplace health and well-being was highest in the Dallas office (27.5 points out of a total of potential 40.0) followed by the Minneapolis office (26.0). Both offices outperformed the other offices in achieving space planning principles to control noises and occupant noise control in open spaces for acoustical privacy. A further examination in the relationships between acoustic strategies and other health and well-being KPIs in these offices revealed complex associations and suggests that guidance to increase occupants' auditory comfort, well-being, and performance should be sought by designers in a holistic and integrative way.

Keywords: acoustic comfort; workplace; open-plan offices; noise annoyance

1. Introduction

Ever since new workspaces configurations for offices started to emerge over the past decades, the acoustic comfort of the workers has always been a major concern. Recently, flexible layouts such as open-plan offices or activity-based offices have gained momentum in many public and private companies, but this often came with increased pressure on the occupants' comfort, which in turn often led to increased psychophysical distress and decreased productivity (Haapakangasa, Hongisto, Varjo, & Lahtinen, 2018) (Haapakangas, Hallman, Mathiassen, & Jahncke, 2018). Noise is constantly reported to be one of the most frequent reasons for complaints from workers in these kinds of office environments as it elicits task interruption, loss of concentration, irritation and lowered level of productivity for employees; thus, the acoustics of such spaces has been thoroughly investigated in the past (e.g., (Hay & Kemp, 1972) (Boyce, 1974) (Banbury & Berry, 2005) (Seddigh, Berntson, Jönsson, Bodin Danielson, & Westerlund, 2015)).

The topic is generally highly regulated in different national legal documents in terms of room acoustics and sound insulation requirements that open-plan offices should provide; this led the international community of researchers and practitioners to work on standards *ad hoc* to measure the acoustic qualities of these spaces (International Organization for Standardization, 2012). Yet, it is still hard to identify clearly established design guidelines of these spaces for practitioners to use at the planning and design stage (Warnock, 2004), and this might be related to the lack of awareness of professionals involved in the architectural design about the acoustic implications that their proposals can lead to (Şentop & Bayazıt, 2016). Indeed, a lot of research efforts went towards identifying the possible underpinning mechanisms that connect acoustics and noise exposure conditions with individual cognitive and perceptual outcomes in office spaces. These included studies that considered both personal factors and other non-acoustical factors that play a role in environmental sounds perception (e.g., (Keighley, 1966) (Keighley, 1970) (Sundstrom, Town, Rice, Osborn, & Brill, 1994) (Kjellberg, Landstrom, Tesarz, Soderberg, & Akerlund, 1996) (Newsham, Veitch,

& Charles, 2008) (Ding, 2008)). However, scientific works looking specifically at recommending acoustic strategies and/or design guidelines in open-plan offices are less frequent than those aimed at "characterising the problem" (e.g., (Kjellberg & Landstrom, 1994) (Kjellberg & Landstrom, 1994) (Bradley, 2003) (Virjonen, Keränen, & Hongisto, 2009)). Overall, the focus of noise control engineers and architects dealing with the acoustics of open-plan offices is gradually shifting from the acoustic performance of single building elements (e.g., windows, partitions, etc.) to the acoustic performance of the space as a whole and move towards more perception-driven and user-centred approaches to the design process (Dokmeci Yorukoglu & Kang, 2017), and this is boosting the emerging scientific discipline of "indoor soundscaping", which is currently receiving considerable research attention, as it can be observed from the increasing number of publications and special issues in international journals and conferences (Aletta & Astolfi, 2018) (Kang, 2019).

The purpose of this paper is proposing an easy-to-use assessment tool that can support practitioners in designing more acoustically sensible spaces. This study is part of a broader research initiative, PROWELL: Online Workplace Health and Well-being Evaluation Tool, conducted at the Innovative Workplace Institute (IWI) about workplace health and well-being (Lee, Osburn, & Wolkoff, 2018). PROWELL should be considered as both a theoretical framework and a methodological tool of analysis. It is a theoretical framework as it identifies a set of workplace health and well-being dimensions under the three core domains that are aligned with the definition of health by the World Health Organization (WHO). It is also a methodological analysis tool as it provides protocols for the acoustics-related assessment of different workspaces. Within the context of this research, this study explored what would possible acoustic protocols and strategies for open-plan workplaces be, and assessed them in a case study. The set of protocols was identified and finalized based on a literature review and a focus group interview organised with a group of experts that consisted of leading practitioners in architecture, design, facility management, and workplace strategy. Acoustic protocols and strategies are either actions/measures implemented on site, or passive acoustic requirements met in a specific case study. This paper reports on a pilot where the protocols and strategies were examined with four architectural firms across the United States, in Minneapolis, Durham, Dallas, and Chicago. All of these offices were either certified with FITWEL (Facility Innovations Toward Wellness Environment Leadership), a health and well-being building certification system developed by the US governmental agencies, or pursuing a FITWEL certification along with a combination of a green building certificate, and/or a WELL building certificate, another health and well-being building certification system developed by the International Well Building Institute in the US.

2. Methodology

2.1. PROWELL development and its workplace health and wellbeing KPIs

PROWELL was developed as a free online analytic platform for practitioners to assess the level of workplace environmental performance in health and well-being indicators in their day-to-day practice by IWI. Its basic version provides a free assessment tool that analyses the workplace health and well-being performance in an instantaneous manner, informing practitioners of already enhanced features as well as features to be improved in the workplace being assessed. The goal was to provide a comprehensive tool for workplace health and well-being evaluation to promote evidence-based practice. Funded by the American Society of Interior Designers, it was developed in collaboration between industry leaders from various workplace-related fields and IWI. In the development of the instrument, first, a literature review was conducted to identify dimensions and key performance indicators (KPIs) in each dimension of workplace health and well-being. Second, focus group interviews followed with the industry leaders to review, revise, and finalise the dimensions, KPIs, and measures. The main purpose of the integration of the expert group interviews was that the functions of PROWELL Basic© were to combine the proper level of academic rigour and pragmatism in practice. The expert focus group was attended by 17 leading practitioners and scholars in health and well-being enhanced workplaces in the United States and the United Kingdom, who voluntarily accepted the role in the development of PROWELL Basic©. The group consisted of practitioners from architecture, design, facility management and workplace strategy, as well as scholars in the health and well-being research community. The expert focus group was formed as an open discussion platform, from July 2017 to February 2018, and a total of four group interviews rounds were conducted during this period. The first interview was held in July-August 2017, the second interview in September 2017, the third interview in October 2017, and the last interview in February 2018. All interviews were conducted via video-conferencing tools to minimise traveling and time conflicts between the focus group members in different time zones. Each interview was divided into several sessions in different times, to limit the total number of participants to smaller groups for constructive discussions and feedback.

