INDOOR ENVIRONMENT AND WELL-BEING

THE SAINT-GOBAIN BUILDING SCIENCE HANDBOOK

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SAINT-GOBAIN

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INTRODUCTION

On human beings, natural and built environments

It is 3 billion or so years since life first appeared on Earth. Mammals emerged around 220 million years ago, followed by modern man about 20,000 years ago – very recently, one might say.

Like all mammals, we are relatively fragile beings, particularly in the first and last years of our life. Avoiding exposure to excessive heat, cold, rain or wind is one of our primary needs. And so, over the course of our history and development, we have come up with a variety of strategies to protect ourselves from the outside environment.

The importance of the indoor environment was discussed and written about as early as the first century BC. The Romans regulated access to natural light, displayed a clear understanding of the importance of thermal comfort, mastered the workings of acoustics, and were particularly concerned about air quality.

From caves, to huts, to houses, we have gradually transformed our habitat and way of living. The advent of farming, around 10,000 years ago, encouraged settlements to develop, with denser populations. Villages, towns and cities progressively grew, bringing with them new health and social issues, which urban regulations were gradually created to address.

European industrialisation of the late 18th century marked the beginning of great change in the way people lived and their living standards. Urban communities sprang up around new work opportunities, the ownership and exploitation of agricultural land was largely restructured, and wealth grew. Building practices reflected the new possibilities of industrialised manufacture – bricks, window glass, roof tiles and slates gradually became commonplace building materials. As the 19th century progressed, the conversion from wood and bio-fuels to coal, together with the invention of electricity, meant that people could heat and light buildings more efficiently and permanently. This transformation in our way of living, which had far-reaching socio-economic consequences, encouraged the desire to better control indoor climates.

It was at the beginning of the 20th century that the environmental conditions and human needs within a building were accepted as specific subjects for consideration. As a result, the gradual recognition of factors that ensured well-being, 'comfort', in the use of buildings, slowly became incorporated into the building process.

Today, people are spending more and more time indoors whether at home, at work or as part of their day-to-day activities. In the urbanised western world, we spend around 90% of our time in an enclosed space. Studies show that time spent in the home is increasing and today can represent up to 19 to 20 hours per day for children and the elderly[1]. Thus the importance of being comfortable during these hours is increasing.

OVER THE COURSE OF OUR HISTORY, WE HAVE THOUGHT UP A VARIETY OF STRATEGIES TO PROTECT OURSELVES FROM THE OUTSIDE ENVIRONMENT.

4 MAIN FACTORS AFFECT PEOPLE'S PERCEPTION OF INDOOR COMFORT.

What is comfort?

Comfort is a state of physical ease and well-being in a given environment. Within the built environment, various provisions are necessary to enable occupants to perform comfortably the activities specific to the space. Safety, security, and adequate space are necessary conditions for comfort. However, they are not sufficient conditions for indoor comfort.
When considering the building fabric, the four main factors, that affect people's perception of indoor comfort can be summarised as follows:

- thermal comfort (determined by air temperature, humidity, draughts, etc.),
- visual comfort (determined by parameters such as view, luminosity, glare, etc.),
- acoustic comfort (determined by parameters such as noise from outdoors, vibrations, intelligibility of speech, etc.),
- air quality (determined by parameters such as fresh air supply, pollutants, odours, etc.).

Other factors such as aesthetics, ease of maintenance and connectivity, also come into play. However, the four main factors described above are structural features of the indoor climate that we live in and which we can control to make our buildings more comfortable and healthier.
Whatever the environment – home, work, school, etc. – it is today possible to avoid shivering with cold, straining our eyes because of insufficient light, needing earplugs to block out the noise of traffic, or experiencing breathing difficulties through polluted air.

How does comfort work?

Individuals can feel more or less comfortable in a given building at a given time for many reasons over which the built environment has no control – they are hungry, they have had a family quarrel, an important work deadline is looming .... Obviously these cannot be addressed directly through building design. However, a comfortable indoor environment can have a profound effect on how we feel. The four factors of thermal, visual and acoustic comfort, plus air quality, which have been much researched over the last few decades, are today relatively well understood, and in combination are powerful tools in designing a happy, healthy, energy-efficient building.

We require indoor temperatures of relative stability, neither too hot nor too cold, to function comfortably. We need the right type and right amount, neither too much nor too little, of light for specific tasks – bedtime reading, performing heart surgery, schoolwork. Our acoustic environment should be well balanced to block out unwanted, harmful noise and enhance those sounds that we need and wish to hear. Indoor air needs to be kept fresh and clean, and harmful pollutants, whatever the source, must be avoided.

The correct balance of these combined factors gives us indoor environments that we are happy to occupy, where we function efficiently and feel well. As we shall see in the following chapters, effects go beyond direct health issues.

The general public, and indeed many building industry professionals, are not always aware of the full extent to which our habitat affects our life, health, happiness and efficient performance. As awareness grows, the value of investing in healthy and comfortable buildings is gradually becoming accepted. As comfortable conditions differ according to the type of activity performed, and individual preferences can vary significantly, creating indoor environments which occupants have the ability to control and adjust to suit their individual needs, is also becoming a design objective.

INDIVIDUALS CAN FEEL MORE OR LESS COMFORTABLE IN A GIVEN BUILDING FOR MANY REASONS.

The role of Building Sciences

Building Sciences form a body of scientific knowledge and experience that makes it possible to analyse building performance and its impact on human comfort and health.
The objective of Building Sciences is to understand and improve the built environment, with a strong focus on materials and building envelope systems. Fire protection is often added to the main areas of thermal, acoustic, lighting and air quality comfort.
Building Sciences have greatly developed over the last decades, and are now part of the standard curriculum in most schools of architecture and building design. Initially, Building Sciences were mostly concerned with 'hard sciences' such as physics, mechanics and thermal science, but increasingly they tend to promote a more syncretic approach, incorporating medical and 'soft' sciences such as physiology, sociology, and both individual and collective psychology.
The main questions raised by Building Sciences fall into the following two categories:

- How can we design, build and maintain buildings in which people can efficiently perform their tasks and feel well?
- How can we achieve this with the lowest possible environmental impact and at a reasonable economic cost?

Comfort and health improvement on one hand, and environmental impact reduction on the other, can sometimes appear as conflicting goals. It is the ultimate role of Building Sciences to help find the best possible solutions.

THE CORRECT BALANCE OF THESE COMBINED FACTORS GIVES US INDOOR ENVIRONMENTS THAT WE ARE HAPPY TO OCCUPY, WHERE WE FUNCTION EFFICIENTLY & FEEL WELL.

Why is comfort important?

HEALTH

Technological advances at the beginning of the 20th century led to the improvement of many aspects of the indoor environment, particularly artificial lighting and heating/cooling. However, these same advances also introduced previously unknown health and comfort problems.

Numerous studies illustrate the complex links between present-day housing conditions and man's health and general well-being. An early 1990s report estimated that in the US people complained about health-, comfort- and safety-related issues in over 40% of enclosed environments, with a 2000 report classifying only 20% of housing stock as healthy[2].

Many advances have been made to improve the situation, in areas such as minimising or banning the use of harmful materials, and improving lighting and ventilation. A growing awareness of the financial implications of sub-standard buildings is also helping to advance better building practices. Improving the health, comfort and safety within indoor environments has huge potential for economic and societal benefits through increased productivity, reduced sick leave and medical costs, and fewer casualties. One study in the US estimated the cost of ill health due to building environments at anywhere between billions and hundreds of billions of dollars a year[3]. Spending on healthy buildings is increasingly recognised as a wise investment.

ENVIRONMENTAL IMPACT

The negative impact of human activities on our environment has been increasing steadily since the beginning of the industrial revolution. The extensive use of fossil fuels and non-renewable natural resources has been shown to have drastic consequences. When looking for comfort and creating buildings to protect ourselves from the natural environment, we create artificial indoor environments. To construct, operate and maintain these, we use up significant natural resources. In industrialised countries, buildings represent around 40% of the total primary energy consumption, two-thirds of which is used for heating, and to a lesser extent cooling, buildings[4]. Much of the energy consumed in buildings is wasted due to inefficient systems and design, but as we spend more and more time inside, energy consumption for heating, cooling, ventilating, lighting and so forth, is likely to increase.
Resource efficiency should be our common objective. In this respect, reconciling comfort and energy efficiency is far from being the only issue at stake. It is nevertheless one of the most pressing and also one in which appropriate design of the building envelope can make a huge difference.

PRESENT DAY HOUSING CONDITIONS DO NOT ALWAYS GUARANTEE MAN'S HEALTH AND GENERAL WELL-BEING.

HOW CAN WE DESIGN, BUILD AND MAINTAIN BUILDINGS IN WHICH PEOPLE CAN EFFICIENTLY PERFORM THEIR TASKS AND FEEL WELL?

How can we currently assess comfort?

Assessing (and possibly predicting) comfort in a given building requires considering at least three different dimensions, each with distinct criteria:

1) user well-being,
2) quality of indoor environment,
3) performance of the building fabric.

