DEGREE PROJECT IN ENVIRONMENTAL ENGINEERING,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2017

Utvärdering av inomhusklimat och produktivitet – från etablerad praxis till innovativa metoder

Assessing Indoor Climate and Occupant Productivity – From Established Practice to Innovative Approaches

KONSTANTINOS VRETTOS

KTH ROYAL INSTITUTE OF TECHNOLOGY
SCHOOL OF ARCHITECTURE AND THE BUILT ENVIRONMENT

TRITA IES 2017:07

Abstract

As societies evolve, offices have become the places were the majority of working activities take place. Occupants' comfort in office buildings has always been a very important issue in the building sector and therefore guidelines regarding indoor comfort standards have been developed throughout the years. Nevertheless, there is a need for investments on new and innovative ideas which will go beyond the existing guidelines and move towards a more sustainable and human oriented office environment.

The present thesis aims at promoting this idea of sustainable offices by developing and presenting an innovative technological method which will provide the opportunity to measure the office workers' perceived comfort in real time. This in its turn will enable the building sector stakeholders to operate office buildings in a more sustainable way in terms of building services provision to their occupants.

In order to achieve these objectives, the first part of the thesis is dedicated in describing the basic indoor environmental components of the office environment as well as the possible associations between improved indoor environmental quality and occupants' health, wellbeing and productivity. The second part aims to provide a detailed presentation of the existing or emerging methods which are currently used in order to predict or directly measure occupants' perceived comfort in office places while in the same time discussing their current capabilities and limitations. In the final part, our proposed method, which could be used for the purposes of real time perceived comfort measurements, is presented. This proposed method includes four different steps which are separately presented with detailed instructions regarding their proper implementation.

Acknowledgments

I would like to thank first and foremost my supervisor Prof. Ivo Martinac, from the Royal Institute of Technology (KTH), for introducing me to the field of Building Services and Energy Systems through the quality course of ‘’Sustainable Buildings - Concept, Design, Construction and Operation’’. His rich knowledge and kindness were an inexhaustible source of inspiration for me and without his constant support, guidance and encouragement it would never have been possible to take this work to completion.

I would also like to express my gratitude to all my professors in the master of ‘’Environmental Engineering and Sustainable Infrastructure’’ for helping me to develop my knowledge and skills and for being my close companions in this exciting journey the last two years.

Last, but not least, I would like to thank my family for their immeasurable love and moral support which have always encouraged me to pursue my dreams. I would be ungrateful if I did not offer my special thanks to my brother, Dr. Vrettos Evangelos, for his valuable advice and assistance throughout my studies.

Table of Contents

1. Introduction

It is an undeniable fact that buildings were always closely connected to human life and survival. Their initial purpose was to provide shelter to the people and protect them from the weather conditions. As time went by and the technology evolved buildings were developed and transformed into a safe place where people could live, work and fulfil their aspirations. The proper design and operation of a building is of outmost importance in order to provide the desirable services to its occupants. The present thesis focuses on office buildings and examines their performance in terms of the quality of the services that they provide to their occupants. More specifically, it examines all the factors that affect their indoor environmental quality and attempts to draw the line between a good or bad indoor environment. The main point is to determine how indoor conditions affect the office workers and which can be the impacts on their health, well-being and productivity. Given the fact that staff costs typically account for about 90% of the total building operating costs it becomes clear that even a slight improvement of workers' satisfaction and productivity will bring considerable financial profit to the company. Based on that, the recent years more and more emphasis has been given on creating comfortable indoor environments and more importantly on understanding what is workers perception regarding the indoor conditions. The challenge of our times is to transform the model of building services provision and make it more dynamic and human oriented. It is essential to take into consideration the particularities of every individual and adapt the building services to their needs and desires. One of the key objectives in the field of building services and energy systems is the development of innovative technological products that are capable of measuring and recording in real time how the employees perceive the indoor environmental conditions. As described in chapter 5, many attempts have been made in this direction and several methods have been developed but there is still room for further improvements. Finally, it is worth mentioning that investing on this kind of technologies is profitable from every perspective since they improve human health, well-being and productivity, increase the financial profit of the company, decrease the operating costs through energy conservation and protect the environment by promoting a model of sustainable development.

2. Objectives

In the present thesis significant concepts related to indoor environmental quality, human health, wellbeing and productivity and assessment of perceived indoor comfort are presented and discussed in detail. More specifically, the main objectives of this thesis are to:

1) Provide an overview of the indoor environmental components and their related parameters as well as to thoroughly describe their influence on human health, wellbeing and productivity.
2) Present the existing and emerging methods for measuring-assessing the perceived comfort of the employees in office buildings while in the same time discussing about their capabilities and limitations.
3) Develop a method for real time evaluation of perceived indoor comfort, based on a different approach, which will go beyond the limitations of the currently used methods and provide new innovative solutions.

3. Indoor Environmental Components

3.1 Indoor air qualityClas

There is widespread agreement that modern lifestyle forces people to spend most of their time indoors mainly due to their professional duties. But apart from the workplace, people spend a significant part of their time in other indoor environments such as dwellings, schools, hospitals or other public buildings. Indoor air is the air that people breathe while being in these built environments and it is of vital importance. Sufficient evidence from scientific studies has shown that indoor air may have a great influence on the occupants of the buildings depending on its qualitative characteristics. According to its definition, indoor air quality ‘’is an indicator of the types and amounts of pollutants in the air that might cause discomfort or risk of adverse effects on human or animal health’’ [1]. From a building perspective, the sources of these pollutants can be either external or internal. Natural background sources such as forest fires, emissions from land and water, volcanoes and other geothermal sources are some of the most common external sources. However, apart from the natural sources, human activities such as industrial plants or vehicles emissions are considered as external sources of air pollutants. Indoor air pollutants can also come from internal sources which may include combustion processes, existing building materials, human activities and the presence of people, animals or plants. Indoor air quality is one of the most critical components of the indoor environmental quality in a building but in the same time one of the most complex one in terms of studying, understanding and controlling. This section aims to categorize the most common indoor air pollutants as well as to identify their sources. In addition to this, the guidelines regarding the recommended limits for these pollutants will be presented and an effective strategy in order to counter the indoor air quality problems will be analyzed. As mention before, addressing the problem of poor indoor air quality is a challenging task mainly due to the large number of different types and sources of the air pollutants. Based on that, and in order to facilitate this process, we will proceed by categorizing these pollutants in five distinct classes as follows: 1) organic pollutants, 2) inorganic pollutants, 3) classical pollutants, 4) indoor air pollutants and 5) bio aerosols.

3.1.1 Organic pollutants

Organic pollutants	**Sources**
Acrylonitrile	It may be released to the environment during the processes of production, handling, storage, transportation and disposal of wastes [2] Guideline: As low as possible
Benzene	External sources: Vehicle emissions, petrol stations and industries concerned with oil, coal, natural gas, chemicals and steel. Internal sources: Building and furnishing materials (such as plywood, particleboard furniture, flooring adhesives, fiberglass wood paneling, PVCs, rubber floorings and nylon carpets), heating and cooking systems, stored solvents and human activities (such as painting, cleaning, using mosquito repellents, printing, photocopying and smoking tobacco) [3] Guideline: As low as possible
Butadiene	Natural sources: Incomplete combustion in forest fires External sources: Vehicle emissions, petroleum refining, biomass burning, production of synthetic elastomers (such as tires and latex) and extraction of oil and gas. Internal sources: Smoking tobacco [4] Guideline: No guideline value available
Carbon disulfide	Natural sources: Released during the metabolic action of plants and soil bacteria External sources: During the manufacturing process of cellophane film and viscose fibres [5] Guideline: $\leq 100 \mu g/m^3$
Carbon monoxide	External sources: Vehicle emissions, incomplete combustion of fuels like gasoline, kerosene, natural gas, wood, coal or oil. Internal sources: Oven, stove, fireplace, water heater, space heater, clothes dryer, furnace, boilers and tobacco smoke.[6] Guideline: $\leq 100 mg/m^3$ (90ppm) for 15min $\leq$ 60mg/m3 (50ppm) for 35min $\leq$ 30mg/m3 (25ppm) for 1h $\leq$ 10mg/m3 (10ppm) for 8h
1,2-Dichloroethane	External sources: During the manufacture of vinyl chloride monomers and the synthesis of chlorinated solvents.[7] Guideline: $\leq 0.7 mg/m^3$
Dichloromethane	External sources: Manufacture of paint stripper, solvents, pharmaceuticals, photographic film base and numerous cleaning products. Internal sources: Released from hair-spray aerosols, paint strippers, cleaning products, lubricating products in aerosol form

	and room deodorants. [8] Guideline: $\leq$ 3 mg/ m^3
Formaldehyde	Outdoor sources: Smoke from forest fires, vehicle emissions, volcanoes, industrial emissions and power plants. Indoor sources: Furniture and wooden products (such as plywood, particleboard and fibreboard), insulating materials, paints, glues, textiles, adhesives, cleaning products (such as disinfectants, detergents, softeners and shoe products), electronic equipment (such as computers and photocopiers) and cosmetics (such as shampoos, liquid soaps and nail varnishes).[9] Guideline: $\leq$ 0.1 mg/ m^3 as a 30-min average
Polycyclic aromatic hydrocarbons	Outdoor sources: Emissions from vehicles, power generation plants, industrial plants, open burning and waste incinerators. Indoor sources: Smoking tobacco, fireplaces burning wood, fossil fuel and biomass combustion, cooking and heating practices which include combustion of solid fuels like dung, coal, agricultural residues and wood. [10] Guideline: As low as possible
Polychlorinated biphenyls	Indoor sources: Caulk and other sealants, fluorescent light ballasts, paints, bust, varnish, and several building materials such as ceiling tile, floor tile, laminate and fiberboard.[11] Guideline: No guideline value available
Polychlorinated dibenzodioxins and dibenzofurans	Outdoor sources: Production process of other chemicals such as chlorinated phenols, waste incineration, production of steel and iron, Chlorine bleaching of pulp and paper and car exhausts.[12] Guideline: No guideline value available
Styrene	Natural sources: Plants, trees and fungal and microbial metabolism External sources: Industrial processes involving products that contain styrene or its polymers such as plastics and rubber, automobile exhaust Indoor sources: insulation materials, fiberglass, plastic pipes, packing materials, photocopiers and tobacco smoke.[13] Guideline: : $\leq$ 0.26 mg/ m^3 (weekly average)
Tetrachloroethylene	Outdoor sources: Neighboring dry cleaning facilities, contaminated soil and industrial emissions. Indoor sources: Paint removers, printing inks, adhesives, spot and stain removers, water repellents, fragrances, wood cleaners and dry-cleaned fabrics. [14] Guideline: : $\leq$ 0.25 mg/ m^3
Toluene	Outdoor sources: Vehicle emissions and stored fuel vapours coming from attached garages Indoor sources: Paints, finishes, personal care products, adhesives and tobacco smoke. [15] Guideline: : $\leq$ 0.1 mg/ m^3 as a 30-min average
Trichloroethylene	Outdoor sources: Industrial processes such as cold cleaning of manufactured metal parts, dry cleaning, printing ink and paint production and extraction processes. Indoor sources: Wood stains, lubricants, adhesives, finishes, paint removers, cleaning products and typewriter correction fluid.[16]

	Guideline: As low as possible
Vinyl chloride	Outdoor sources: Emissions from industries which produce plastic such as vinyl chloride and PVC, bacterial degradation of chlorinated solvents, combustion of coal and incineration of municipal waste. Indoor sources: Tobacco smoke. [17] Guideline: As low as possible

3.1.2 Inorganic pollutants

Inorganic pollutants	**Sources**
Arsenic	Natural sources: Arsenic is a natural element of the earth's crust Outdoor sources: Emissions from industries concerning the processing of textiles, paper, glass, metal adhesives and wood preservatives. Indoor sources: Tobacco smoke [18] Guideline: As low as possible
Asbestos	Indoor sources: Asbestos is commonly found in constructions built before 1980 in cement roofs, insulation materials, textured paint, ceiling joints, wood burning stoves, vinyl floor tiles, adhesives, water pipes, boilers and in some soundproofing and decorative material. [19] Guideline: As low as possible
Cadmium	Natural sources: Cadmium can be found in the earth's crust Outdoor sources: Waste incineration, fossil fuel combustion and industrial emissions from processes such as metal mining and refining and production of phosphate fertilizers. Indoor sources: Tobacco smoke. [20] Guideline: ≤ 5 ng/ m^3
Chromium	Natural sources: Topsoil and rocks Outdoor sources: Oil and coal combustion, emissions from metal industries, incineration facilities, chemical plants, cement dust. Indoor sources: Tobacco smoke, cement, copiers, paints, pigments, textiles, porcelain and ceramics and wood preservatives. [21] Guideline: As low as possible
Hydrogen sulfide	Natural sources: Hot springs, volcanoes, underwater thermal vents and break down of plant and animal mater from bacteria. Outdoor sources: Industrial processes which include: natural gas and petroleum extraction, paper and textile manufacturing, chemical production and waste disposal. Indoor sources: Drain waste pipe leaks, failing septic system, septic tank leakage and ventilation system defects. [22] Guideline: ≤ 7 μg/ m^3 as a 30-min average
Lead	Outdoor: Lead mining and smelting, emissions from industries which produce batteries, plastics, rubber products, ceramics and waste incineration facilities. Indoor sources: Lead-based paint in buildings which were built before 1980. [23] Guideline: No guideline value available

Mercury	Natural sources: Forest fires and volcanoes. Outdoor sources: Hydroelectric plants, mining, paper industries, municipal and medical waste incineration, coal-fired power generation and manufacture of metal and cement. [24] Indoor sources: Thermostats, thermometers, lighting and electrical applications such as fluorescent lamps and LCD screens and latex paints used before 1990. [25] Guideline: ≤ 1 µg/ m^3
Nickel	Natural sources: Earths' crust Outdoor sources: Nickel mining, burning of fuel oils and municipal waste incineration Indoor sources: Coins, jewelry, decorations, stainless steel and electronics and tobacco smoke. [26] Guideline: No guideline value available

3.1.3 Classical pollutants

Classical pollutants	**Source**
Nitrogen dioxide	Natural sources: Intrusion of stratospheric nitrogen oxides, bacterial action and volcanoes. Outdoor sources: Combustion of fossil fuels for heating and power generation purposes, emissions from vehicles with internal combustion engines, production of nitric acid and use of explosives. Indoor sources: Tobacco smoke, oil and gas stoves, welding, kerosene heaters. [27] Guideline: : ≤ 40 µg/ m^3
Ozone	Outdoor sources: Ozone is created when short wavelength radiation from the sun reacts with nitrogen dioxide. This process is accelerated in the presence of volatile organic compounds and high temperatures. Indoor sources: Office equipment like photocopiers and laser printers, electrostatic air filters and electrostatic precipitators. [28] Guideline: : ≤ 100 µg/ m^3
Carbon dioxide	Natural sources: Volcanic eruptions, plant and animal respiration. Outdoor sources: Industrial processes such as cement production, combustion of fossil fuels for purposes like transportation and production of heat and power. Indoor sources: Occupants respiration. [29] Guideline: 650-1000 ppm (parts per million)
Particulate mater	Outdoor sources: Volcanic eruptions, dust storms, forest fires, animal fragments, plant debris, pollen, spores, algae, fungi, bacteria, viruses, industrial operations, traffic, mining, waste incineration, metal smelting and combustion of biomass and fossil fuels. Indoor sources: Human hair, skin flakes and tobacco smoke. [30] Guideline: No guideline value available
Sulfur dioxide	External sources: Vehicle emissions, incomplete combustion of fuels like gasoline, kerosene, natural gas, wood, coal or oil. Internal sources: Oven, stove, fireplace, water heater, space

	heater, clothes dryer, furnace, boilers and tobacco smoke. Guideline: 24 hours: 20 μg/m^3 10-min: 500 μg/m^3
Radon	Outdoor sources: Radon comes from the natural decay of radium and uranium which can be found in nearly all rocks and soils. Radon penetrates the buildings through cracks in floors and walls, construction joints, gaps in suspended floors and gaps around pipes. Indoor sources: Earth-derived building materials such as concrete, gypsum, cement, sand-lime bricks and ceramics. [31] [32] Guideline: As low as possible

3.1.4 Bioaerosols

Bioaerosols	**Sources**
Bacteria	Indoor sources: Human, pets, plants and poor maintained ventilation systems [33]
Fungi	Fungal spores enter the building from the outdoor environment. Indoor locations (such as carpets, furniture, showers, bathrooms and potted plants), act as amplification sites for the fungi growth. Specific indoor conditions such as high humidity, moisture and relatively high temperatures can accelerate the growth of fungi. [34]
Viruses	Indoor sources: Occupants and pets [35]
	Guideline for Bioaerosols: Total number of bioaerosol particles <1000 CFUs/m^3 (colony-forming units per m^3)

**The guideline values regarding the presence of the air pollutants in the indoor environment were retrieved from:* http://www.ca-perfection.eu/media/files/Perfection_D13_final.pdf

3.1.5 Countering indoor air quality problems

Indoor environmental quality and thus occupants' health, wellbeing and productivity is highly dependent on indoor air quality and this is something that will be further explained and analyzed in the following chapter. Therefore, it is necessary to take actions in order to achieve and maintain a high indoor air quality. Based on the number of potential contamination sources and the complex processes that influence the presence and the fate of the indoor air contaminants it becomes clear that the strategy that should be followed in order to guarantee indoor air of high quality is not simple. It requires scientific approach, technical knowledge and it involves the following phases:

Prevention

The first phase is relatively straightforward and it is the so called ''prevention phase''. In this phase the potential pollution sources should be identified and their characteristics become known. In this way it will be easier to avoid the occurrence of the indoor air pollutants by eliminating or isolating their sources.

Ventilation system

The second step involves the proper installation of the ventilation system. Modern mechanical ventilation systems provide controlled ventilation in combination with air filtration and temperature control. Air filtration acts like a trap for the outdoor airborne contaminants preventing them from penetrating the building and the temperature control hampers the generation and growth of certain indoor air contaminants. In addition to this, ventilation systems are responsible for the provision of fresh air within the buildings and the simultaneous removal of the contaminated air contributing in this way to a cleaner, safer and more pleasant indoor environment.

Air purification mechanisms

Although prevention and ventilation phases are two very effective mitigation measures regarding indoor air contamination the occurrence of certain contaminants, even in lower concentrations, in the indoor environment is inevitable. This is where air purification phase is needed. The purpose of the air purification mechanisms is to remove or capture the indoor contaminants. There are different air purification techniques that can be applied and they are selected according to the type and characteristics of the dominant indoor contaminants.

The first and most widespread technique is the utilization of air filters. Air filters are incorporated in HVAC systems and constitute a mechanical procedure of pollutants removal. The selection of the appropriate air filter should be done based on the characteristics of the main air contaminants (concentration, shape and dimensions) in order to achieve the highest efficiency possible.

Apart from the air filters, there are other air purification devices which take advantage of the electrical forces. Their operation principle is based on the fact that the electrically charged particulate contaminants can be trapped by the use of electrical fields. More specifically, they remove particulate pollutants through deposition on horizontal surfaces. Although this technique can be proven to be up to 95% efficient there are some disadvantages that need to be taken into account. For instance, its efficiency is gradually decreasing due to dust and particles accumulation on its surface. Moreover, air purification mechanisms based on electrical forces demand relatively large amounts of electricity in order to function and they are also responsible for high levels of ozone production. Finally, prolonged use of such devices is proven to cause damage to indoor furniture.

Other air purification methods involve chemical procedures in order to achieve the desirable result. Utilization of ozone activators is one of these methods during which ozone reacts with indoor air pollutants making them harmless for the occupants. Chemical absorption is another technique where chemical reaction of the pollutants takes place in the absorption medium but again the effectiveness of this technique depends on the indoor temperature and relative humidity. A last chemical method is the photocatalytic oxidation which is known for its technical advantages such as low electricity consumption, long life, low maintenance and low operating costs. However some disadvantages are also related with the utilization of this method with the most important to be its sensitivity to moisture and the potential inactivation of the catalyst due to pollution.

Monitoring and maintenance

Monitoring and maintenance of the installed equipment is something that should not be underestimated because these are the processes which determine the extent to which a comfortable indoor environment will be achieved. Therefore, visual inspections of the installed HVAC systems are deemed necessary in order to ascertain if they are properly designed and installed. Regular replacement of filters and other relevant maintenance interventions are also required in seek of the highest equipment efficiency. Finally, identifying and keeping records of indoor activities, defects, repairs or complaints and being able to constantly adjusting the system according to these changing needs and building characteristics, contributes decisively to a more dynamic and effective confrontation of the indoor air quality problems [37] [38].

3.2 Thermal environment

One of the most significant factors regarding the indoor environmental quality is the thermal comfort. Therefore, it is essential to define what thermal comfort stands for and in which ways it can affect the indoor environment. There are different definitions of thermal comfort with the most comprehensive to be the following: "Thermal comfort is a state of mind that expresses satisfaction with the thermal environment'' [39]. Despite the fact that this definition is commonly accepted it can be argued that it is a broad definition but this is inevitable since it attempts to describe a concept that is related to many different factors. More specifically, there are six basic factors that are directly related to thermal environment which will be individually examined and presented. The first four of them belong to the category which is called environmental factors while the two last are the so called personal factors [40].

Environmental factors	**Personal factors**
1. Air temperature	1. Clothing insulation
2. Radiant temperature	2. Metabolic rate
3. Air velocity	
4. Humidity	

Table 1.Factors affecting the thermal comfort [40]

3.2.1 Environmental factors

3.2.1.1 Air temperature

The first factor, air temperature, is a relatively simple concept that can be defined as the temperature of the air that is surrounding the human body and it is commonly measured in degrees Celsius (°C).

3.2.1.2 Radiant temperature

Radiant temperature is a more complicated concept which could have a significant impact on the occupants' thermal comfort. There are several warm objects that can be considered as radiant heat sources that can emit thermal radiation and consequently have an impact on how a person lose or gain heat to the environment. Examples of radiant heat sources could be: the sun, ovens, cookers, dryers, hot surfaces machinery etc. It is important to mention that air temperature does not affect the radiant heat loss or gain that a person experiences. For instance, when someone stands under the sun during a cold day of winter he can feel the radiant heat gain from the sun despite the fact that the ambient air temperature is low. Another example could be when a person is inside a room with a high air temperature but stands in front of a cold wall. He can still sense that heat is emitted from his body to the cold surface and this will definitely have an impact on his thermal comfort. The Mean Radiant Temperature (T_{mr}) of an environment is defined as'' that uniform temperature of an imaginary black enclosure which would result in the same heat loss by radiation from the person as the actual enclosure'' and can be calculated by the following equation:

$\bar{t}_r = \sqrt[4]{F_{p-i}(t_i + 273)^4}$-273 where t_i is the surface temperature of surface i [^{0}C]

F_{p-i} is the angle factor between the person and surface i $\sum F_{p-i} = 1$

.

As it can be understood measuring the radiant temperature can be an ambiguous and time consuming process. This is due to the fact that there is a constant variation of the angle factors as a person moves while working and changes his position, posture and body orientation [41].

3.2.1.3 Air velocity

Air velocity is another factor that can influence the thermal environment in office buildings. For example, as the indoor air is moving across the employees it can cool them if the air is cooler than the surrounding environment. On the contrary, even slight air movements in relatively cool or cold environments can be perceived as a draught by the employees degrading in this way their perceived comfort. Health problems such as stuffy nose as well as odor occurrence are attributed to still or stagnant air in the indoor environments. An example where air movements can be beneficial is in warm or humid indoor conditions since it can facilitate the process of heat loss through convection without changing the air temperature. Scientific research has shown that the tolerance of the office workers is high when the moving air is warm and it gets lower as the temperature of the air is decreasing.

3.2.1.4 Humidity

Humidity in office places is another determinant factor regarding occupants' thermal comfort. When examining the thermal comfort in offices there are two main types of humidity that need to be taken into consideration: the absolute and the relative humidity. According to their definitions:

Absolute Humidity [g/m^3] is ''the mass of dissolved water vapor, m_w per cubic meter of total moist air, V_{net}'' $AH = \frac{m_w}{V_{net}}$ [40].

Relative humidity is ''the ration of the partial vapor pressure of water to the saturation vapor pressure of water at a certain temperature of the moist air'' [40].

Excessively high or low levels of relative humidity can both be the cause of discomfort. More specifically, increased relative humidity combined with high temperatures can be particularly dangerous since it can even lead to a heat stroke. This is due to the fact that when the relative humidity is higher than the permissible limits, the human body loses his ability to naturally decrease its temperature because the process of perspiration and evaporation are hindered. As a result the employees may perceive indoor temperatures to be higher than they actually are. Individuals with asthma or heart problems are strictly recommended to avoid being exposed to such conditions for a prolonged period of time. High levels of relative humidity not only promote the growth and spread of mold but it can also trigger allergic reactions or contribute to the ongoing ones. On the other hand, humidity levels need to be kept above a threshold in order to maintain a pleasant indoor environment. Low relative humidity may lead to high levels of static electricity, dry nose, skin, lips and hair and itching. As mucous membranes in throat and nose dry out, the discomfort and the susceptibility to respiratory illness and colds are significantly increased. It would be useful to mention that too high or low relative humidity levels can have impacts on the interior of the building itself. As it has already been mentioned high humidity promotes the growing of mold on the building surfaces while low humidity levels damage the woodwork and furniture and lead to shrinkage, warping, hardwood separation and drawers loosen [43][44]. The degree of comfort in relation to the humidity levels depends on several factors such as age, activity, health, clothing and body characteristics and therefore there is a strong debate concerning the recommended humidity levels. However, extensive research has shown that the following limits can be used as a general guideline:

Relative Humidity	Winter temperature	Summer Temperature
30%	68.5°F – 75.5°F	74.0°F -80.0°F
40%	68.0°F – 75.0°F	73.5°F – 80.0°F
50%	68.0°F – 74.5°F	73.0°F – 79.0°F
60%	67.5°F – 74.0°F	73.0°F – 78.5°F

Table 2.Recommended ranges of temperature and relative humidity during winter and summer assuming typical winter and summer clothing at sedentary activity levels [42]

3.2.2 Personal factors

3.2.2.1 Clothing insulation

Clothing insulation belongs to the so called ''personal factors'' and is strongly related to thermal comfort. The main purpose of clothing is to insulate and protect the human body and to prevent the extensive heat loss that may lead to thermal discomfort.

Hence, clothing is classified according to the degree to which it can fulfill its purpose, meaning its insulation properties. The unit for the clothing insulation is the Clo unit where 1Clo = 0.155 $m^{2o}C/W$. According to the Clo scale the value for a naked person is 0.0 Clo and the corresponding value for a person wearing a typical business suit is 1.0 Clo. Every clothing unit has its characteristic Clo value so that the total Clo value for a person's entire clothing derives by just adding all the individual Clo values of the clothing units. Traditionally, office workers in companies are obligated to wear a specific uniform which may be elegant and formal but in some cases it can be the cause for thermal discomfort. In order to avoid that, more and more companies are adopting a new more dynamic model of clothing that enables their employees to adjust their clothing according to the environmental conditions in order to achieve maximum levels of thermal comfort [41].

3.2.2.2 Metabolic rate

Human metabolism can be considered as the body's motor and the energy that is released from the body in the form of heat depends on muscular activity. High levels of muscular activity result in increased metabolic rate which in its turn is the cause for increased heat production in the human body. Metabolism is measured in Met (1 Met = 58.15 W /m 2 of body surface area) and the heat production for a normal person (with a body surface area of 1.7m^2) with an activity level of 1Met is approximately 100W. Different activities have different Met values according to the intensity of the physical activity. More specifically, the metabolic rate for a person who is sleeping is equal to 0.8 Met, for a person during sports activities can reach the value of 10 Met the metabolic rate that corresponds to normal work in an office is 1.2 Met. Metabolic rate is of critical importance regarding employyes' thermal perception. For example, when the metabolic rate of an employee increases due to intensive physical activity, he starts having the impression that the indoor temperature is higher even if it has remained constant [41].