The literature review focused on examining well-being and health-related components in the built environment that were established as standards or guidelines by professional organizations as well as standard practices in architectural planning. First, it examined major standards and guidelines for green buildings and health-promoting built environments, including BREEAM, LEED, Living Building Challenge, WELL, FITWELL, Green Globes, Active Design Guidelines, the World Health Organization, the European Network for Workplace Health Promotion (ENWHP), and the US Occupational Safety and Health Administration (OSHA). Second, it utilized a method called content and visual analysis that examined visual and written contents published in major workplace-related sources in order to capture the conventional practices for health-promoting built environments of design professionals who don't typically express their opinions in peer-reviewed journals nor employ systematic methodologies for their research. The sources of visual and written contents examined included reputable architectural and design magazines and professional blogs written by reputable professionals in architecture, workplace strategy, facility management, and interior design.

This method was incorporated to embrace two typical approaches to achieving health in the built environments. One is via environmental designs of spatial layout and design features, and the other via environmental control and monitoring of toxins and chemicals as well as provision of human comfort factors (Lee Y. , 2019). To understand newly emerging design practices to promote health in the built environment, it was decided to employ the content and visual analysis. Once all dimensions, KPIs, and measures were finalised from the discussions with the focus group, an online analytic system was implemented. The online analytic system consisted of an automated analysis and a result reporting system to provide an instant result report. A benchmark system was also integrated to the reporting system to indicate the level of the overall performance and specific performance levels of each dimension of a workplace being assessed.

The concept of health defined by the WHO, a state of complete physical, mental and social well-being, was used to identify three domains of well-being including physical, mental, and social well-being for the PROWELL framework (WHO, 2019). Under the three domains, a total of seven dimensions of well-being relevant to the workplaces were identified and integrated to the PROWELL framework (Lee & Schottenfeld, 2017). The seven dimensions of workplace well-being comprised Physical Fitness (PF), Physical Comfort (PC), Physical Nourishment (PN), Environmental Well-being (EnW), Cognitive Well-being (CW), Emotional Well-being (EW), and Social Well-being (SW). PF, PC, PN, and EnW fall under the domain of physical well-being, CW and EW under the domain of mental well-being, and SW under the domain of social well-being. Each dimension of workplace well-being consisted of a set of KPIs and a correspnding set of measures under each KPIs. Figure 1 illustrates the overall structure of PROWELL framework with seven dimensions of workplace well-being and KPIs and measures under each dimension within the three domains of well-being. The measures in PROWELL Basic© are all objective and prescriptive measures. Prescriptive measures typically evaluate presence/absence of certain properties or features that are defined to be of characteristics of a pursued topic agreed on by experts in the field.

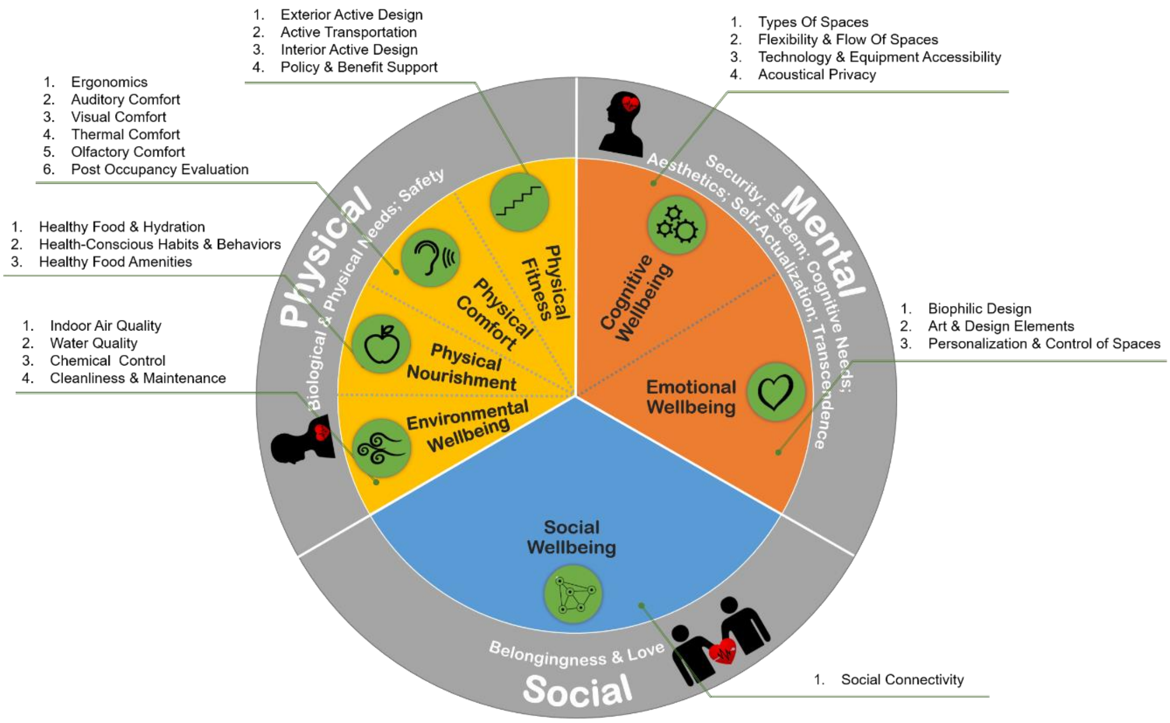

Figure 1. PROWELL framework (Innovative Workplace Insitute, 2018)