Ideally, when constructing or renovating a building, comfort objectives should be set out by the building owner together, wherever possible, with the building's users. These overall comfort objectives can be expressed in terms of expectations for health, satisfaction, productivity and so on. These expectations can then be translated by architects into targets for indoor environment quality, particularly when it comes to thermal comfort, acoustic comfort, visual comfort and air quality. Eventually these targets can be converted by architects and contractors into specifications of technical performances for the different parts of the building fabric: for instance facade elements, floors, ceilings, and heating/cooling/ventilation systems.
Obviously, the indicators that describe these different dimensions are of a different nature and range from qualitative to quantitative. Their monitoring takes place at different stages between the construction and use phase of the building. Ensuring a satisfactory end result requires consistency throughout the whole design and building process.

How can we build for comfort?

DESIGNING FOR COMFORT

Early research treated each of the factors that go towards indoor comfort individually and independently. It was the first computer simulation models of the 1980s that enabled the beginnings of a more holistic approach, with the acknowledgement in the 1990s that overall building performance is more complex than a series of individual prescriptions.

This holistic approach is fully embraced by today's increasingly sophisticated simulation models, into which specific data can be factored – for example, how many days a year occupants might tolerate sweating, as well as the psychological weightings of individual control over environment, etc.

However, more accurate prediction of what will be experienced in a given building remains a lively research field.

Obviously it must be stressed that adequate design alone is not sufficient to ensure comfort. The construction organization and quality are crucial, particularly in countries where many different trades are involved with no clear overall responsibility.

Also, if designing for comfort is a key issue, renovating for comfort is an even more important one in the many parts of the world where the building stock is in need of major improvement.

STANDARDS AND REGULATIONS

In some countries, regulations and standards prescribe certain comfort levels in buildings. But there can be discrepancies between these current standards and the end-users' needs. Most regulatory organisations today agree that indoor environments can pose a threat to one's health, and that indoor environmental parameters can themselves contribute to that threat. So although standards are met, user-oriented and long-term aspects are often given insufficient consideration in the early stages of a project. Achieving a project that fully satisfies occupant needs requires making many subtle decisions. In order to do so, a good understanding of physics, physiology, psychology, sociology, and design are needed within the design team. Hence, the importance of Building Sciences.

IN SOME COUNTRIES REGULATIONS & STANDARDS PRESCRIBE CERTAIN COMFORT LEVELS IN BUILDINGS.

How can Saint-Gobain contribute?

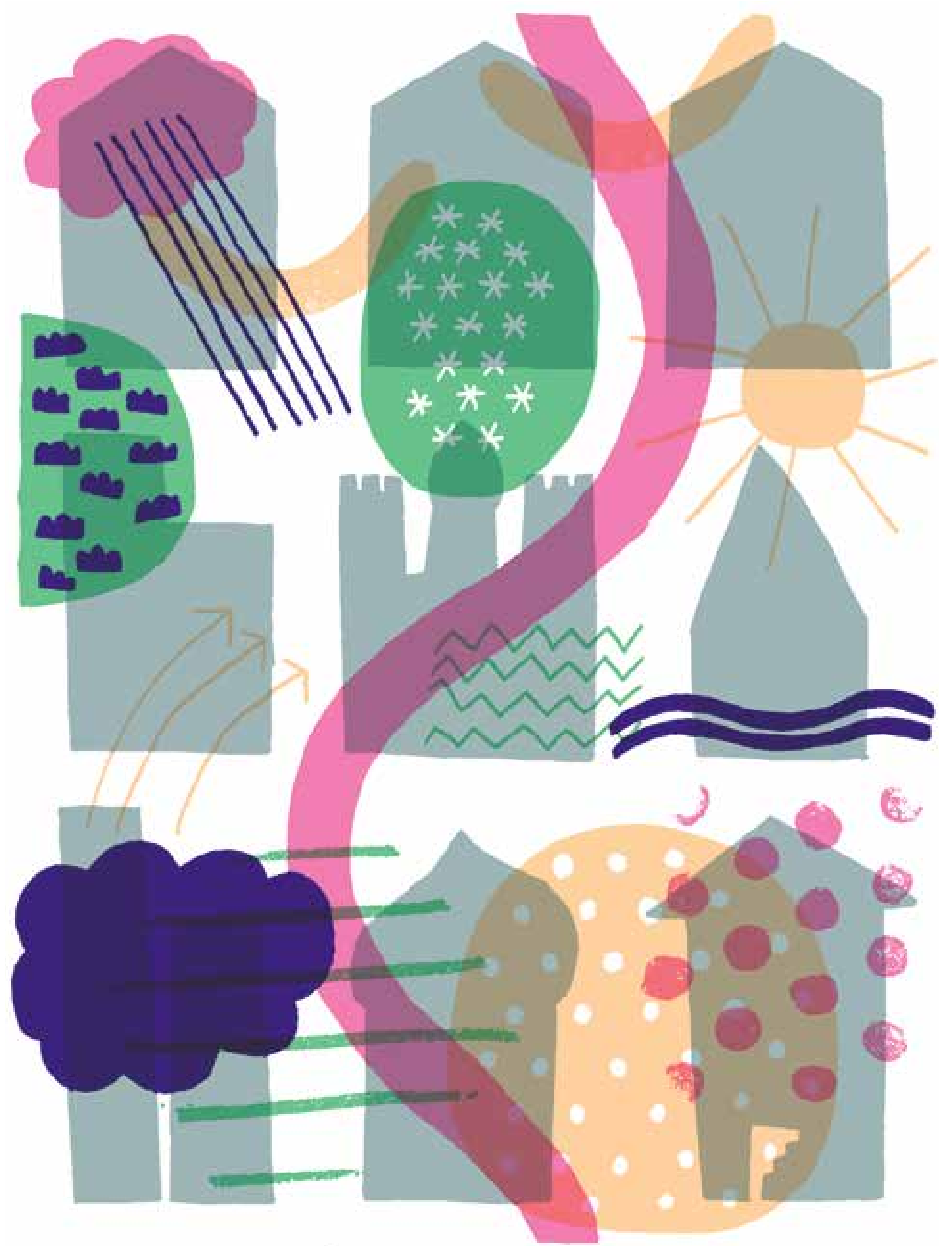
For the last 350 years, Saint-Gobain has been manufacturing, transforming and distributing building materials to the best of its expertise. Saint-Gobain was founded at a time when people's living standards were quite different from today's. Initially founded in 1665 to supply large mirrors to the upper classes of French society (and thus improve their visual comfort, one might say), Saint-Gobain gradually developed into a worldwide specialist in several kinds of building envelope materials: from glazing to insulation, plasterboard, mortars, cladding and roofing products.

A building is always the tangible outcome of a complex chain of decision-making and construction. Saint-Gobain's objective is to deliver the best possible solutions to guarantee comfort and efficiency to the occupants of homes, schools, offices, hospitals... Saint-Gobain's objective is also to ensure that these solutions can be easily implemented on construction sites, maintained throughout their use phase, and eventually efficiently deconstructed. Understanding the main principles underlying the design of comfortable, healthy and efficient indoor environments is key for all stakeholders in the building industry: architects, installers, builders, operators, as well as the occupants themselves.

The following chapters summarize how a common understanding of Building Sciences can help to achieve this, and how Saint-Gobain solutions can contribute to building more sustainably.

SAINT-GOBAIN'S OBJECTIVE IS TO DELIVER THE BEST POSSIBLE SOLUTIONS TO GUARANTEE COMFORT & EFFICIENCY TO OCCUPANTS OF HOMES, SCHOOLS, OFFICES, HOSPITALS...

THERMAL COMFORT



INCREASINGLY REFINED KINDS OF SHELTER WERE DEVELOPED TO GIVE GREATER COMFORT THROUGHOUT THE SEASONAL VARIATIONS OF THE YEAR.

Early settlement began in mild climates. As man gradually moved north, so his needs evolved from just shade and an open fire outside. More refined kinds of shelter were developed to give greater comfort throughout the seasonal variations of a year, also enabling more variety in terms of usage. The building envelope, as filter between the interior and exterior, gradually gained in sophistication to provide a better experience for the inhabitant – what today we recognize as comfort[5].

During the 20th century, advances in technology gave us unprecedented control over our thermal environment, feeding our desire for comfort and an appetite for energy-consuming equipment to provide it[6]. As we advance into the 21st century, urbanised areas continue to grow apace all around the world, and expectations of comfort are high, particularly in emerging economies where hot and humid climates are especially demanding. Energy efficiency is critical. It is important, in striving to reduce energy dependency in building, that the issue of user comfort be correctly taken into account.

What is thermal comfort and why is it important?

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment[7] and is ultimately assessed by subjective evaluation.

Today's growing urban populations spend most of their lifetime indoors, where the expectation is to experience a level of thermal comfort that ensures well-being and good health, enabling the efficient performance of daily tasks.

While extremes in temperature, hot or cold, can be fatal, even gentle fluctuations have marked us all with pleasure or discomfort – too hot to sleep at night, too cold to work in the day, etc. Scientific experiments and statistical evidence consistently show that manual dexterity, concentration and occurrence of accidents are influenced by both high and low temperatures.

Although thermal sensitivity varies from one person to another, according to age (the very young and very old being particularly sensitive), gender, dress, activity, cultural habits, etc., the basic principles behind thermal comfort are largely universal[8].