3.3 Visual environment

Given the fact that almost 80% of the information that we obtain through our senses is obtained through sight it becomes clear that visual comfort is a key aspect for a pleasant working environment. Visual comfort is a factor that needs to be approached with caution due to its importance and complexity. Its complexity lies to the fact that it depends on a combination of physical parameters such as illumination, luminance, luminous spectrum and risk of glare but also on physiological and psychological parameters associated to the individual such as his age-visual acuity and the possibility to have a view outside.

3.3.1 Illuminance

According to its definition ‘‘ Illuminance is the amount of light reaching a defined surface area’’ [45] and it is one of the most predominant factors for a comfortable visual environment. Illuminance is measured in lux and it is represented by the symbol E. The recommended levels of illuminance are determined according to the activity that takes place in the room and more specifically to the precision that is required for the visual task. As it can be seen in the figure below, the recommended illuminance levels for office spaces with normal visual task ranges between 500 and 1000 lux [46].

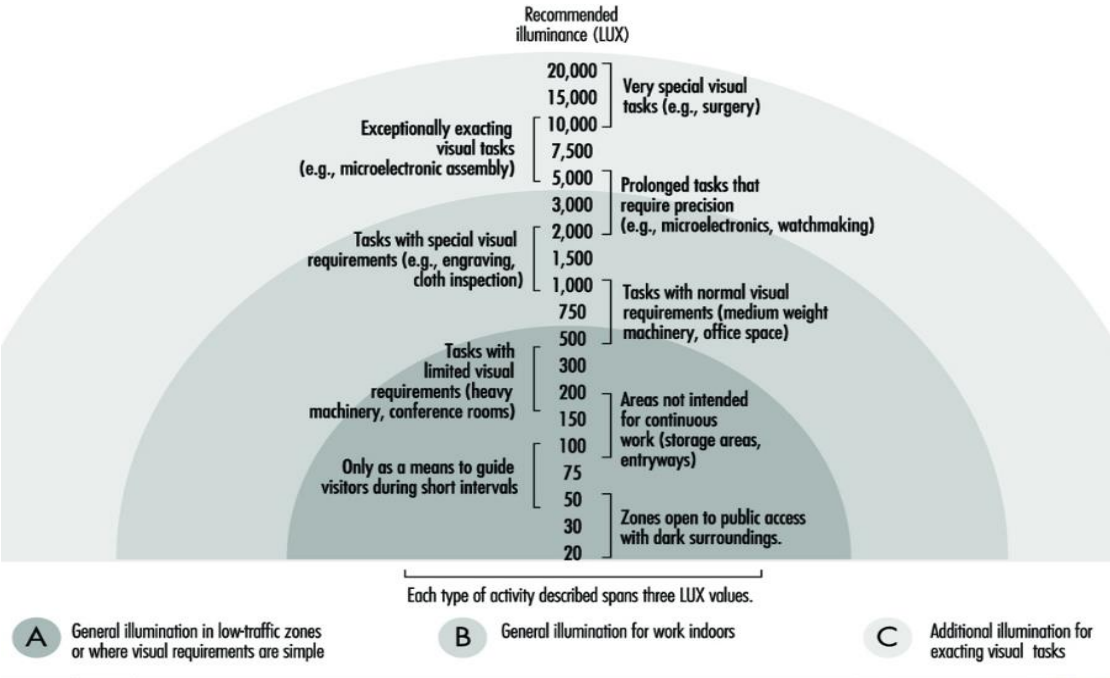


Figure 1. Reccomended illuminance levels as a function of performed tasks [46]

3.3.2 Luminance, Luminous flux and Luminous intensity

There are some more relevant magnitudes that are commonly used in the field of illumination with the most important of them to be the a) luminance, b) luminous flux and c) luminous intensity. The following figure provides a comprehensive and enlightening illustration of the meaning, definitions, S.I. units and the used symbols for these relevant magnitudes [45].

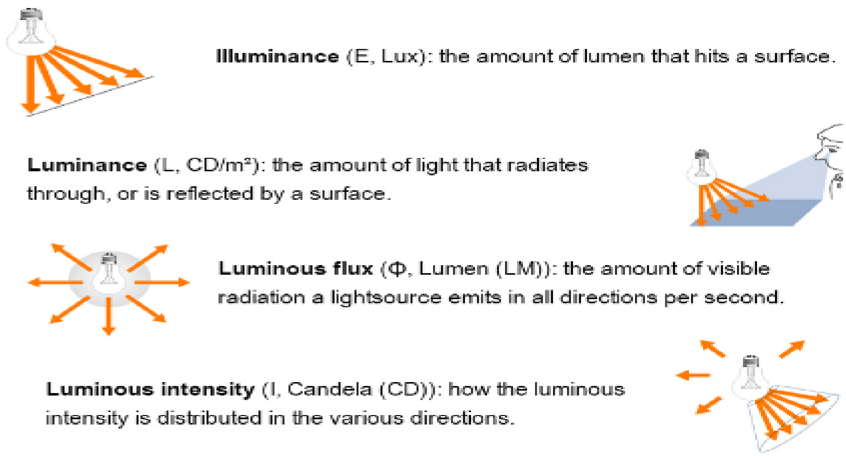


Figure 2. Representation of commonly used illumination magnitudes and their definitions, S.I. units and symbols [45]

3.3.3 Luminous distribution

Luminous distribution is a factor that has a considerable effect on how office workers perceive the visual environment. There are three main criteria related to the luminous distribution that need to be fulfilled in order to create a comfortable visual environment. The first one is the quality of light distribution. Light distribution can be a) uniform, which means that there is a general level of illumination in the space, b) localized, meaning that there is auxiliary lighting in specific areas where the visual task requires more intense light and c) mixed, meaning that apart from the general illumination a complementary lighting is used in areas where is needed. In order to achieve uniform illumination by efficiently exploiting the natural light, it is important to locate the furniture in a way that it does not obstruct apertures and place the desks in the areas where the natural light is maximal.

The second criterion is the luminance ratios. The main idea behind this criterion is the need to keep a balance between the bright and dark zones within the working place. In other words, extensive luminance differences must be avoided since they can be the cause for occupants' dissatisfaction. When such extreme differences in luminance occur in the field of vision the human eye must adapt to them. However, this is a process that decreases the vision performance and leads to tiredness. On the other hand, an office place with a completely uniform luminosity may lead to an impression of monotony which is equally dissatisfactory for the human eye. Concluding, different luminous zones within the working environment can be maintained under the condition that their differences regarding their luminosity ranging between acceptable limits.

The last criterion is the degree to which undesired shadows are avoided. Shadows can be created by the presence of an object between the source of light and the visual task and they can considerably decrease the visual comfort. The main reason is that shadows decrease the contrast between the visual task and its background making it difficult for the human eye to precisely perceive all the details of the object of interest. An effective solution for this particular case would be to adjust the source of light according to if a person is left or right handed. So, light coming from the left would be more convenient for right-handed people while light coming mainly from the right would enhance the visual comfort of left-handed people [46].

3.3.4 Risk of glare

Excessive luminance or extreme luminance differences in the visual field can be the cause for the phenomenon of glare. Glare is directly connected to visual discomfort since it decreases the capacity of the eye to distinguish objects and therefore actions towards the avoidance of this phenomenon within the workplace are required. The first step is to ensure that the luminance of the source of the light ranges between specific recommended limits. Research has shown that the maximum acceptable luminance by direct observation is 7.500cd/m^2. Selection of lighting equipment with higher luminance values than this, involve high risk of producing glare. Apart from the luminance of the source of light, its location is crucial regarding the risk of glare.

As it can be seen in the figure below, the risk of glare is higher when a) the source of light is located within a 45^{o} angle of the individual's line of sight b) the height of the source of light is considerably low and c) the size of the room is large enough to allow the presence of glare [46].

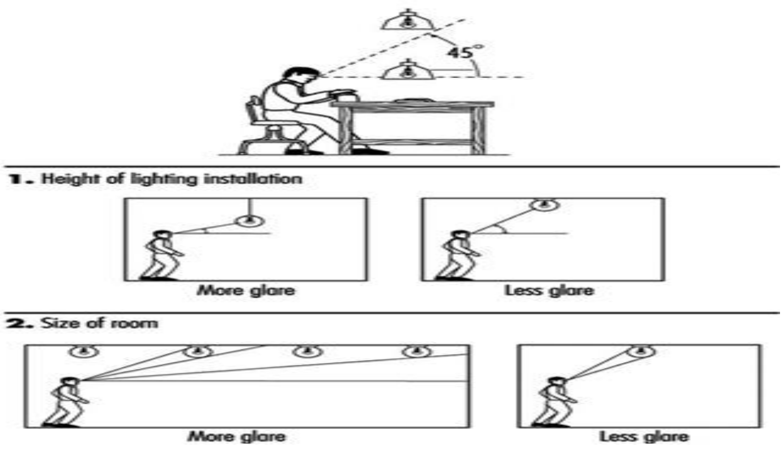


Figure 3. Factors affecting the occurrence of glare [46]

3.3.5 Luminance ratios

Another factor related to the occurrence of glare is the luminance ratios among the different surfaces and objects within the field of vision. As the differences in illuminance among the objects and surfaces increases, the risk of glare gets higher as well and thus the visual comfort of the occupants deteriorates. The suggested luminance ratios for an optimal visual performance are presented below:

Visual task – work surface: 3:1

Visual task – surroundings: 10:1

Although respecting the recommended luminance levels and luminance ratios is the first and most important steps towards avoiding risk of glare, the time of exposure should not be underestimated. Glare can be present even when a person is exposed to relatively low luminance but for a prolonged period of time [46].

3.3.6 Color rendering

The color rendering of a light source expresses its capacity to reproduce the color of an object in a realistic and faithful manner. Light sources emitting spectrum similar to the natural light are considered to have a satisfying color rendering. According to CIE (International Lighting Commission), light sources are classified in five different groups according to their R_a value. R_a values indicate the quality of color rendering of the light sources and they range between 20 and 100. Low R_a values indicate poor color matching while high values indicate more accurate color matching. The highest R_a value can only be given to light sources with a spectrum similar to the spectrum of natural light. It is important to select the appropriate lighting equipment according to the requirements of the place where it will be installed. The careful selection of the lighting equipment, in terms of its color rendering capacity, is of great importance since it can influence the visual comfort of the occupants. There is a direct relationship between some colored radiations and psychological or physiological effects on the occupants' nervous system. White light and yellow-green radiations are stimulating and promote concentration while grey and dark colors can lead to a depressing atmosphere. It is also proven that blue color can have an impact on circadian cycle. In addition to this, perception of colors can modify the apparent dimension of the room. In buildings of exaggerated size warm colors should be preferred while in rooms of reduced size cold colors are recommended. It should be mentioned that the simultaneous presence of both warm and cold colors in a room can interfere with the nervous system and lead to visual disturbances.

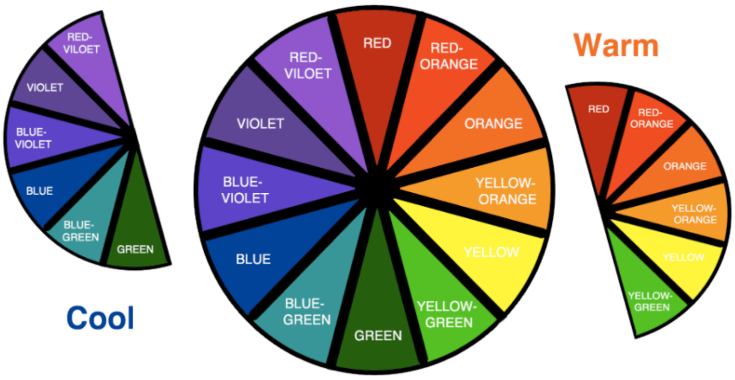


Figure 4. Representation of cold and warm colors in a color wheel [181]

So far the physical parameters which are associated to the visual comfort where presented and examined but there are also some physiological and psychological parameters that are worth mentioning [46].

3.3.7 Age and Visual acuity

The most common physiological parameter is called visual acuity and it reflects the clarity of the vision of an individual. Visual acuity deteriorates with time and the relationship between age and visual acuity is presented in the following figure:

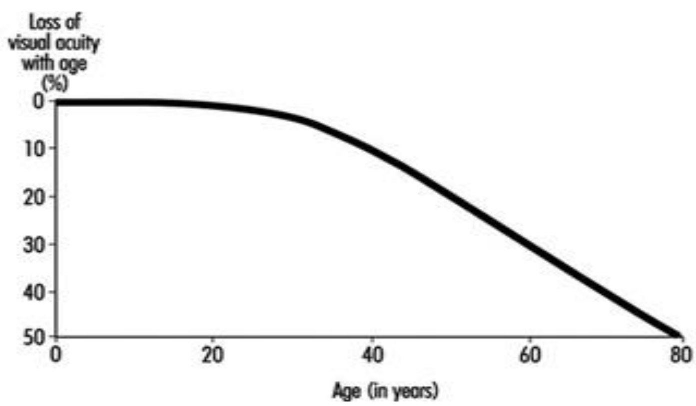


Figure 5. Relationship between age and loss of visual acuity [46]

This relationship needs to be taken into consideration when calculating the proper levels of illumination in a working place, meaning that the level of illumination needs to be adjusted to each individual's visual acuity [46].

3.3.8 Views outside and Biophilia

This chapter describes how the presence of a window near to the office of an employee can enhance his visual comfort. There are two main ways in which windows can be proven beneficial for the office workers. The first advantage is the provision of daylight that penetrates the building through the window. Natural light not only has a positive influence in the psychosomatic wellbeing of the occupants but also consist the ideal source of light since the sensitivity of the human eye is naturally adapted at the light of the sun. Moreover, windows provide the occupants with the opportunity to have a view outside which is something that greatly affects their visual satisfaction. Longer distance views break the monotony of the constant focus on screens or written documents and allow the eye to adjust and re-focus. Recent studies have also revealed that the benefits of the views outside can be even greater if the view is aesthetically pleasing and more particularly if it features nature. This is supported by the Biophilia hypothesis which supports the idea that humans have an innate tendency to be in contact with nature. In this perspective, a window that provides a view in nature satisfies this inner human instinct and promotes physical and mental health [47].

3.4 Acoustical environment

Sound is a mechanical wave that can be transmitted through a solid, liquid or gas. More specifically, sound is transmitted through the oscillation (back and forth movement) of the medium particles with frequencies that can stimulate the human organs of hearing. Sound is essential for our everyday life since it is the dominant means of communication between humans but there are cases where sound can be disturbing. When the pressure of the sound wave exceeds a specific limit then the sound becomes noise. In this sense, noise is an unwanted sound or an environmental pollutant that can have negative psychological or physiological effects. The most commonly used unit for measuring the strength of sound pressure is called decibel and its symbol is the dB. The figure below presents indicative examples of different activities with their corresponding dB levels:

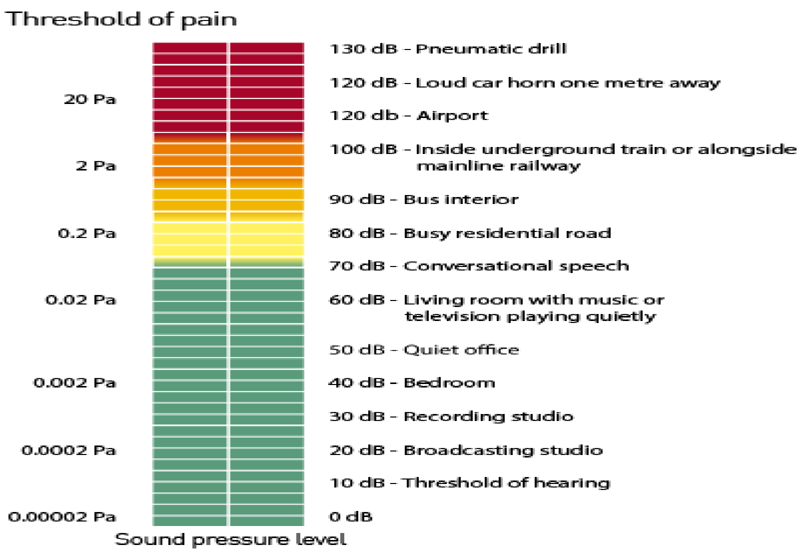


Figure 6. Different activities with their corresponding dD levels [182]

Noise resulting from internal or external sources may have a negative influence on the occupants of office buildings. In fact, distraction from noise is one of the leading causes of workers' dissatisfaction with the office environment. Therefore, office buildings' designers need to set noise redaction as a priority in order to create a pleasant and satisfying acoustical environment for the employees. Achieving the objective of acoustical comfort in office buildings requires special attention on the three following topics:

- Room acoustical quality
- Sound insulation between rooms
- Background noise [48]

3.4.1 Room acoustical quality

The topic of the room acoustical quality contains two subtopics that will be presented and analyzed separately. The first of them is the so called ''reverberation time'' that greatly affects the acoustical quality of the room. Reverberation time is the time needed for the sound pressure to drop 60 dB below its original level (after switching of the source of the sound). A general rule is that sound absorbing materials in the working space decrease the reverberation time while sound reflecting materials make it longer. Reverberation time in a room can be calculated by using the formula: $T_{60}=1/6*(V/A)$ where T_{60} is the reverberation time, V is the total volume of the room in m^3 and A is the total absorption in the room. Based on this formula it becomes clear that reverberation time is proportional to the size of the room and inversely proportional to the total surface of the absorbing materials in the room. Measuring the total volume of the room may be straightforward but in order to measure the total absorption in m^2 the next equation can be used: $A= a_1*S_1+a_2*S_2+a_3*S_3+\ldots$ where S_n is the surface area of the material in m^2 and a_n is the absorption coefficient of the materials which can take values between 0 and 1. It is worth mentioning that an open window is considered as a totally absorbing material with an absorption coefficient equal to 1 since all the sound will escape the room through it. By using the two previous formulas the representative reverberation times for different types of rooms where calculated and they are illustrated below [48]:

Type of room	Reverberation time T (sec)
Furnished room	0.5
Office space	0.5 – 0.7
Landscape office	0.7 – 0.9
Classroom	0.6 – 0.8
Music room	0.8 – 1.2
Theatre	0.9 – 1.3
Chamber music hall	1.2 – 1.5
Opera	1.2 – 1.6
Concerthall	1.7 – 2.3
Church (organ music)	1.5 – 2.5

Table 3. Different types of rooms and their representative reverberation times [48]

The second issue to be examined regarding the acoustical performance of the room is the presence of undesirable echo's and reflections. When two people talk to each other in a room the one of them acts as a source of sound and the other as a receiver. During this process the receiver experiences not only the original (direct) sound but also its reflections from the walls, ceiling and nearby reflective objects such as room furniture. The first reflections are called ''pseudo-direct sound'' and they are perceived within the first 20 milliseconds. Then the so called ''early reflections'' arrive within about 20 – 80 milliseconds and finally the ''late reflections'' are perceived in the form of an unpleasant echo. Both early and late reflections can negatively affect speech intelligibility and thus acoustical comfort of the occupants. The extent to which reflected sounds and echoes appear in a room depends on the size and shape of the room and the presence and location of the absorbing materials. Generally speaking long rooms and tall ceilings create the preconditions for the existence of reflections and echoes which however can be mitigated by the installation of sound absorbing materials such as acoustic panels or the proper placement of furniture with sound absorbing properties [49][50].

3.4.2 Sound insulation between rooms

Sound insulation between rooms is crucial in order to ensure a satisfying acoustical environment for its occupants. When examining the acoustical quality of a room, there are two main types of sounds that are of interest: 1) the air-borne sounds and 2) the structure borne sounds. Both types can be proven very annoying for the occupants and lead to high levels of dissatisfaction.

3.4.2.1 Air-borne sound

Air-borne sound is transmitted through the air and is typically generated by a) speech, b) television or radio and c) animals sounds. Poor standards of workmanship may be the cause for direct transmission of airborne sounds between spaces. However, even if the separating element between two rooms provides a sufficient sound insulation, airborne sounds can be transmitted in the form of flanking sound through gaps around the edge of the door, voids such as suspended ceilings and wall cavities, penetrating joists or ductwork and pipework. A last type of airborne sound is the ‘’circulation sound’’ which is transmitted between rooms through an adjacent space such as a plenum. Addressing airborne sound can be challenging and requires action early in the design stage of the building. Proper design and minimization of the inadvertent downgrading of the sound insulation during the construction phase will prevent the transmission of the sound through the building fabric. Moreover, the installation of sound absorbing materials inside the building spaces will enhance their acoustical quality by reducing the sound that is reflected from the surrounding building elements such as ceiling and walls. Finally, particular attention should be given to the junctions between elements in order to eliminate any gaps, voids that may provide a flanking route through which airborne sound will be transmitted [51].

3.4.2.2 Structure borne sound

Structure borne sound is the sound that is generated by a vibration against or an impact on a part of the building fabric. Structure borne sound is then transmitted through the building structure to adjacent building parts such as neighboring rooms until it finally completely attenuates. Although there is the tendency to separately study and examine the causes and the results of the airborne and structure borne sounds within a building, there is a strong relation between them. This lies to the fact that building elements may vibrate when an airborne sound wave strikes them resulting in a structure borne sound but also structural vibrations may radiate from building elements resulting in air borne sound generation. Typical examples of structure borne sounds are footsteps, sliding chairs or falling objects. The ‘’life’’ of a structure borne sound comprises five different phases which are outlined below:

1) Generation of sound (the source of a vibration or oscillation)
2) Transmission (the transmission of the oscillatory energy from its source to the building structure)
3) Propagation (the distribution of the energy through the building structure)
4) Attenuation (Sound wave gradually fades away as it is transmitted throughout the building fabric)
5) Radiation (the sound emission from a building surface)

Building designers have developed modern techniques that can be applied in order to reduce or even eliminate structure borne sound and its annoying consequences. These techniques comprise solutions such as:

1) Carpets or covering foil (prevention of structure borne sound generation)
2) Resilient underlay (similar effect to carpets and covering foil)
3) Soundproofing compounds (applied between two rigid surfaces in order to absorb the vibrations caused by structure borne sound waves)
4) Suspended ceiling systems (prevention of structure borne sound emission)

5) Floating floors (they are constructed over the subfloor creating a gap between these two surfaces which is then filled with a sound absorbing material which in its turn prevents the transmission of structure borne sound) [52].

3.4.3 Background noise

The last parameter that can affect the indoor acoustical conditions in office buildings is the background noise. Background noise is a category of noise that comprises of two other subcategories named a) installation noise and b) environmental noise.

The cause for the installation noise is the operation of the technical installations that are necessary for a building in order to provide quality services to its occupants. Typical examples of installations that are responsible for the background noise generation are the air-conditioning units, sanitary systems and elevators. Building designers have developed a simple but effective strategy in order to protect building occupants from background noise. This strategy is based on the fact that sound attenuates with distance and consequently building's technical installations are located as far as possible from working or living spaces. The presence of background noise is highly dependent on the noise coming outside the building. This kind of noise is called environmental noise and possible sources of such a noise can be traffic (cars, trains and airplanes), industry or crowded places [48].

4 Indoor Environmental Quality - Human health, wellbeing and productivity

4.1 Introduction

In the third chapter the most significant factors which affect the indoor environmental quality in buildings were presented. The aim of the present chapter is to reveal the hidden links between Indoor Environmental Quality and occupants' health, well-being and productivity by focusing in office buildings. It is anticipated that presenting the available scientific evidence will act as a strong incentive and motivation for all the relevant stakeholders to invest in improved indoor environmental quality.

The terms of health, wellbeing and productivity will be used quite frequently in this work and hence the clarification of their meaning will be attempted. We should however mention that strictly defining these terms is a tricky process due to their strong interdependence relationships. Health is referring to physical and mental health while the term of wellbeing is used to describe broader feelings of happiness or perceptions of satisfaction with the indoor environment. Although superficially health and wellbeing seem to describe two completely distinct situations there is actually a deeper relationship between them. For instance, one could say that wellbeing is the equivalent of having a positive mental health. Productivity mainly refers to business oriented outputs and it involves several task performance related metrics. Given the fact that health and wellbeing directly affect productivity, it becomes more evident that delineating between these three terms is a challenging task which is not always necessary [47].

There is hardly anything more important than our health and well-being, and as it will be discussed latter in this chapter, both of them are very closely related to the Indoor Environmental Quality of the office buildings. In addition to this, a healthy and satisfied workforce is the main component of a productive and successful business. There is a huge difference between a simply not harmful office environment and environments where health and wellbeing are encouraged and employees' productivity is promoted in practice. Even though the previous statements sound very obvious, they do not seem to have a great influence on the real estate sector yet, in the sense that they are not seriously taken into consideration during building's design and construction or other financial decision making processes. Therefore, it would be essential to clearly illustrate how investing in improved indoor environmental quality of office buildings is beneficial in the long run for the owner of the building, the employer and the employees.

People spend approximately 90% of our time indoors and a significant part of this percentage corresponds to the time that we are working in our office. Another meaningful statistic is that staff costs typically account for 90% of the business' total operating costs [47]. Given these two facts, it becomes clear that even the slightest improvement in the health, wellbeing and productivity of the employees can have a great financial impact for the company. After having explicitly stated that investing in improved indoor environmental quality is profitable and beneficial for everyone, it is now time to discuss how these benefits are shared among the different stakeholders. There are two common scenarios regarding the ownership of the building that is used as an office space. So, either the employer of the company is the person who owns the building or the owner of the building (lessor) leases his building to the employer (lessee). Based on these two scenarios, illustrative schematic representations will be provided in order to describe the way in which the building owners, employers, building occupants and society are favored through the investment on improved IEQ. As it can be seen in the following figure, in the first scenario of owner occupied buildings the way in which the building owner benefits is relatively straightforward. He makes an investment for a better IEQ which in its turn results in higher productivity, less complaints and less sick leave from an employee perspective. Increased productivity and money savings from lower sick leave incidents are translated into economic benefits which are then directly return to the owner of the building [53].

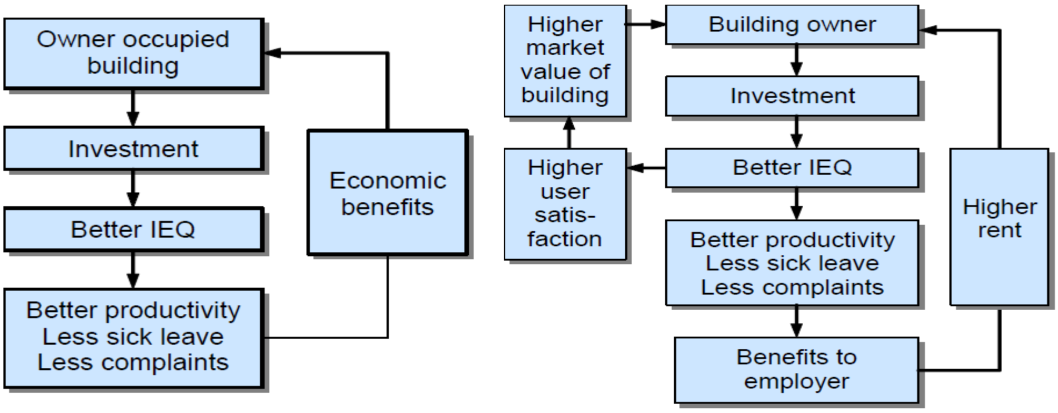


Figure 7. Schematic representation of the benefits of better IEQ in two different building ownership scenarios (first scenario on the left, second scenario on the right) [53]

In the second scenario, it is again the owner of the building how invests his money for a better IEQ, but in this case the way in which his investment pays off is different. This time, the improved IEQ implies higher occupants’ satisfaction which results in a higher market value for the building. In addition to this, the building owner may request a higher rent from the employer due to the better indoor environment that he provides. In the same time, the employer is benefited from the increased productivity, less sick leave and fewer occupants complains which is of course a result of the improved IEQ.