2.2. The PROWELL acoustic performance KPIs and measures

Acoustic performance-related KPIs are considered under PC and CW. There are a total of four KPIs for acoustic planning and strategies for workplace health and well-being under these two dimensions. Three topics are addressed under PC, including KPI 1: Space planning principles to contain unwanted sounds, KPI 2: Technical measures for indoor noise control, and KPI 3: Construction methods for sound control. The fourth topic is housed under CW: KPI 4: Acoustic privacy: occupant noise control in open spaces. There are a total of 19 items adopted within these four topic. The principle of establishing these measures was to identify acoustic strategies from a multi-layered approach to tackle a complex issue of noise control, speech privacy, and supporting concentration work in the prevalent open-plan workplaces without relying on only one-dimensional acoustic solutions. Thus, the protocols are a combination of acoustic solutions in spatial planning (SP), technical measures (TM), construction methods (CM), and workplace policy (WP), as reported in Table 1.

KPI 1 Spatial planning measures included zoning practice, placement of spaces, and shapes of rooms. KPI 2 Technical measures for noise control employed three typical principles of sound-proofing: sound absorption, sound blocking, and sound masking by using noise reduction coefficient ratings of interior finish materials, noise criterion levels of background sound, and sound masking systems in place. The measures in KPI 3 Construction methods focused on details to decrease sound propagation and increase sound insulation via noise insulation class ratings of interior partitions, placement of gypsum boards, door construction details and acoustic accessories, and use of sound insulation hardware. KPI 4 measures mainly addressed options for occupant control of noise for acoustic privacy. This is for people to be able to conduct tasks requiring concentration without noise that creates hindrance to cognitive working memory. Indeed, not only is people's ability to focus and maintain information limited, but also is working memory easily distracted by noises (Venetjoki, Kaarlela-Tuomaala, Keskinen, & Hongisto, 2006). Thus, the issue of providing acoustic privacy has a significant impact on cognitive performance of people in the workplace. The measures in acoustic privacy to provide occupant control of noise included a combination of strategies in zoning practice, provision of acoustically treated spaces, and workplace policy to reinforce behavioural changes to reduce noises generated by people.

The protocol used is reported in Table 1. In terms of assessment, each of the 19 measures is considered as a condition that is met or not in the investigated facility; thus for each item, a 0-1 score is assigned and their sum counts towards the overall assessment. As part of the standardized scoring system developed for

PROWELL, the scores between the four topics were normalised with a total of 10 points possible in each topic (KPI), and consequently a grand total of 40 points available to assess acoustic planning and strategies for workplace health and well-being.

Table 1. List of the 19 measures, grouped according to the main four KPIs, used in the case study

KPIs	ID	Measures (present/absent)	Approach
1. Space planning principles exercised to control noises	1	Grouping similar types of areas together	SP
	2	Placing buffer spaces to separate noisy spaces	SP
	3	Avoiding room shapes causing sound to reflect or focus in specific spots	SP
	4	Staggering doorways to avoid a straight path for noise	SP
	5	Placing quiet spaces away from noise sources such as major traffic roads and copy rooms	SP
2. Technical measures for internal noise control exercised	6	Ceiling finish materials with a minimum noise reduction coefficient (NRC) of 0.9 and wall finish materials with NRC of 0.8 for open offices	TM
	7	Ceiling finish materials with a minimum noise reduction coefficient (NRC) of 0.8 and wall finish materials with NRC of 0.8 for conference and teleconference rooms	TM
	8	Mechanical equipment with a maximum noise criterion (NC) of 40 for open offices	TM
	9	Mechanical equipment with a maximum noise criterion (NC) of 30 for conference rooms and 25 for teleconference rooms	TM
	10	Sound masking systems in open offices	TM
3. Sound controlling construction methods specified and used	11	Interior walls with a minimum Noise Isolation Class (NIC) of 40 (35 if a sound masking system is used) in enclosed offices and a minimum NIC of 53 for conference and teleconference rooms	CM
	12	Interior walls constructed with staggering gypsum board seams	CM
	13	Interior walls with an acoustical ratings sealed at the top and bottom racks	CM
	14	Doors with non-hollow core, gaskets or sweeps in conference and teleconference rooms and private offices	CM
	15	Noise reducing sound isolation hardware used such as resilient channel clips or floor isolation hardware	CM
4. Acoustic privacy: occupant control of noise in open offices	16	Separate focus/ concentration spaces provided away from open workspaces	SP
	17	Small enclosed spaces with acoustical treatment provided for confidential or private (phone) use	SP
	18	Space planning for noise separation applied to individual workspace planning to establish quiet zones and noisy/ interaction zones	SP
	19	Policy in place addressing proper workplace etiquette to promote courteous behaviours related to generating unwanted noises for other people surrounding	WP

SP: Spatial planning   TM: Technical measure   CM: Construction method   WP: Workplace policy

3. Case studies

A pilot case study was carried out in the spring of 2018 with an international architectural company in the US. It voluntarily accepted the invitation to participate in the pilot case study as it was strategically pursuing health and well-being architecture in its practices and integrating such practice to their own workplaces. A total of four offices were chosen as these offices recently went through a renovation or moved into a new place, applying various health and well-being strategies to the new offices. The locations of these offices were: Minneapolis, Durham, Chicago, and Dallas. A point of contact was established as a workplace strategist in the Chicago office who coordinated with architects, designers and workplace strategists in the other locations. The selected professionals for the study either had knowledge of architectural features for health and well-being or participated in the office renovation that followed a building guideline for health and well-being such as FITWEL or WELL and/or a green building standard such as LEED. Each office was given a week to complete the printed version of PROWELL Basic© assessment instrument for convenient data gathering between several people in each office. For the acoustic performance sections, space planning strategies and construction methods used in offices were identified by architects and designers, workplace policy by workplace strategists, and technical measures by the staff who were involved in the certification of a health and well-being building standard that required physical measurements of acoustic performance. Once the forms were returned a week later, the data were uploaded to the online system. This paper focused on the acoustic performance analysis of these offices. The first part of the analysis investigated the overall acoustic performance and specific measures achieved across the four offices, and the second part of the analysis analysed the relationships between the acoustic performance and other workplace health and well-being indicators.