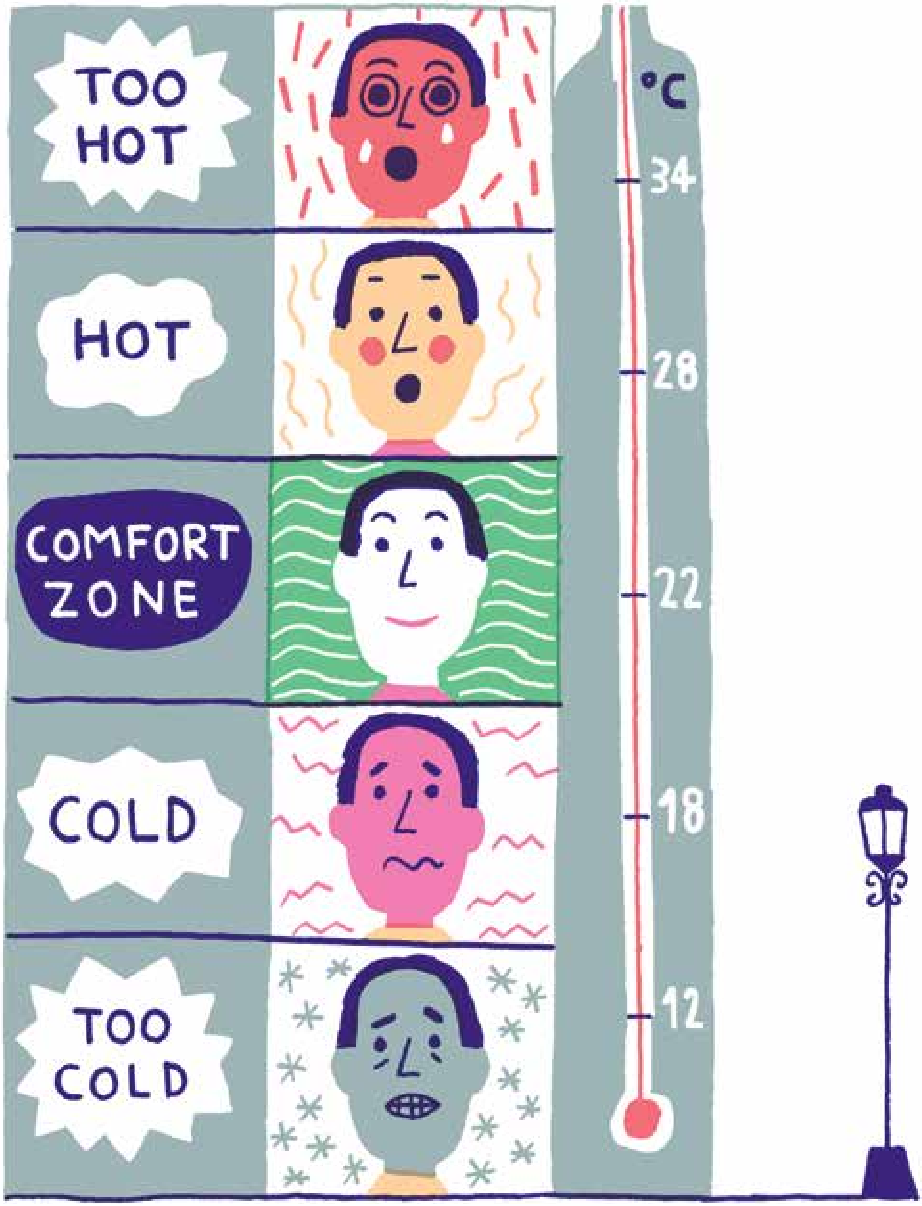
How does thermal comfort work?

Thermal satisfaction is experienced via a number of conscious and unconscious interactions between three areas:

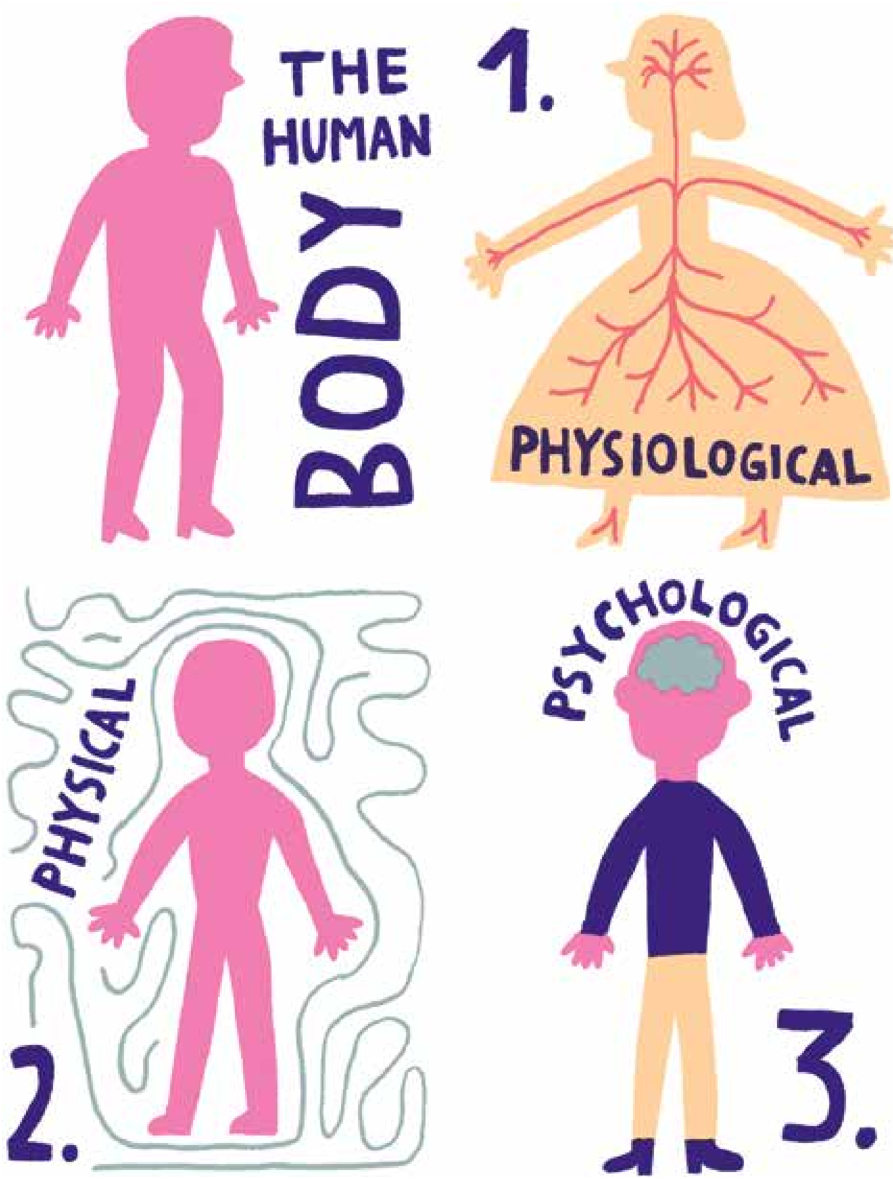
- Physiological – the way our bodies work and interact with our environment;
- Physical – the main parameters of the environment around us (air temperature, air humidity, air movement, room surface temperature);
- Socio-psychological – the way we feel as a whole (if we are tired, stressed, happy...) and the kind of social environment we live in.

THE PHYSIOLOGICAL ASPECT OF THERMAL COMFORT

The objective of our metabolism is to regulate our body temperature. Our internal core and organs must be maintained at 37°C on average, while the outer layer of our body and our skin need to be slightly cooler, at 34°C. Thanks to internal and skin sensors, we are able to detect and therefore react to the temperatures both inside and outside our body.



WHILE EXTREMES IN TEMPERATURE, HOT OR COLD, CAN BE FATAL, EVEN MINOR FLUCTUATIONS CAN BRING PLEASURE OR DISCOMFORT.



THERMAL SATISFACTION IS EXPERIENCED VIA A NUMBER OF CONSCIOUS AND UNCONSCIOUS INTERACTIONS BETWEEN THREE AREAS.

Human bodies, as with all mammals, are thermal engines that generate and dissipate energy – a constant exchange with the environment, whether outdoors or indoors. For example, one person seated in a temperate room generates about 100 watts[9], which explains why fully occupied theatres or very well insulated houses usually don't require any additional heating.

Regulation systems within our bodies continuously strive to balance our heat exchanges with the environment. For example, by speeding up or slowing down our heart beat to modify our blood flow and regulate heat distribution; by shivering when too cold in order to increase heat production; by perspiring more when too hot to reduce skin temperature thanks to evaporation.

One of the first steps to achieving thermal comfort is in limiting the efforts that our bodies need to make to regulate body temperature, establishing a good energy balance. But this state of 'thermal neutrality' alone is not enough to define and ensure thermal comfort.

THE PHYSICAL ASPECT OF THERMAL COMFORT

In the physical environment within which the body is situated, thermal energy (heat or cold) can be transferred by three means: conduction, radiation and convection. Conduction is energy transfer via a solid (floor, wall...), convection is the energy transferred via mass movement within fluids (air, water ...), radiation is the energy emitted from a surface.

In our body's perception of the physical environment around us, all three of these phenomena, combined with moisture fluctuations, can play a role:
- through air movement (convection, evaporation of moisture on the skin),
- by direct contact with a surface (walking barefoot, touching walls, etc.),
- by exposure to sources of heat or cold (radiated heat transfer from sun, fireplace, surfaces, etc.),
- through breathing (convection, evaporation).

