Acoustic comfort contribution to the overall indoor environmental quality in workplaces

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Abstract
Indoor Environmental Quality (IEQ) expresses the combined effect of thermal, acoustic, lighting conditions and indoor air quality, for its impact on comfort perception in workplaces. The importance assigned to the four IEQ domains is not equal in the main Building Performance Certification Programs (LEED, WELL, BREEAM). Acoustic comfort is one of the less accounted despite it significantly affects occupants' global comfort, health, well-being and work productivity, due to noise disturbance. Furthermore, acoustic comfort perception is influenced by occupants' behavior and related to the concepts of anthropic noise, speech privacy and discretion.
This study analyses the different weight of IEQ domains on global comfort and defines parameters functional to occupants' comfort assessment. To this aim, acoustic parameters have been analyzed and selected among the ones defined by standards and Building Performance Certification Programs, to additionally ascertain that defined values ensure comfort conditions.

Keywords: acoustic comfort, indoor environmental quality, office, protocol, standard

1 Introduction

Acoustic comfort, thermal comfort, visual comfort and indoor air quality (IAQ) are the main concerns of environmental comfort, that deals with the perception that people have about the environment nearby themselves. According to the European Commission assessment [1], people spend about 90% of their time in closed spaces, thus indoor conditions strongly affect occupants' comfort, well-being, health and work productivity [2–6]. The measure of the conditions that characterize a specific environment, from thermal, acoustic, lighting and IAQ point of view is addressed in the Indoor Environmental Quality field.
Acoustic comfort represents a physical condition where a person, in a specific environment, experiences a sense of well-being related to the hearing conditions. It is affected by the levels and the nature of the sound experienced in a space; thus, well-being or dissatisfaction, from an acoustic point of view, is not only determined by the level of noise. For this reason, silence is not necessarily associated to a real sense of comfort.
Indoor Environmental Quality in workplaces has been investigated for several decades and is an ongoing research [7]. In particular, acoustic comfort has been one of the most challenging aspects to deal with.

Providing acoustic comfort in offices consists in minimizing intruding noise and in guaranteeing satisfaction with the workspace, avoiding discomfort, stress and tiredness.
Standards, such as ISO 3382-3 [8], NF S31-080 [10] and ISO 22955 [9], define indexes for acoustic comfort assessment: noise levels, reverberation time, sound insulation, spatial decay and distraction distance are the indexes evaluated for acoustic environmental quality in offices.
Nevertheless, people's perception of comfort indoors can also be influenced by non-physical variables, not considered in standards [11–14], such as personal variables (psychological, social, economic, etc.) and contextual variables (building, office and work characteristics, etc.).
Methods for building and environmental assessment were established to define the quality of a building and the surrounding environment. Building Performance Certification Programs, such as LEED, WELL and BREEAM, refer to the entire life cycle of a building, evaluating the impact on the environment and on people's health throughout all its phases. Despite the high influence of acoustic comfort on global comfort, it is the less accounted domain in all these protocols, compared to the other domains (visual comfort, IAQ, thermal comfort). In recent years, to best detect the reference values based on subjects' perception, research moved towards desk monitoring systems of IEQ factors, that collect occupants' feedbacks.
This paper shows the results of the analysis of a literature review on indoor environmental factors and their effects on occupants' comfort, well-being, health and work productivity in offices, considering the influence of personal and contextual variables and highlighting the need to develop new methods for assessing the interactions between IEQ domains and those variables, to set new comfort thresholds, implement regulations and define design guidelines. In particular, the following paragraphs include the Building Performance Certification Programs which are applied to certify IEQ, the standards that codify the IEQ indexes and their reference values, the identification of other variables beyond the IEQ indexes which affect global comfort, the monitoring of indoor environmental parameters and the representation of results. Finally, the definition of new comfort ranges, able to guarantee global comfort in workplaces and based on the reference values included in the standards and protocols and on personal and contextual variables, is proposed.

2 Building Performance Certification Programs

In recent years, researchers demonstrated a growing interest in Building Performance Certification Programs, which assign specific scores to the different comfort domains. Figure 1 shows the weights given to the four comfort domains by the main Building Performance Certification Programs: LEED sets 47% of credits for IAQ and 35% for lighting environment, whereas BREEAM, DGNB, ITACA, LiderA (the result of an European research on the definition of a framework for sustainable buildings), CASBEE and HQE assign to each domain similar credits: 25-33% for IAQ, 17-33% for thermal environment, 17-33% for lighting environment and 17-22% for acoustic. On the other side, the WELL protocol is organised in seven concepts that influence the quality of indoor environment. Concerning this protocol, the weight percentages for the four environmental factors were rescaled with respect to their original values since they represent only four out of seven influencing aspects. Nevertheless, recently also LEED and BREEAM have expanded their credit structure, considering social and economic well-being, safety and security.
Despite it has not been widely considered, acoustic comfort strongly affects occupants' global comfort. It has an important role during the design phase of workplaces and particularly of open spaces, due to their layout. They are affected by many drawbacks to users from acoustic point of view, such as noise and distraction, lack of privacy, stress, greater risk of illness.