3.1. Overall acoustic performance of the four offices

The Minneapolis office was located in an urban setting with a total of 69 people in 9,800 SF (910 m^2). As a workplace strategy, free address (unassigned desks) was implemented (Figure 2). It was FITWEL-certified at the time, while pursuing other green building certificate such as the Leadership in Energy and Environmental Design (LEED) and Living Building Challenge (LBC). The Durham office was situated in an urban environment with a total of 50 people in 12,000 ft^2 (1,115 m^2). It had assigned desks and was FITWEL-certified at the time. The Chicago office was also located in an urban area with a total of 280 people in 60,440 ft^2 (5,615 m^2). Desks were assigned. It was pursuing a FITWEL certificate as well as a LEED certificate at the time. The Dallas office was also situated in urban with a total of 188 people in 40,000 ft^2 (3,716 m^2). It had assigned desks and was pursuing multiple certificates in FITWEL, WELL, and LEED (Figure 2).

The Dallas office achieved a highest score (27.5) for the overall acoustic planning and strategies for workplace health and well-being, followed by the Minneapolis office (26.0), as shown in Figure 3. The majority of scores for both offices came from two KPIs: KPI 1: Space planning principles to control noise and KPI 4: Acoustical privacy: occupant noise control in open offices. The Dallas office achieved 10 points out of 10 points possible in both KPIs and the Minneapolis office 10 points for KPI 1 and 7.5 points for KPI 4. The Durham office achieved KPI 1 and KPI 4 more than the other KPIs, and the Chicago office KPI 1 and KPI 3: Sound controlling construction methods specified and used more than the other KPIs. Overall, KPI 2: Technical measures for internal noise control was the least achieved KPI across all four offices.

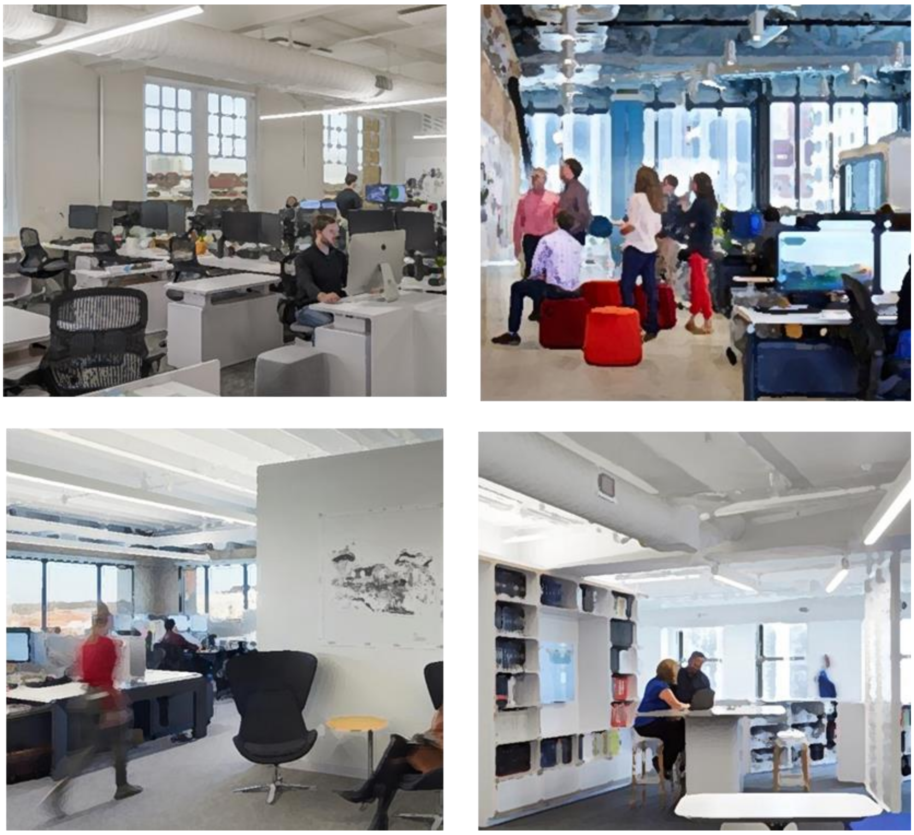

Figure 2. Images of the four offices in the open-plan environment (photos are modified for privacy and confidentiality issues); the Dallas (top left) and Minneapolis (top right) offices employed a zoning practice separating between quiet and noisy spaces and a sound masking system in the open-plan office; the Durham (bottom left) and Chicago (bottom right) offices used interior walls with an acoustical ratings sealed at the top and bottom racks to contain sound propagation