At this point it is important to emphasize that the building owner and the employer are not the only ones who receive the benefits from the initial investment. Building occupants are the first who perceive the effects of the improved IEQ which is something that has an obvious positive consequence in their health and wellbeing. Finally, society is also benefited through a process which is not very evident. Improved IEQ contributes to a healthier workforce which means less sick people. Given the fact that medical care costs for the employees are usually covered from the national budget, the reduced number of sick employees can be translated into less deduction of money from the national budget. This money can then return to the society in the sense that they can be used to cover other current social needs [53].

4.2 Thermal environment and human health

According to World Health Organization’s guidance on thermal comfort, the temperature of the ambient environment in office places should range between 18^{o}C and 24^{o}C. Chronic exposure of the employees in temperatures that do not complie with these limits can harm their health. The consequences from such an exposure vary from short term health effects to permanent damages or even death in extreme cases.

4.2.1 Health effects from hot environments

-When ambient temperature rises above the reccomended limits there is an increasing risk of heat stress. The immidiate consequences of heat stress is the body’s dehidration and its inability to maintain its normal temperature.

-Another dangerous situation is the heat exhaustion which is also caused by increased temperatures and it can be developed into heat stroke which is a life-threatening condition. Common warning signs of the heat exhaustion may be increased sweating and heart rate, muscle cramps, dizzines, headache, nausea, weakness, faining and vomiting.

-Heat stroke is a life-threatening condition which requires immediate medical assistance. Heat stroke occurs when the temperature of the human body is rissing rapidly and the symptoms are similar to the heat exhaustion with the difference that the skin may be dry and without sweating.

- Excessive heat may also be the cause for skin rashes.

-Long term exposure to high indoor temperatures may exacerbate the health condition of people suffering from other chronic ilnesses which may include respiratory conditions such as asthma, cardio-vascular conditions, arthritis and diabetes [54].

4.2.2 Health effects from cold environments

-Hypothermia is the most serious health threat from prolonged exposure to cold environments and requires immediate medical care.

Other important cold-related health effects are: 1) Loss of co-ordination and slurred speech, 2) decreased mental skills, 3) pain and lower finger dexterity, 4) slow breathing and drowsiness, 5) Shivering, 6) disease flare-ups (asthma) and 7) increased risk of muscle injuries [54].

4.2.3 Health effects related to Relative Humidity

Apart from ambient temperature, the presence of relative humidity should also be limited within the recommended values in order to protect the health of the building occupants. Too low or too high levels of relative humidity in the indoor environments can have a direct effect on occupants health since they mostly affect the nose cell membrane. This can lead to respiration problems due to contraction and nose tissue inflammations or fever and influenza. In addition to this, relative humidity has indirect effects on human health since it promotes the growth of respiratory diseases and allergies and the existance and dispersion of diseases such as fungi, house dust mite, protozoa, bacteria and virus (e,g, flu, common cold). Humidity levels may also affect the intensity of the chemical pollution by interacting with the materials that are used inside the buildings. Although the existance of humidity in the indoor environments is inevitable, it should be maintained between acceptable levels in order to minimize its adverse health effects on human beings. The figure that is presented below provides a comprehensive overview of the relationship between the relative humidity levels and the magnitude of the corresponding health threats [55].

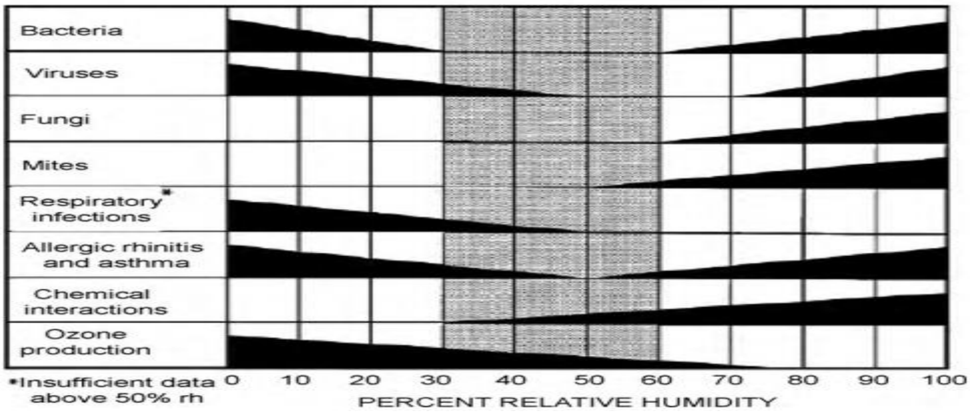


Figure 8. Adverse health effects occurrence in relation to relative humidity levels – optimum relative humidity range [55]

4.3 Thermal environment and productivity

Productivity is a vital concept for every company because it is one of the major factors which determine its financial sustainability. Therefore, it would be necessary to define what productivity is and how it is related to thermal environment. In principle,'' productivity is an index ration of output relative to input'' [53]. Based on this definition and from a company's perspective, productivity can be enhanced either by reducing the costs (input) or by improving the performance of the employees meaning the quantity and/or quality of the service or product that they deliver (output). Thus, any intervention that could lead to increase performance will also contribute towards improved productivity. Improved thermal environment could be one of these interventions since, as it will be discussed in the present section, it may have a great influence on employees' performance. There are several mechanisms through which thermal conditions in office places can affect the performance of the employees. The most significant of them are illustrated in the following diagram [56]:

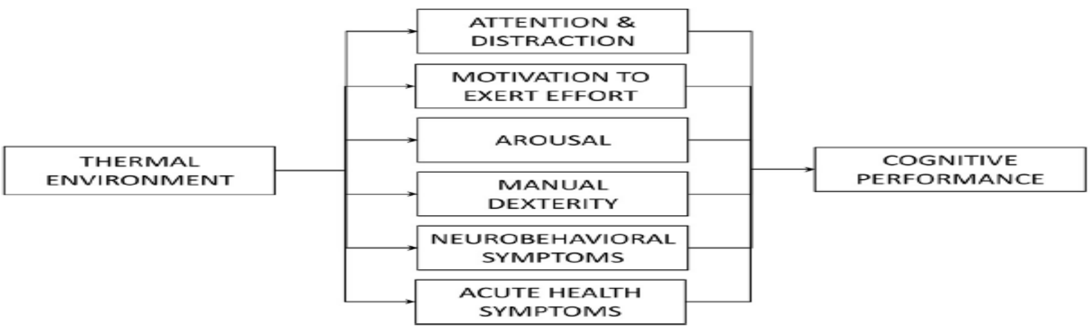


Figure 9. Different mechanisms through which thermal environment may affect human cognitive performance [60]

As it can be seen, thermal discomfort leads to distraction of the attention of the employees and decreases their motivation to exert more effort. Also, as a consequence of cold indoor environments, the temperature of the fingers decreases and consequently the manual dexterity of the employees declines as well. In addition to this, the physiological responses to heat stress result in reduce arousal which means that the state of activation of the employees is significantly reduced. Finally, warmth exacerbates the prevalence of the so called Sick Building Syndrome (SBS) which have a great influence on employees' productivity and therefore a special reference to it will be done in Chapter 4.4 ''Indoor air quality – human health and well-being''.

Several studies have been conducted in order to determine the relationship between the performance of the employees and the thermal conditions in office places. The common characteristic of these studies is that they tried to measure objective indicators of performance that were relevant to office work activities. Typical examples of such indicators include text processing, simple mathematical calculations (like addition and multiplication) and handling time per customer in service call centers. According to the findings of these surveys, indoor temperature is the dominant factor of the thermal environment which mostly affects employees' performance. Some indicative examples of the results of these surveys are presented below in order to provide a more quantitative view of the relationship between indoor temperature and employees' performance [53].

- The average talk-time of the operators in a telecommunication call-center was 5-7% lower when they were working in temperatures lower than 25^{o}C comparing to the operators of the same call-center who were working under higher temperatures.
- The wrap-up time of qualified nurses working in a call-center was 16% higher (16% decrease in performance) when the indoor temperature was above 25.4^{o}C.
- Decreased indoor temperature by 2^{o}C (from 24.5^{o}C to 22.5^{o}C) combined with normal outdoor air supply rate of 10 L/s per person led to a 4.9% improvement of call-center operator performance.
- Scientific evidence has shown that employees are more tolerant to low temperatures than to moderately high ones. More specifically, a 4% reduction in performance is observed at cooler temperatures while the corresponding percentage at warmer environments is 6%.

Other studies indicate that when office workers are capable of controlling their thermal environment, they tend to be more satisfied and consequently more productive. For instance, individual control over temperature within a range of 4^{o}C resulted in 3% increase of logical thinking performance and 7% improvement in typing performance.

Decisive was the contribution of a study undertaken in the Helsinki University of Technology [57]. The goal of this particular study was to assemble and process all the available information regarding the relationship between indoor temperature and performance in order to present a more complete and accurate overview of this relationship. Twenty-four relevant studies were examined and their results were statistically analyzed. Weighting factors were assigned to each performance metric included in these studies, according to the extent to which each metric was assumed to influence the overall office work performance. The outcomes of the study were summarized and presented in the form of the two following diagrams which will be further explained.

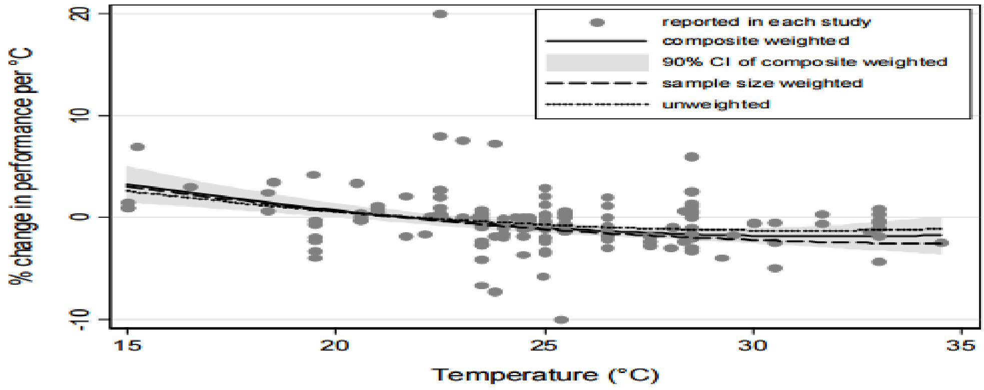


Figure 10. Relationship between temperature and percentage change in performance [57]

The above diagram illustrates the relationship between temperature and percentage change in performance. Each dot represents the result of a specific study and its position in the diagram has a special meaning. More specifically, dots with positive values indicate improved performance with increased temperature while dots with negative values indicate reduced performance with increased temperature. As it can be seen from the diagram the performance increases with increased temperature up to the limit of 21-22^{o}C and then decreases for temperatures above 23-24^{o}C. The curve intersects the horizontal axis at the temperature of 21.75^{o}C which is the temperature where the performance appears to be maximal. The results of the study also suggest that there is a ‘’no-effect temperature range’’ between 21 and 24^{o}C which means that temperature fluctuation within this interval does not have a significant effect on the productivity of the employees.

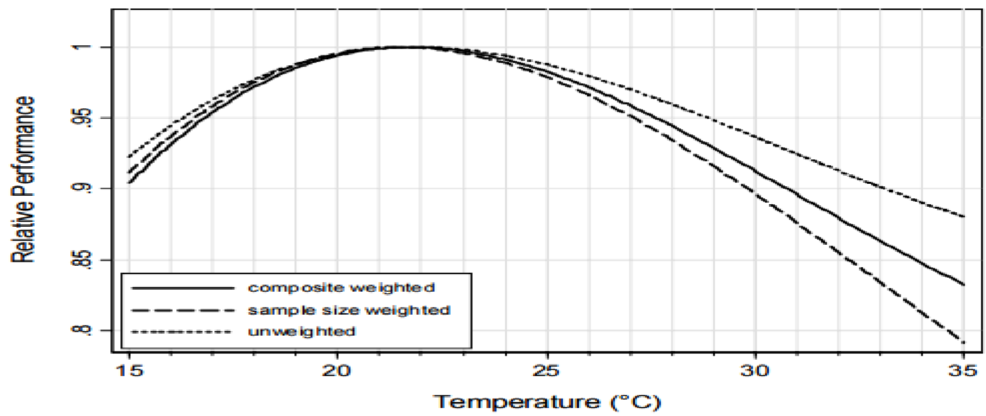


Figure 11. Schematic representation of the relationship between temperature and relative performance [57]

The curve in Figure 11 presents the relationship between relative performance and temperature. It was developed based on the data presented in Figure 12 which indicate that performance gets maximal at the temperature of 21.7^{o}C. Thus, by using this temperature (21.7^{o}C) as a reference point and by setting the performance equal to one for this specific temperature, the curve presented in Figure 11 is derived. The slope of the curve indicates that every 1^{o} C change (increase or reduction) of temperature from the reference point (22^{o}C) corresponds to a decline of performance by almost 1%. For instance, as it can be seen, extreme indoor temperatures like 16 or 30^{o}C are responsible for a performance reduction of 9% in relation to the maximum.

4.4 Indoor air quality – human health and well-being

Indoor environmental quality in office buildings depends to a large extent on the quality of the indoor air meaning the presence, the type and the concentration of air pollutants. Maintaining a good indoor air quality is an issue on which great attention should be given due to its direct relationship with occupants' health and well-being. There are several ways in which indoor air pollutants can affect human health and well-being and the severity of their consequences vary significantly. In many cases it is very challenging to distinguish which symptoms affect the human health and which have an influence on well-being.

4.4.1 Sick Building Syndrome (SBS)

- The most relevant term in the scientific literature which associates the poor indoor air quality with effects on occupants' health and well-being is the so called ''Sick Building Syndrome'' (SBS). According to United States Environmental Protection Agency, a building suffers from SBS when its occupants are complaining about symptoms which are associated with acute discomfort, e.g. eye, nose, throat or skin irritation, headache, dry cough, nausea and dizziness, fatigue, difficulty in concentrating and sensitivity to odors. Although these symptoms appear to be linked with time spend in the building, they cannot be attributed to a specific cause and their effects on occupants fades away quickly when they leave the building. The most common causes of the SBS according to the literature are: 1) Poor ventilation rates, 2) chemical pollutants from indoor and/or outdoor sources, and 3) biological contaminants [58].

In order to provide an overview of how SBS symptoms affect human health and well-being the following figure can be used [59]:

Common Symptoms of SBS

- **In the central nervous system**

-Fatigue
-Headaches
-Dizziness,nausea
-Memory loss
-Sleep disturbances
-Difficulty in concentration
-Stress
-Nervousness
-Lethargy

- **In the immune system**

-Susceptibility to disease
-Allergy problems
-Symptoms similar to flu

- **In the respiratory system**

-Asthma
-Bronchitis
-Rhinitis
-Tightness in chest
-Breathelessness

- **Other**

-Disturbances in the digestive system
-Cramps
-Constipation
-Skin irritation
-Eye problems(dryness/irritation/sensitivity)
-Problems in the neck (dryness)
-Fever
-Aching muscles and joints

Figure 12. Overview of the most common symptoms of Sick Building Syndrome on human organism [59]

A concept which is worth mentioning, is the ‘’Building Related Illness’’ (BRI). For both SBS and BRI there is an important common parameter which is that occupants’ health and well-being is negatively affected due to their presence in the building. However, there are some substantial differences between these two concepts. First of all, in contrast with SBS, the symptoms of BRI can be attributed directly to a specific airborne contaminant. This means that the cause of the Illness can be identified and then treated accordingly. A second essential difference is that while SBS symptoms disappear almost immediately after exiting the building, the symptoms of BRI persist for longer time and require prolonged recovery after leaving the building [58].

4.4.2 Indoor pollutants and potential health effects

Assessing the potential damage that poor indoor air quality can cause to human health is not a simple task. The first factor that complicates the situation is the presence of more than one air contaminants in the office environment in the same time. This means that scientists need to study not only the individual health effects deriving from each one of these contaminants but also the effects that this ‘’mixture of air contaminants’’ may cause. Apart from that, the concentration of these contaminants is of utmost importance regarding their influence on human health and well-being. The higher the concentration of a specific air contaminant in the indoor environment the higher is the risk for the health and wellbeing of the building occupants. Time of exposure is another determinant factor regarding the potential effects which an air contaminant may cause to the human organism. More specifically, extended exposure time is associated with more severe consequences in comparison with shorter periods of exposure. Finally, human susceptibility is another parameter that seems to determine the extent to which an individual will be affected by his exposure to a contaminated indoor environment. Susceptibility levels are associated with several factors such as age, gender, genetic factors, pre-existing diseases, nutrition status, asthma, allergies and tobacco smoking. For all the above reasons establishing a clear link between human health and indoor air quality is not straightforward and requires thorough and extensive studies. However, guidelines (as outlined in chapter 3.1) have been proposed in order to ensure that human exposure to the most common indoor air pollutants is maintained under safe limits. The objective of the following table is to provide an overview of the potential effects on human health and wellbeing in case of violating the recommended guideline values. As it will be seen the severity of the health effects on building occupants ranges from discomfort to serious diseases with high fatality rates such as different kinds of cancer.

Type of pollutant	**Potential health effects**
Acrylonitrile	Irritation of nose and throat, chest tightness, breathing difficulty, nausea, weakness, dizziness, headache, convulsions and impaired judgment. There is limited evidence about its carcinogenicity in humans but it is proven to cause cancer in animals and thus it is treated as if it was a human carcinogen [60][61]
Benzene	Dizziness, headaches, rapid heart rate, tremors, confusion and

	unconsciousness. Long term exposure effects: anemia due to red blood cells decrement, weakening of the immune system and increased susceptibility to infections, irregular menstrual periods in women and reduction in the size of their ovaries. Human carcinogen causing leukemia [61][62]
Butadiene	Nausea, dry nose and mouth, headache, decreased heart beat and blood pressure. Human carcinogen increasing the risk for cancers of blood, stomach and lymphatic system [63]
Carbon disulfide	Headaches, tiredness, sleep disorders or even life-threatening effects on nervous system at very high exposures. Not classified as human carcinogenic due to lack of sufficient evidence [64]
Carbon monoxide	Headache, weakness, dizziness, upset stomach, vomiting, confusion and chest pain. Extended exposure to high concentrations can cause fainting or even death [65]
1,2-Dichloroethane	Kidney and liver diseases, lung and nervous systems disorders. Possible human carcinogenic [66]
Dichloromethane	Impairment of the central nervous system function, respiratory problems and risk for lethal consequences in case of acute inhalation of significantly high concentrations [67]
Formaldehyde	Nasal, eye and throat irritation, headache, neurological problems, asthma, allergic reactions, eczema and effects on lung function. It is proven to be a human carcinogen affecting mostly the upper human respiratory tract [68][71]
Polycyclic aromatic hydrocarbons (PAHs)	Although animal studies have shown increased possibilities of birth defects, lower body weights, effects on skin and deterioration of the immune system, there is no evidence that these consequences affect humans as well. PAHs are reasonably expected to be human carcinogens [61] [70]
Polychlorinated biphenyls (PCBs)	Skin related illnesses such as rashes and acne and possible association to liver damage. Classified as probable human carcinogen [71]
Polychlorinated dibenzodioxins and dibenzofurans	Endocrinological effects e.g. thyroid hormone modulation and alteration of the testosterone levels in plasma, decreased tolerance in glucose and neurological effects with currently unknown clinical significance [72]
Styrene	Change in color vision, concentration problems, tiredness, feeling drunk, increased reaction time and balance problems. Classified as a possible human carcinogen [73]
Tetrachloroethylene	Dizziness, headache, incoordination, disorder of vision, memory, mood and reaction time. High levels may lead to unconsciousness or even death. Probable human carcinogen [74]
Toluene	Headaches, dizziness, unconsciousness, incoordination, vision and hearing loss, cognitive impairment, effects on nervous and

	immune system, kidneys, liver and increased risk of spontaneous abortions. Classified as not human carcinogen [75]
Trichloroethylene	Headaches, sleepiness, dizziness, change in the heart beat, liver and kidney damage, effects on sperm quality, sex drive and reproductive hormones, coma and even death. Human carcinogen increasing risk of malignant lymphoma and liver and kidneys cancer [76]
Vinyl chloride	Dizziness, sleepiness, liver damage, unconsciousness or even death. Increased risk of brain, liver, lung and blood cancer [77]
Arsenic	Sore throat, ‘’pins and needles’’ sensation in hands and feet, darkening of the skin, irritated lungs, nausea, vomiting, reduced levels of red and white blood cells, change in heartbeat or even death. Carcinogenic to humans, known to cause several types of cancer such as liver, bladder, skin and lung cancer [84]
Asbestos	Breathing problems and asbestosis (damage in the lungs and the membrane that surrounds them) Human carcinogen causing lung cancer and mesothelioma [79]
Cadmium	Effects on lungs, kidneys and bones. Known as a human carcinogen [80]
Chromium	Nose irritation, runny nose, cough, asthma, wheezing and breathing problems. Prolonged Chromium inhalation may lead to lung cancer [81]
Hydrogen sulfide	Eyes, nose and throat irritation, difficulty in breathing, headaches, tiredness, poor memory, balance problems and loss of consciousness. Inadequate data for carcinogenic evaluations.
Lead	Abdominal pain, tiredness, headaches, irritation, loss of memory and appetite, tingling or pain in the hands or feet, weakness, depression, distraction, nausea and feeling of being sick. Classified as probable human carcinogen [82]
Mercury	Nausea, diarrhea, vomiting, increased blood pressure and/or heartbeat, skin rash, effects on kidneys, problematic fetal development, and brain damage which may lead to irritability, tremors, shyness, memory loss and changes in hearing or vision. Possible human carcinogen [83]
Nickel	Allergic reactions such as skin rashes, asthma attacks, chronic bronchitis and problematic lung function. Probable human carcinogen causing lung and nasal sinus cancer [84]
Nitrogen dioxide	Eyes, nose and throat irritation, cough, chronic bronchitis, chest pain, decreased lung function, pulmonary edema, mucoid sputum, tachypnea, cyanosis, and tachycardia. Not classified as carcinogen for humans [85][86]
Ozone	Cough, irritation of lungs and throat, wheezing, breathing difficulties, worsening of the symptoms of asthma,

	emphysema and bronchitis [87]
Carbon dioxide	Headaches, dizziness, fatigue, increased blood pressure and/or heartbeat, potential effects on the metabolism, suffocation, unconsciousness or even death. Not related to cancer development in humans [88][89]
Sulfur dioxide	Breathing difficulties, burn effects on nose and throat, lung dysfunction, or even death in extremely high concentrations. The probability of cancer development on humans due to sulfur dioxide cannot be assessed due to insufficient scientific evidence [90]
Radon	Considered as human carcinogen. Smoking in combination with exposure to radon can significantly increase the probability of lung cancer development in humans [91]
Bacteria	Infections such as legionellosis, tuberculosis and brucellosis, irritation of the mucous membrane, fever, difficulty in breathing and pneumonia [61][92]
Fungi	Increased risk of asthma development or asthma morbidity for those who already have asthma, allergic bronchopulmonary mycoses, rhinitis, allergic, hypersensitivity pneumonitis, toxic pneumonitis, chronic fatigue syndrome, tremors and kidney failure. Studies have shown that there is association between human exposure to fungi and lung cancer development [93][94]

4.5 Indoor air quality and productivity

Indoor air quality and productivity are two very closely related concepts. Their relationship lies on the fact that there are several mechanisms through which productivity levels can be affected by indoor air quality. There are three main indicators regarding productivity in office places which are: 1) individual performance, 2) absenteeism and 3) turnovers. Poor indoor air quality may potentially affect all three of the above factors, either directly or indirectly. This chapter is dedicated in presenting and quantifying these effects with the help of percentages, figures and diagrams. Maintaining good indoor air quality highly depends on the presence of air contaminants in the office. According to scientific literature, as the air pollution load increases, the productivity in office places decreases substantially. Scientific experiments have been contacted in order to examine this relationship and their findings can be summarized in the following figure [56]:

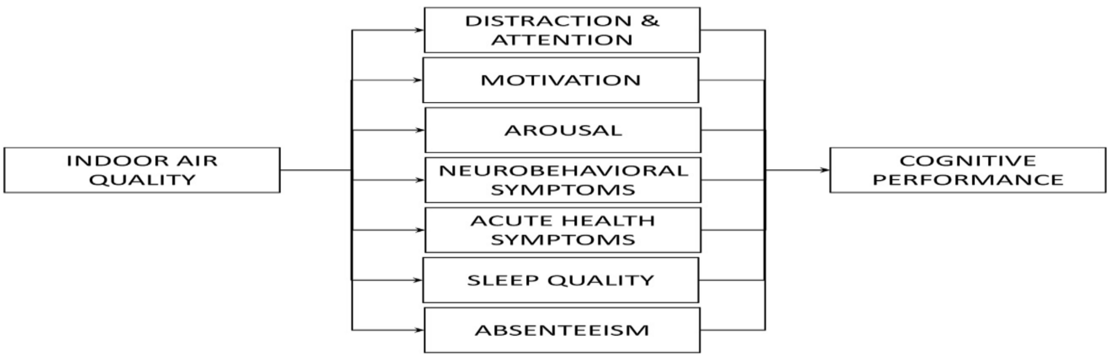


Figure 13. Different mechanisms through which indoor air quality may affect human cognitive performance [56]

Figure 13 illustrates the potential ways through which cognitive performance may be degraded due to poor indoor air quality. High-level cognitive skills are essential for a productive workforce and thus most of the studies are trying to quantify the effects of poor indoor air quality on them. A typical example of such a study conducted by Wargocki et al. [96] and showed that by removing an air pollution source (20-year-old carpet) from an office, while maintaining the same ventilation rates, the cognitive skills of the employees were significantly improved. More specifically, a 6.5% improvement in typing speed and an 18% reduction in error rate were observed.

Lagercrantz et al. [97] replicated the study of Wargocki et al. by using the same carpet but a different study group. This time, the results showed that the typing speed and the error rate of the employees were improved by 1.5% and 15% respectively.

The two following studies examined how poor indoor air quality due to high levels of CO_2 in classrooms may affect the students' absence. The experimental subjects of these studies may be students but their results may be applicable to office workers as well, predicting the level of their short-term sick leave due to high CO_2 concentration in their office environment.

- As Shendell et al. [99] showed in their study which conducted in 434 American schools, a 1000ppm reduction in the concentration of the CO_2 may lead to a 10 – 20% decrease in the students' absence from the school.
- The results of a similar study carried out by Gaihre et al. [100] showed that for every 100ppm increase of CO_2 concentration the corresponding increase in students' absence rates is 0.2%.

Ventilation rate is another determinant factor with regard to productivity since it directly affects parameters like individual cognitive performance, short-term sick leave and sleep quality. Several experiments have been conducted in order to investigate the relationship between ventilation rates and productivity, the outcomes of which reveal and quantify the direct and strong relation of those two concepts. In these field experiments call-centers were mainly selected since the duties of their operators require concentration, logical thinking, verbal communication and visual attention which are skills that are required for the majority of the office tasks. Therefore if call center performance is influenced by changes in indoor air quality, other office tasks may be similarly affected. The most indicative examples of these experiments, their findings and some complementary charts will be presented below in a bullet form:

- According to Wargocki et al., 2000a, [101] when the outdoor air supply rate changed from 3 to 10 and then to 30L/s per person, the text typing performance improved by about 1% for every two-fold increase in the air supply rate despite the fact that the pollution source (an old used carpet) was still present in the office.
- Increased air supply rate from 2.5 to 25L/s per person at a call-center in Denmark resulted in an 6% increase in operators' performance when new ventilation bag filters were used while for the same increase of air supply rate but with used bag filters, the performance of the operators decreased by 8% [102].
- Another study that took place in California indicated an improvement of 9% in the performance of the call-center operators when the outdoor air supply rate

changed from 10 to 23L/s per person in a ventilation system which was not using bag filters [104].