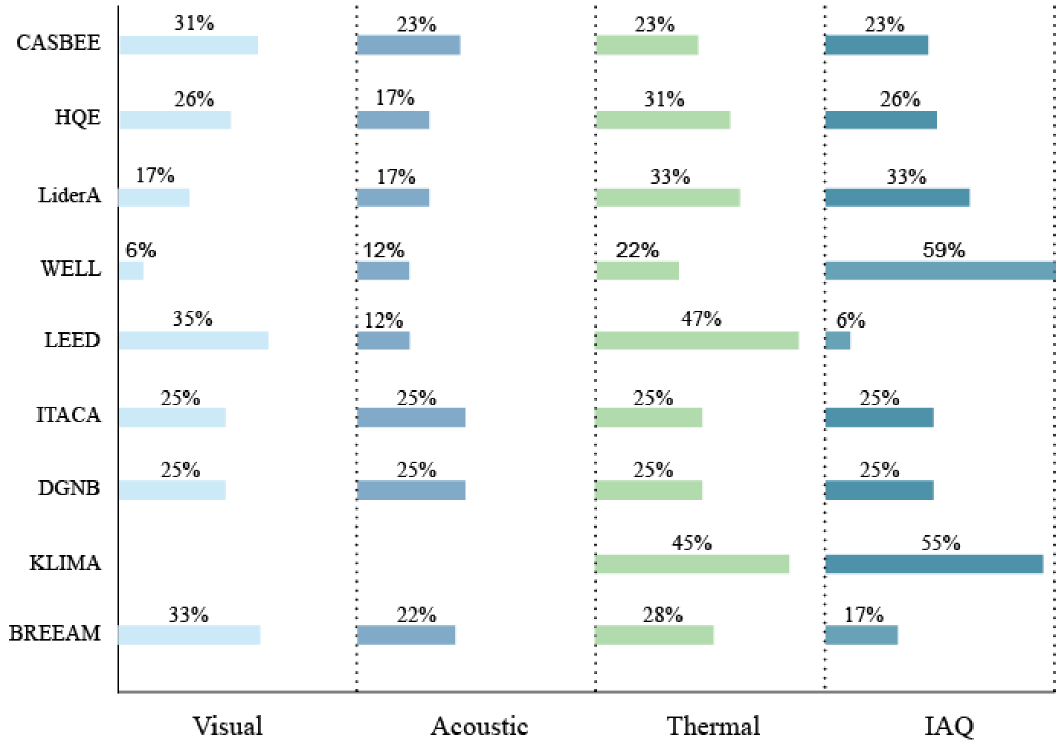

Figure 1 – Weights given to the four comfort domains by the main Building Performance Certification Programs. Concerning the WELL protocol, the weight percentages for the four environmental factors were rescaled with respect to their original values, so that their sum is equal to 100%.

The main acoustic indexes, codified in protocols, are listed in Table 1, that shows the differences between indexes values in the analysed rating systems. ITACA and LEED divide indexes in performance levels, giving specific information to optimize the results, whereas other protocols define only one range.

Table 1 – Acoustic indexes defined by protocols.

PROTOCOLS	Impact noise L'_{nTw} [dBA]	Insulation from internal airborne noise $D_{nT,A}$ [dB]	Reverberation time Tr [s]	Insulation from external noise $D_{m,nT,w}$ [dB]	Equipment noise L_{Aeq} [dBA]
BREEAM		$\geq 35 \div 55$	≤ 0.8		
CASACLIMA	≤ 55			≥ 42	≤ 32
CASBEE			$\leq 0.8 \div 1.5$		
DNGB	$\leq 46 \div 53$		≤ 0.4		
HQE		$\geq 32 \div 38$	$\leq 0.4 \div 0.8$		≤ 38
ITACA		$\geq 45 \div 50$	≤ 1.2	38 base performance 43 high performance	≤ 32 base performance ≤ 28 high performance
WELL		$\geq 35 \div 55$	≤ 0.6		