Additional parameters play a role in the body's energy balance: choice of clothes can help the body to feel more comfortable within a certain environment; different physical activities – sport, deskwork, sleep, and so forth. Sawing wood, for example produces three times as much heat as surfing the web, which itself produces twice as much heat as sleeping[10].
Our bodies are so capable in detecting the slightest variations in temperature that even if the overall environment is well balanced, local phenomena can cause physical discomfort. Unwanted draughts, vertical air temperature differences between head and ankles, radiant asymmetry (when one side of your body receives more heat radiation than the other), and a floor temperature that is too hot or cold, can all affect your feeling of well-being, even when very localised[11]. Having said this, studies do show that some variations in the thermal environment are important to keep our bodies alert!

THE SOCIO-PSYCHOLOGICAL ASPECT OF THERMAL COMFORT

A third area, harder to quantify but crucial to the understanding of thermal comfort, is that of the socio-psychological reasons for certain reactions to environment. Many factors come in to play here:
An individual's current emotional state, mood, level of fatigue, etc. will affect their experience of an environment.
Expectations play an important role in how an individual experiences the physical world: one would expect a beach to be hot and a mountain lodge to be cool, but more generally, perceptions are likely to based on one's own thermal history.
Other environmental factors, noise or glare for example, may influence thermal perception, leading to an increased sensation of overheating.
An individual's social background also plays a role in the way they dress and behave, for instance.

An individual's perception of heat may also be dependent on varying tolerance levels[12]. For example, it has been shown that occupants who can exercise personal control over their thermal environment (opening a window, adjusting the heating, taking off a piece of clothing, etc.) will feel more comfortable, whether or not they actually choose to exert this control. Building-related symptoms of ill health were found to be reduced and greater productivity achieved as the perceived level of personal control increased. It has also been shown that in naturally ventilated buildings, occupants seem to adapt and accept higher indoor temperatures.

THE BASIC PRINCIPLES BEHIND THERMAL COMFORT ARE LARGELY UNIVERSAL, BUT THERMAL SENSITIVITY VARIES FROM ONE PERSON TO ANOTHER.

How can we currently assess thermal comfort?

As explained previously, thermal comfort is the result of several factors. When assessing thermal comfort in a building, one needs to take into account two main sets of indicators related to

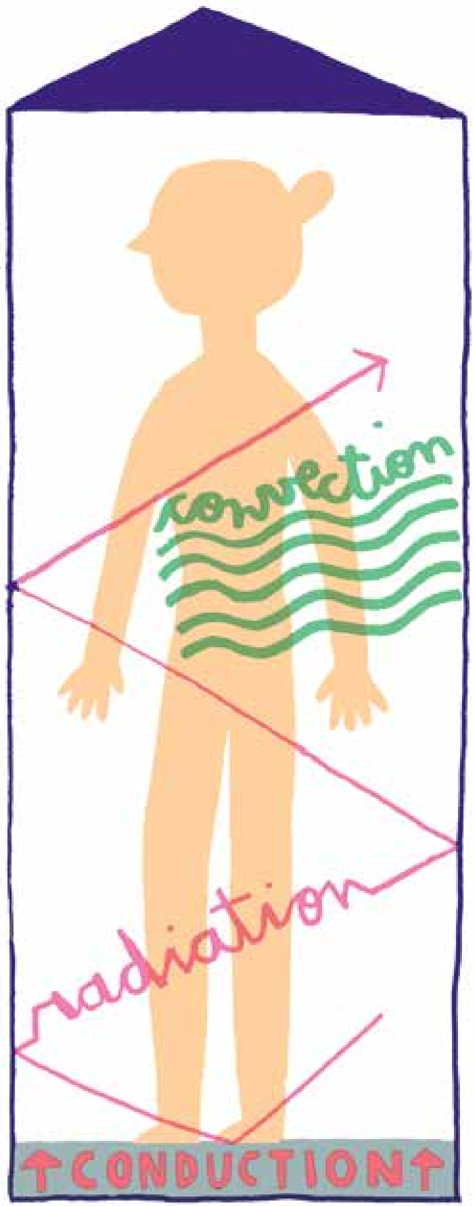
1) global comfort,
2) local discomfort(s).

Regarding global comfort, one can assess the percentage of time when occupants of the building are within a comfort zone defined by taking into account both relative humidity and operative temperature (which is the temperature felt by the human body[13]). Satisfactory targets are around 95% of use time within this hygrothermal comfort zone.
Regarding local discomforts, the main variables to be checked are air velocity (i.e. air movement and unwanted draughts), radiant asymmetry (i.e. when one side of your body receives more heat radiation than the other) and air temperature stratification (i.e. the difference of temperature between head and feet). Absence of such local discomforts is usually guaranteed when the air temperature stratification is less than 2°C, and when during the cold season both air velocity is less than 0.15 meters per second (0.25 m/s. during the warm season) and the radiant asymmetry is less than 5°C (14°C during the warm season).

How can we build for thermal comfort?

Thermal comfort is the outcome of a well-balanced combination of building systems adapted to both the local climate as well as the type of activity performed in a given building or room. Creating thermal comfort for employees in an open-plan office in Madrid will require different solutions to those used for school children in a Stockholm classroom or athletes in a London gym. There is no 'one size fits all' recipe for thermal comfort, but the main ingredients are well known and enable us to produce thermal environments that can be adapted to different needs in a given space and time. Nonetheless, buildings still often lack the level of individual control over indoor climate that we now enjoy in cars, for instance.

HUMAN BODIES ARE THERMAL ENGINES WHICH ARE IN CONSTANT EXCHANGE WITH THE ENVIRONMENT.



THERMAL ENERGY CAN BE TRANSFERED BY 3 MEANS.

LOCAL PHENOMENA CAN CAUSE PHYSICAL DISCOMFORT.

DESIGNING FOR THERMAL COMFORT

One of the first steps is to consider the design of an efficient building envelope. It acts as a filter between the exterior and interior climates. The building envelope can greatly affect the interior thermal environment of the building through its management of the following:

Insulation. Insulating the building envelope, both opaque and glazed, reduces heat loss during the cold season and heat gain in the warm season by conduction through the envelope. It also reduces the ‘cold wall effect’ that can be experienced radiating from windows or walls, as well as surface condensation.

- Solar gain. The building envelope can control how much heat from the sun (solar gain) is allowed to enter into the building. Influencing factors are: the building’s overall shape and orientation, the insulation level of the envelope, the window-to-opaque wall-surface ratio, the ventilation of walls, the ability of surfaces to reflect the heat (i.e. cool roofs, solar-control glazing...), shade from surrounding elements, or from passive or active shading devices.
- Thermal inertia. The mass and materials of a building can provide thermal inertia. Buildings with high inertia will have a delayed reaction in following changes in atmospheric temperature. The position of the inertia materials versus the insulating ones (external or internal) will have an impact on the behaviour of the envelope.
- Air tightness and ventilation. In order to control the indoor thermal environment, we need to manage the air exchanges with the outside. We do this by creating an airtight envelope and then by ventilating the building properly. Natural or mechanical ventilation will influence the evacuation of heat during the warm season or the need for heating during the cold season. Air currents caused by infiltration or by ventilation systems, as well as humidity, may also alter the perception of heat in a space.

All have a crucial impact on energy efficiency, but also on the kind of indoor climate we choose to live in. Traditionally, buildings in hot climates were built with high thermal inertia materials (such as bricks or stones) because in the absence of air-conditioning, an envelope with high inertia ensures that buildings remain cool for longer periods. Conversely, buildings in cold climates tend to be built with much lower thermal inertia materials (such as wood) to ensure that they can heat up quickly in winter. In both zones, insulation is key in managing heat flows and protecting occupants from the outside climate, be it cold or hot.

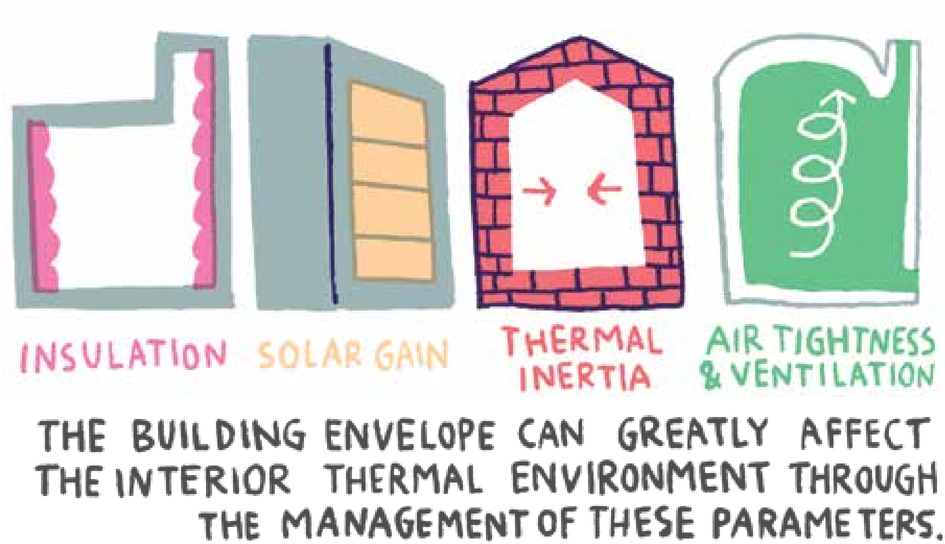
The careful design of a building envelope, taking into account the above criteria within the context of the building's usage, requirements, position, climate, etc., can dramatically reduce the amount of mechanical systems required to ensure thermal comfort, so reducing the carbon footprint of the building.
However, as we have seen previously, thermal comfort does not depend on the performance of the building envelope only. Numerous parameters and phenomena come into play, and several indices and methodologies exist to measure and predict comfort.
Accurate predictions remain complex but continuous progress is being made as we gain experience of modelling tools and building techniques for thermal comfort.