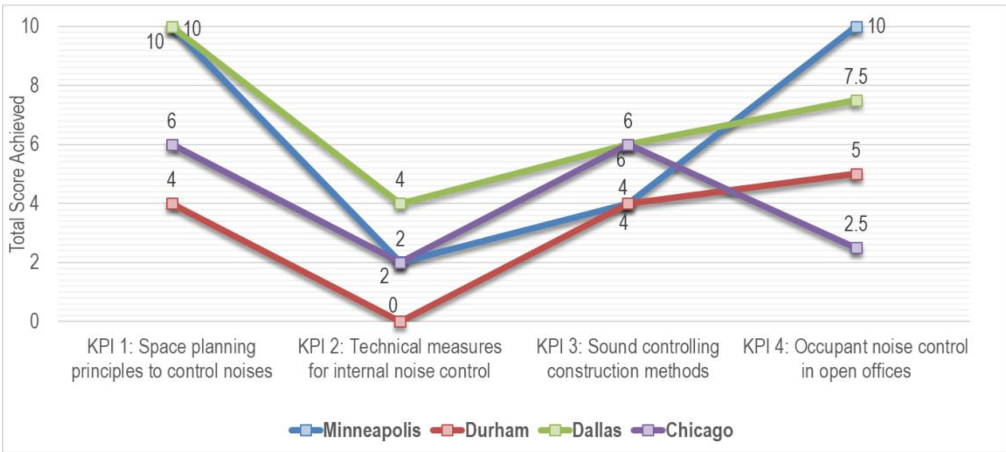

Figure 3. Acoustic performance for workplace health and well-being across four offices

In examining the items under four KPIs, most frequently achieved measures across all four offices were "Grouping similar types of areas together" and "Placing quiet spaces away from noise sources such as major traffic roads and copy rooms" in KPI 1; "Interior walls with a minimum Noise Isolation Class (NIC) of 40 (35 if a sound masking system is used) in enclosed offices and a minimum NIC of 53 for conference & teleconference rooms" in KPI 3; and "Small enclosed spaces with acoustical treatment provided for confidential or private (phone) use" in KPI 4 (Table 2). "Noise reducing sound isolation hardware used such as resilient channel clips or floor isolation hardware" under KPI 3 was pursued by none of the offices. A total of three measures under KPI 2 were not pursued by any of the offices, including "Ceiling finish materials with a minimum noise reduction coefficient (NRC) of 0.9 and wall finish materials with NRC of 0.8 for open offices," "Mechanical equipment with a maximum noise criteria (NC) of 40 for open offices," and "Mechanical equipment with a maximum NC of 30 for conference rooms and 25 for teleconference rooms." The other two measures under the same KPI were achieved by only half of the offices.

Table 2. Achieved measures of acoustic performance KPIs across four offices (measures IDs refer to Table 1)

Measures	*KPI 1*					*KPI 2*					*KPI 3*					*KPI 4*			
Offices	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Minneapolis	●	●	●	●	●	x	x	x	x	●	●	x	x	●	x	●	●	●	●
Durham	●	x	x	x	●	x	x	x	x	x	●	x	●	x	x	x	●	x	●
Dallas	●	●	●	●	●	x	●	x	x	●	●	●	x	●	x	●	●	●	x
Chicago	●	●	x	x	●	x	●	x	x	x	●	x	●	●	x	x	●	x	x

Legend

●	Achieved measures
x	Non-achieved measures

3.2. Associations between acoustic performance and other workplace health and well-being KPIs

In the second part of the analysis, potential associations were investigated between the acoustic performance and the other KPIs of PC in the four offices. These included: Ergonomics, Visual Comfort, Thermal Comfort, and Olfactory Comfort (Lee, 2019). These KPIs of PC were correlated with Acoustic performance, which was a combination derived from Auditory Comfort and Acoustical Privacy. Considering the limited sample size (four offices) and the lack of data normality, a non-parametric approach was sought in an exploratory data analysis. A Spearman's rank-order correlation was run to assess the relationship between all the variables reported in Table 3. A preliminary analysis showed all those relationships to be monotonic, as assessed by visual inspection of a scatterplots. However, it was observed statistically significant, strong positive correlation only between Acoustic Performance and Olfactory Comfort, $r_s(2) = .999$, $p < .0001$. All other associations resulted to be non-statistically significant ($p > .05$).

Table 3. Spearman's correlational analysis

Correlations

			Acoustic Performance	Ergonomics	Visual Comfort	Thermal Comfort	Olfactory Comfort
Spearman's rho	**Acoustic Performance**	Correlation Coefficient	1.000	.400	-.211	.447	.999**
		Sig. (2-tailed)		.600	.789	.553	.000
		N	4	4	4	4	4
	Ergonomics	Correlation Coefficient		1.000	.316	0.000	.400
		Sig. (2-tailed)			.684	1.000	.600
		N		4	4	4	4
	Visual Comfort	Correlation Coefficient			1.000	-.943	-.211
		Sig. (2-tailed)				.057	.789
		N			4	4	4
	Thermal Comfort	Correlation Coefficient				1.000	.447
		Sig. (2-tailed)					.553
		N				4	4
	Olfactory Comfort	Correlation Coefficient					1.000
		Sig. (2-tailed)					
		N					4

**. Correlation is significant at the 0.01 level (2-tailed).

4. Discussion

The open-plan office type has been most frequently pursued in the contemporary workplace due to efficient real estate management to place more people in a smaller footprint and the need of eliminating visual barriers to promote interaction and collaboration. Interaction and collaboration issues have become vital in the innovation economy where economic growth is possible through entrepreneurship, technological interventions, and innovative business methods and strategies, not by the traditional economic models based on increments of inputs and outputs. However, such an open environment has created considerable adverse impacts on auditory comfort by significantly increasing the amount of undue noises and reducing speech privacy and intelligibility, which contributes to mental stress, physical fatigue, and lower cognitive performance (Krasnov, Green, Engels, & Corden, 2019) (Di Blasio, Shtrepi, Puglisi, & Astolfi, 2019). Despite these known acoustic issues in the open-plan office context, providing a satisfactory acoustic environment is a great challenge due to multi-dimensional factors related to noise perception as a whole in the workplace.