LEED				≥ 43 (Lev. I) ≥ 40 (Lev. II) ≥ 37 (Lev. III) ≥ 37 (Lev. IV)	≤ 25 (Lev. I) ≤ 28 (Lev. II) ≤ 32 (Lev. III) ≤ 37 (Lev. IV)

3 Acoustic comfort indexes

International standards define threshold values of acoustic comfort indexes set for the assessment of indoor acoustic conditions in workplaces. Standards analysis shows that acoustic regulations are organised in different ways. Standards ISO 22955 [9] and ISO 3382-3 [8] provide information to achieve acoustic quality in open space offices, whereas EN 16798 [15] is concerned with all the fours domains: thermal, acoustic, visual and IAQ.
Open spaces present more unfavourable conditions than other office typologies due to their dimensions and to the influence of occupants' behaviour: indeed, the perception of comfort is strongly related to the concepts of anthropic noise, speech privacy and discretion. Irrelevant speech noise (anthropic noise generated from conversations between colleagues, telephone calls and laughter) represents the main source of annoyance in open spaces [16]. Nevertheless, also other office layouts report other problems in acoustic comfort perception, therefore French acoustics standard NF S 31-080 [10], more accurate, sets indexes for three different office typologies: single office, shared office (from two to five people) and open space.
Furthermore, NF S 31-080 defines acoustic values for three different ranges of performance, overcoming the concept of comfort linked to a definition of well-being as risk avoidance, to guarantee different flexible ranges of comfort (starting from the satisfaction of minimum requirements). The "standard" level is the minimum threshold, that does not guarantee acoustic comfort, the "efficient" level ensures good and comfortable working conditions, the "highly efficient" level regards the maximum acoustic performance level, related to wellness and comfort. It is a qualitative notion related to office activity and use, in relation to the different typologies of tasks and workplaces.

4 Contextual and personal variables with influence on acoustic comfort perception

The process began with the analysis of papers (selected through "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" PRISMA method on Scopus search engine) on IEQ and environmental comfort perception in offices. Through this overview it was possible to select accurately articles on acoustic comfort and to investigate the relation between acoustic comfort and contextual and personal variables.
The result shows that occupants' perception of their workplace is due to measurable physical factors (regulated by standards and protocols) and influenced by contextual and personal variables.
Contextual variables, listed in Table 2, are encompassed in the categories: office characteristics, work characteristics and occupants' control on building systems and environment.
Personal variables, listed in Table 3, affecting acoustic comfort perception can be physiological, psychological, related to location, social status and work-related variables.
Both contextual and personal variables have a great influence on occupants' acoustic comfort perception, thus acoustic indexes are not sufficient to ensure comfort.
To analyse these non-IEQ variables, Post Occupancy Evaluation surveys are used [13][17–20]. They require different data (building properties, users' feedback and IEQ parameters) that are collected through interviews and on-site IEQ measurements [18–19]. Nevertheless, the reliability of subjective feedbacks collected through this instrument has been investigated, because it is based on occupants' responses about personal comfort perception [20–23].

New methods for assessing the interactions between IEQ factors and contextual and personal variables may be useful to implement regulations [23] and provide new design guidelines.
An optimal design of indoor conditions could ensure occupants' health, comfort and well-being. Particularly, a proper sound design of workplace allows to improve concentration and productivity, enabling a better communication and blocking unwanted noise.

Table 2 – Main contextual variables that influence acoustic comfort perception.

Category	**Variable**	Reference
Building characteristics	Building typology	[11]
Office characteristics	Office type	[13,24,25]
	Office layout	[26]
	Workspace location	[5,25,27]
	Proximity from a window	[27]
Work characteristics	Lack of privacy	[25]
	Work task	[25]
	Occupancy hours	[13]
Occupants' control on building systems and environment	Building automation	[26]
	Ease of use and knowledge of how to operate	[12]
	Noise management	[28]

Table 3 – Main personal variables that influence acoustic comfort perception.