MANY FACTORS INFLUENCE THERMAL PERCEPTION.

BUILDING REGULATIONS FOR THERMAL COMFORT

While considering a certain number of criteria for measuring the performance of the internal environment of a building, most building regulations do not integrate the full complexity of the criteria involved in estimating thermal comfort. Several international standards do describe and recommend comfort ranges. American and European standards have recently converged to take into account comparable parameters and methodologies.

THERMAL COMFORT IS THE OUTCOME OF A WELL-BALANCED COMBINATION OF BUILDING SYSTEMS ADAPTED TO THE LOCAL CLIMATE & THE TYPE OF ACTIVITY PERFORMED.



THE FUTURE

Although our comfort needs will probably remain the same, two important aspects are likely to change in the future: our outdoor environment, and our understanding of thermal comfort.
Climate change will play an increasingly important role in the design of the built environment. With the growing influence of exterior climate over interior, systems and materials will continue to be developed and refined. Both changing climate and changing approach to energy consumption will require buildings to be capable of evolving over time. The rising costs of energy and the question of its affordability for the majority of the world's population will become more and more pressing issues. A key factor in this evolution will also be an increased critical reflection of what levels of thermal comfort will be considered acceptable, i.e. should we just put on a jacket rather than turn up the heat. The integration of such concerns in building design is known as 'future proofing', and will become an increasingly dominant topic at the forefront of discussions on building design.

Another topic of discussion will be about what constitutes a healthy indoor climate. In this respect, new scientific discoveries regarding the impact of climate variations on our body and immune system will be key. The advent of digital tools and the ability for most to measure both their local comfort and health conditions thanks to affordable connected sensors will greatly accelerate this evolution.

How can Saint-Gobain contribute?

Saint-Gobain invents, manufactures and distributes many components of the building envelope that have a direct impact on the daily life of people in their habitats. Saint-Gobain holds a key position of responsibility within the building industry, together with the numerous other stakeholders of any given project – investor, developer, architect, contractor, regulator and end-user.

Saint-Gobain offers a wide range of products and solutions for building envelopes. The following have a direct effect on thermal efficiency and comfort:

- Glass in windows and facades can either let sun radiation enter the building, or block it, depending on the season. Conversely, glass can either conserve heat produced by occupants or heating systems within the building, or let it evacuate out, depending on the kind of coating or film that is deposited on the glass;
- Insulation materials, such as mineral wools, and their integration into facade systems will help reduce heat losses or gains;
- Air-tightness membranes will allow limiting unwanted air infiltration, and vapour control membranes will allow internal humidity to exit the building, while preventing the humidity from outside from entering, preserving the insulation performance and the integrity of the building structure;
- Ventilated ceiling or roofing systems will enhance thermal efficiency;
- Mortars will help reduce the humidity transfer from the outside and improve insulation;
- Plasters and plasterboards will bring thermal inertia to the envelope and improve thermal comfort by remaining lukewarm;
- The choice of wall – or floor-covering materials will influence the surface temperature perception by occupants.

All these solutions, when applied appropriately, will greatly improve the usability of indoor spaces, for instance by preventing cold/hot wall effects. The right use of materials is dependent on characteristics required of each material, and the role each plays within an overall design strategy for the building. The final specification should not only optimise energy consumption, but also provide for user comfort, and so it is important that the specifier understands the basic principles of the various phenomena in question, and how the characteristics of the specified materials will influence the building's performance in all its complexity and seasonal variations.

However, when it comes to choosing a solution for a given design, experience is key. This is where Saint-Gobain's expertise in building science makes a material difference.

CHANGES IN LIVING HABITS, IN CLIMATE AND IN ATTITUDES TOWARDS ENERGY CONSUMPTION WILL REQUIRE BUILDINGS TO BE CAPABLE OF EVOLVING OVER TIME.

ACOUSTIC COMFORT

THE COMBINATION OF URBAN DENSIFICATION WITH GREATER NUMBERS OF NOISE-PRODUCING EQUIPMENT & ACTIVITY BRINGS NEW CHALLENGES TO OUR DAY-TO-DAY LIVES.

Human habitats and activities have changed dramatically over the ages, and the sound environment in which we live today would have been unimaginable even a hundred years ago.
Today's world is often noisy. More than half the population now lives in cities, which continue to densify. In Europe alone, 331 million people have adjoining neighbours[14]. Mechanised transport – cars, trains, planes, etc. – has become cheap and easy and has been wholly adopted. In Europe, as well as in the United States of America, on average one in two people have a private car[15].
The combination of this urban densification with its landscape of buildings and skyscrapers, along with greater numbers of noise-producing equipment and activity, brings new acoustic challenges to our day-to-day lives. Our ears were developed to function – to warn us of approaching danger – within natural environments, where they feel comfortable. So feeling well in today's sound environment often requires some adjustment and is always the result of a subtle balance. Over the next few pages we look at how to provide acoustic comfort.

What is acoustic comfort and why is it important?

Acoustic parameters significantly influence our perception of space. In an acoustically 'comfortable' environment, we are not only able to hear the sounds we want to hear (speech, music, etc.), but also to concentrate, to feel physically comfortable and calmed. This is obtained by the absence, or reduction, of unwanted sounds (noise), combined with the adequate level and quality of desired sounds. One could also say that being able to make sound – play the piano, or argue with someone – without annoying other people is another aspect of experiencing acoustic comfort.

There are two ways of assessing the effects of acoustic comfort: firstly, by looking at the way good acoustics can make indoor living easier and more enjoyable; secondly, by explaining the far-reaching consequences of noise on our bodies and minds. Both have been extensively studied by psycho-acousticians and physicians alike, but while the former is readily understood, the latter is less easy to quantify.

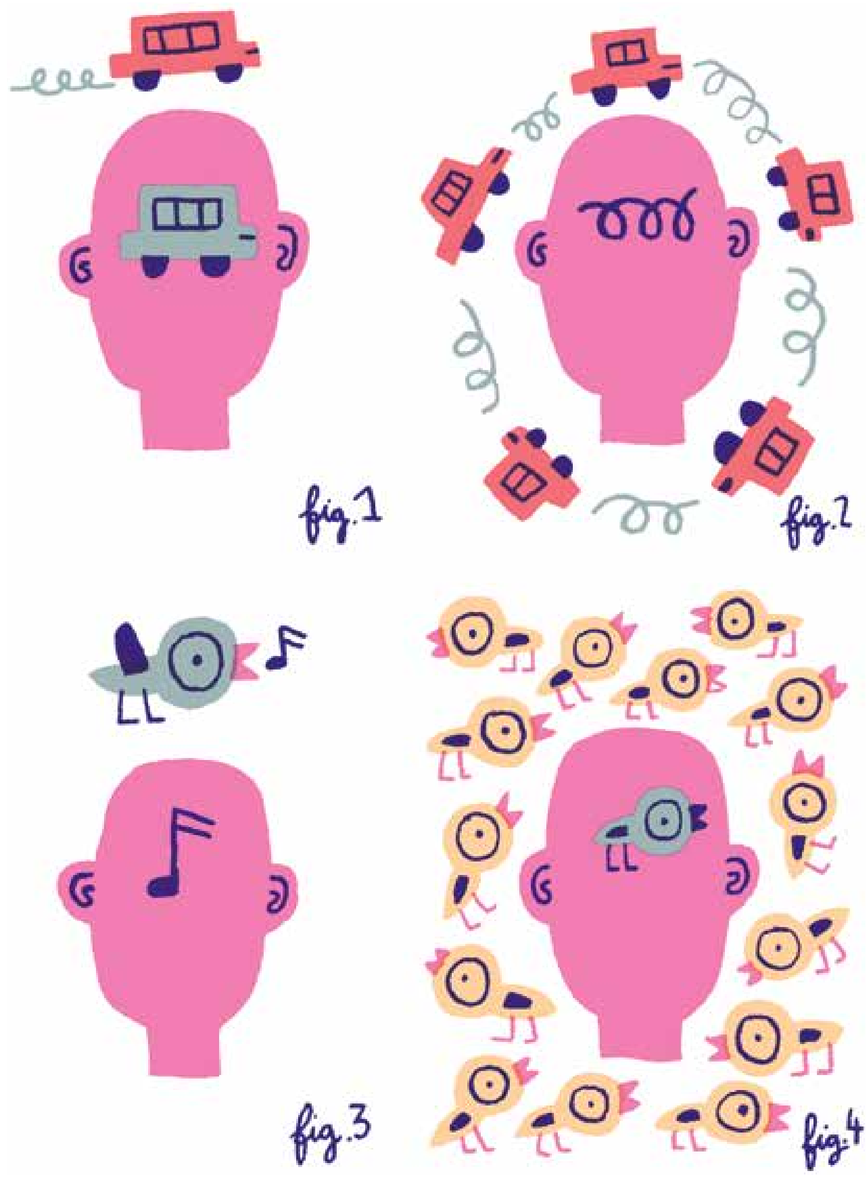
Research has proven that well-designed sound environments in offices or schools favour concentration and facilitate communication, so having a positive effect on the interaction and behaviour of occupants[16]. Learning is clearly more effective and less tiring when students can comfortably hear and understand. In hospitals, reducing noise levels reduces stress and improves sleep quality, helping patients recover faster and facilitating the work of the staff. In homes, protection from noise contributes to a sense of security and privacy, as well as reducing stress.
The net result is that when we are acoustically comfortable, we are more productive, happier, and experience fewer health issues.