- An alteration in ventilation rates from 5 to 10 and then to 20L/s per person led to an increase of 2.5%-5% in the performance of the experimental subjects with regard to typing, memorization and addition. Main pollution source for this experiment were the new finishing materials which were located inside the chamber and which were emitting volatile organic compounds [105].
- Field studies performed in school classrooms located in Denmark showed that by increasing the air supply rate from 3 to 9.5 L/s per person the language and numerical performance skills of the children were significantly improved. More specifically, the increase of their performance in terms of speed was around 8% on average while the corresponding effect on the observed error rate was negligible [106].

Of particular interest are the diagrams that are presented below which were derived from the results of a study conducted by Seppanen et al. [108]. Figure 14 illustrates the relationship between ventilation rate and performance when the reference ventilation rate is set at 6.5 L/s per person (left) and 10L/s per person (right) while figure 15 shows how performance is increased for every 10L/s per person increase of ventilation rate. The conclusion that can be derived from the latter figure is that, the effects of improved ventilation on performance are stronger when the initial ventilation rates are low and attenuate as the initial ventilation rates are getting higher.

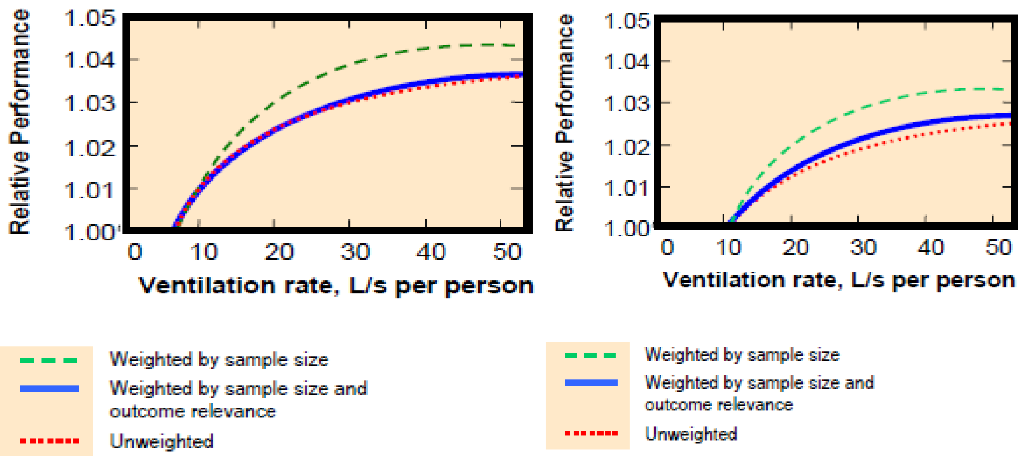


Figure 14. Relationship between ventilation rate and performance when the reference ventilation rate is set at 6.5 L/s per person (left) and 10L/s per person (right) [108]

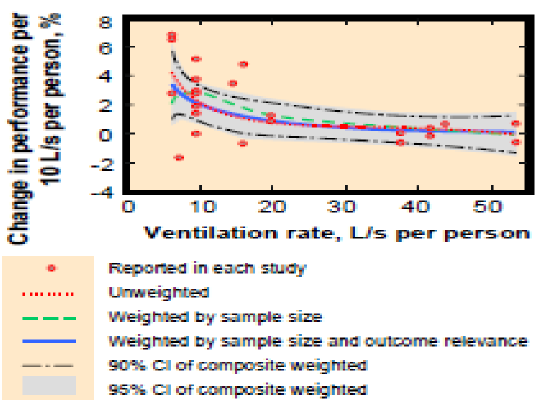


Figure 15. Increase of performance in relation to ventilation rate [108]

Apart from directly affecting the employees' performance skills and consequently their productivity, poor indoor air quality is responsible for high absenteeism in the workplace. For example, an employee who suffers from a respiratory disease, caused by the poor indoor air quality in his office, will be absent from his work and thus not productive at all. Numerous studies have been conducted in order to establish a relationship between indoor air quality and productivity and, since air quality is directly connected to ventilation rate, the results of these studies are mostly presenting the association between absenteeism levels and ventilation rates in the workplace:

- Based on a study conducted in offices located in USA, the chances of getting infected by a respiration disease , and thus be unable to work, are 36% higher when the air supply rate is 12L/s per person compared to when it is 24L/s per person [109].
- Similar were the findings of a study conducted by Mendell et al. which examined the relationship between sickness absence and ventilation rate in 162 classrooms in California. The results showed a decrease of 1.6% in sickness absence for each additional 1L/s of ventilation per person [111].
- Fisk et al. developed a mathematical relationship between ventilation rate and sick leave that predicts a 10% reduction in the risk of getting sick at work when the outdoor air supply rate is doubled [112].

The diagram that follows provides a very useful quantitative representation of the relationship between ventilation rate and short-term sick leave. It was derived based on published field data and outcomes of a theoretical model regarding airborne transmission of respiratory diseases:

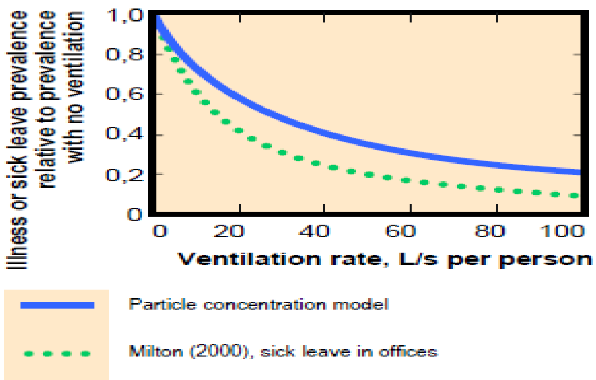


Figure 16. Relationship between Illness or sick leave prevalence and ventilation rate per person [112]

4.6 Visual environment and occupants' health

As discussed in Chapter 3.3, achieving visual comfort in offices is a complex task due to several related parameters that need to be taken into consideration. The common element of all these parameters is the light which can be either natural or artificial. Natural is the light that comes from the sun and penetrates the building through the windows and artificial is the light that is emitted by the installed lighting equipment. Although according to scientific evidence natural light is the most appropriate source of lighting in terms of occupants' health, wellbeing and productivity, the utilization of artificial light in offices is inevitable. In this chapter the negative consequences of artificial lighting as well as the benefits from the occupants' proximity to windows (and thus to natural light and views outside) will be discussed.

There is no doubt that artificial light has become a necessity for humans since we rely on it in order to maintain their comfort, safety and productivity when the sunlight is not adequate or not present at all. Offices are typical examples of places were artificial optical sources which are intended for lighting purposes are used. The practice of using artificial light in offices for a substantial part of the day may have negative consequences on their occupants' health. These consequences may be direct or indirect and they can affect both office workers' physical and mental health. Given the fact that indoor lighting based on artificial optical sources is a relatively recent practice, European commission and more specifically the ‘’ Scientific Committee on Emerging and Newly Identified Health Risks’’ published the results of a review on the health effects of artificial light. The objective of this work was to present a comprehensive assessment of the actual or potential risks to the general population due to utilization of artificial lighting. After reviewing a large number of relevant available studies, European commission determined that artificial light may potentially affect 1) Human eyes and skin, 2) circadian rhythms, 3) sleep, 4) mood 5) alertness and cognitive functions [113]. The conclusions of the European commission risk assessment combined with the outcomes of other relevant studies will be briefly presented below:

4.6.1 Effects on eye and healthy skin

According to the literature, radiation emitted by artificial sources that comply with the European Union's regulations and are intended for indoor lighting purposes is unlikely to cause any serious damage to healthy eye or skin. Health problems may arise only for excessively intensive exposures in very close proximity to the source or during accidental acute exposures [113].

4.6.2 Circadian rhythms disruption

The main mechanism through which the circadian clock is disrupted is the exposure to Artificial Light at Night (ALAN). It is estimated that 75% of the total workforce has been involved in night work or/and shift work. Being exposed to ALAN at work results in the suppression of melatonin secretion and thus in circadian disruption. This desynchronization of the circadian clock due to ALAN exposure is associated with increased risk of several diseases which include: 1) Different types of cancer such as breast cancer, prostate cancer and colorectal cancer, 2) diabetes, 3) cardiovascular problems and 4) obesity [114].

4.6.3 Effects on sleep

Experimental outcomes show that sleep problems are related to circadian disturbances due to ALAN exposure. Such sleep problems may include decreased sleep duration or quality, increased subjective insomnia, incidents of delayed sleep phase disorders and elevated sleep onset latency [115].

4.6.4 Effects on mood

Scientific studies have shown that there could be an association between mood disorders and exposure to artificial light at night (ALAN). An example of such a study conducted by Obayashi et al. and showed that the probability for elderly depression occurrence was significantly higher for the individuals who had higher ALAN exposure [116].

Similarly, the results of the British Household Panel Survey revealed that working at night for at least 4 consecutive years may increase the risk of poor mental health, anxiety or depression [117].

4.6.5 Effects on alertness and cognitive function

The outcomes of the study of Marquié et al. indicate that prolonged ALLAN exposure due to shift work may be the cause for impaired cognitive performance [118].

According to Cajochen et al. light at night exerts an alerting effect to human due to the suppression of the melatonin which it causes [119].

Other studies investigated how cognitive functions and alertness are affected by the wavelength of the emitted light. Their outcomes have shown that shorter wavelength monochromatic light (blue) not only results in higher levels of alertness in comparison to the longer wavelengths but it may also affect cognitive functions as a result of its influence on circadian rhythms and brain structures [113].

4.7 Visual Environment – wellbeing and productivity

There is a need for studies which will go beyond the current standards in order to deeper investigate which are the best lighting strategies in terms of occupants' wellbeing. Jörg Kelter and Caroline Merlin [120] worked towards this direction and carried out a comprehensive study with very valuable outcomes, the implementation of which may have a great impact on employees' wellbeing and consequently on their productivity. The aim of the study was to measure and quantify the extent to which each different lighting strategy can affect occupants' wellbeing and thus contribute to the future improvement of the indoor lighting quality.

The results regarding the type of lighting indicate that the majority of the office workers (almost 82%) prefer a combination of direct-indirect lighting instead of purely direct lighting (Fig. 17).

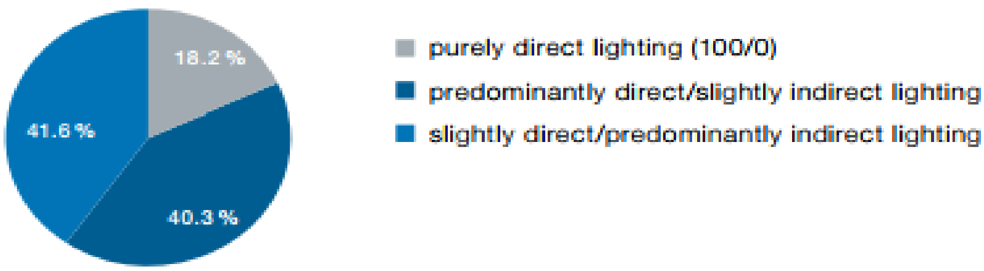


Figure 17. Preference trends regarding the type of indoor lighting in offices [120]

Apart from the type of lighting, the individual control on the lighting is an important factor regarding occupants' wellbeing and lighting quality perception. As it can be seen in the following figure, both sense of wellbeing and satisfaction with visual conditions are increasing as the possibility to individually adjust the lighting is getting higher.

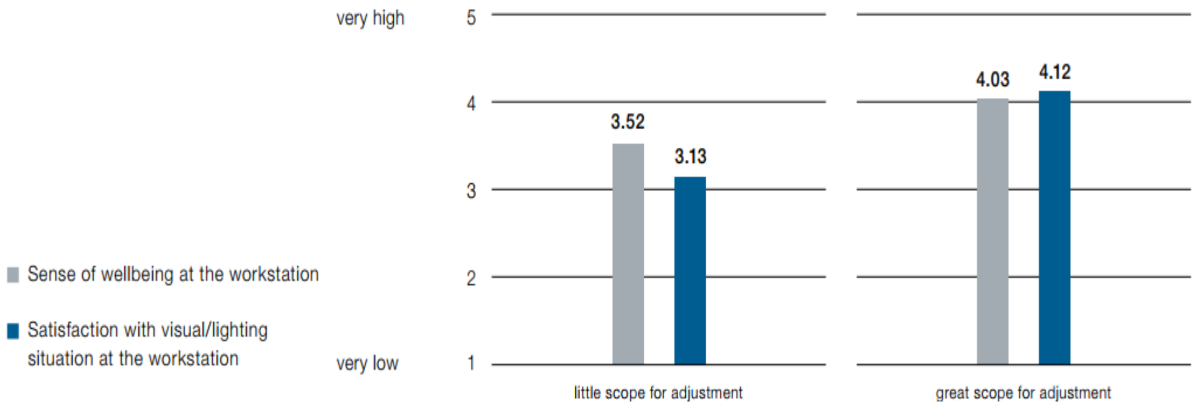


Figure 18. Sense of wellbeing and satisfaction with visual situation in relation to the possibility to individually adjust the lighting conditions at the workstation [120]

Two of the most dominant factors regarding office workers' satisfaction with lighting conditions are the type of the light source and the proximity of the office to a window. The diagrams of the following figure clearly show that LEDs are the most preferable lighting sources and that immediate proximity to a window is associated with higher sense of satisfaction.

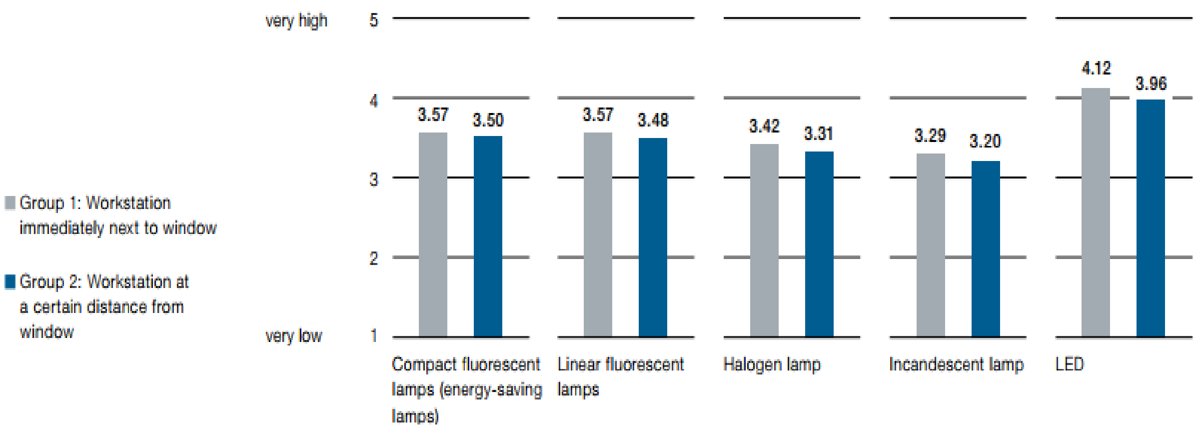


Figure 19. How proximity to a window and type of the light source may influence office workers' satisfaction with visual environment [120]

Another interesting outcome which contradicts the current recommendations is related to the relationship between illumination levels and occupants' wellbeing. More specifically, although the most widely recommended illumination level is around 500 lux, the study showed that more than 60% of the participants prefer illuminance levels at least equal to 800 lux.

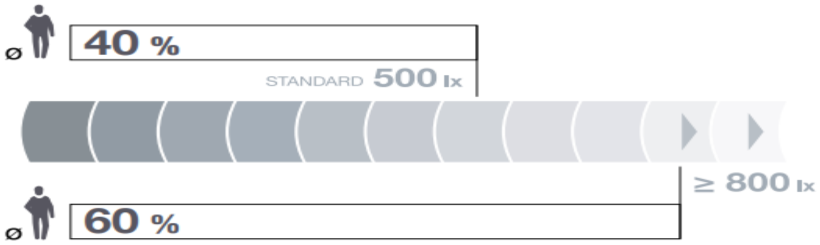
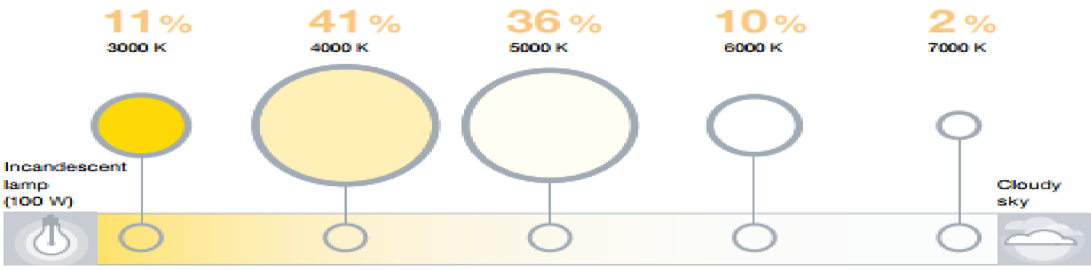


Figure 20. Trends of preferences regarding illumination levels at the workplace [120]

Finally, a characteristic of the light which may influence users' perceived comfort and wellbeing is the color temperature. According to the study's results, color temperatures between 3000K and 7000K are considered as acceptable, with the most desirable ranging between 4000K and 5000K (Fig. 21).



As stated in the beginning of the present chapter, wellbeing and productivity are two

Figure 21. Most preferable color temperatures for a pleasant and comfortable visual environment [120]

closely related concepts in the sense that any action which leads to enhanced wellbeing will also have a positive effect on the productivity of the employees. So, apart from the factors presented above, other lighting factors such as amount of glare, size of visual subject, light spectrum and contrast may also have an impact on employees' performance. However, it seems to be too little evidence in the literature to develop quantitative relationships between visual conditions and office workers' performance [53].

More specific and clear is the association between productivity in offices and proximity to a window. There is an unequivocal tendency of the employees to prefer offices which are located near to windows in order to have access not only to daylight but also to views outside. The importance of the proximity to a window was highlighted by a study conducted by Newsham et al. which showed that lack of access to a window was the most determinant factor regarding dissatisfaction with lighting. This is because, working next to a window provides the opportunity for longer distance views which in its turn allows the eyes to re-focus and adjust. This is a valuable opportunity since it reduces long term symptoms such as headaches, fatigue and eye strain [121].

Health and wellbeing improvements will consequently result in enhanced productivity given the fact that a more satisfied worker is more productive as well. The above hypothesis is confirmed by the scientific outcomes of relevant studies which investigated the relationship between productivity and proximity to a window. An example of such a study was carried out in a call center located in California [122]

and found that provision of better views out of a window is associated with improved overall performance. More specifically, the results showed that:
- Processing of calls by workers with views outside were 7% to 12% faster
- Computer programmers with views outside spent 15% more time on the work assigned to them.
- Computer programmers without views outside spend 15% more time either talking to one another or on the phone.

4.8 Acoustical environment and human health

The main goal in seek of an acoustically pleasant indoor environment is to maintain the sound levels below the so called "noise" limits. Noise is the unwanted sound which may have detrimental impacts on office workers' health, wellbeing and productivity. Sources of noise within the office environment could be common office equipment such as computers, telephones, printers and copiers, conversations between colleagues and building installations such as elevators and air conditioning and heating units. Besides the noise generated inside the building, significant is the influence of the noise coming from the external environment, with the most common source of external environmental noise to be the traffic. Due to the potential severity of noise impacts on employees, several studies have been conducted in order to more precisely identify, examine and quantify them.

The most immediate health impact of noise on office workers is related to their mental health and more specifically to their stress levels. Studies have shown that noisy offices may be the cause of increased stress, anxiety and stress related disorders [124]. Prolonged exposure to stress results in release of specific hormones like epinephrine and norepinephrine which may be the cause for other health consequences such as hearth diseases, insulin resistance, decreased bone density and immune system dysfunction [125].

In addition to this, it have been observed that employees working in noisy environments tend to change their body posture less frequently which lead to musculoskeletal problems such as back pain [126].

Based on the findings of other studies, employees’ health is mainly threatened by noise which is coming from the external environment and more specifically from traffic. World Health Organization Regional Office for Europe published a study according to which 20% of the population of the European Union countries is exposed to traffic noise levels of above 65Db throughout the day [127].
The outcomes of such an exposure are highlighted in a recent study on the effects of road traffic noise on health carried out by the European Environmental Agency according to which:

- Noise is a serious environmental problem with the most common noise deriving from road traffic.
- In Europe, 10000 cases of premature death per year are caused by environmental noise.
- On yearly basis, 43000 hospital admissions are attributed to noise.
- Every year environmental noise causes more than 900000 cases of hypertension.

- 20 million is the number of the severely annoyed adults, while 8 million suffer from sleep related problems due to environmental noise and mostly to traffic noise [128].

Very interesting are the results of other relevant studies which indicate that exposure to traffic noise is associated to severe cardiovascular problems such as stroke and myocardia infraction [129] [130]. Finally, according to Babisch, road traffic noise is the cause for about 3% of the ischemic heart incidents in large cities [131].

4.9 Acoustical environment and wellbeing

Noise distractions either from internal or external sources are considered as one of the main causes of dissatisfaction regarding the office environment. However, the extent to which an employee is affected depends on several parameters such as the task on hand, the noise characteristics and the personal cognitive characteristics [47]. The most frequent response to excessive noise in offices is annoyance. Annoyance is an unpleasant feeling which is defined as a mixture of reported discomfort, feelings of intrusion and anger [132]. From this definition is becomes clear that annoyance from office noise is closely associated with occupants' sense of well-being. The occurrence of the phenomenon of noise annoyance is getting more and more frequent due to the widespread use of the open plan offices in the modern workplaces. Therefore it is an issue which has attracted the interest of the researchers and thus it has been extensively investigated in recent years. The main goal of this investigation was to identify the potential internal or external noise sources which deteriorate the indoor environmental quality and then to proceed to the quantification of their consequences.

Very interesting were the results of a comprehensive study which examined the effects of noise on cognitive performance and annoyance levels in open plan offices [133]. The authors of this particular study focused their experimental interest on the four most common office noise sources: 1) printers, 2) intelligible speech, 3) non-intelligible speech and 4) phone rings. Then they performed their experiment in which 35 individuals were sequentially exposed to each of the four different noise sources. During their exposure they were asked to carry out simple tasks and only at the end of the experiment they were asked to rate their annoyance felt by filling in a simple questionnaire. Based on the results of the measurements, a relationship between the different noise sources and their consequences on the employees' wellbeing (in terms of increased annoyance) was derived. This relationship is illustrated in the following figure:

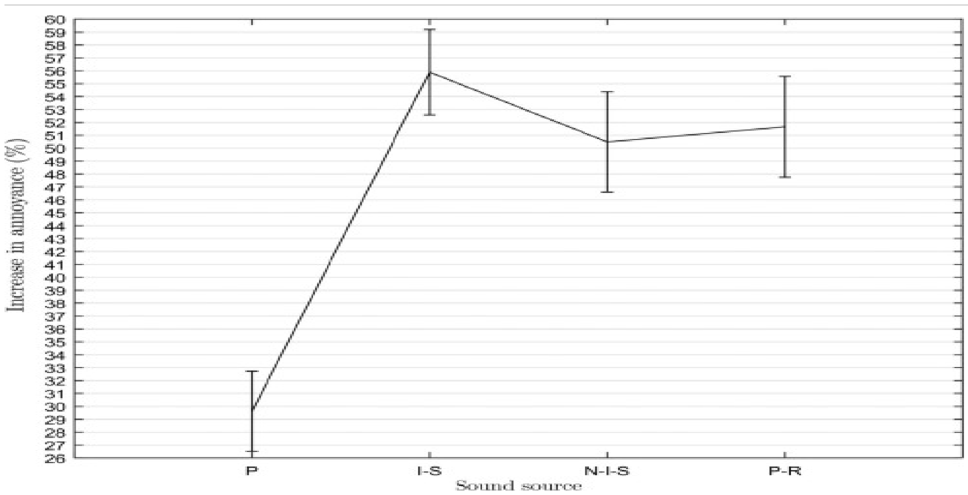


Figure 22. Increase in annoyance (%) in relation to particular noise sources [133]

As it can be seen, the source which causes the greater increase in annoyance felt is the intelligible speech (I-S) which is followed by phone ring (P-R) with 55.9% and 50.5% respectively. The third most annoying noise comes from non-intelligible speech with 50.7% while the least annoying sound out of these four is the noise from printers which is estimated to increase the annoyance felt by 29.6%.

Similar were the results of the study conducted by Pierrete et al. [134] which showed that according the 237 employees which were involved to the study, the most annoying sound within the office environment comes from intelligible conversations followed by unintelligible conversations. Phone rings were the third most annoying sound while noise from machines (such as printers) was the least annoying.

Other interesting results were given by the study of Boyce [135]. According to this study, 67% out of 200 office workers said that phone ring tones were the most upsetting sounds of the indoor environment.

4.10 Acoustical environment and productivity

The relationship between office noise and productivity has been the subject of research for many studies for a long period of time. The results of the vast majority of the studies indicate that office noise can greatly affect the productivity of the employees. According to the scientific evidence, the main reason for this drop in productivity is the decreased performance of the office workers. This is in line with the results of a study carried out in 2005 which showed that 99% of the people participated in the study complained for impaired concentration caused by office noise such as ringing phones and background conversations [136].

Another study conducted by the same authors indicated a 66% drop in employees' performance for a ‘’memory for prose’’ task due to their exposure to different types of typical office noise [138].

Other similar studies presented the association between noise levels and employees performance. For example, subjects reading (number of read words) and proofreading ability were both negatively affected as a result of their exposure to noise at 80 dB in contrast with their previous exposure to 55 dB [139].

Interesting were the results of the study conducted by Witterseh et all. [140] which showed that exposure to noise at 55 Db resulted in a 3% reduction of the rate at which subjects carried out simulated office work in comparison to when they were exposed to noise at 35 Db.

Noise is also expected to have an impact on cognitive performance. A study examined the open plan office noise effects on cognitive performance revealed that office noise has a direct impact on the memory for words. Experimental subjects' ability to remember words was higher in low noise environments compared to environments with higher noise levels [136].

Finally, very interesting were the outcomes of a recent study [133] which examined how different office sound sources are affecting the performance of the employees. As it can be seen in the following figure the sound sources which were examined are the a) printers, b) intelligible speech, c) unintelligible speech and d) phone ring tones.