Category	**Variable**	Reference
Physiological	Age	[11,12,24,29,30]
Location	Context of growth	[25]
	Country of residence	[13]
	Interaction with others	[13]
Social status	Social conditions	[13,30]
	Personal culture	[13]
	Lifestyle	[30]
Work-related variables	Tenure (number of years in the workplace building)	[13,30]
	Hours per week spent in the workplace	[30]
	Work position	[13]

5 Monitoring of indoor environmental conditions and representation of results

Monitoring systems of IEQ that combine multiple sensors in only one tool, can be used for this purpose, through an extensive assessment of the conditions that cause harmful effects on health and affect occupants' comfort and well-being [2].
Findings from the literature analysis highlight the scarcity of models assessing dynamically tracked parameters and employees' comfort perception, not providing the possibility to change the building settings [31–34]. In the research field, interfaces and apps on the monitoring of the combined effect of IEQ factors, able to provide information through the representation of global comfort perception, are rather used as a support tool [35–37]. Nevertheless, it is difficult to guarantee the improvement of acoustic conditions as response of a negative feedback, because often the noise is due to external noises, activities that take place in the office and occupants' behaviour. The process shown in Figure 2 foresees the use of interfaces to collect occupants' feedback regarding indoor environmental quality, combined with a sensor that constantly and simultaneously monitors comfort parameters, to guarantee global comfort in the workplace, increasing the productivity of employees and achieving energy savings. New measuring tools and devices able to communicate through graphic representation of global comfort measurements and perception, considering the dependence of comfort perception on personal variables, may be helpful for the definition of new performance levels of standards.

Figure 2 – Outcomes of the process related to IEQ assessment based on objective monitoring, occupants' feedback, data collection and interaction with the environmental conditions.

6 Standards as minimum performance level for risk avoidance

Since it has been demonstrated the influence on global comfort of these contextual and personal variables, it becomes now necessary to evaluate comfort not only by verifying the compliance with threshold values established by law, but also considering the influence of these variables. Standards define threshold values below which there is the certainty of achieving a discomfort condition, but above which comfort is not guaranteed.
Figure 3 shows the new thresholds and ranges defined by the authors after the analysis of the standards, protocols and literature. The first threshold separates the "discomfort" range from the "habitability" range and is defined by values of indexes set by standards. The "discomfort" range is determined by the failure to reach the minimum values required by law. The "habitability" range is determined by the reaching of the threshold values. When habitability threshold is reached, it is possible to overcome it to reach the "comfort" range. Thus, a new threshold is defined, that separates "habitability" range from "comfort" range, which can

be divided into two sub ranges: minor than 80% of occupants satisfied, and major than 80% of occupants satisfied. The ability to overcome this last threshold is due to the contribution of other factors, identified through the analysis of literature, that can improve comfort perception.
Hence, environmental settings defined by current regulations permit to avoid discomfort and ensure functional indoor conditions [38]. Protocols and standards were set to evaluate physical conditions of the indoor environment, not considering occupants' perception, owing to the great influence of demographic and contextual factors, that cannot be objectively quantified [11–12]. However, in recent years, Building Performance Certification Programs have given specific attention to comfort perception through scores assignment to each domain [18,39].
With these different comfort ranges, it may be possible to guarantee indoor environmental conditions in relation to occupants' needs and office tasks.

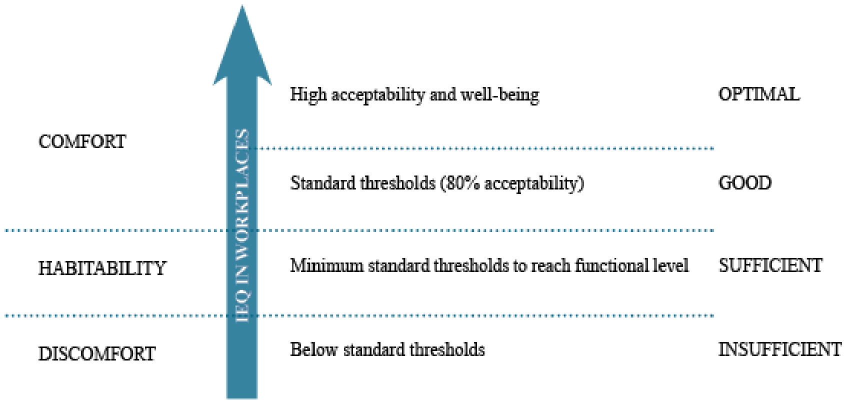

Figure 3 – Occupants' experience of IEQ in workplaces (adapted from [38]).

7 Conclusion

The analysis of acoustic comfort in relation to the overall comfort highlighted the great influence of this domain on occupants' indoor environmental perception.
Research results demonstrate that protocols don't give acoustics the proper importance. On the other side, standards define indexes values that allow to reach a minimum performance level.
The aforementioned comfort ranges, defined considering contextual and personal variables, may be used to better assess acoustic indoor conditions and acoustic comfort in relation to occupants' needs and office tasks, thus satisfying customer requests through different design solutions.

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