Since noise is unwanted sound, noise perception in open-plan offices, and at the workplace more generally, is most likely to be significantly affected by subjective factors such as personality traits (Lindborg & Friberg, 2016) or noise sensitivity factors (Kjellberg, Landstrom, Tesarz, Soderberg, & Akerlund, 1996) (Park, et al., 2017) (Aletta, et al., 2018). Specific groups of users might be more irritated by noises and more affected by noise annoyance (Beheshti, Roohalah Hajizadeh, Borhani Jebeli, & Tajpoor, 2018). In addition, less extroverted and more conscientious people might be associated with higher noise sensitivity levels (Shepherd, Heinonen-Guzejev, Hautus, & Heikkilä, 2015). Such a complexity requires comprehensive strategies to provide a satisfactory level of acoustic performance in open-plan office environments. Thus, the PROWELL KPIs address acoustic environment in the workplace through four approaches including spatial zoning and planning, technical measures, construction detailing methods, and workplace etiquette policy to mitigate noise issues and provide speech privacy. In general, this kind of assessment also offers an opportunity for reflection about whether certified buildings that are efficient according to established protocols, actually achieve also high performances in terms of indoor environmental quality from the occupants' perspective, as a holistic approach (Lee, 2011) (Lee, 2019).

The case study shows a snapshot of an imbalanced focus in practice related to acoustic environments. The most frequently achieved type of measures across the four offices was spatial zoning and planning strategies followed by construction method strategies (Figure 3). Specifically, there are five spatial planning measures that were achieved by at least three offices: grouping similar types of areas together; placing buffer spaces to separate noisy spaces; placing quiet spaces away from noise sources such as major traffic roads and copy rooms; interior walls with a minimum noise isolation class (NIC) of 40 in enclosed offices and a minimum NIC of 53 for conference and teleconference rooms; door with non-hollow core, gaskets or sweeps in conference and teleconference rooms and private offices; and small enclosed spaces with acoustic treatment provided for confidential or private (phone) use. These spatial planning principles, specifying NIC ratings of interior partitions, and door details tend to be quite fundamental and a standard practice in architectural design practice for acoustics.

Providing small enclosed spaces (phone booths) is a recent spatial solution adopted in practice to offer quiet enclosed spaces for not only confidential and personal conversations but also phone calls or one-on-one video conferences in open-plan offices. Since this spatial solution helps separate noisy activities from focus/concentration areas, it will likely be effective in supporting cognitive performance.

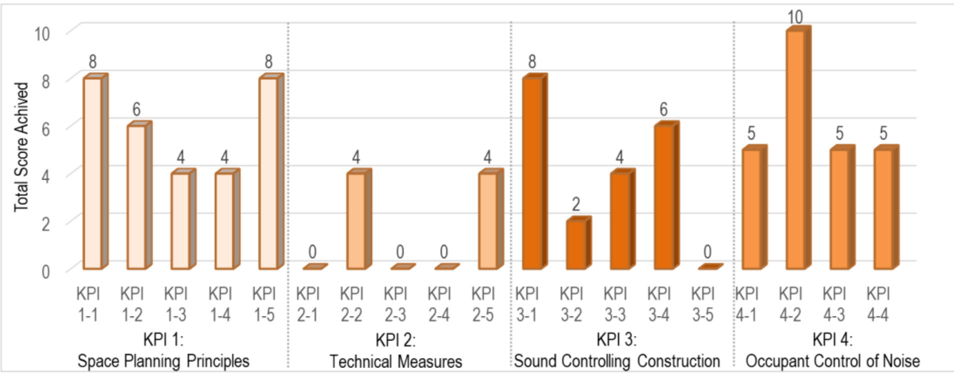

Figure 4. Frequency distribution of achieved measures across four offices

The set of protocols that none of the offices pursued included four items: three from the technical measures and one from construction detailing. These are: ceiling finish materials with a minimum noise reduction coefficient (NRC) of 0.9 and wall finish materials with NCR of 0.8 for open offices; mechanical equipment with a maximum noise criterion (NC) of 40 for open offices; mechanical equipment with a maximum NC of 30 for conference rooms and 25 for teleconference rooms; and noise reducing sound isolation hardware used such as resilient channel clips or floor isolation hardware. While a NRC 0.7-0.8 is considered a good option for sound absorption in private offices and conference rooms, a minimum of NRC 0.9 for ceilings and a minimum NRC 0.8 for walls are recommended for open-plan offices or spaces requiring a high acoustic performance (The US GSA, 2011; The US GSA, 2014). The same guidelines recommend a maximum NC of 40 for open-plan office where normal speech privacy is necessary; a maximum NC of 30 for spaces requiring confidential speech privacy, and a maximum NC of 20-25 for other meeting, training, and teleconference rooms. Lastly, utilizing sound insulation hardware in wall or floor assemblies is a recommended construction method to reduce noise by reducing contact points between studs and substrates/gypsum boards. This method is called decoupling: while it eliminates direct paths of sound propagation in the energy component mechanically transmitted via the structural elements, additional insulation solutions should be considered to tackle other frequency ranges (e.g., multiple sheeting and other sound-absorbing materials in the cavity of the walls).

In addition to these approaches, two of the offices also achieved noise control via a workplace policy to promote courteous behaviours. The important role of workplace etiquette in providing acoustic privacy in open-plan offices has been emphasized in many studies (Newsham, 2003). The major source of noises in the workplace is known to be people (Di Blasio, Shtrepi, Puglisi, & Astolfi, 2019). The two most distracting noises in the workplace are people's conversations with other people or in phone calls and telephone left ringing which are perceived significantly more distracting than noises from office equipment or outside the building

(Banbury & Berry, 2005). Thus, a workplace policy encouraging courteous behaviours to reduce noise at the root of the source is an effective way to achieve acoustic privacy.