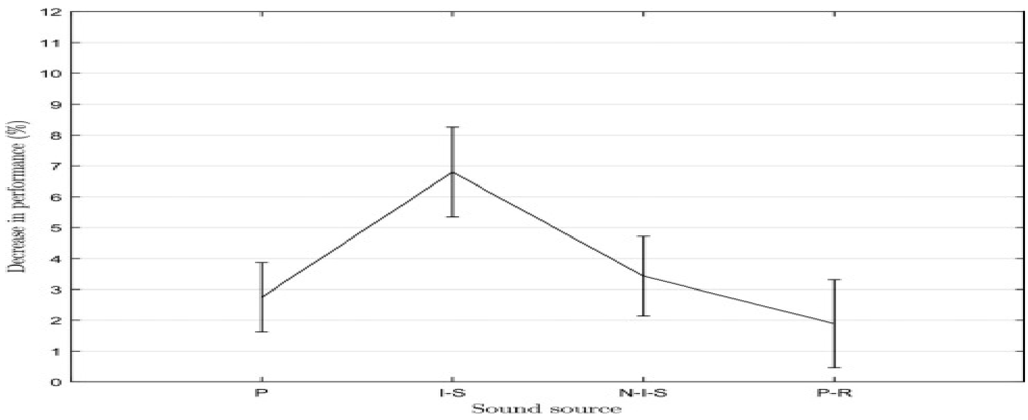


Figure 23. Decrease in performance (%) in relation to particular noise sources [133]

Between these four sound sources, intelligible speech was proven to have the greatest impact on employees' performance. More specifically, it was found to decrease employees' average performance by 6.8% while the corresponding decrease cause by unintelligible speech was equal to 3.4%. Printers influence was slightly lower than this of intelligible speech and equal to 2.7%. Phone ring tones with a percentage of 1.9% were the sound source causing the lowest impact on employees' performance.

5. Existing and emerging methods for indoor comfort evaluation

5.1 The Predicted Mean Vote (PMV) model

The importance of thermal comfort in the indoor environments led to scientific research the purpose of which was to predict or measure the thermal comfort of the building occupants as accurately as possible. The first attempts were mainly focused on predicting the indoor thermal comfort and at present two distinct approaches-models have prevailed and coexist. The first is the classic steady-state (rational or heat-balance) model developed by Fanger and the second is the adaptive thermal comfort model. Both models along with their particularities, potentialities and limitations will be presented in detail in the present chapter.

The heat-balance approach, which was developed by Fanger in 1970s, is based on experiments in climate chamber with controlled conditions were 1296 Danish students participated. The goal of these experiments was to predict the mean thermal sensation of a large group of people and the corresponding percentage of dissatisfaction expressed through the indices of Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). In order to achieve that, a specific experimental procedure was followed. More specifically, the experimental subjects (students) were dressed in standardized clothing and then they were introduced in the chamber where they were asked to perform standardized activities while being exposed to varying thermal conditions (air temperature, mean radiant temperature, humidity and air velocity). Then they were asked to state their level of comfort. More specifically, the seven-point ASHRAE thermal sensation scale running from (-3) Cold to (+3) Hot was given to the subjects and they were asked to select the number that was best representing their comfort sensation. The aim was to identify which combination of thermal variables is considered from the subjects as ‘’neutral’’ or ‘’comfortable’’. After having identified the relationship between thermal variables and subjects thermal perception it was possible to use it in order to predict the ‘’comfort conditions’’ under similar circumstances elsewhere [141]. At this point it would be important to present an illustration of the scale of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) which was used for the needs of the aforementioned experiment:

ASHRAE descriptor	Numerical equivalent
Hot	3
Warm	2
Slightly warm	1
Neutral	0
Slightly cool	−1
Cool	−2
Cold	−3

Table 4. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) scale descriptors [142]

The ‘’Predicted Mean Vote’’ (PMV) index was introduced by Fanger in order to predict the average thermal response of a large number of subjects according to ASHRAE thermal sensation scale. The PMV index is an equation which describes thermal comfort as the imbalance between the heat flow from the human body in a specified thermal environment and the heat flow which is required for optimum comfort (i.e. neutral) for a specified activity. The PMV equation has the following form:

$PMV= [0.303e^{-0.036M} + 0.028]* L$

where M is the metabolic rate and L is the thermal load on the body (i.e. the difference between the internal heat production and the heat loss to the ambient environment for a person who is hypothetically kept at comfort values of skin temperature (T_{sk}) and evaporative heat loss (E_{rsw}) at the given activity level. According to ASHRAE the recommended PMV value for a comfortable indoor environment in office buildings should range between (-0.5) and (+0.5).

Based on the PMV the concept of Percentage of the People Dissatisfied (PPD) can derive. In fact, PPD is a function of PMV in the sense that as PMV fends off from zero (neutral) the PPD value increases. The guideline from ASHRAE 55 indicates that an acceptable PPD value should not be higher than 10%, which means than no more than 10% of the people should be dissatisfied by the indoor thermal conditions. The relationship between PMV and PPD is given by the equation:

$PPD = 100 - 95exp[-(0.03353PMV^4 + 0.2179PMV^2)]$ while the empirical relationship between the PMV and PPD values is illustrated in the following diagram [141]:

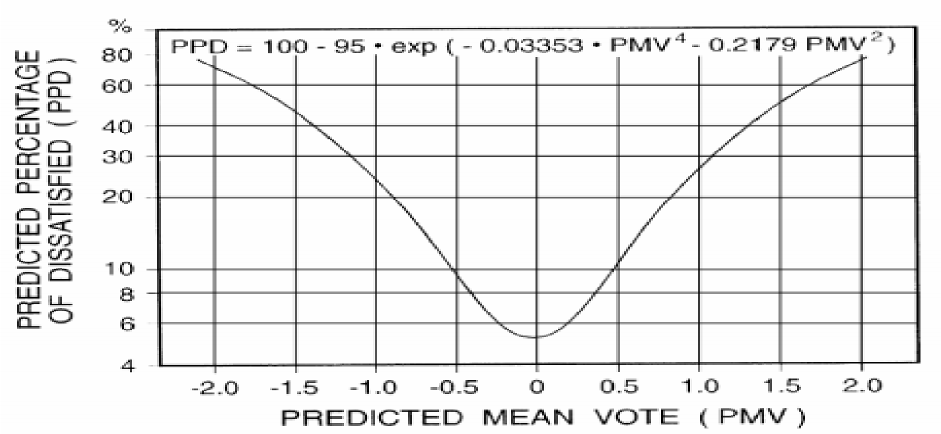


Figure 24. Empirical relationship between the Predicted Mean Vote (PMV) and the Percentage of People Dissatisfied (PPD) with the thermal environment [143]

Although PMV model is an effective tool for predicting the thermal comfort in indoor environments and has been widely used the last decades, it also has some drawbacks. First of all, the development of the mathematical equation was based on data acquired from experiments which were conducted in climate chambers. This means that, despite the fact that the climate chambers attempted to simulate the real conditions as accurately as possible, it would be impossible to achieve that one hundred per cent and this may lead to uncertainties regarding the final thermal comfort predictions. In addition to this, the PMV model was initially developed for air-conditioned spaces and it was just recently extended to non-air-conditioned buildings with the help of a new improved model. Another disadvantage is related to the fact that the calculation of the PMV is based on the so called personal parameters (i.e. clothing insulation and metabolic rate) which are difficult to be objectively measured. Due to this fact the most common practice is to include their standardized estimated values for the required calculations which in its turn lead to uncertainties regarding the accuracy of the predicted results. Also, as it can be understood by the terms of “steady state’’ or ‘’heat balance’’ which are used to describe the PMV model, one of its basic particularities is that it can be accurate for persons involved in sedentary activities under steady state conditions. This implies that PMV model is based on consistent and static conditions and thus it could be proven less efficient in real work situations which are changeable and inconsistent. More specifically, the main drawback is that it only focuses on body’s physiological processes (such as sweat rate and mean skin temperature) and heat balance without considering at all that humans are active and capable of restoring their comfort. Researchers focused their interest on this fact and attempted to develop a new improved model for thermal comfort prediction called “The adaptive model”.

5.2 The adaptive thermal comfort model

The adaptive thermal comfort model constituted an innovation regarding the determination of thermal comfort since it introduced a completely different methodological approach. The main idea behind the development of this model is based on the so called “adaptive principle” which supports the idea that: if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” [144].

The process described by the adaptive principle is called thermal adaptation and is related to several factors such as climate, geographic location, age, race, gender and cultural background of the occupant and can be attributed to three factors: a) behavioral adaptation, b) physiological adaptation and c) psychological adaptation [145].

Behavioral adaptation includes all conscious and subconscious actions of a person in order to restore his body’s thermal balance. Such actions could be personal adjustments (clothing, cold-hot food and drink, activity), technological adjustments (opening-closing windows or controlling HVAC systems) and cultural adjustment (dress codes, siestas and scheduling activities).

Physiological adjustment is the modification of the physiological responses (due to the exposure to the thermal environment) which result in an occupant who is less susceptible and more tolerant. For instance, prolonged exposure (days or weeks) to thermal environmental stressors may lead to permanent modifications of the physiological thermoregulation system, which is a process that is commonly known as acclimatization.

Psychological adaptation refers to an alteration in the way in which a person perceives and reacts to sensory information. In other words, the chronic exposure of a person to an environmental stressor modifies his indoor climatic expectations and forces him to re-adjust his comfort set points [39] [146].

As it can be understood, the main difference between the adaptive thermal approach and the PMV model is that the former considers the building occupants as active and capable of adjusting to their thermal environment while the latter as passive. Another difference is that the adaptive model was developed based on field studies conducted in naturally ventilated buildings while the PMV was based in climate chamber simulations [147]. From the analysis of the results of these studies, linear regressions between indoor operative temperatures and prevailing outdoor air temperatures were identified. More specifically, it was found a direct relationship between indoor comfort temperatures and outdoor climate. Based on these studies, Humphreys [146] developed two mathematical equations which best describe the relationship between indoor comfort temperature (T_c) and outdoor climate (T_m) for both free-running (naturally ventilated) and climate-controlled (centralized HVAC) buildings. These two equations are presented below:

$T_c = 11.9 + 0.534\ T_m$ (free-running buildings)

$T_c = 23.9 + 0.295\ (T_m - 22)\exp(-((T_m - 22) / (24\sqrt{2}))^2)$ (climate-controlled buildings)

As it can be seen in the previous equations, the outdoor climate which was parametrized as mean monthly outdoor temperature (T_m) has a much more evident and direct influence on the indoor comfort temperature (T_c) in the free-running buildings in comparison to the climate-controlled buildings where the correlation is less pronounced but still highly significant. Concluding, the adaptive model enables us to predict the indoor comfort temperature by taking into account only the outdoor climate expressed in terms of mean monthly outdoor temperature and this is considered as its main advantage in relation to the PMV model.

Although the aforementioned models have been widely used in order to predict the thermal comfort in indoor spaces their precision has frequently been questioned. Recent studies have been conducted in order to ascertain if the predictions regarding the occupants' comfort are consistent with the actual perceived comfort of the occupants. A very interesting example of such a study was carried out in university classrooms located in Italy with the participation of 126 students [148]. The aim of this particular study was to predict the thermal comfort of the students by using the PMV and the adaptive thermal models and then to compare the predicted results with the actual thermal perception or Actual Mean Vote (AMV) of the students. In order to achieve that the indoor environmental parameters were constantly measured during the lessons at two minute time intervals by the following instruments: a) Globe thermometer, b) hot-wire anemometer and c) temperature and relative humidity sensors. In addition to this, questionnaires were distributed to the students which enabled the researchers to analyze the students' thermal perception. More specifically, the aim of the questionnaires was to collect data regarding:

- General information (age, gender, individual position in the classroom)
- Individual vote on thermal environment (Thermal vote was expressed on Fanger scale and allowed the researchers to evaluate the Actual Mean Vote (AMV) and the Actual Percentage of Dissatisfied (APD) and compare them with the PMV and PPD respectively.
- Clothing insulation of the students
- Possibility to control indoor environmental parameters

After having collected all the required data for the PMV and the adaptive models as well as having analyzed the questionnaire results, the researchers presented their final conclusions regarding the capability of the PMV and adaptive model to accurately predict the perceived thermal comfort of the students.

Before presenting the evidence regarding the Fanger PMV model we need to mention that a sedentary activity of 1.2 met was considered while the clothing insulation values were provided from the questionnaires. The following table illustrates the comparison between the Fanger indices and the questionnaire results:

Classroom	**T. outdoor (^oC)**	**T. indoor (^oC)**	**Fanger indices**		**Questionnaire results**	
			PMV	**PPD**	**AMV**	**PD**
21	14.6	22.6	-0.05	5.0%	0.17	5.9%
10	13.5	22.2	0.03	5.0%	0.07	0.0%

As it can be observed, although the predicted values were very close to those obtained from the questionnaires, the model predictions slightly overestimated the cold sensation (-0.05) in comparison with questionnaire results (0.17).

Regarding the adaptive model, the En15251 and the ASHRAE 55 standards were used to calculate the Optimul Internal Operating Temperature (T_{op}) while the Mean Monthly Outdoor Temperature (T_{mm}), the Running Mean Temperature (T_{rm}), the measured Indoor Temperature (T_{indoor}) and the measured Outdoor Temperature ($T_{outdoor}$) were also taken into account. The results are illustrated in the following table:

Classroom	$T_{outdoor}$ (^oC)	T_{mm} (^oC)	T_{rm} (^oC)	T_{indoor} (^oC)	Adaptive model results			Questionnaire results	
					PPD	T_{op} (ASHRAE)	T_{op} (EN 15251)	AMV	PD
21	14.6	10.0	11.5	22.6	<10%	21±2.5	22.6±3	0.17	5.9%
10	13.5	10.2	11.6	22.2	<10%	21±2.5	22.6±3	0.07	0.0%

It can be observed that the measured indoors temperature (T_{indoor}) was within the optimum temperature range predicted by the adaptive model (T_{op}) and according to the questionnaire results the actual percentage of dissatisfied is less than 10% and more particularly 0% and 5.9% in classrooms 10 and 21 respectively.

5.3 The modified Predicted Mean Vote (mPMV) model

A different and improved version of the PMV model was developed in order to enhance its thermal prediction accuracy. This innovative model is called modified Predicted Mean Vote (mPMV) and it aims to bridge the gap between PMV and AMV by more precisely estimating the personal parameters which are required for the calculation of the PMV. One of the disadvantages of the PMV model is that it requires the estimation of personal parameters such as the clothing insulation and the activity level (also known as metabolic rate) which is a process which involves uncertainties. This lies in the fact that even under similar indoor conditions, individuals with different physiological state exhibit different metabolic rates. The results of a recent study [149] provided a solution which could address this problem. The relationship between the metabolic rate and the Mean Arterial blood Pressure (MAP) of each individual was investigated and it was found that there is a very strong correlation between these two values with a confidence level of 96%. More specifically, the mathematical equation which expresses their relationship was established:

Activity level (metabolic rate) = $(0.303e^{-0.036(0.1092*\exp(MAP*0.0296))}) + 0.028)$.

The above equation provides a more personalized way of determining the activity level (metabolic rate) of each individual, reducing the uncertainties and thus predicting his thermal comfort more accurately in comparison to the conventional PMV method. In other words, instead of assuming a metabolic rate of 1.2met (typical metabolic rate for office work), we calculate the metabolic rate of each person individually based on measurements regarding his Mean Arterial blood Pressure. The superiority of the mPMV was reflected in the results of the study which showed that while the overestimation of the thermal sensation of the PMV model was 54%, the corresponding percentage of the mPMV model was only 22%. Finally, the PPD deviations of the PMV and the mPMV models were calculated to be 28% and 8% respectively.

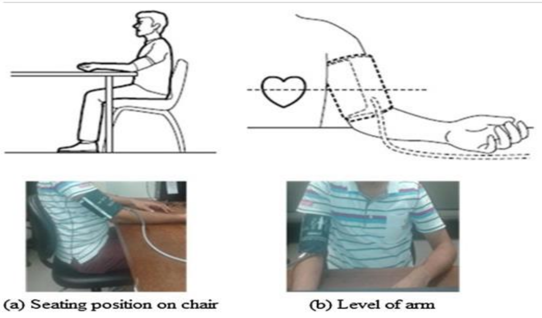


Figure 25. Schematic (up) and real (down) representation of the method used for the Mean Arterial blood Pressure measurement [149].

5.4 Questionnaire based methods

As it has been already discussed, being able to evaluate the perceived comfort of the occupants is very important and therefore several different methods have been developed in order to achieve that. The most widely used of these methods will be presented and discussed later in this chapter.

The first and most commonly used method involves the utilization of questionnaires. The idea behind this method is that by using questionnaires researchers can collect data which will reflect occupants' comfort with regard to air quality and to thermal, visual and acoustical indoor environment. The main advantage of questionnaires is that they provide the opportunity to measure the occupants' perceived comfort in a personalized way. This means that with this method we ask each occupant to report his comfort level individually instead of just trying to predict the average thermal comfort of a large group of people as is the case with the PMV and adaptive models. In addition to this, questionnaires enable the researchers to measure the comfort of the occupants in real time whenever they think that this is necessary. Finally, this method is relatively cheap and in case that the questionnaires have been developed in a scientifically correct way so that they will meet some basic specifications, they can provide very accurate and reliable results. However, apart from the aforementioned opportunities which this method provides, it also has an important disadvantage which limits its implementation in real world conditions. Distributing questionnaires in order to measure occupants' perceived comfort may be an effective way to collect the desired data but it cannot be repeated many times throughout the same working day for practical reasons. This means that this method could be used for specific experimental purposes and for limited and predetermined period of time otherwise it would lead to increased occupants' (or employee's) distraction and consequently to potentially decreased productivity. Below, some typical examples where the questionnaire method was used in order to measure the occupants' comfort will be briefly presented:

- In a study conducted by Vecchi et al., (2017) in Brazil online questionnaires were used in order to record office workers perceptions regarding their environment [150]. More specifically, employees were asked to asked to assess their thermal comfort via ''right-here-right-now'' online questionnaires while indoor conditions measurements were also carried out in situ. This study was carried out in three different buildings two of which had a mixed-mode ventilation system while the other one was permanently air-conditioned. A total number of 617 occupants participated in this study and 2688 questionnaires were collected. The questionnaires were sent to each participant via e-mail at a 20 minutes time interval for a total period of 100 minutes. The purpose of the questionnaires was to register the occupants' thermal comfort, preference, sensation, acceptability and air movement acceptability. The format of the used questionnaire was the following:

1	**Thermal Sensation:** Right now, how do you feel?	- Hot	+3
		- Warm	+2
		- Slightly warm	+1
		- Neutral	0
		- Slightly cool	−1
		- Cool	−2
		- Cold	−3
2	**Thermal Preference:** Would you prefer to be:	- Warmer	+1
		- No change	0
		- Cooler	−1
3	**Thermal Acceptability:** Is the current thermal environment acceptable for you?	- Yes	0
		- No	−1
4	**Thermal Comfort:** At this moment, how would you consider this thermal environment?	- Comfortable	0
		- Uncomfortable	−1
5	**Air Movement Acceptability:** Right now, how would you classify the air movement in your space?	- Unacceptable, air movement too slow	+2
		- Acceptable, air movement slow	+1
		- Acceptable, appropriate air movement	0
		- Acceptable, air movement fast	−1
		- Unacceptable, air movement too fast	−2
6	**Air Movement Preference:** Right now, which air movement option would you prefer?	- More air movement	+1
		- No change	0
		- Less air movement	−1

Figure 26. Format of the used thermal comfort online questionnaire [150].

- In another study [151], where the applicability of the adaptive comfort model in mixed-mode buildings (combination of mechanical cooling and natural ventilation systems) was investigated, questionnaires were used to register occupants' thermal responses. More specifically, occupant's perceived comfort (subjective sensations), expressed through their thermal sensation vote (TSV), thermal comfort vote (TCV), thermal acceptance and thermal preference was determined. In total 50 subjects participated in this web-based comfort questionnaire survey and 834 valid questionnaires were collected. The format of the distributed questionnaires is illustrated in the following figure:

Scale	TSV	TCV	Thermal acceptance	Thermal preference
4	–	Unbearable	–	–
3	Hot	Very uncomfortable	–	–
2	Warm	Uncomfortable	Very acceptable	–
1	Slightly warm	Slightly uncomfortable	Just acceptable	Warmer
0	Neutral	Comfortable	–	No change
−1	Slightly cool	–	Just unacceptable	Cooler
−2	Cool	–	Very unacceptable	–
−3	Cold	–	–	–

Figure 27. Thermal comfort questionnaire [151].

- Similar was the methodology that was followed in a study conducted in mixed mode office buildings in Spain in order to examine the applicability of adaptive model in both free-running and air-conditioned buildings [152]. During this study, which was carried out for one year, users were asked to complete a longitudinal survey with a frequency from one up to four times a day and two additional questionnaires on a weekly basis. The aim of the survey was to collect data directly from the users regarding their personal variables (such as clothing) and their thermal sensation, preference and acceptability. During this study, users were free to develop their usual daily activities without any external intervention by the researchers. In total, 5132 thermal responses were collected and analyzed over the period of this year. A representation of the format of the questionnaire which was used for the purposes of this particular study is illustrated below:

Thermal sensation	warm (w), slightly warm (sw), neutral (n), slightly cool (sc), cool (c)
Thermal preference	much cooler (mc), a bit cooler (bc), no change (nc), a bit warmer (bw), much warmer (mw)
Acceptability	unacceptable (uc), acceptable (ac)

Figure 28. Thermal comfort questionnaire used in the filed study[152].

5.5 Thermal Comfort Dial

An interesting and slightly different method was employed by Ioannou, A. and Itard L. in a study carried out in 30 residential dwellings in Netherlands [153]. In this particular study, instead of distributing questionnaires in order to determine occupants' thermal comfort, a simple but effective electronic device was used. This device is called "Comfort Dial" and it was developed by the Technology's Department of Industrial Design of Delft University. Comfort Dial is a portable and wireless device with a relatively small size which enabled tenants to carry it anywhere in their house and digitally record their perceived comfort. As it can be seen in the following figure, the configuration of this device was simple and allowed the tenants to report their real-time perceived thermal comfort level on a 7-point scale ranging from -3 (cold) to +3 (hot).

Figure 29. Illustration of the "Comfort Dial" device which was used to evaluate occupants' perceived comfort in real time [153].

5.6 Thermal comfort manikins

As technology evolves scientists develop new more sophisticated and advanced techniques in order to assess occupants' comfort in the indoor environment. The utilization of thermal manikins in experimental investigations is such a technique [154]. Thermal manikins are electrically heated dummies made from aluminum or plastic whose purpose is to simulate the human body during the comfort evaluation investigations. The first models of manikins that were manufactured comprised of a few segments without joints and they were only capable to stand. This fact was limiting their utilization to certain experimental situations and therefore new and improved versions were developed. These improved versions are considered as mobile thermal manikins since they have more than 100 segments, several joints and they can precisely simulate the various positions and movements of the human body. Another advantage of the modern thermal manikins is that, since they are even equipped with a system of breathing and sweat production, they are almost capable of "acting as a human". Simulating the human body and motion that accurately, manikins are widely used in thermal studies to measure temperature, heat transfer, thermal resistance of clothing, indoor air quality, humidity and distribution of pollutants. They also provide the opportunity for long-term repeated measurements, under extreme or dangerous situations for the human body which otherwise could subjectively influence the results of the measurements. Concluding, thermal manikins are very useful instruments with regard to thermal comfort measurements but their utilization is limited due to their relatively high price. A representation of a thermal manikin which could be used for the purposes of a thermal comfort study can be seen in the following figure:

Figure 30. Representation of a thermal manikin used in sophisticated thermal comfort studies [154].

5.7 Medical examination and observational monitoring

Very interesting were the results of the review conducted by Blussen et all., (2011) which describe three different scientific approaches with regard to comfort assessment in indoor office environments [155]. One of the main objectives of this paper was to present the methods which could be used in order to determine the relationship between indoor conditions and human wellbeing (health and comfort) by assessing the short or long-term effects of the indoor stressors (thermal factors, air quality, lighting aspects and noise conditions) on the human organism (body and brain). These methods are divided into three main categories:

- Questionnaires
- Medical examination
- Observation and monitoring

Since the method which involves the distribution of questionnaires has already been discussed, our interest will be focused on describing the other two methods.

5.7.1 Medical examination

Medical examination is a relatively new method in the field of IEQ investigations but it should be studied more due to the new opportunities which it could provide. We could say that the main goal of this method is to gather information regarding the physical and physiological states of the human organism (objective responses) and use them as indicators about the occupants' comfort level. For example, with respect to the autonomic nervous system, it was found that the heart rate variability (HRV) can be related to indoor air temperature, noise levels and presence of particulate matter in the indoor air. In addition to this, HRV can also be a predictor for mortality. Another indicator could be the levels of cytokines (category of proteins) in blood. Although cytokines are involved in several physiological processes, encouraging associations between a particular cytokine (IL6) and cognitive impairment, stress and depressed mood have been found. Regarding the endocrine system, studies have revealed an association between the production and release of different hormones in blood and specific changes in environmental conditions. In particular, the concentration of salivary cortisol and salivary a-amylase in relation to thermal comfort was studied while an association between chronic stress in humans and increased levels of hair cortisol was identified. Furthermore, a strong relation between the level of salivary chromogranin A (CgA) and noise exposure was revealed. Significant correlations were also found between exposure to indoor air pollutants and to the concentration of nitric oxide in the exhaled air. Finally, the peripheral endothelia function was measured with a finger plethysmograph in relation to mental stress. It needs to be mentioned that although the above described indicators can be used in order to assess the comfort of an individual specific their applicability is hindered by specific parameters. The first of these parameters are the ethical considerations which may arise and thus limit the implementation of these methods.

Financial limitations may be another obstacle regarding the utilization of the medical examination method due to the fact that it involves relatively expensive processes. Finally, further studies are required in order to more accurately assess the level of comfort of an individual by measuring the physical and physiological responses of his organism caused by his exposure to indoor stressors (such as thermal, lighting, noise and air quality aspects).

5.7.2 Observation and monitoring

The main objective of this method is to gather as much information as possible regarding how office workers respond (activity patterns) to certain situations (events) during a working day. In other words, this method enables the researchers to associate specific behaviors and physical responses (reactions of eyes, face, body etc.) of the employees to stimuli-stressors from the indoor environment (such as thermal, lighting, noise and air quality aspects). The implementation of this method can be achieved by a technique called behavioral monitoring which includes four different processes:

- Behavioral diary: In this technique the individual reports which is his response (actions/activities) to certain stimuli, or vice versa.
- Systematic observation: According to which the researcher is responsible to observe the real time (or video recorded) behavior of the employees and to note their actions in relation to the different events that take place during the working hours.
- Automatic sensing and logging: In that case, the observation has the form of an automatic process of recording specific context or behavioral data with the use of technologically advanced electronic devices. Examples of such devices could be: sensors which record the utilization of the HVAC systems, motion sensors capable of recording presence, pressure sensors to detect alterations in sitting positions, cameras to register movement patterns, face readers to record facial expressions and eye-tracking systems to record pupil diameter or attention.
- Performance: This technique requires that the employees perform a task or answer a question under various indoor environmental conditions in order to determine the influence of each environmental condition on them.

Although the utilization of the aforementioned techniques is suitable for the purposes of indoor comfort investigations there are some limitations that need to be mentioned. For example, behavioral diary is considered to involve subjectivity since it is written by each individual separately and one could say that the automatic sensing and logging technique should be preferred instead due to its objective characteristics. However, the problem with the automatic sensing and logging is that it is an emerging technique in the first stages of its development and thus it will be fully available on the short or medium term. Finally, concerning the systematic observation, it is a tedious and time-consuming technique while as for the performance technique it may be a very interesting and promising technique but it is in its very early stages and thus further in depth studies are needed before it could be effectively used in practice [155].

5.8 Wearable devices

As discussed previously, PMV model is one of the most widely used tool to predict the thermal comfort of the building occupants and in order to achieve that several factors are taken into. These factors include the environmental parameters (e.g. air temperature, radiant temperature, air velocity and relative humidity as well as the personal parameters (e.g. metabolic rate and clothing insulation). Although measuring the environmental parameters is a relatively straightforward process and which can be done with the help of the appropriate scientific equipment, the estimation of the personal parameters is more difficult. For this reason, the values of the personal parameters are usually assumed to be constant and more specifically, the typical metabolic rate and clothing insulation values in office environments are assumed to be 1.2 and 1.0 Clo respectively [41]. This assumption is one of the main drawbacks of the PMV comfort model, since it misses the opportunity to detect potential comfort variation due to metabolic rate and clothing. Modern technology provides a solution to this problem by enabling the researchers to accurately measure the metabolic rate of each individual in a more personalized way. This can be achieved by the utilization of wearable devices which are capable of providing continuous feedback regarding occupants' metabolic rate in real time. A typical example of such a device which was used in a study conducted by Li, D. et all. is illustrated in the following figure [156]:

Figure 31. Microsoft band 2.