ACOUSTIC COMFORT IS OBTAINED BY THE ABSENCE OR REDUCTION OF UNWANTED SOUNDS COMBINED WITH THE ADEQUATE LEVEL AND QUALITY OF DESIRED SOUNDS.

NOISE HAS FAR-REACHING CONSEQUENCES ON OUR BODIES AND MINDS. GOOD ACOUSTICS CAN MAKE LIVING INDOORS MORE ENJOYABLE.

In the 1990s the relationship between noise and health was recognised as a serious cause for concern, particularly at night in its effects on our sleep patterns[17]. Significant vibrations, which are caused mainly by external sources, can be particularly disturbing. This led to the first steps in protecting the indoor environment.
Traffic noise alone affects the health of nearly one in three European[18]. Depending on its properties (loudness, frequency …) noise can have numerous undesirable effects. The obvious effect on health is hearing loss due to high sound levels. But aside from direct damage to hearing, other consequences of noise exposure have been identified, including cardiovascular disease, high blood pressure, headaches, hormonal changes, psychosomatic illnesses, sleep disorders, reduction in physical and mental performance, stress reactions, aggression, constant feelings of displeasure and reduction in general well-being[19]. Epidemiological studies have shown, for instance, that the risk of heart attack for those living close to very frequently used streets is around 20% higher than for residents of quieter streets, and that the risk of obesity increases with the proximity of an airport[20].

Another area of concern is the link between noise pollution and air pollution. Letting air in through a building envelope can also mean letting noise in. Therefore providing air ventilation and its filtering can be quite challenging, particularly in urban areas, and creates a reliance on mechanical ventilation.
The effects of noise pollution are recognised today. European Directives ensure that member states work to try to control and reduce the harmful effects of noise exposure and protect both the home and school environments from excessive noise[21]. Health and safety regulations within the workplace address the indoor environment at work. Nonetheless, there is continued pressure on achieving a satisfactory level of acoustic comfort within the various indoor environments we inhabit.



ACOUSTIC COMFORT IS AFFECTED BY THE NATURE AND THE LEVELS OF THE SOUNDS EXPERIENCED IN A SPACE.

How does acoustic comfort work?

Acoustic comfort is affected by the levels and the nature of the sound experienced in a space. In order to better understand this, we need some understanding of how hearing and sound work.

THE PHYSIOLOGICAL ASPECT OF ACOUSTIC COMFORT

The human ear is comprised of three parts: the outer, middle and inner ears, which respectively receive, transmit and detect sound. Sound pressures set the eardrum in vibration and this movement is transmitted to the inner ear, where nerves are stimulated[22]. Hearing is the only human sense that fully functions while we sleep.

THE PHYSICAL ASPECT OF ACOUSTIC COMFORT

Sound is a mechanical disturbance of a medium, which may be gas, liquid or solid. For example, in air, sound waves are generated by a source, producing fluctuations in pressure. When these vibrations are intercepted by a receiver of sound, such as the human ear, they are collected and transmitted as information to the brain: they are 'heard'.
The distinction between loud and quiet sounds is made by the difference in scale of the pressure changes. Given the wide range of sound pressures to which the human ear responds, the magnitude of an acoustical quantity is given in decibels (dB), the decibel being one tenth of a bel. To give an idea of their values, our day-to-day experiences might include the following:

- Bedroom at night time: 30dB
- Normal conversation at 1 metre: 60dB
- Car traffic at 10m: 80dB
- Peak levels in a night club: 110dB
- Baby crying in your arms: 115dB
- Jet plane take-off: 120dB
- Threshold of pain: 130dB.

The pitch of a sound is expressed as 'frequency' in Hertz (Hz), which is the number of cycles of vibration per second. The greater the number of cycles, the higher the perceived pitch. The healthy human ear is sensitive to a very wide range of frequencies, from around 20Hz to 20,000Hz. Low frequency sound vibrations (20–150Hz), may be perceived as very annoying (air conditioning units, for example), while the ear is most sensitive to frequencies of between 500–5,000Hz. It is interesting to note that in human speech, it is the consonants that provide most of the intelligibility[23]. This explains why the chances of non-native pupils to succeed at school are largely determined by the level of acoustic comfort in their classroom. If the reverberation time in the room is over 0.6 seconds, children seated beyond the first rows will have a very hard time distinguishing consonants and therefore will not be able to learn properly[24].

The quality of sound in an indoor space depends on the control of the sources of sound or noise (indoors and outdoors). Four types of sound may be experienced within a building:

- **exterior noise** (mainly from transportation),
- **interior noise** (music, conversations...),
- **impact noise** (footsteps...),
- **equipment noise** (coming from pipes, elevators, washing machines, ventilation systems...).

These noises can either be transmitted through the air or through the building fabric. The way sound behaves within the space will depend on levels of absorption within the room – somewhere between the booming reverberation of a Gothic cathedral and the insulated absorption of a padded cell is the comfortable space. The parameters used to describe the distribution of sound are:

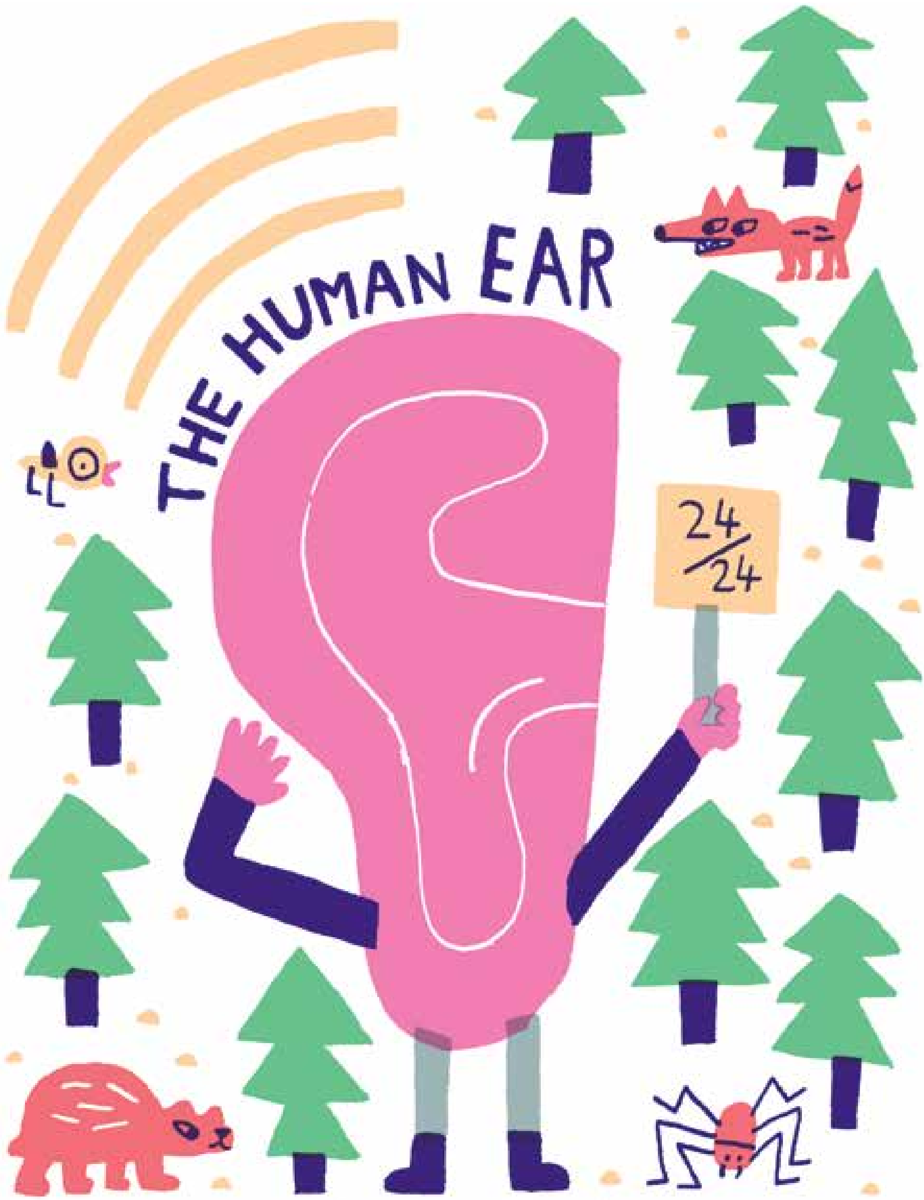
- **reverberation time:** the time that it takes for the sound level to decrease after the source of sound has been turned off;
- **sound insulation:** the material characteristics of the surface areas within a space, which determine sound transmission.

THE SOCIO-PSYCHOLOGICAL ASPECT OF ACOUSTIC COMFORT

Finally, the sound in the space is dependent on how it is perceived and interpreted.