The correlational analysis between acoustic performance and the other KPIs in PF exhibited a positive relationship between the levels of acoustic performance and olfactory comfort. In a further examination, it was observed that the protocols to control odour might also result in beneficial effects for acoustic performance. The three Olfactory Comfort protocols that were achieved by at least one of the offices included deck-to-deck partitions; separate exhaust; and interstitial rooms, vestibules or hallways separating these spaces and other regularly occupied spaces. Deck-to-deck partitions (i.e., partitions that extend from the floor up to the underside of the next floor deck instead of up to the suspended ceiling) are a well-known construction detail to isolate sound. While floor-to-ceiling interior partitions are more frequently used for easy construction, cost saving, and flexibility, sound can easily propagate over the top of the partitions and plenums to adjacent rooms. So, deck-to-deck is often recommended for spaces requiring a higher level speech privacy and noise isolation (Ermann, 2015). The relationship between separate exhaust and acoustic benefits is unknown at this stage and for the specific investigated cases: empirical data and on-site measurements would be desirable to explore possible causal connection between these two dimensions. Lastly, providing interstitial rooms, vestibules or hallways between noise-generating spaces and regularly occupied spaces can contribute to noise isolation and blocking of sound propagation. This method is similar to the space planning principle to control noise by placing buffer spaces to separate noisy spaces. Thus, such Olfactory Comfort measure can also be an indirect effective method for increased acoustic performance in the workplace.

5. Conclusions

This study examined the 19 protocols in four approaches suggested for a comprehensive acoustic planning and strategies for open-plan offices (Table 1). In a case study with four offices, the two most pursued approaches were space planning principles and occupants' control of noises, while the least pursued approaches, technical measures and sound controlling construction methods, accordingly. To facilitate the use of those two underutilized approaches in practice, a couple of suggestions can be made. Broadening the set of technical measures can be a good way to address various issues related to acoustic environments and practicality of employing particular technical measures that individual workplace may encounter and prefer to solve its own unique problems. Other technical measures that could be considered for inclusion in the list of KPIs are reverberation time (RT) and sound transmission class ratings (STC). The recommended RT in open-plan offices is below 0.8s to ensure speech intelligibility (USGSA, 2011; USGBC, 2019). A recommended STC is at least 45 between standard offices, and at least 50 between private offices/conference rooms (US GSA, 2014; USGBC, 2019).

For construction details to mitigate noises, as discussed earlier, a measure of Olfactory Comfort such as a deck-to-deck wall construction method can be added to the list. A deck-to-deck method contributes to preventing sounds from propagating to adjacent spaces, which is crucial to speech privacy in private offices and conference rooms. Such a method is important in these enclosed spaces mentioned above as speech privacy is based on the partition noise reduction capability measured by noise insulation class (NIC) and NC. In a standard practice, a deck-to-deck wall partition that is known to yield a NIC rating of 40 which is considered a good level of noise reduction, while for interior partitions up to the underside of ceilings, a NIC rating of 30 which is considered as a poor level of noise reduction. Another method to add to the construction details to mitigate noises approach is to construct interior walls with extra layers of gypsum board; this can be applied to either one side or both sides of interior walls in a space that requires noise control or speech privacy. When two layers of the typical ½" gypsum boards are attached to both sides of studs for interior partitions, the STC rating of such walls are known to exceed 45 in practice.

Providing satisfactory acoustic environments in open-plan offices for enhanced health and well-being in the workplace is a complex task. Thus, it is desirable to seek solutions and interventions in a comprehensive manner. When addressing such a complex problem as handling acoustic functions in open-plan offices, multi-disciplinary approaches are more desirable since they offer solutions in an ecosystem of various parts in a collective and systematic way, bringing diverse professionals together. This allows exploring solutions in more than one dimension, which is deemed to be necessary in any successful acoustic planning.

Acknowledgments: The authors are grateful to the staff members of the four architectural offices who supported the researchers for data collection.

References

Aletta, F., & Astolfi, A. (2018). Soundscapes of buildings and built environments. *Building Acoustics, 25*(3), 195-197. doi:https://doi.org/10.1177/1351010X18793279

Aletta, F., Vander Mynsbrugge, T., Van de Velde, D., De Vriendt, P., Thomas, P., Filipan, K., . . . Devos, P. (2018). Awareness of 'sound' in nursing homes: A large-scale soundscape survey in Flanders (Belgium). *Building Acoustics, 25*(1), 43-59. doi:https://doi.org/10.1177/1351010X17748113

Banbury, S. P., & Berry, D. C. (2005). Office noise and employee concentration: Identifying causes of disruption and potential improvements. *Ergonomics, 48*(1), 25-37.

Beheshti, M. H., Roohalah Hajizadeh, R., Borhani Jebeli, M. B., & Tajpoor, A. (2018). The role of individual and personality traits in noise annoyance. *Annals of Medical and Health Sciences Research, 8*, 133-138.

Boyce, P. R. (1974). User's assessments of landscaped office. *Journal of Architectural Research, 3*, 44-62.

Bradley, J. S. (2003). The acoustical design of conventional open plan offices. *Canadian Acoustics, 27*(3), 23-30.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral & Brain Sciences, 24*(1), 87-185.

Di Blasio, S., Shtrepi, L., Puglisi, G. E., & Astolfi, A. (2019). A Cross-Sectional Survey on the Impact of Irrelevant Speech Noise on Annoyance, Mental Health and Well-being, Performance and Occupants' Behavior in Shared and Open-Plan Offices. *International Journal of Environmental Research and Public Health, 16*(2), 280. doi:https://doi.org/10.3390/ijerph16020280

Ding, S. (2008). Users' privacy preferences in open plan offices. *Facilities, 26*(9-10), 401-417.

Dokmeci Yorukoglu, P. N., & Kang, J. (2017). Development and testing of Indoor Soundscape Questionnaire for evaluating contextual experience in public spaces. *Building Acoustics, 24*(4), 307-324. doi:https://doi.org/10.1177/1351010X17743642

Ermann, M. (2015). *Architectural Acoustics Illustrated.* Hoboken, NJ: John Wiley & Sons.

Haapakangas, A., Hallman, D. M., Mathiassen, S. E., & Jahncke, H. (2018). Self-rated productivity and employee well-being in activity-based offices: The role of environmental perceptions and workspace use. *Building and Environment, 145*, 115-124. doi:10.1016/j.buildenv.2018.09.017

Haapakangasa, A., Hongisto, V., Varjo, J., & Lahtinen, M. (2018). Benefits of quiet workspaces in open-plan offices – Evidence from two office relocations. *Journal of Environmental Psychology, 56*, 63-75. doi:10.1016/j.jenvp.2018.03.003

Hay, B., & Kemp, M. F. (1972). Measurements of noise in air conditioned, landscaped offices. *Journal of Sound and Vibration, 23*, 363-373.