The name of this particular device is "Microsoft band 2" and as it can be observed it is a comfortable, lightweight and portable device which combines affordable price with powerful functionalities with accuracy levels up to 95%. Apart from metabolic rate it is also capable of measuring heart rate, light intensity, skin temperature, skin resistance, etc. The main contribution of devices like that is that their recordings can be wirelessly transferred to smart phones or tablets in real time. Then these recordings can be processed in conjunction with the environmental data collected from indoor sensors (air temperature, humidity, radiant temperature etc.) as well as with real time human feedback (clothing insulation, thermal sensation vote etc.) and thus assess their thermal comfort in a much more accurate and personalized way in comparison to previously presented methods [156] [157].

6. Proposed method

6.1 Objectives

As discussed in the previous chapters, Indoor Environmental Quality in office buildings is of utmost importance since it directly influences their occupants' health and wellbeing. Apart from that, it can also have a significant impact on employees' productivity and thus affect company's financial sustainability. For all the reasons above, it would be very useful for the owner of the company to know how satisfied his employees are in relation to the indoor conditions. As shown in the previous chapter, different approaches have been followed and several methods have been developed in order to assess the employees' perceived comfort in office places but there is still room for improvements. Therefore, the main objective of the present chapter is to develop and present an innovative technique which could be used in order to measure and record office workers' perceived comfort in real time.

This technique should meet certain conditions that will make it practicable and as effective as possible. The first condition is to provide a fast, accurate and purely personalized way of assessing the perceived comfort of the office workers. In addition to this, it should not be disturbing and/or distracting for the employees so that they can stay focused on their tasks. Another requirement is the subconscious provision of the desired data by the office workers which is something that will increase the objectivity of the collected data. Finally, financial considerations should also be included in the development of this technique meaning that it should have a relatively low implementation and operation cost.

6.2 Methodology

The development of the technique for real-time measurement of the office workers' perceived comfort is based on a fundamental assumption. This assumption refers to the possible existence of a correlation between the indoor environmental conditions in office space and their influence on the employees' working activities. Based on this assumption, our Null hypothesis (H_o) is formulated which then is put into a test, against the alternative hypothesis (H_1), in order to be either confirmed or rejected. The hypothesis testing phase requires the implementation of the proposed method which is an experimental process comprising of four different stages. By implementing the proposed method, conclusions of great importance regarding the correctness of the Null hypothesis and thus the applicability of this innovative technique, will derive. Ideally, the statistical examination of the results of the proposed method will reject the Null hypothesis and confirm the alternative hypothesis. Otherwise, in case that the Null hypothesis will be confirmed, this will indicate that the technique is inapplicable and thus the idea behind it should be abandoned. The present chapter is dedicated in presenting both the Null and the alternative hypothesis, the different steps of the hypothesis testing process as well as the potential contribution of this technique in case that it will be proven as applicable and finally recommendations regarding future work.

6.2.1Null and alternative Hypothesis

Considering the objectives and their requirements, our Null hypothesis was formulated which could be tested by implementing the proposed method which will be presented in detail later in this chapter. The Null hypothesis (H_{O}) is the following:

H_O **:** *"Perceived indoor environmental quality has no significant effect on the way in which employees operate their personal computer and more specifically on computer related working activities such as:*

- *Typing speed*
- *Pressure applied on the keys of the keyboard*
- *Pressure applied when clicking the mouse*
- *Rotation frequency of the scroll wheel.''*

The alternative hypothesis (H_1) will be accepted in case that the null hypothesis will be disproved after being tested. The alternative hypothesis (H_1) has the following structure:

H_1 **:** *"Perceived indoor environmental quality has a significant effect on the way in which employees operate their personal computer and more specifically on computer related working activities such as:*

- *Typing speed*
- *Pressure applied on the keys of the keyboard*
- *Pressure applied when clicking the mouse*
- *Rotation frequency of the scroll wheel.''*

6.2.2 Hypothesis testing

In order to accept or reject the Null hypothesis the proposed method will be used. This method will have the form of an experiment comprising of the four following stages:

1) Development of a technological system comprised of very sensitive sensors being able of in real-time measuring and recording the aforementioned computer related working activities.
2) Development and distribution of questionnaires in order to ascertain office workers' perceived comfort with their office environment.
3) Installation of the appropriate technological equipment which will allow the objective measurement of data regarding indoor conditions such as temperature, air quality, lighting and noise levels.
4) Investigation of possible significant statistical correlations between the measurement records of the sensors and the questionnaire results with the help

of the complementary scientific evidence from the objective measurements of the third step.

6.2.2.1 Experimental Stage 1.

Development of a technological system comprised of very sensitive sensors being able of in real-time measuring and recording the aforementioned computer related working activities.

The first stage of the proposed method requires that every employee will use the appropriate technological equipment on a daily basis in order to carry out his working tasks. This means that employees' personal computers and their peripheral devices will be equipped with hardware or software programs which will be capable of measuring and recording their computer related activities. Before further explaining the purpose of this first step, it would be important to mention that this is a very cost effective process. More specifically, measuring scrolling and typing speed can be done with special software programs which are provided on the internet even for free. Regarding the measurement and recording of the pressure applied on the mouse or on the keys of the keyboard a relatively more sophisticated technology is required. This technology already exists, is not costly and its operation principle will be briefly presented below [158].

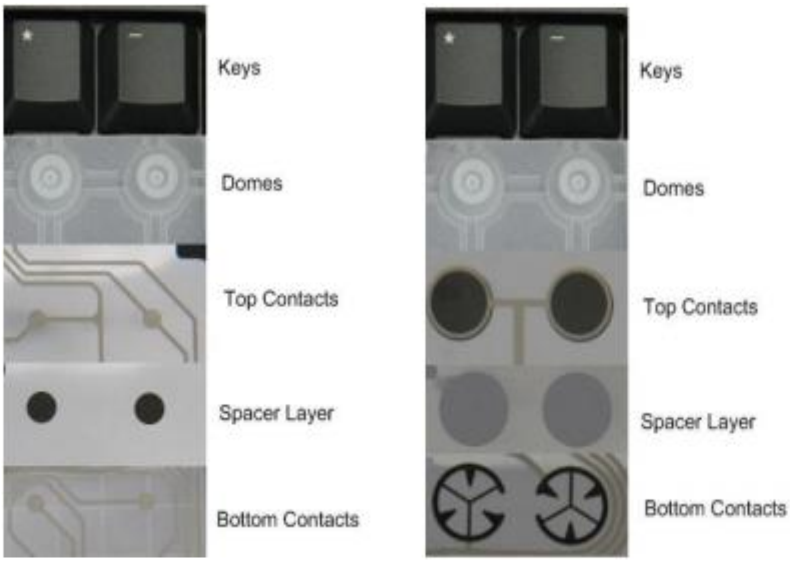


Figure 32. Inner structure of a ''flexible membrane technology'' keyboard (on the left) and a ''pressure sensitive membrane technology keyboard (on the right) [158]

As it can be seen in the left part of the figure above, conventional keyboards use the so called ''flexible membrane technology'' in which every switch is formed by three plastic sheets. The top and the bottom sheets are covered with conductive ink (silver-based material) at the places were each switch is located. The middle sheet acts as a spacer meaning that it is used to prevent the top and bottom sheets from touching each other. It also has holes at the switch points so that when pressure is applied on a specific switch, the top sheet penetrates into the hole and consequently touches the bottom sheet. As a result, the conductive material of the top and bottom sheets are brought into conduct generating an electrical signal indicating that the specific switch is pressed. On the right side of the same figure the structure of the so called ‘’pressure sensitive membranes’’ is illustrated. The operating principle of this technology is quite similar to the previously described technology with the only difference that it not only indicates when the switch is pressed but it can also measure the pressure that is applied on the switch. This special capability is a result of the more sophisticated design of the three sheets and of the higher quality of the conductive material (carbon based material) of the top and bottom sheets. As pressure starts to be applied on the switch, the conduct area between the conductive materials of the top and bottom sheets has the shape of a small dot. Subsequently, and as the pressure starts to increase the top sheet penetrates deeper into the hole of the middle sheet and thus the contact area is increasing as well. This increased contact area between the conductors of the top and bottom sheet generates a stronger electrical signal which indicates that higher pressure is applied on the specific switch.

The purpose of using this kind of software and hardware technologies is to accurately measure and record how office workers operate their personal computers and their peripheral devices in terms of typing and scrolling speed and pressure applied on mouse and keyboard. According to the proposed method, these data should be measured, recorded and stored on a daily basis for a sufficient period of time which will provide a statistically reliable sample size regarding the recorded measurements. It is approximated that a 30-day period will be sufficient in order to meet the experimental process goals. Then, the collected data will be used in order to create diagrams which will be representative for every employee. In order to further explain the purpose of these diagrams, two typical examples will be presented below. At this point, it would be useful to note that similar diagrams regarding the "Pressure applied when clicking the mouse" and "Rotation frequency of the scroll wheel" would have arisen and therefore it was not considered necessary for them to be illustrated.

The first diagram (Fig. 33) could be a qualitative representation of the pressure which an employee applies on the keys of his keyboard when he is using his personal computer. The illustrated values were calculated based on approximations and therefore they may contain some uncertainty. Based on the literature the average force exerted on the keys of the keyboard is 12.9 N [159] and as it was approximated the contact area between the fingertip and the key is $0.35cm^2$. Based on the following mathematical equation: $P=F/A$ where P is the pressure, F is the exerted force and A is the contact area, it derives that the average pressure that is applied on the keys is around $37*10^4$ Pascal. Based on that, and as it was anticipated, the applied pressure fluctuates around this average value of 37*10. However, it is important to mention that sudden but quite persistent changes in the amount of the applied pressure can also been observed.

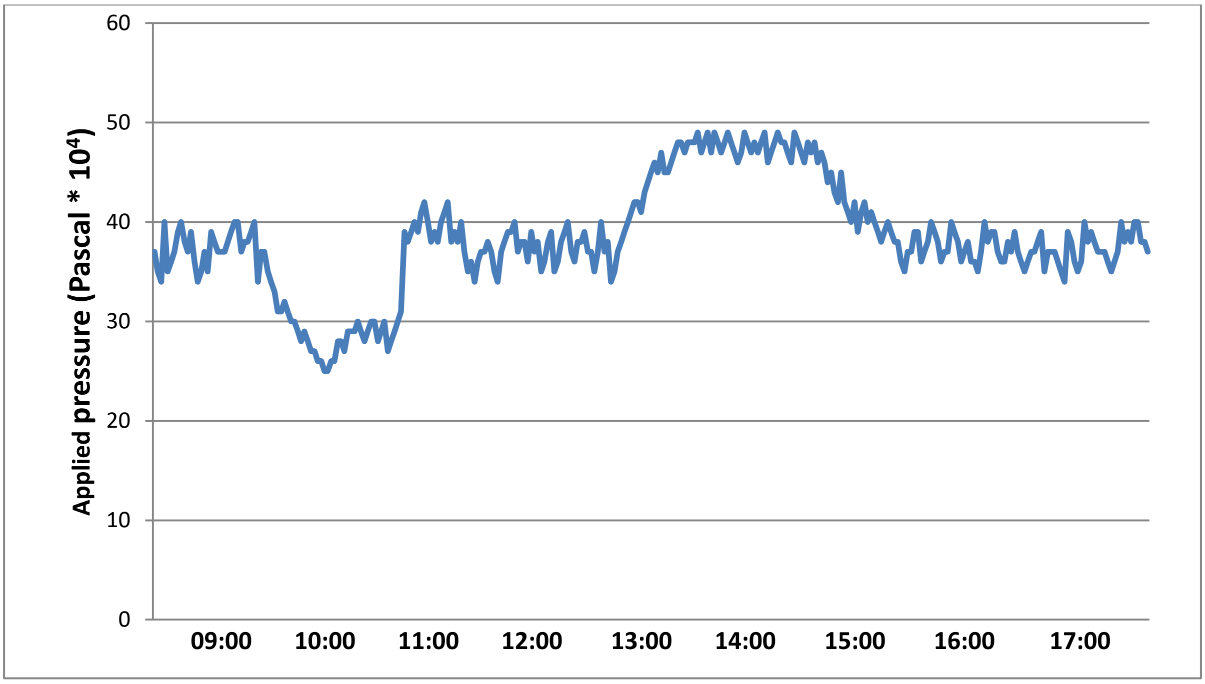


Figure 33. Graphical representation of a hypothetical scenario about the pressure that an employee applies on the keys of his keyboard during a typical working day

The second diagram (Fig. 34) illustrates how a typical example of an employee's typing speed over time could be. It can be seen, that typing speed ranges around 195 characters per minute (CPM) which, according to the literature, is the average typing speed of a person belonging to the general population [160]. However, there is the possibility that abrupt fluctuations (like the ones observed in the following figure) may occur.

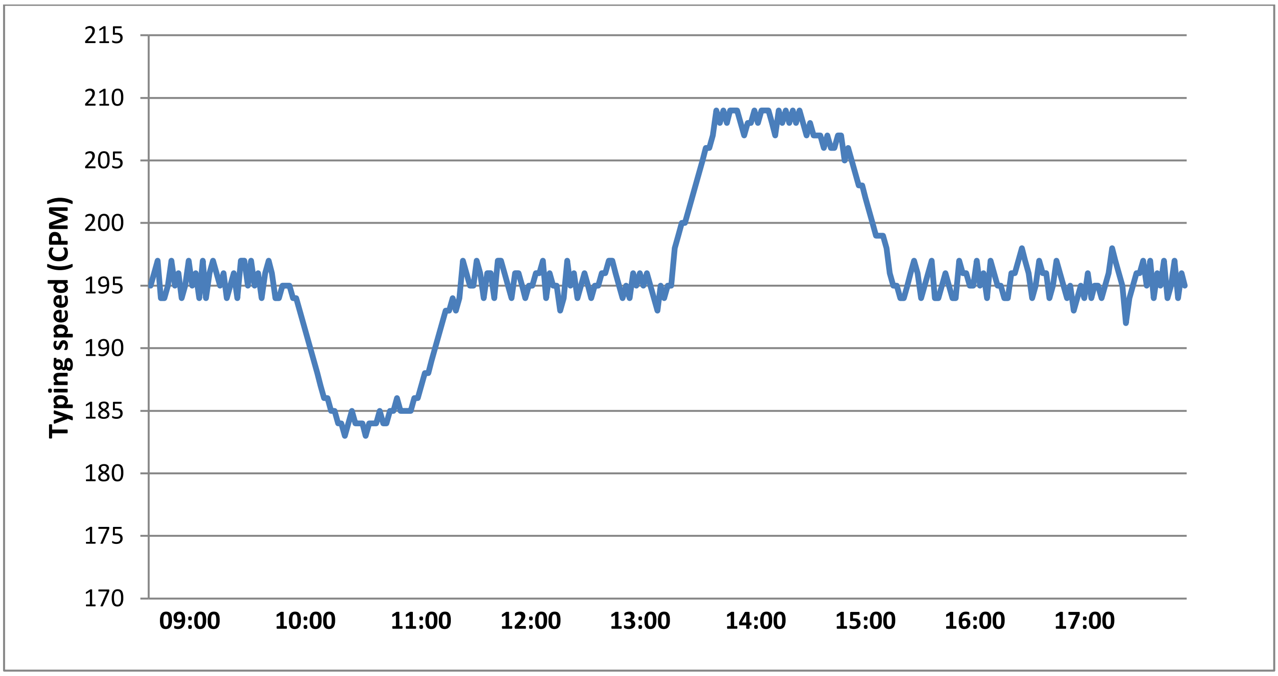


Figure 34. Graphical representation of a hypothetical scenario about the typing speed trends of an employee during a typical working day

6.2.2.2 Experimental Stage 2.

Development and distribution of questionnaires in order to ascertain office workers' perceived comfort with their office environment.

The second step of the proposed method requires that employees should fill in questionnaires which will be distributed to them at regular time intervals throughout the working hours. The purpose of distributing these questionnaires is to capture even the slightest changes in employees' perceived comfort levels during these time intervals. The frequency of the distribution of the questionnaires should be such that both the statistical reliability of the results and the distraction of the employees will be kept within acceptable limits. Therefore it was estimated that a time interval of 30 minutes would be appropriate for the purposes of our method. Apart from the distribution schedule of the questionnaires there are two more parameters that need to be taken into consideration. The first is the actual content of the questions, meaning what is that which will be asked and the second is the format of the questionnaires, meaning how these questions will be organized and presented. A questionnaire is a research instrument that enables the acquisition of information from the respondents. An effective questionnaire is the one which attempts:

1) To maximize the response rate, which means to collect as many responses as possible and
2) To ensure the accuracy of the obtained information [161].

There are some scientific design guidelines that a questionnaire should follow, in order to accomplish its main objectives. One of the most important aspects of a successful questionnaire is its length. Relatively short questionnaires with clear and concise questions tend to have higher response rates than long questionnaires with complex and ambiguous questions. Questions referring to aspects that are familiar to the majority of the respondents are more preferable than questions regarding difficult and vague concepts. Questions where the participants have the possibility to choose between specific provided options, the so called ''closed-ended'' questions, are easy and quick to fill in and this is why they are more widely used in surveys. On the contrary, ''open-ended'' questions, where possible answers are not provided and the respondents are asked to formulate the answer in their own words, is better to be avoided. Double questions and questions involving negatives should be avoided due to the fact that they can confuse the respondents and lead to false answers. A useful practice to draw respondents' attention is to start with interesting and simple questions and keep the more complicated for later. In addition to this, questions should be presented in a logical order and go from general to particular. A last technique for higher response rates is to avoid overfilling the pages or make the text look too dense because this will subconsciously affect the people and will discourage them from participating in the survey [162][163].

Finally, as it can be observed in the questionnaire below, regarding the questions for which the answer could be selected among multiple choices, a particular design strategy was followed. More specifically, the range of the possible choices was intentionally designed to be quite large (e.g. from 1-10) in order to achieve as high levels of accuracy as possible. The reason for this is that the purpose of the questionnaire is to detect even the slightest changes in office workers' perceived comfort caused by alterations of the conditions of their office environment. Thus, by providing a wide range of possible choices, these changes will be easier to be pinpointed.

Four different questionnaires are required for the purposes of this method. More specifically, questionnaires regarding a) air quality, b) thermal comfort, c) noise and acoustics and d) visual comfort need to be developed. Below, a typical example of how the questionnaire regarding thermal comfort should be will be presented. It should be noted that it was created based on the rules and guidelines mentioned above but nevertheless improvements may be required [164][165][166].

Thermal comfort questionnaire

Participant ID:

Date __/__/__

Time __-__

1) How would you rate the thermal environment at your desk at this moment?

	1	2	3	4	5	6	7	8	9	10	
Very acceptable	○	○	○	○	○	○	○	○	○	○	Very unacceptable

2) Please identify which of the following conditions represents the best how you feel at this moment. Note that there is the possibility to tick in between two categories.

○ cold
○ -
○ cool
○ -
○ slightly cool
○ -
○ neutral
○ -
○ warm
○ -
○ slightly warm
○ -
○ hot

3) In case that you could alter the temperature of your office, you would like it to be:

- ◯ warmer
- ◯ slightly warmer
- ◯ no change
- ◯ slightly cooler
- ◯ cooler

4) Please indicate how you feel about the humidity of the air in your office at the moment?

- ◯ The air is too dry
- ◯ the air is dry
- ◯ the air is ok
- ◯ theair is humid
- ◯ the air is too humid

5) Please indicate the part of your body which you feel to be cooler or warmer than the rest of your body. Note that there is the possibility of multiple options. In case that you do not feel any difference in any particular part of your body, please proceed to the next question.

	cooler	cooler and uncomfortable	warm	warmer and uncomfortable
head	◯	◯	◯	◯
shoulder	◯	◯	◯	◯
back	◯	◯	◯	◯
chest	◯	◯	◯	◯
arms and/or hands	◯	◯	◯	◯
feet and/or legs	◯	◯	◯	◯

6) Please indicate how you feel about the air movement at your desk at the moment.

	1	2	3	4	5	6	7	8	9	10	
Very comfortable	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Very uncomfortabl e

7) In case that you could make a change regarding the air movement at your desk , you would require:

- ◯ more air movement
- ◯ no change
- ◯ less air movement

8) Please indicate if you changed something in your clothing during the last 30 minutes?

- ◯ Increased the length of the sleeve of the shirt
- ◯ Decreased the length of the sleeve of the shirt
- ◯ Put on the jacket
- ◯ Took off the jacket
- ◯ Other activity, please describe:_______________________________________

9) What best describes how you feel about your clothing at the moment?

	1	2	3	4	5	6	7	
I wear more clothes than I want	◯	◯	◯	◯	◯	◯	◯	I wear less clothes than I want

10) Please report whether you consumed any of the following products within the last 30 minutes.

- ◯ Hot drink
- ◯ Cold drink
- ◯ Caffeinated drink
- ◯ Meal or snack
- ◯ Cigarette

6.2.2.3 Experimental Stage 3.

Installation of the appropriate technological equipment which will allow the objective measurement of data regarding indoor conditions such as temperature, air quality, lighting and noise levels.

This step can be considered as complementary and it was included in the experimental process in order to provide additional scientific data to the researchers. This data could later be combined with the data derived from the two previous steps and then be used as supporting evidence in order to accept or reject the Null hypothesis. Obtaining objective measurements of the indoor conditions in offices requires the utilization of specialized scientific equipment. In the following paragraphs, examples of the main scientific equipment which could be used for the purposes of the proposed experimental method will be briefly described.

➢ Regarding the measurements of the thermal comfort the appropriate instruments which are available in the market are the following:

- For the air temperature measurement an indoor air temperature sensor can be used. An air temperature sensor is a simple device comprising of a main sensor which measures the air temperature and a thermal radiation shield which protects the sensor from being influenced by the radiant temperature such as sunlight. Its price is relatively low, it is easy to be installed and its typical operating range is from -30^{0}C to 100^{0}C [167].

Figure 35. Indoor air temperature sensor [167]

- Apart from air temperature, radiant temperature may affect office workers thermal comfort. For measuring the mean radiant temperature the most commonly used instrument is the globe thermometer. Its structure is very simple comprising of a thin-walled black globe in the center of which a temperature sensor (resistance thermometer) is located. The outer surface of the globe is commonly painted with a matt black paint in order to increase its absorptivity. Its diameter is around 15 centimeters and its response time is about 20 – 30 minutes [168][169].

Figure 36. Globe thermometer [168]

- There is a wide range of instruments which can be used to measure the humidity levels in an office. These instruments may use different technologies but they have a common purpose, to measure the:
  - Relative humidity (expressed as mass of water vapor per volume of air)
  - Absolute humidity (expressed as a percent)
  - Dew point temperature (the temperature to which the air is saturated and dew is formed)

  The name of each instrument is based on the technology which it uses and the most commonly used are the psychrometers, capacitive, dielectric, chilled mirror, resistivity and strain gage instruments [170].

Figure 37. Psychrometer [183]

- The most common instrument for measuring the velocity of the air is called anemometer. There are anemometers of different technologies ranging from simple and inexpensive devices with relatively low measurement capabilities to more sophisticated and expensive instruments with higher measurement accuracy. The most known and used types of anemometers are the:
  - Windmill or propeller anemometers
  - Hot wire anemometers
  - Laser Doppler anemometers
  - Ultrasonic anemometers

For the purposes of our experimental process an ultrasonic anemometer would be preferred since it is relatively inexpensive and provides high accuracy measurements of both the speed and the direction of the air. As it can be seen in the following figure, it comprises of four sensors arranged in a square formation and has no moving parts. It operates by measuring the transmit time of an ultrasonic sound wave sent between two opposite sensors. As the air moves between the sensors the transmitted sound waves are disrupted and as a result their transmit time changes. The sensors are detecting even the slightest changes in air movement by calculating the corresponding changes in the transmit time of the ultrasonic sound waves. More specifically their measurement range regarding air speed is 0 – 90m/s with a resolution of 0.01m/s while regarding air direction it is $0 – 359^0$ with a resolution of 1^0 [171] [172].

Figure 38. Ultrasonic anemometer [171]

- The surface temperature of different elements of the office environment such as desk, floor and walls can be measured by two different types of surface temperature sensors: 1) the contact thermometers and 2) the infrared thermometers. As it can be understood by its name, a contact thermometer needs to be in physical contact with a surface in order to measure its temperature while the infrared thermometers do not require physical contact since they can calculate the temperature by sensing the infrared radiation which is emitted by a surface or object [173].

Figure 39. Contact thermometer (on the left) and infrared thermometer (on the right) [173]

- Regarding the monitoring of the indoor air quality there are plenty of available devices in the market which are capable of detecting the most common environmental pollutants.

These devices have a relatively small size and can be either fixed or portable. Besides their small size they have great capabilities since they can not only measure temperature and humidity but they can also detect the majority of the pollutants which can be found indoors, including carbon dioxide, carbon monoxide, smoke and other particulate matter, Volatile Organic Compounds (VOCs) and radon. These instruments are designed for easy operation combined with high levels of accuracy and reliability. Their price is affordable, they have a long life time and they provide auxiliary capabilities, such as data recording and statistical analysis of the stored data [174] [175]. Typical examples of air quality monitors of different sizes and shapes are presented in the figure below:

Figure 40. Typical examples of air quality monitors of different sizes and shapes [175]

- For the purposes of indoor lighting measurements the following instruments can be used:

The most useful instrument that is commonly used for indoor lighting measurements is called photometer. A photometer is a device which allows the user to measure the illuminance in lux (the amount of light that hits a surface) and the luminous intensity in candela (how the luminous intensity is distributed in the various directions). Apart from the light coming from the conventional lighting systems, modern photometers can also measure the properties of light coming from LED lighting systems [176].

Figure 41. Photometer [184]

Other auxiliary instruments which can be used for the purposes of indoor lighting measurements are colorimeters and the reflectometers. Colorimeters are used to precisely define and quantify color by measuring the absorbance of specific wavelengths of light. They are designed so that they can imitate the human eye-brain perception or in other words they are designed to see colors as humans do [178].

Figure 42. Colorimeter [177]

Reflectometers are devices which are used to determine the reflection properties (reflectivity and reflectance) of reflecting surfaces. The above measurement instruments are portable and easy to operate. Another advantage is their affordable price which is combined with the provision of high accuracy measurements. They are also capable of recording and saving multiple measurements in an internal data logger or memory [178].

- Sound level measurements are performed by instruments called sound level meters.

Sound level meters are equipped with a microphone which is capable of detecting the changes in air pressure caused by ambient sound. Then these changes are converted into electrical signals (volts) which in their turn are taking the form of digital displays on the screen of the device indicating the measured sound pressure levels in decibels (dB). They are extremely sensitive, accurate and reliable instruments providing the possibility of a sampling time of two times per second. Typically, their measuring level range is from 30 to 130 dB with an accuracy of +/- 1.5 dB and a resolution of 0.1dB. They have a small size and weight, they are very user friendly and their price is not expensive. Finally, they are designed for real time monitoring and recording of sound levels and they can also store in their internal memory up to around 250000 readings [179][180].

Figure 43. Typical examples of sound level meters [179]

6.2.2.4 Experimental Stage 4.

Investigation of possible significant statistical correlations between the measurement records of the sensors and the questionnaire results with the help of the complementary scientific evidence from the objective measurements of the third step.