The effects of a sound on the well-being (annoyance and health) of a person are based on an individual's psychological response to a sound. Parameters include the predictability and familiarity of a sound, its controllability, personal attitude and sensitivities, information on the content of the sound, and the necessity of the sound. For instance, we are always more tolerant of noise from well-liked neighbours than from unliked neighbours. And no matter how loud birds can chirp or waves at the beach can sound, most people will prefer these noises to those of a single motorbike passing by.

The acceptance of a given sound depends on many factors that vary according to the type of building, the type of activity performed, the social and cultural habits of the occupants.



OUR EARS DEVELOPED IN NATURAL ENVIRONMENTS, WHERE WE ARE STILL THE MOST ACOUSTICALLY COMFORTABLE. THEIR MAIN PURPOSE HAS ALWAYS BEEN TO WARN US OF APPROACHING DANGER AND TO ALLOW VERBAL COMMUNICATION.

How can we currently assess acoustic comfort?

When assessing acoustic comfort in a building, many different indicators can be taken into account as there are a variety of noise sources and types to consider. There is also a variety of activities to consider. However, the main two dimensions to be analysed are:

1) the sound level,
2) room acoustics.

The sound level can be evaluated through measurement of both the background noise (through the equivalent sound pressure level) and the peak noise levels (which is the maximum sound pressure level). For instance, to feel comfortable in an open-plan office, one needs to have a background noise of less than 35dB, with peak noise levels below 40dB. A comfortable bedroom will require a background noise of less than 25dB, with peak noise levels below 35dB.

The three most representative indexes of room acoustic comfort are: a) the Reverberation Time (i.e. the time it takes for sound to decrease by 60 dB), b) the intelligibility level (or Speech Transmission Index), which qualifies the quality of speech transfer to the listeners, with STI=1 when speech transmission is perfect or, when needed, c) the privacy level (which is measured with the Spatial Decay, i.e. the extent to which the sound decreases when the distance is doubled).

Obviously, room acoustic comfort needs to be assessed according to the function of the room. Different functions will have different acoustic requirements. For instance, intelligibility levels will be key in a concert hall, while privacy levels will be essential in an open plan office where Spatial Decay should be over 7dB and Reverberation Time around 0,4 seconds.

NOISE CAN BE TRANSMITTED THROUGH THE AIR OR THROUGH THE BUILDING FABRIC.

THE ACCEPTANCE OF A GIVEN SOUND DEPENDS ON MANY FACTORS THAT VARY ACCORDING TO THE TYPE OF ACTIVITY PERFORMED, THE SOCIAL & THE CULTURAL HABITS OF OCCUPANTS.

How can we build for acoustic comfort?

Up until the 1960s noise was considered a mere disturbance. A shift in attitude (and regulation) is apparent from the beginning of the 1970s, with the understanding that noise was something that threatened our health. During the 1970s and '80s regulations began to emerge, which led to significant noise reductions from specific sources. For example, in Europe between 1970 and the end of the century, individual car noise was reduced by 85%, lorries by 90%, and aircraft by a factor of nine. However, the considerable increase of traffic has partly offset these improvements[25].

DESIGNING FOR ACOUSTIC COMFORT

Designing for acoustic comfort today, we must first understand the needs of the building's occupants, taking into account the activities to be performed, as well as a variety of external and architectural factors:

- Activity – work (high-concentration or low), sleep, health-care, teaching, etc.,
- Sociological and cultural habits (varied national reactions to shouting down telephones in the lobby, for example),
- Types of noise to be managed (protecting from incoming levels of noise, but also perhaps from polluting the environment with noise produced within the building – factory, concert hall, etc.),
- Spectrum of noise to be managed – low or high frequencies,
- The construction system and materials. Mass is traditionally perceived as the best provider of acoustic insulation, so in today's frequently lightweight constructions, special care must be taken in considering the specification and detailing of construction systems.

Designing a specific acoustic atmosphere can be quite subtle: for instance in a restaurant, sufficient sound reflection will be needed to create a feel of energy in space, but not so much that diners cannot hear a conversation.

In any case, the site should be analysed for existing and predicted external noise levels. A brief will be drawn up based on performance requirements for the various spaces, the building fabric and the technical equipment of the building itself.

However, sound is difficult to predict. Although computer simulation tools are available, and laboratory testing of systems will frequently be undertaken for sensitive areas where the performances of constructions are unknown, the experience of an acoustic engineer is important. Acoustic performance is often dependant on workmanship, especially with regards insulation, so on-site testing may be undertaken to ensure that specified performance is achieved.

BUILDING REGULATIONS/STANDARDS FOR ACOUSTIC COMFORT

There are different ways of approaching noise control through standards and regulations:

- **to minimise the noise produced** (the sources);
- **to minimise the noise received** (blocking, in the form of insulation and absorption);
- **human health and comfort requirements** with respect to sound and/or noise.

With the growing understanding of noise as a health threat rather than simply an inconvenience, the first acoustic regulations appeared in the 1970s, first in Japan, then the US, and then Europe[26]. These mainly concerned the workplace and construction sites, but slowly the notion of environmental noise pollution was integrated. Several European Directives have imposed maximum limits for noise produced by road traffic, aircraft, industry and other sources. From the reception point of view, minimum values exist for the sound insulation characteristics for internal and external walls, and for the sound absorption characteristics of materials in spaces.

However, these are complicated to compare due to the different concepts and principles that are used[27]. In several countries, the required sound insulation of facades depends on existing outdoor noise levels, sometimes with different day and night requirements. Other countries define a certain limit for acceptable indoor levels, with additional requirements for events.

Over recent years, initiatives have been launched in order to simplify and to harmonize concepts used in Europe for sound insulation requirements, one of which is the working group of the European Acoustical Association and the European COST action TU0901[28].

WHEN DESIGNING FOR ACOUSTIC COMFORT, IT IS KEY TO UNDERSTAND OCCUPANT NEEDS: ACTIVITIES TO BE PERFORMED, TYPES OF NOISE TO BE MANAGED, CONSTRUCTION SYSTEM AND MATERIALS.

THE FUTURE

The development of better-insulated buildings will increase the need to protect building occupants from internal noises. Particularly as changes in living habits will mean that more and more activities will need to coexist in the same buildings: people will increasingly work from home, rest or shop at the office. Indoor acoustic landscapes will necessarily change in the coming decades.

Also, as with the other indoor environmental factors, acoustic comfort will be affected by global climate change. Any increased use of air-conditioning systems will add to general noise levels. Increased wind speeds and frequency of storms will also cause noise and vibration.

Materials, construction systems and technology will have to evolve to counteract these growing challenges.

How can Saint-Gobain contribute?

Acoustic comfort in a building is dependent on the acoustic characteristics of the building fabric, as regards acoustic transmission and absorption.

Saint-Gobain offers several product categories that have a direct impact on acoustic comfort:

- Materials that provide sound insulation by having low acoustic transmission, such as glass in windows and facades, and mineral wools, will help protect building occupants from outside noise. It is to be noted that the transmission characteristics of a material is dependent on the frequency of the sound being transmitted.
- Absorbing materials, such as mineral wools in ceiling tiles or wall panels, mortars, or acoustic plasterboards, will help reduce airborne and impact noises inside the building, which will also be influenced by the choice of wall or floor covering.

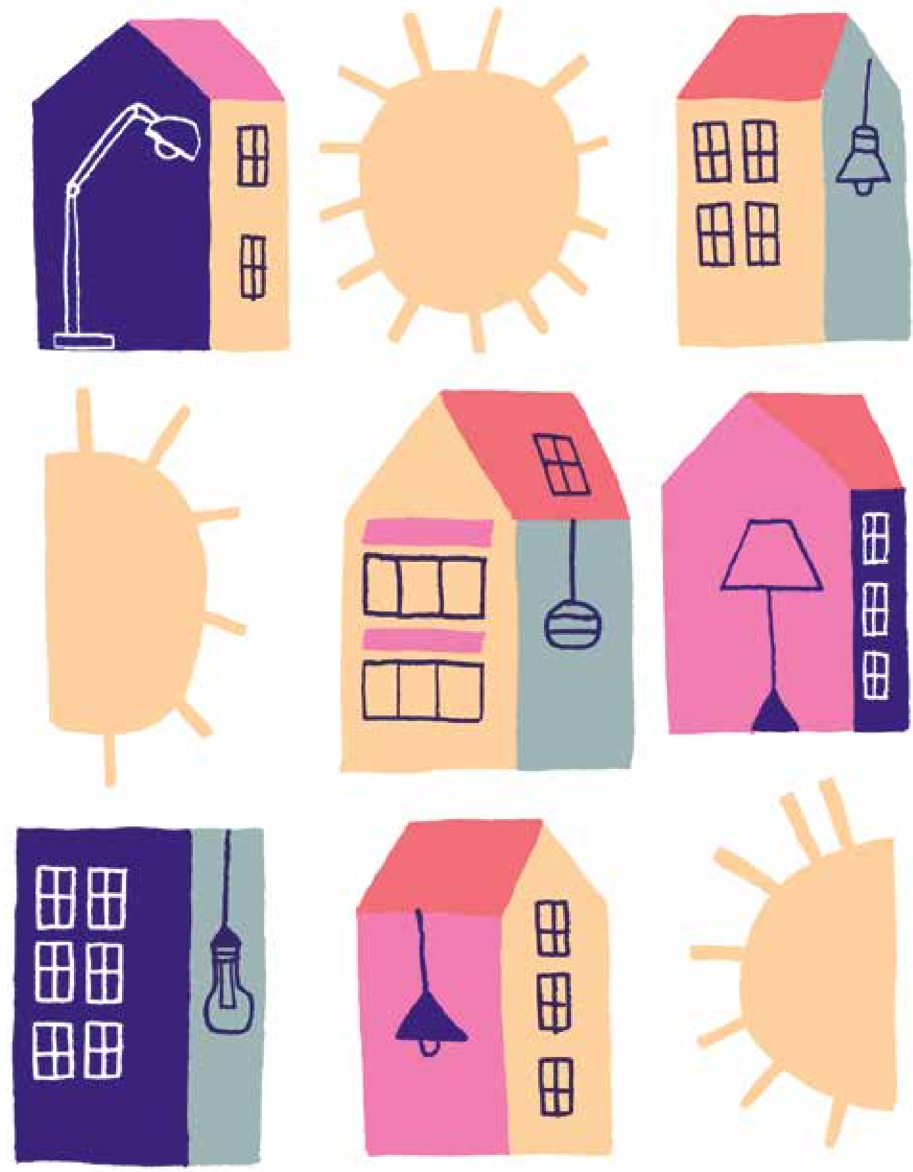
AS OUR LIVING AND WORKING HABITS CONTINUE TO CHANGE, SO WILL OUR INDOOR ACOUSTIC LANDSCAPE AND WHAT WE CONSIDER COMFORTABLE.