Innovative Workplace Insitute. (2018, January 8). *Workplace Wellbeing Assessment: PROWELL©*. Retrieved from Innovative Workplace Institute: https://www.innovativeworkplaceinstitute.org/workplace-wellbeing-prowell.php

International Organization for Standardization. (2012). *ISO 3382-3:2012 Acoustics — Measurement of room acoustic parameters — Part 3: Open plan officese.* Geneva: ISO.

Kang, J. (2019). Welcome to Acoustics—A New Open Access Journal for the Growing Multidisciplinary Scientific and Engineering Community and Beyond. *Acoustics, 1*(1), 1-2. doi:10.3390/acoustics1010001

Keighley, E. C. (1966). The determination of acceptability criteria for office noise. *Journal of Sound and Vibration, 4*(1), 73-87.

Keighley, E. C. (1970). Acceptability criteria for noise in large offices. *Journal of Sound and Vibration, 11*(1), 83-93.

Kjellberg, A., & Landstrom, U. (1994). Noise in the office: Part I - Guidelines for the practitioner. *Industrial Ergonomics, 14*, 87-91.

Kjellberg, A., & Landstrom, U. (1994). Noise in the office: Part II - The scientific basis (knowledge base) for the guide. *Industrial Ergonomics, 14*, 93-118.

Kjellberg, A., Landstrom, U., Tesarz, M., Soderberg, L., & Akerlund, E. (1996). The effects of nonphysical noise characteristics, ongoing task and noise sensitivity on annoyance and distraction due to noise at work. *Journal of Environmental Psychology, 16*, 123-136.

Krasnov, A., Green, E. R., Engels, B., & Corden, B. (2019). Enhanced speech privacy in office spaces. *Building Acoustics, 26*(1), 57-66.

Lee, Y. (2011). Lighting Quality and Acoustic Quality in LEED-Certified Buildings Using Occupant Evaluation. *Journal of Green Building, 6*(2), 139-155. doi:https://doi.org/10.1177/1420326X11409453

Lee, Y. (2019). Workplace Health and Its Impact on Human Capital: Seven Key Performance Indicators of Workplace Health. In O. Korhan (Ed.), *Indoor Environment and Health.* London: IntechOpen. doi:DOI: 10.5772/intechopen.85936

Lee, Y., & Schottenfeld, M. (2017). Use of well-being metrics by firms and industries. *OECD Workshop 2017: Measuring business impacts on people's well-being.* Paris: OECD.

Lee, Y., Osburn, M., & Wolkoff, J. (2018). Promoting workplace health and wellness through an open source analytics PROWELL. *International Facility Management Association.* Chicago.

Lindborg, P., & Friberg, A. (2016). Personality Traits Bias the Perceived Quality of Sonic Environments. *Applied Sciences, 6*(12), 405. doi:doi:10.3390/app6120405

Newsham, G. R. (2003). *Making the open-plan office a better place to work.* Ottawa: National Research Council of Canada.

Newsham, G. R., Veitch, J. A., & Charles, K. E. (2008). Risk factors for dissatisfaction with the indoor environment in open-plan offices: an analysis of COPE field study data. *Indoor Air, 18*(4), 271-282.

Park, J., Chung, S., Lee, J., Sung, J. H., Cho, S. W., & Sim, C. S. (2017). Noise sensitivity, rather than noise level, predicts the non-auditory effects of noise in community samples: a population-based survey. *BMC Public Health, 17*, 315. doi:10.1186/s12889-017-4244-5

Seddigh, A., Berntson, E., Jönsson, F., Bodin Danielson, C., & Westerlund, H. (2015). The effect of noise absorption variation in open-plan offices: A field study with a cross-over design. *Journal of Environmental Psychology, 44*, 34-44. doi:10.1016/j.jenvp.2015.08.004

Şentop, A., & Bayazıt, N. T. (2016). A tool to support the integration of noise control criteria in building design. *Building Acoustics, 23*(2), 92-109. doi:10.1177/1351010X16645972

Shepherd, D., Heinonen-Guzejev, M., Hautus, M. J., & Heikkilä, K. (2015). Elucidating the relationship between noise sensitivity and personality. *Noise and Health, 17*(76), 165-171.

Sundstrom, E., Town, J. P., Rice, R. W., Osborn, D. P., & Brill, M. (1994). Office noise, satisfaction, and performance. *Environment and behaviour, 26*(2), 195-222.

The US GSA. (2011). *Sound matters: How to achieve acoustic comfort in the contemporary office.* Washington, DC: The US GSA.

The US GSA. (2014). *Facilities standards for the public building services.* Washington, DC: The US GSA.

US GSA. (2014). The facilities standards for the public buildings service. Washington, DC, USA.

USGBC. (2019). LEED v4 Building Design and Construction.

USGSA. (2011). Sound matters: how to achieve acoustic comfort in the contemporary office. Washington, DC, USA.

Venetjoki, N., Kaarlela-Tuomaala, A., Keskinen, E., & Hongisto, V. (2006). The effect of speech and speech intelligibility on task performance. *Ergonomics, 49*(11), 1068-1091.

Virjonen, P., Keränen, J., & Hongisto, V. (2009). Determination of acoustical conditions in open-plan offices: proposal for a new measurement method and target values. *Acta Acustica united with Acustica, 95*(2), 279-290.

Warnock, A. C. (2004). *Acoustical design guide for open offices.* Ottawa: NRC Institute for Research in Construction.

WHO. (2019, January 08). *Constitution of WHO: principles*. Retrieved from World Health Organization: https://www.who.int/about/mission/en/

World Health Organization. (2018). Global action plan on physical activity 2018–2030: more active people for a healthier world. Geneva.