This last step is the most significant one since it will determine if the Null hypothesis will be confirmed or not. After having gathered all the experimental data from the two previous steps, the goal is now to follow a specific procedure in order to investigate possible correlations between them. This means that the recordings derived from each of the sensors will be examined against the results of each question of the questionnaire. The goal is to reveal the time intervals where the sensors recordings and the questionnaire results present simultaneous changes with respect to their averages. For simplicity purposes, the description of the required procedure will be based on a specific “pair” of sensor recordings and questionnaire responses, but the same procedure should be followed for every possible combination-pair of sensors recordings and questionnaire responses. In our case, the recordings of the typing speed sensor (Fig. 44) against a hypothetical scenario of potential responses to the second question of the *Thermal comfort questionnaire* will be examined. It would be important to mention that both the recordings of the typing speed sensor and the hypothetical scenario of potential responses to the second question of the Thermal comfort questionnaire were recorded in the same day of the experimental period.

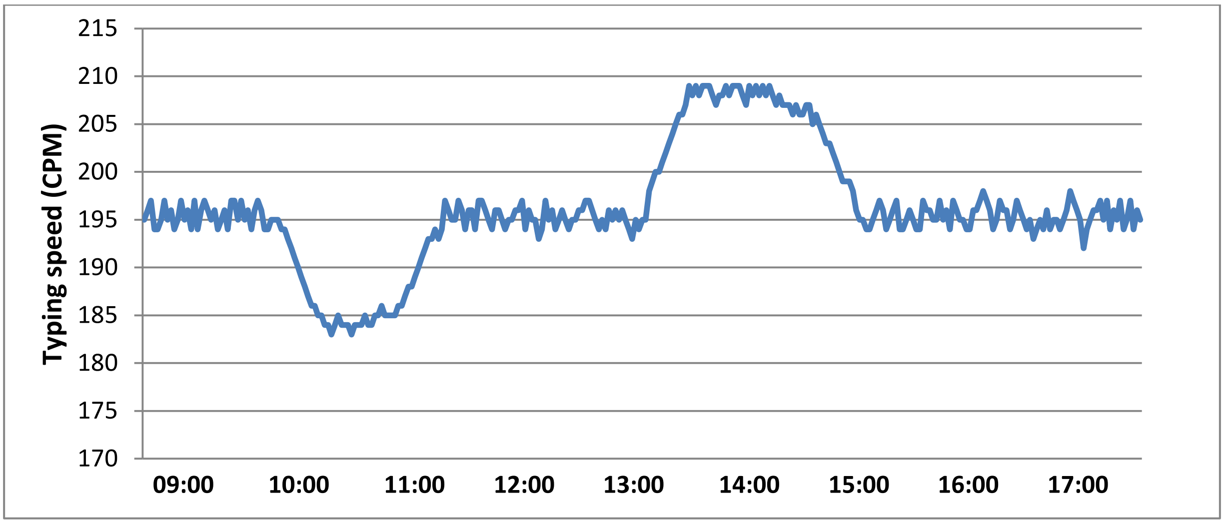


Figure 44. Graphical representation of a hypothetical scenario about the typing speed trends of an employee during a typical working day

From the figure above it can be seen that the typing speed of this particular employee was ranging around the value of 195 characters per minute for the most of the working hours except from the period between 10:00-11:00 and 13:00-15:00 where it presented a sharp decline and increase respectively. Based on that, it can be assumed that there is a specific cause for this alteration in typing speed which needs to be determined. In order to achieve that we need to investigate if there is any correlation between the alterations in typing speed and potential changes in the employees' perceive thermal comfort as it has been recorded in the results of the second question of the *Thermal comfort questionnaire*. More specifically, our attention needs to be focused on the particular time intervals where the typing speed alteration was observed. A hypothetical scenario (in case that we had already conducted the experiment) could be that during the time intervals of 10:00-11:00 and 13:00-15:00 the employee's answers, in the second question of the *Thermal comfort questionnaire*, also presented a sudden change, and from neutral turned into hot and cool respectively (Fig. 45).

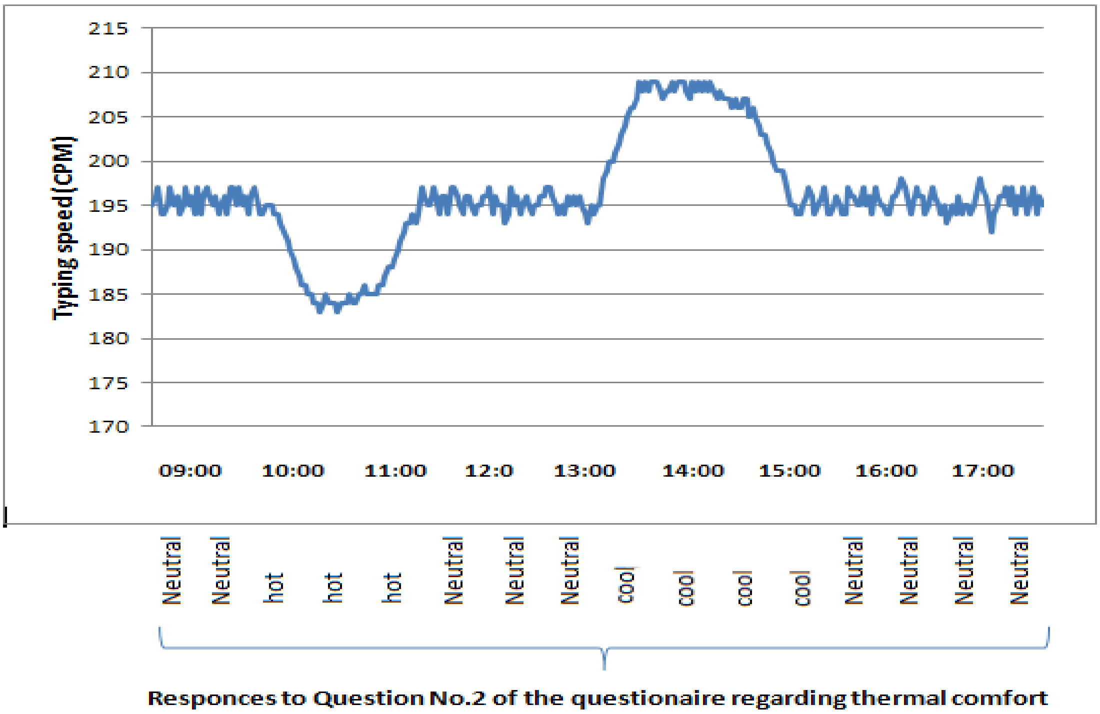


Figure 45. Graphical representation of a hypothetical scenario about the typing speed trends of an employee during a typical working day in combination with the corresponding responses to Question No.2 of the Thermal comfort questionnaire

According to this scenario, a correlation between the employee's typing speed and perceived thermal comfort is observed. This correlation lies on the fact that both the change in the typing speed of the employee and the alteration regarding his perceived thermal comfort (questionnaire responses) were observed during the same time intervals. This could be an indication that when this particular employee feels that the temperature is high, his typing speed decreases, while when he feels cool, his typing speed increases. However, one could be right to argue that the observed correlation was completely coincidental. At this point, and in order to guarantee the correctness of our conclusions the statistical evaluation of the experimental data is deemed as necessary. This implies that we need to examine the experimental data derived from both the sensors recordings and the questionnaire responses and attempt to detect every possible correlation between them. The experimental period of 30 days will provide as with a reliable sample size in order to not only detect possible correlations but also to determine if they are statistically significant, meaning if it would be scientifically correct to attribute the observed changes in the activities to alterations in employees perceived comfort. In other words, the outcomes of this statistical evaluation process will be used in order to either confirm or reject the Null hypothesis. However, the development of a method which could be used for the statistical evaluation of the experimental results is beyond the scope of this work and thus it will not be presented at the present chapter.

In order to further support the confirmation of the initial hypothesis the objective measurements acquired during the third step will now be used. For the purposes of our example the objective measurements which will be examined are the ones regarding air temperature. In the ideal scenario that the air temperature measurements follow the same trend with the typing speed measurements (meaning they present an increase between 10:00-11:00 and a decrease between 13:00-15:00) this could be used as additional scientific evidence providing further support to the confirmation or rejection of the Null hypothesis (Fig. 46).

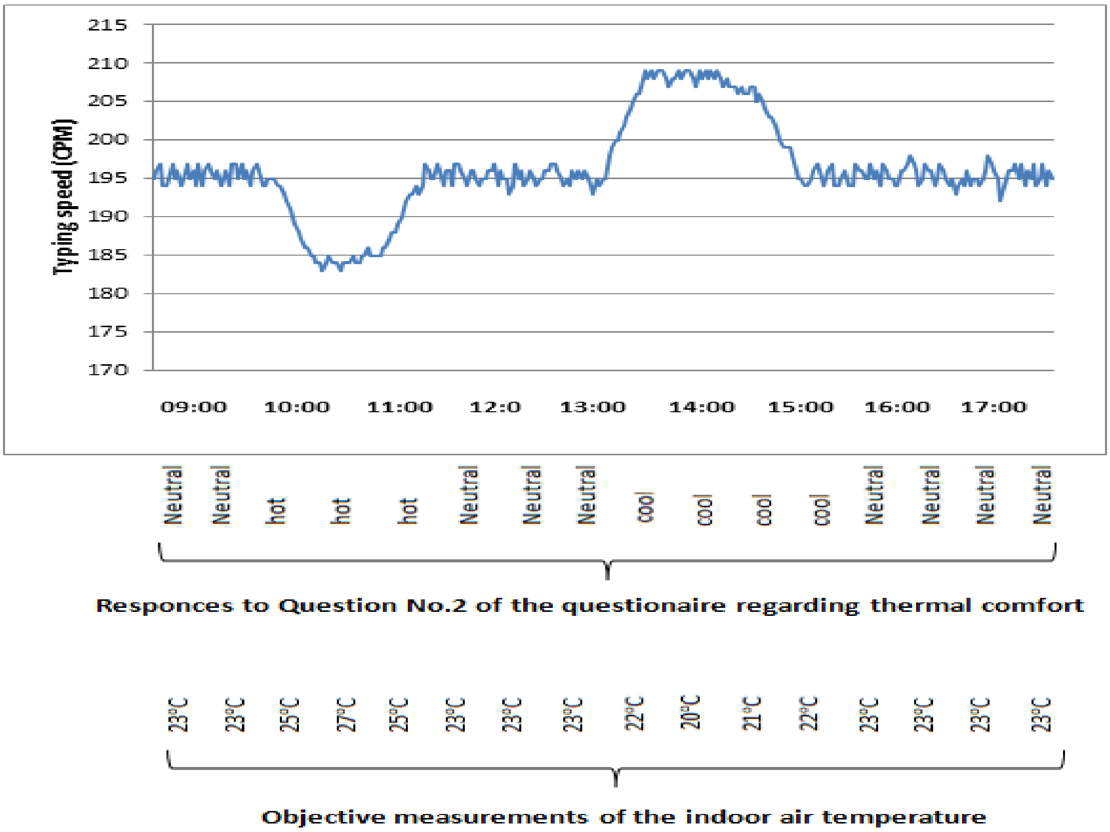


Figure 46. Graphical representation of a hypothetical scenario about the typing speed trends of an employee during a typical working day in combination with the corresponding responses to Question No.2 of the questionnaire regarding thermal comfort and the complimentary data concerning the objective measurements of the indoor air temperature

In other words, the objective measurements of air temperature may further confirm that the observed changes in the typing speed were not coincidental, but they were caused due to alterations of the indoor air temperature and consequently to the perceived thermal comfort of the office workers.

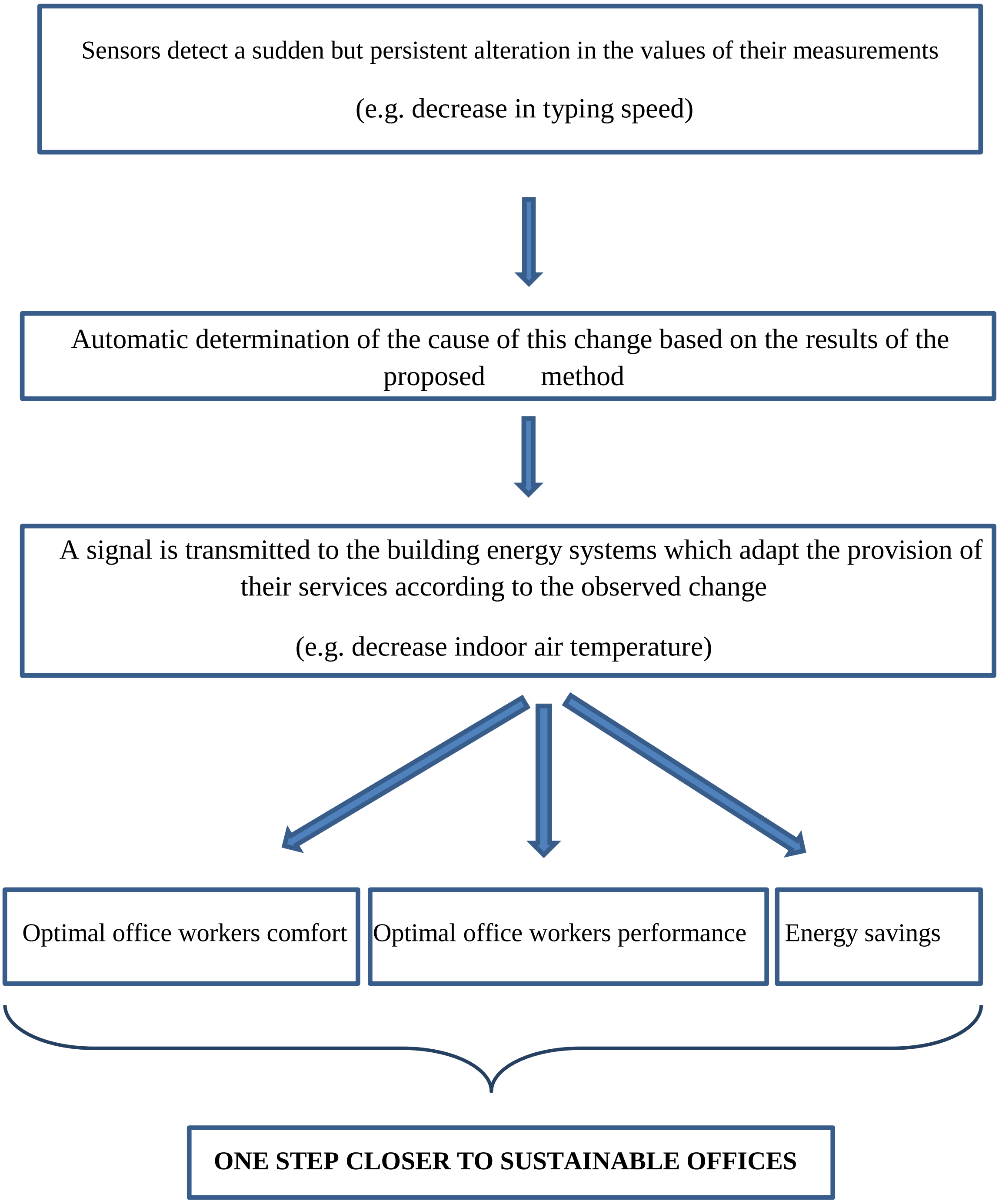
6.3 Final contribution of the proposed method

The main contribution of the proposed method is the development of a so called ‘’Personal comfort Identity’’ (PCI) for each employee. This innovative concept will be the result of the four steps described above and it could change the way that building services and energy systems are functioning in order to meet the needs of the office workers. The idea behind the PCI is that after conducting the proposed experimental method, very specific and accurate personal data for each employee will be available. First of all, the comfort set points (meaning the limits of their comfort zone) of every employee will be known personally. This means that, in contrast with the general indoor comfort standards and guidelines, this method will help to develop a more personalized way of determining the ideal indoor conditions for each employee providing higher levels of accuracy.

In addition to this, the average values of activities like:

- Typing speed
- Pressure applied on the keys of the keyboard
- Pressure applied when clicking the mouse
- Rotation frequency of the scroll wheel,

will be known for each employee personally. Apart from that, the reason behind potential fluctuations around these averages throughout the day will be easier to be identified. This means that, every time that a change in, for example, typing speed of a particular employee is observed (in real time), the cause of this change will be determined immediately. In other words, it will be immediately understood that the observed change in, for example, typing speed resulted from the employee’s thermal discomfort due to, for example, elevated indoor temperature. This will be a huge advantage since it will provide the opportunity to optimize the provision of services through the building energy systems by automatically adjusting their operations according to the observed change. In other words, this innovative, dynamic and human oriented strategy of building services provision will contribute towards a healthier, more satisfied and more productive workforce. A graphical representation of the sequence of the actions described above and their immediate consequences is presented below:


Sensors detect a sudden but persistent alteration in the values of their measurements
(e.g. decrease in typing speed)
Automatic determination of the cause of this change based on the results of the proposed method
A signal is transmitted to the building energy systems which adapt the provision of their services according to the observed change
(e.g. decrease indoor air temperature)
Optimal office workers comfort
Optimal office workers performance
Energy savings
ONE STEP CLOSER TO SUSTAINABLE OFFICES

6.4 Future work

Having presented our initial idea in the form of a hypothesis as well as described the proposed method in the form of an experimental procedure, the objective of the future work will be conduct an experiment and carry out all the steps of the proposed experimental method. This means that, we need to pass from theory to practice and conduct this experiment in a simulated office environment where experimental subjects will perform typical office tasks.

Conducting an experiment like this is the only way to acquire reliable experimental data which will be as close as possible to the real-world conditions. Then, the next step should be to select an appropriate statistical method which will be used in order to process the collected data and proceed to the statistical evaluation of the observed correlations between sensors recordings and questionnaire results. In other words the data which will derive from this experiment in the simulated office environment will determine if our Null hypothesis is correct and therefore our method have the potential to be implemented in real office places.

In addition to this, this experiment will provide the opportunity not only to detect and correct possible practical complications which may arise but also to optimize the proposed method by introducing improvements which will increase its effectiveness and guaranty its applicability to real office conditions. Such improvements could concern specific issues such as the format and the content of the questionnaires, the frequency of the distribution of the questionnaires, the total duration of the proposed experimental process or other relevant issues.

7. References

1. Dvorakova, P. (2013).Lecture No 3: Indoor air quality. Faculty of Civil Engineering, Prague.
2. World Health Organization. (2000). Chapter 5.1: Acrylonitrile. Regional Office for Europe, Copenhagen, Denmark. Retrieved from: http://www.euro.who.int/__data/assets/pdf_file/0016/123055/AQG2ndEd_5_1acrylonitrile.pdf?ua=1
3. Harrison, R. Juanna, M. Sborit, D. Dor, F. and Henderson, R. World Health Organization. (2010). Guidelines for indoor air quality: Selected pollutants. Benzene. Retrieved from: https://www.ncbi.nlm.nih.gov/books/NBK138708/
4. Scorecard, The pollution information site. 1,3-Butadiene. Retrieved from: wOhttp://scorecard.goodguide.com/chemical-profiles/html/13butadiene.html
5. World Health Organization. (2002). Geneva. Concise International Chemical Assessment Document 46. Carbon disulfide. Retrieved from: http://www.who.int/ipcs/publications/cicad/cicad46_rev_1.pdf
6. Minnesota Department of Health. Carbon Monoxide poisoning in your home. Retrieved from: http://www.health.state.mn.us/divs/eh/indoorair/co/
7. World Health Organization. (1998). Geneva. Concise International Chemical Assessment Document 1. 1,2-Dichloroethane. Retrieved from: http://www.who.int/ipcs/publications/cicad/en/cicad01.pdf
8. World Health Organization. (2000). Chapter 5.7: Dichloromethane. Regional Office for Europe, Copenhagen, Denmark. Retrieved from: http://www.euro.who.int/__data/assets/pdf_file/0013/123061/AQG2ndEd_5_7Dichloromethane.pdf?ua=1
9. Kaden, D. Mandin, C. Nielsen, G. and Wolkoff, P. World Health Organization. (2010). Guidelines for indoor air quality: Selected pollutants.Formaldehyde. Retrieved from: https://www.ncbi.nlm.nih.gov/books/NBK138711/
10. Choi, H. Harrison, R. Komulainen, H. and Juana M. Delgado Saborit. World Health Organization. (2010). Guidelines for indoor air quality: Selected pollutants.Polycyclic aromatic hydrocarbons. Retrieved from: https://www.ncbi.nlm.nih.gov/books/NBK138709/
11. United States Environmental Protection Agency. Polychlorinated Biphenyls (PCBs). Retrieved from: https://www.epa.gov/pcbs/polychlorinated-biphenyls-pcbs-building-materials
12. World Health Organization. (2000). Chapter 5.11: Polychlorinated dibenzodioxins and dibenzofurans. Regional Office for Europe, Copenhagen, Denmark. Retrieved from: http://www.euro.who.int/__data/assets/pdf_file/0017/123065/AQG2ndEd_5_11PCDDPCDF.pdf?ua=1
13. Agency for Toxic Substances and Disease Registry. (2012). Toxic Substances Portal – Styrene. Retrieved from: https://www.atsdr.cdc.gov/phs/phs.asp?id=419&tid=74

14. Nijhuis, N. Loh, M. and Harrison, P. World Health Organization. (2010). Guidelines for indoor air quality: Selected pollutants. Tetrachloroethylene. Retrieved from: https://www.ncbi.nlm.nih.gov/books/NBK138706/
15. Government of Canada. (2012). Toluene in Indoor Air. Retrieved from: https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/air-quality/toluene-indoor-air-environment-workplace-health.html
16. Bonvallot, N. l Harrison, P. and Loh, M. (2010). World Health Organization. Guidelines for indoor air quality: Selected pollutants. Trichloroethylene. Retrieved from: https://www.ncbi.nlm.nih.gov/books/NBK138713/
17. Agency for Toxic Substances and Disease Registry. Vinyl Chloride. Potential for human exposure. Retrieved from: https://www.atsdr.cdc.gov/toxprofiles/tp20-c6.pdf
18. World Health Organization. (2016). Arsenic. Retrieved from: http://www.who.int/mediacentre/factsheets/fs372/en/
19. MesotheliomaHelp. (2017). Asbestos in older homes. https://www.mesotheliomahelp.org/asbestos/in-homes/
20. Agency for Toxic Substances and Disease Registry. (2012). Toxic Substances Portal – Cadmium. Retrieved from: https://www.atsdr.cdc.gov/phs/phs.asp?id=46&tid=15
21. Agency for Toxic Substances and Disease Registry. (2013). Environmental Health and Medicine Education. Chromium Toxicity. Retrieved from: https://www.atsdr.cdc.gov/csem/csem.asp?csem=10&po=5
22. New York State. (2005). Department of Health. Hydrogen Sulfide Chemical Information Sheet. Retrieved from: https://www.health.ny.gov/environmental/chemicals/hydrogen_sulfide/
23. Agency for Toxic Substances and Disease Registry. (2013). Toxic Substances Portal – Lead. Retrieved from: https://www.atsdr.cdc.gov/csem/csem.html
24. Mercury in the Environment and Water Supply. Sources of Mercury. Retrieved from: https://people.uwec.edu/piercech/Hg/mercury_water/sources.htm
25. Colorado Department of Public Health and Environment. Mercury: Household sources and reducing exposure. Retrieved from: https://www.colorado.gov/pacific/sites/default/files/HHW_Mercury_Hg-Household-Sources-FS.pdf
26. World Health Organization. (2000). Chapter 6.10: Nickel. Regional Office for Europe, Copenhagen, Denmark. Retrieved from: http://www.euro.who.int/__data/assets/pdf_file/0014/123080/AQG2ndEd_6_10Nickel.pdf?ua=1
27. World Health Organization. (2000). Chapter 7.1: Nitrogen Dioxide. Regional Office for Europe, Copenhagen, Denmark. Retrieved from:

http://www.euro.who.int/__data/assets/pdf_file/0017/123083/AQG2ndEd_7_1nitrogendioxide.pdf

28. Weschler, C. (2000). Ozone in Indoor Environments: Concentration and Chemistry. Retrieved from: http://www.4office.ca/wp-content/uploads/Tab-12b-Indoor-Ozone.pdf
29. What is your impact? Main sources of carbon dioxide emissions. Retrieved from: https://whatsyourimpact.org/greenhouse-gases/carbon-dioxide-emissions
30. Giere, R. and Querol, X. (2010). Solid Particulate Matter in the Atmosphere. https://eclass.uoa.gr/modules/document/file.php/GEOL105/%CE%A3%CE%A7%CE%95%CE%A4%CE%99%CE%9A%CE%97%20%CE%92%CE%99%CE%92%CE%9B%CE%99%CE%9F%CE%93%CE%A1%CE%91%CE%A6%CE%99%CE%91/atmosperedust1giere.pdf
31. United States Environmental Protection Agency. Radon in Homes and Buildings. Retrieved from: https://www3.epa.gov/radtown/radon-homes-buildings.html
32. Najam, L.A. , Tawfiq, N. F. , and Mahmood, R. H. (2013). Radon Concentration in Some Building Materials in Using CR-39 Track Detector. International Journal of Physics. Retrieved from: http://pubs.sciepub.com/ijp/1/3/3/#
33. Prussin, A. J., & Marr, L. C. (2015). Sources of airborne microorganisms in the built environment. *Microbiome*. Retrieved from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4688924/
34. Leventin, E. (n.d.) Airborne Fungi in Indoor Environments. University of Tulsa. Retrieved from: http://pollen.utulsa.edu/Spores/Indoor.htm
35. World Health Organization. (1990). Indoor air quality: biological contaminants. Regional Office for Europe, Copenhagen, Denmark. Retrieved from: http://www.euro.who.int/__data/assets/pdf_file/0005/156146/WA754ES.pdf
36. Thatcher, T. L. and Layton D. W. (1994). Deposition, resuspension and penetration of particles within a residence. Pergamon. Great Britain. Retrieved from: http://centerforhealthyhousing.org/Portals/0/Contents/Article0645.pdf
37. Dvorakova, P. (2013).Lecture No 3: Indoor air quality. Faculty of Civil Engineering, CTU Prague.
38. United States Environmental Protection Agency. (1991). Introduction to Indoor Air Quality Reference Manual. Retrieved from: https://nepis.epa.gov/Exe/ZyNET.exe/000000S0.txt?ZyActionD=ZyDocument&Client=EPA&Index=1991%20Thru%201994&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C91THRU94%5CTXT%5C00000000%5C000000S0.txt&User=A

NONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r105g16/r105g16/x150y150g16/i600&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=20&ZyEntry=5&slide
39. Kabele, I. K. (2013). Lecture No 3: Thermal comfort. Faculty of Civil Engineering, CTU Prague.
40. The six basic factors. Health and Safety Executive. Retrieved from: http://www.hse.gov.uk/temperature/thermal/factors.htm
41. Thermal comfort. (1997). INNOVA, AirTech Instruments. Retrieved from: http://www.labeee.ufsc.br/antigo/arquivos/publicacoes/Thermal_Booklet.pdf
42. Thermal comfort in office settings. University of Connecticut. Department of Environmental Health and Safety. Retrieved from: http://ehs.uconn.edu/docs/Officecomfort.pdf
43. Indoor Comfort Issues: Too much or too little humidity. Coolray. Retrieved from: https://www.coolray.com/help-guides/indoor_comfort_issues_to_much_or_too_little_humidity
44. Steward Unsdorfer. (n.d.). Managing ideal indoor humidity for maximum comfort. Central heating and air-conditioning. Retrieved from: http://www.centralhtg.com/blog/managing-home-humidity-for-maximum-comfort
45. The importance of light at the office. (2015). Modular lighting instruments. Retrieved from: http://www.modular.nl/en/blog/46-the+importance+of+light+at+the+office
46. Calleja, H., Perez, A. R. and Fernando. (2011). Conditions required for visual comfort. Encyclopedia of Occupational Health and Safety. Retrieved from: http://www.iloencyclopaedia.org/component/k2/item/284-conditions-required-for-visual-comfort
47. Health, Wellbeing and Productivity in Offices: The Next Chapter for Green Buildings. World Green Building Council. Retrieved from: http://www.jll.com/Research/Health_Wellbeing_Productivity.pdf?1a56c1ad-7be7-4d6d-8f32-74bb6e72fa3f
48. Dvorakova, P. (2013).Lecture No 5: Acoustical comfort. Faculty of Civil Engineering, CTU in Prague.
49. Scavone, G. P. (n.d.). Room acoustics. McGill University. Retrieved from: https://www.music.mcgill.ca/~gary/307/week3/rooms.html
50. Perry, T. (n.d.). How to create a killer sweet spot in your room. Arquen acoustics. Retrieved from: http://arqen.com/acoustics-101/reflection-free-zone/
51. Airborne sound. (2017). Designing Buildings Wiki. Institution of Civil Engineering. Retrieved from: https://www.designingbuildings.co.uk/wiki/Airborne_sound

52. Structure borne sound. (2017). Designing Buildings Wiki. Institution of Civil Engineering. Retrieved from: https://www.designingbuildings.co.uk/wiki/Structure-borne_sound
53. Wargocki, P. , Seppanen, O. , Andersson, J. , Boestra, A. , Croome, D. C. & Fitzner, K. , Hanssen, S. O. (2007). Indoor climate and productivity in offices. Federation of European Heating, Ventilation and Air Conditioning Associations. Finland: Forssan Kirjapaino Oy.
54. Ormandy, D. , and Véronique Ezratty, V. (n.d.). Thermal Discomfort and Health: Protecting the Susceptible from Excess Cold and Excess Heat in Housing. Division of Health Sciences, Warwick Medical School, University of Warwick. Retrieved from: https://www2.warwick.ac.uk/fac/med/research/hscience/sssh/publications/publications14/thermal.pdf
55. Sookchaiya, T. , Monyakul, V., and Thepa, S. (2010). Assessment of the thermal environment effects on human comfort and health for the development of novel air conditioning system in tropical regions. Division of Energy Technology, School of Energy Environment and Materials, King Mongkut's University of Technology Thonburi, Bangkok, Thailand. Retrieved from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.657.7543&rep=rep1&type=pdf
56. Wargocki, P. ,and Wyon, D. P. (2016). Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. Building and Environment. Retrieved from: http://www.sciencedirect.com/science/article/pii/S0360132316304449
57. Seppanen, O. , Fisk, W.J. , & Lei, Q.H.(2006). Room temperature and productivity in office work. Lawrence Berkeley National Laboratory. Retrieved from: http://escholarship.org/uc/item/9bw3n707
58. 11 United States Environmental Protection Agency.(1991). Indoor Air Facts No.4: Sick Building Syndrome. Retrieved from: https://www.epa.gov/sites/production/files/2014-08/documents/sick_building_factsheet.pdf
59. Dvorakova, P. (2013).Lecture No 3: Indoor air quality. Faculty of Civil Engineering, Prague.
60. Agency for Toxic Substances and Disease Registry. (1999). Toxic Substances Portal – Acrylonitrate. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=446&tid=78
61. StenkenS, P. & Loomans, M. (2010). T1.3 Performance Indicators for Health and Comfort. Perfection. Retrieved from: http://www.ca-perfection.eu/media/files/Perfection_D13_final.pdf
62. Agency for Toxic Substances and Disease Registry. (2007). Toxic Substances Portal – Benzene. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=38&tid=14

63. Agency for Toxic Substances and Disease Registry. (2009). Toxic Substances Portal – 1,3-Butadiene. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=458&tid=81
64. Agency for Toxic Substances and Disease Registry. (1997). Toxic Substances Portal –Carbon Disulfide. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=473&tid=84
65. U.S. Department of Health & Human Services. (2015). Carbon Monoxide Poisoning. Retrieved from: https://www.cdc.gov/co/faqs.htm
66. Agency for Toxic Substances and Disease Registry. (2001). Toxic Substances Portal –1,2-Dichloroethane. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=591&tid=110
67. World Health Organization. (2000). Chapter 5.7 Dichloromethane. Regional Office for Europe, Copenhagen, Denmark. Retrieved from: http://www.euro.who.int/__data/assets/pdf_file/0013/123061/AQG2ndEd_5_7Dichloromethane.pdf?ua=1
68. Agency for Toxic Substances and Disease Registry. (2015). Toxic Substances Portal – Formaldehyde. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=219&tid=39
69. California Environmental Protection Agency. (2013). Health Effects of Indoor Pollutants. Retrieved from: https://www.arb.ca.gov/research/indoor/healtheffects1table1.htm
70. Agency for Toxic Substances and Disease Registry. (1996). Toxic Substances Portal – Polycyclic Aromatic Hydrocarbons (PAHs). Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=121&tid=25
71. Agency for Toxic Substances and Disease Registry. (2014). Toxic Substances Portal – Polychlorinated Biphenyls (PCBs). Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=140&tid=26
72. World Health Organization. (2000). Chapter 5.11 Polychlorinated dibenzodioxins and dibenzofurans. Regional Office for Europe, Copenhagen, Denmark. Retrieved from: http://www.euro.who.int/__data/assets/pdf_file/0017/123065/AQG2ndEd_5_11PCDDPCDF.pdf?ua=1
73. Agency for Toxic Substances and Disease Registry. (2012). Toxic Substances Portal –Styrene. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=420&tid=74
74. Agency for Toxic Substances and Disease Registry. (2014). Toxic Substances Portal – Tetrachloroethylene (PERC). Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=264&tid=48
75. Agency for Toxic Substances and Disease Registry. (1999). Toxic Substances Portal – Toluene. Retrieved from: https://www.atsdr.cdc.gov/phs/phs.asp?id=159&tid=29
76. Agency for Toxic Substances and Disease Registry. (2016). Toxic Substances Portal – Trichloroethylene (TCE). Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=172&tid=30

77. Agency for Toxic Substances and Disease Registry. (2006). Toxic Substances Portal – Vinyl Chloride. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=281&tid=51
78. Agency for Toxic Substances and Disease Registry. (2007). Toxic Substances Portal – Arsenic. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=19&tid=3
79. Agency for Toxic Substances and Disease Registry. (2016). Toxic Substances Portal – Asbestos. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=29&tid=4
80. Agency for Toxic Substances and Disease Registry. (2008). Toxic Substances Portal – Cadmium. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=47&tid=15
81. Agency for Toxic Substances and Disease Registry. (2016). Toxic Substances Portal – Chromium. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=61&tid=17
82. U.S. Department of Health & Human Services. (2017). Lead: Health Problems Caused by Lead. Retrieved from: https://www.cdc.gov/niosh/topics/lead/health.html
83. Agency for Toxic Substances and Disease Registry. (1999). Toxic Substances Portal – Mercury. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/TF.asp?id=113&tid=24
84. Agency for Toxic Substances and Disease Registry. (2005). Toxic Substances Portal – Nickel. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=244&tid=44
85. Agency for Toxic Substances and Disease Registry. (2014). Toxic Substances Portal – Nitrogen Oxides. Retrieved from: https://www.atsdr.cdc.gov/mmg/mmg.asp?id=394&tid=69
86. National Institute for Occupational Safety and Health. (2016). Nitrogen dioxide. Retrieved from: https://www.cdc.gov/niosh/npg/npgd0454.html
87. National Center for Environmental Health. (2016). Ozone and Your Health. Retrieved from: https://www.cdc.gov/air/ozone.html
88. National Institute for Occupational Safety and Health. (2015). Carbon Dioxide. Rterieved from: https://www.cdc.gov/niosh/ipcsneng/neng0021.html
89. Canadian Centre for Occupational Health & Safety. (2017). Carbon Dioxide. Retrieved from: https://www.ccohs.ca/oshanswers/chemicals/chem_profiles/carbon_dioxide.html
90. Agency for Toxic Substances and Disease Registry. (1999). Toxic Substances Portal – Sulfur Dioxide. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=252&tid=46
91. Agency for Toxic Substances and Disease Registry. (1999). Toxic Substances Portal – Radon. Retrieved from: https://www.atsdr.cdc.gov/toxfaqs/tf.asp?id=406&tid=71

92. World Health Organization. (1988). Indoor air quality: biological contaminants. Regional Office for Europe, Copenhagen, Denmark. Retrieved from: http://www.euro.who.int/__data/assets/pdf_file/0005/156146/WA754ES.pdf
93. Sorenson, W.G. (1999). Fungal Spores: Hazardous to Health? Environmental Health Perspectives. Retrieved from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1566211/pdf/envhper00520-0083.pdf
94. Baxi, S.N. , Portnoy, J.M. , Larenas-Linnemann, D. , Phipatanakul, W. (2016). Exposure and Health Effects of Fungi on Humans. Jurnal of allergy and clinical immunology. Retrieved from: https://www.ncbi.nlm.nih.gov/pubmed/26947460#
95. Wyon, D. P. & Wargocki, P. (2016). Ten questions concerning thermal and indoor air quality effects on the performance of office work. Building and Environment. Retrieved from: http://www.sciencedirect.com/science/article/pii/S0360132316304449
96. P. Wargocki, D. Wyon, Y. Baik, G. Clausen, P. Fanger. (1999). Perceived air quality, Sick Building Syndrome SBS. symptoms and productivity in an office with two different pollution loads, Indoor Air.
97. Lagencrantz, L. , Wistrand, M. , Willen, U. , Wargocki, P. , Witterseh, T. , Sundell, J. (2000). Negative impact of air pollution on productivity: previous Danish findings repeated in new Swedish test. Proceedings of the Health Buildings 2000 Conference.
98. Z. Bak_o-Bir_o, P. Wargocki, C. Weschler, P. Fanger. (2004). Effects of pollution from personal computers on perceived air quality, SBS symptoms and productivity in offices, Indoor Air 14, pp. 178-187.
99. D. Shendell, R. Prill, W. Fisk, M. Apte, D. Blake, D. Faulkner. (2004). Associations between classroom CO2 concentrations and student attendance in Washington and Idaho, Indoor Air 145, pp. 333-341.
100. S. Gaihre, S. Semple, J. Miller, S. Fielding, S. Turner. (2014). Classroom carbon dioxide concentration, school attendance, and educational attainment, J. Sch. Health 849, pp. 569-574.
101. 105. P. Wargocki, D. Wyon, P. Fanger. (2000). Productivity is affected by the air quality in offices, in: Proceeding of Healthy Buildings 2000, 1, ISIAQ, Espoo, Finland, pp. 635-640.
102. 106.P. Wargocki, D. Wyon, P. Fanger. (2004). The performance and subjective responses of call-centre operators with new and used supply air filters at two outdoor air supply rates, Indoor Air 14, pp 7-16.107
103. C. Federspiel, W. Fisk, P. Price, G. Liu, D. Faulkner, D. Dibartolemeo, D. Sullivan,M. Lahiff. (2004). Worker performance and ventilation in a call-center: analyses of work performance data for registered nurses, Indoor Air 14, pp. 41-50.
104. K. Tham, H. Willem, S. Sekhar, D. Wyon, P. Wargocki, P. Fanger. (2003). Temperature and ventilation effects on the work performance of

office workers (study of a call center in the tropics), in: Proceedings of Healthy Buildings 2003 vol. 3, pp. 280-286.
105. J. Park, C. Yoon. (2011). The effects of outdoor air supply rate on work performance during 8-h work period, Indoor Air 21, pp. 284-290.
106. P. Wargocki, D. Wyon. (2007). The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children: ASHRAE 1257-RP, HVAC&R Res. 132, pp. 165-191.
107. Z. Bak_o-Bir_o, N. Kochhar, D. Clements-Croome, H. Awbi, M. Williams. (2007) Ventilation rates in schools and learning performance, in: Proceedings of CLIMA 2007, FINVAC, Helsinki, Finland, pp. 1434-1440.
108. Sappanen, O. , Fisk, W. , Lei, Q.H., (2006a). Ventilation and performance in offece work. Indoor Air Journal, pp. 28-35.
109. D. Milton, P. Glencross, M. Walters. (2000). Risk of sick-leave associated with outdoor air supply rate, humidification and occupants complaints, Indoor Air 10, pp. 212-221.
110. E. Simons, S. Hwang, E. Fitzgerald, C. Kielb, S. Lin. (2010). The impact of school building conditions on student absenteeism in upstate New York, Am. J Public Health 1009, pp. 1679-1686.
111. M. Mendell, E. Eliseeva, M. Davies, M. Spears, A. Lobscheid, W. Fisk, M. Apte. (2013). Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools, Indoor Air 236, pp. 515-528
112. W. Fisk, O. Seppanen, D. Faulkner, J. Huang. (2003). Cost benefit analysis of ventilation control strategies in an office building, in: Proceedings of Healthy Buildings 2003, vol. 3, NUS, Singapore, pp. 361-366.
113. European commission. (2012). Health Effects of Artificial Light. Scientific Committee on Emerging and Newly Identified Health Risks. Retrieved from: https://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_035.pdf
114. Touitou, Y. , Reinberg, A. , Touitou, D. (2017). Association between light at night, melatonin secretion, sleep deprivation, and the internal clock: Health impacts and mechanisms of circadian disruption. Journal of Life Sciences. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0024320517300450
115. YongMin Cho, Seung-Hun Ryu, Byeo Ri Lee, Kyung Hee Kim, Eunil Lee & Jaewook Choi. (2015). Effects of artificial light at night on human health: A literature review of observational and experimental studies applied to exposure assessment. The Journal of Biological and Medical Rhythm Research. Retrieved from: file:///C:/Users/User/Downloads/effect%20of%20ALAN.pdf

116. Obayashi, K. , Saeki, K. , Iwamoto, J. , et al. (2013a). Exposure to light at night and risk of depression in the elderly. J Affect Disord.
117. ‘’A.C. Bara, S. Arber. (2009). Working shifts and mental health – findings from the British Household Panel Survey (1995–2005). Scand. J. Work Environ. Health, pp. 361–367.
118. J.C. Marquié, P. Tucker, S. Folkard, C. Gentil, D. Ansiau. (2015).Chronic effects of shift work on cognition: findings from the VISAT longitudinal study,Occup. Environ. Med., pp. 258–264.
119. Cajochen, C. (2007). Alerting effects of light. Centre for Chronobiology, Psychiatric University Clinics. Retrieved from: http://www.chronobiology.ch/wp-content/uploads/publications/2007_06.pdf
120. Jörg Kelter, J. , & Merlin, C. (2014). Lighting quality perceived in offices. Zumtobel Research. Retrieved from: http://www.zumtobel.com/PDB/Ressource/teaser/en/com/Study_Office_Perceived_Lighting_Quality.pdf
121. Newsham GR. Aries M. Mancini S. and Faye G. (2008). Individual Control of Electric Lighting in a Daylit Space. Lighting Research and Technology 40, pp. 25-41.
122. Heschong Mahone Group. (2003). Windows and Offices: a Study of Worker Performance and the Indoor Environment (Technical Report) for California Energy Commission. Retrieved from: http://www.energy.ca.gov/2003publications/CEC-500-2003-082/CEC-500-2003-082-A-09.PDF
123. Elzeyadi, I. (2011). Daylighting-Bias and Biophilia: Quantifying the Impact of Daylighting on Occupant Health. Available: https://www.usgbc.org/resources/daylighting-bias-and-biophilia-quantifying-impact-daylighting-occupants-health
124. Kamarulzaman, N. ,Saleh, A.A. , Hashim, S.Z. , Hashim, H. & Abdul-Ghani, A.A. (2011). An Overview of the Influence of Physical Office Environments Towards Employee. Journal of Procedia Engineering. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S1877705811029730
125. Maxwell, L.E. (n.d.).Noise in the office workplace. Facility Planning and Management. Department of design and environmental analyses, College of Human Ecology, Cornell University. Retrieved from: http://www.human.cornell.edu/dea/outreach/upload/FPM-Notes_Vol1_Number11.pdf
126. Evans & Johnson. (2000). Stress and open-office noise, Journal of Applied Psychology, pp. 779-783.
127. Tobias, A. , Recio, A. , Diaz, J. , Linares, C. (2015). Health impact assessment of traffic noise in Madrid. Journal of Environmental Research. Retrieved from:

http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0013935114004629

128. European Environment Agency. (2014). Noise in Europe. Luxembourg: Publications Office of the European Union 2014. Retrieved from: https://www.eea.europa.eu/publications/noise-in-europe-2014/file

129. Babisch W. (2006). Transportation noise and cardiovascular risk. Review and synthesis of epidemiological studies. Dose-effect curve and risk estimation. Retrieved from: http://www.bruit.fr/images/stories/pdf/babisch_transportation_noise_cardiovascular_risk.pdf

130. J. Selander, M.E. Nilsson, G. Bluhm, M. Rosenlund, M. Lindqvist, G. Nise, *et al. (2009).* Long-term exposure to road traffic noise and myocardial infraction. Epidemology, pp. 272-279.

131. W. Babisch. (2008). Road traffic noise and cardiovascular risk. Noise Health, pp. 27-33.

132. Stansfeld, S.A. & Shipley, M. (2015). Noise sensitivity and future risk of illness and mortality. Journal of Science of the Total Environment. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0048969715003289

133. Brocolini, L. , Parizet, E. & Chevret, P. (2016). Effect of masking noise on cognitive performance and annoyance in open plan offices. Journal of applied acoustics. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0003682X16302067

134. M. Pierrette, E. Parizet, P. Chevret & J. Chatillon. (2014).Noise effect on comfort in open-space offices: development of an assessment questionnaire. Ergonomics, pp. 96-106.

135. Boyce, P. Users' assessments of a landscaped office. Journal of Architectural Research, pp. 44-62.

136. Jahncke, H. , Hygge, S. , Halin, N. , Green, A.M. & Dimberg, K. (2011). Open-plan office noise: Cognitive performance and restoration. Journal of Environmental Psychology, pp. 373-382. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0272494411000429

137. Bandury, S.P. & Berry, D.C. (2005). Office noise and employee concentration: identifying causes of disruption and potential improvements. Ergonomics, pp. 25-37.

138. Banbury, S.P. & Berry, D.C. (1998). Disruption of office-related tasks by speech and office noise. British Journal of Psychology, pp 499–517’’

139. Jones, D.M. & Broadbent, D.E. (1979). Side-effects of inference with speech by noise. Journal of Ergonomics, pp. 1073-1081.

140. Witterseh, T. , Wyon, D.P. & Clausen, G. (2004). The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance of office work. Indoor air, pp. 30-40.
141. Djongyang, N. , Tchinda, R. & Njomo, D. (2010). Thermal comfort: A review paper. Renewable and Sustainable Energy Reviews. Retrieved from: https://www-sciencedirect-com.focus.lib.kth.se/science/article/pii/S1364032110002200#sec0010
142. Nicol, J. F., Humphereys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0378778802000063
143. Predicting Thermal Comfort. (n.d.). Civil, Environmental and Architectural Engineering. University of Colorado. Retreived from: http://ceae.colorado.edu/~brandem/aren3050/docs/ThermalComfort.pdf
144. Humphreys, M.A. , Nicol, J.F. , (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings. Retrieved from:http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0378778802000063
145. Al horr, Y. , Mohammed Arif, M. , Katafygiotou, M. , Mazroei, A. , Kaushik, A. , Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. International Journal of Sustainable Built Environment. Retrieved from: http://www.sciencedirect.com/science/article/pii/S2212609016300140
146. Brager, G.S. , Dear, R.J. (1997). Thermal adaptation in the built environment: a literature review. Energy and Buildings. Retrieved from: https://www-sciencedirect-com.focus.lib.kth.se/science/article/pii/S0378778897000534
147. Rupp, R.F. , Vasquez, N.G. & Lamberts, R. (2015). A review of human thermal comfort in the built environment. Energy and Buildings. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0378778815301638
148. Nico, A.M. , Liuzzi, S. ,Stefanizzi, P. (2014). Evaluation of thermal comfort in university classrooms through objective approach and subjective preference analysis. Applied Ergonomics. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0003687014002877
149. Ali, M. , Khan, M.H. , Gilani, S.I. (2016). Revisiting Fanger's thermal comfort model using mean blood pressure as a bio-marker: An experimental investigation. Applied Thermal Engineering. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S1359431116313965

150. Lamberts, R. , Dear, R. , Candilo, C. & Vecchi, R.D. (2017). Thermal comfort in office buildings: Findings from a field study in mixed-mode and fully-air conditioning environments under humid subtropical conditions. Building and Environment. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0360132317303281
151. Luo, M., Caao, B., Damiens, J., Lin, B., Zhu, Y. (2014). Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate. Building and Environment. Retrieved from: https://www-sciencedirect-com.focus.lib.kth.se/science/article/pii/S036013231400211X
152. Barbadilla, E., Lissen, J.M.S., Martin, J.G., Ruiz, P.A., Brotas, L. (2017). Field study on adaptive thermal comfort in mixed mode office buildings in southwestern area of Spain. Building and Environment. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0360132317302779
153. Ioannou, A., Itard, L. (2016). In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands. Energy and Buildings. Retrieved from: http://www.sciencedirect.com/science/article/pii/S0378778816311057
154. Croitoru, C., Nastase, I., Bode, F., Meslem, A., Dogeanu, A. (2014). Thermal comfort models for indoor spaces and vehicles—Current capabilities and future perspectives. Renewable and Sustainable Energy Reviews. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S1364032114009332
155. Kluizenaar, Y., van de Brink, L., Janssen, S. & Bluyssen, P.M. (2011). Assessment of wellbeing in an indoor office environment. Building and Environment. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S036013231100206X
156. Li, D., Menassa, C.C. & Kamat, V.R. (2017). Personalized human comfort in indoor building environments under diverse conditioning modes. Building and Environment. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0360132317304535
157. Rafaie, M., Alsaleem, F. & Hasan, M.H. (2016). Sensitivity study for the PMV thermal comfort model and the use of wearable devices biometric data for metabolic rate estimation. Building and Environment. Retrieved from: http://www.sciencedirect.com.focus.lib.kth.se/science/article/pii/S0360132316304000
158. Dietz, P.H. , Eidelson, B. , Westhues, J. & Bathiche, S. (2009). A Practical Pressure Sensitive Computer Keyboard. The Applied Sciences

Group, Microsoft Corporation. Retrieved from: file:///C:/Users/User/Downloads/uisttn190-dietz.pdf
159. Dennerlein, J. T. , Diao, E. , Mote, C.D. & Rempel, D.M. (1999). In Vivo Finger Flexor Tendon Force while Tapping on a Keyswitch. Journal of orthopaedic research : official publication of the Orthopaedic Research Society, pp.178-184. Retrieved from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2665300/
160. Stone, D. (n.d.). What Is a Good Typing Speed Per Minute? Chron. Retrieved from: http://smallbusiness.chron.com/good-typing-speed-per-minute-71789.html
161. Leung, W. C. (2001). How to design a questionnaire. Retrieved from: http://www.dpcdsb.org/NR/rdonlyres/138975AC-B110-4D1E-902F-81C8E69BF9A0/107060/How_to_design_a_questionnaire.pdf
162. How To Write A Good Survey. (1998). InfoPoll. Retrieved from: http://www.accesscable.net/~infopoll/tips.htm
163. Agriculture and Consumer Protection.(n.d.). Marketing research and information systems. Chapter 4: Questionnaire Design. Retrieved from: http://www.fao.org/docrep/w3241e/w3241e05.htm
164. Hutcheson, K. (n.d.). Sample Thermal Comfort Survey. Eco-Forte. Retrieved from: http://ra-lingreenway.groupsite.com/file_cabinet/files/573395/download/Thermal%20Comfort%20Survey.pdf?m=1355928365
165. Health and Safety Executive.(n.d). Thermal comfort checklist. Retrieved from: http://www.hse.gov.uk/temperature/assets/docs/thermal-comfort-checklist.pdf
166. Thermal Comfort questionnaire. Survey Monkey. Retrieved from: https://www.surveymonkey.com/r/7CK9Q7H
167. WIKA. Ambient temperature sensor. Retrieved from: http://en-co.wika.de/tf41_en_co.WIKA
168. Testo. Globe Probe. Retrieved from: https://www.testo.com/en-US/globe-probe-o-5-9/p/0602-0743
169. Aparicio, P. , Ruiz, A. , Sanchez, F.J. & Brotas, L. (2016). The globe thermometer in comfort and environmental studies in buildings. Retrieved from: http://www.scielo.cl/pdf/rconst/v15n3/art06.pdf
170. Bell, S. (2011). A beginner's guide to humidity measurement. National Physical Laboratory. Retrieved from: http://www.npl.co.uk/upload/pdf/Beginner%27s%20guide%20to%20humidity%20measurement%20(draft%20for%20comment).pdf
171. GILL. Wind speed anemometer. Retrieved from: http://gillinstruments.com/products/anemometer/wind_ob2.htm
172. Ganguly, P. (2008). Types of Anemometers. Retrieved from: http://www.buzzle.com/articles/anemometer.html
173. Campbell Scientific. Infrared Radiometer with Standard Field of View. Retrieved from: https://www.campbellsci.com/si-111

174. Montgomery, L. (2017). 7 Best Indoor Air Quality Monitors Can Help You Breathe Easier This Allergy Season. Retrieved from: https://www.electronichouse.com/home-energy-management/beat-allergies-with-an-indoor-air-quality-monitor/
175. Which Indoor Air Quality Monitors Are Best And Why. (2016). Retrieved from: http://energysmartohio.com/uncategorized/which-indoor-air-quality-monitors-are-best-and-why/
176. Wilson, R. (2015). Photometer measures LED brightness and spectrum. Retrieved from: https://www.electronicsweekly.com/news/photometer-measures-led-brightness-and-spectrum-2015-11/
177. SciChem. Colorimeter WPA Model C07500. Retrieved from: https://education.scichem.com/Catalogue/ProductDetail/colorimeter-wpa-model-c07500?productID=3fcfba5d-4e52-4abf-8659-51afe320ec85&catalogueLevelItemID=922b97d7-2b7d-4784-a845-e72573fd0c30
178. Helena, K. (2016). Colorimeter vs. Spectrophotometer: Knowing the Differences Among Color Measurement Technologies. Retrieved from: https://www.hunterlab.com/blog/color-measurement-2/colorimeter-vs-spectrophotometer-knowing-the-differences-among-color-measurement-technologies/
179. Sound level meters. AliExpress. Retrieved from: https://www.aliexpress.com/store/product/LA-958-Professional-Sound-Level-Meter-with-Data-logger-Noise-dB-Decibel-Tester-with-USB-Interface/100653_32523710219.html?spm=2114.12010612.0.0.150cec65LPv6S5
180. PCE Instruments. Sound Level Meter / Noise Level Meter. Retrieved from: https://www.pce-instruments.com/english/aboutus
181. Neuner, C. (2015). Photo Tips and Tricks: Warm and Cool Colors. Cee’s Photography. Retrieved from: https://ceenphotography.com/2015/01/02/photo-tips-and-tricks-warm-and-cool-colors/
182. Sound pressure level. How loud is it? Rockfon. Retrieved from: http://exp.rockfon.com/performance/acoustics/what+determines+room+acoustics-c7-/sound+pressure+level#
183. Sierra. Extech instruments. Psychrometer and IR Thermometer. Retrieved from: https://sierracontrol.com/product-detail/Extech-HD500-Psychrometer-and-IR-Thermometer,-30:1/15770
184. Gama scientific. RadOMA Spectroradiometers. Retrieved from: http://www.gamma-sci.com/products/handheld-radiometersoptometer/