VISUAL AND LIGHTING COMFORT

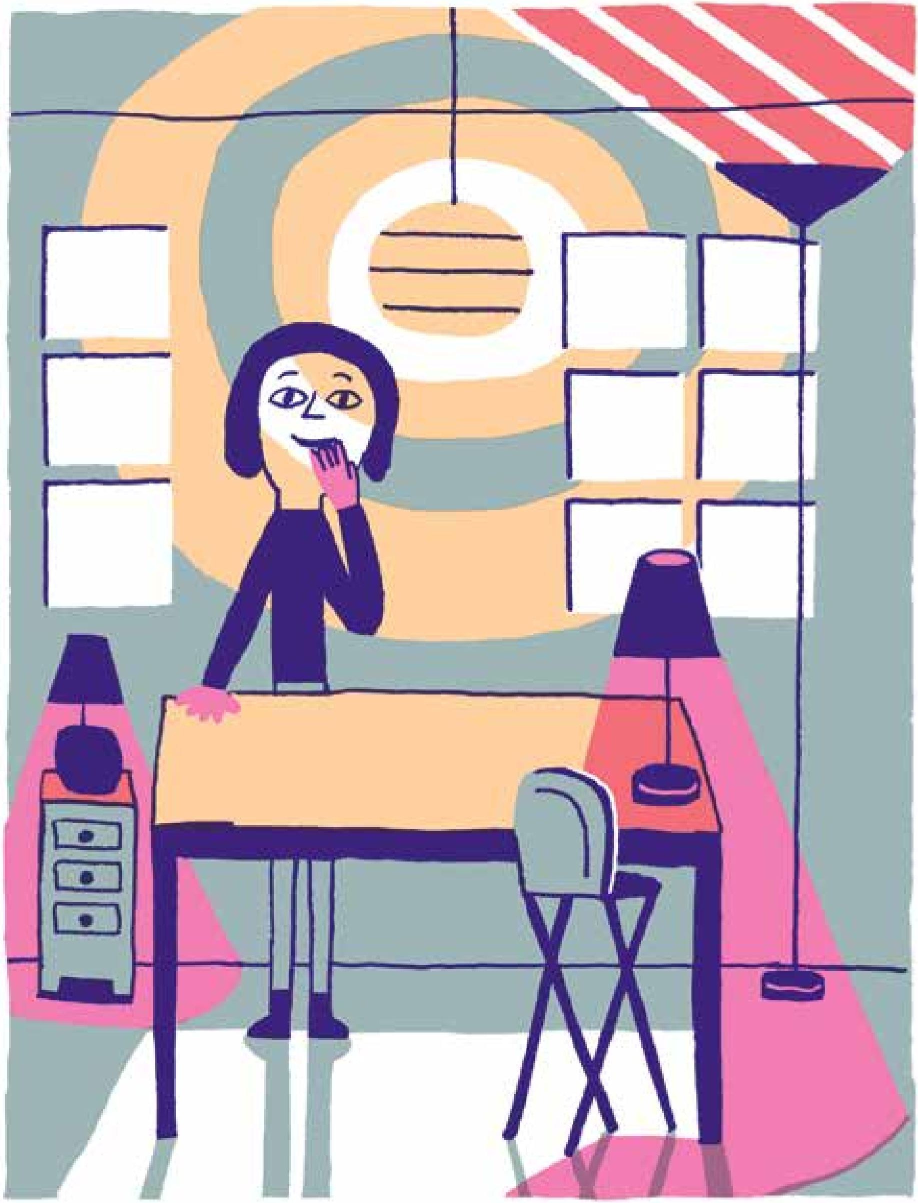
Without light, there would be virtually no life, human or otherwise, and the world would be a very different place. It is largely through light and vision that we are able to experience the world and learn about what is around us. So for mankind, light has always been closely associated with warmth, safety, health and happiness.

From very early on man has sought means of replicating natural light, and over the years has developed artificial lighting to provide light on demand. While the early forms of artificial lighting – by fire, candles, gas-light or oil lamps – did provide some light, these were expensive and only gave a weak light, so the hours of daily activity generally closely followed the hours of available natural daylight. However, advances in cheap and powerful artificial lighting in the late 19^{th} century transformed the way we were able to lead our lives, freeing us from total daylight dependence and enabling us to spend more and more time indoors. Along with this new-found freedom from following daylight hours, came a freedom in building design and the development of new visual environments indoors.

Today, a careful balance between natural and artificial lighting is recognised as optimum, in terms of both comfort and health. The next few pages look at how and why the combination of these two sources can be successful in ensuring visual comfort.



A CAREFUL BALANCE BETWEEN NATURAL & ARTIFICIAL LIGHTING IS RECOGNISED AS OPTIMUM FOR BOTH HEALTH & COMFORT.



LIGHT HAS QUALITATIVE ASPECTS
AS WELL AS QUANTITATIVE.

What is visual comfort and why is it important?

At its most basic, visual comfort is being able to position oneself within the environment and see well enough to perform a task safely with physical ease. But it is not enough to define visual comfort through lack of discomfort. Visual comfort is much further reaching than basic visual performance. It encompasses a variety of aspects, such as aesthetic quality, lighting ambiance and view.

Comfortable lighting does not flicker, glare or blind. It produces good colour renderings, with limited levels of reflection and a uniform distribution of light. Inside a building, many factors contribute to the overall lighting ambiance and visual comfort: the contrast between task lighting and ambient lighting, as well as different levels of views and daylight openings. Availability of daylight is a key ingredient of visual comfort, but its variable and dynamic nature makes it a challenging one.

Light has qualitative aspects as well as quantitative. To be able to fully describe light, one needs to discuss its source, distribution, colour and intensity, which all play a role in our perception of light quality. Assessing a visual environment requires the analysis of three main factors – the sources of light (artificial/natural), the distribution of light within the space, and its perception, all of which will be detailed in the following pages.

It is also important to note that the sensation of physical ease, well-being and satisfaction with a visual environment also depends largely on information not directly related to the task in hand.
For instance, connection with the outside world through views is crucial, both during the day and at night. Working in a window-less office, even under adequate light conditions, and working in an office with a view, are totally different experiences. Abundant scientific studies show positive impacts of the latter on mood and job satisfaction[29].

Being able to control light intensity is also key for visual comfort. Both too little and too much light can cause visual discomfort. Important changes in light levels or sharp contrast (which is perceived as glare) can cause stress and fatigue as the human eye is permanently adapting to light levels. Being able to control light intensity can also help manage unwelcome counter-effects, such as overheating from too much light.
Moreover, light has a direct effect on the regulation of several of our biological functions, such as sleep, mood, alertness, etc., as explained below.

Knowing more about light and how to control it is crucial, as light directly influences our health and well-being, as well as our perception and experience of the surrounding environment.

How does visual comfort work?

We can experience visual comfort in a broad range of diverse situations, from the glimmering lights of a city at night, to sunlight filtering through leaves, watching a play under stage lighting, to the diffuse light of an overcast sky by the seaside. In all situations, visual comfort is a subjective reaction to the combination of the quantity and the quality of light within a given space at a given time.
It is the interaction of a physical phenomenon, light, with a biological organ, the eye, in combination with the brain, that allows us to see.

THE PHYSIOLOGICAL ASPECT OF VISUAL COMFORT

The human eye is a light-sensitive organ composed of:

- a diaphragm adjusting the total quantity of light entering the eye – the iris and pupil;
- a lens adjusting the focus;
- black and white low-light sensors – the cones;
- synchronisation cells – the photosensitive retinal ganglion cells.

It is only recently that scientists have begun to understand how light influences our body and mind. Our eyes contain cells that do not contribute to the formation of images, but are responsible for 'non-visual effects'. These retinal ganglion cells, which were only identified a decade ago, in the early 2000'[30], are key for our biological clock – the part of our brain that regulates our sleep–wake rhythms, our heartbeat, and the workings of our organs. They therefore play an essential role in keeping us healthy[31].

PLEASANT VIEWS CONTRIBUE TO PEOPLE'S HEALTH & WELL-BEING.

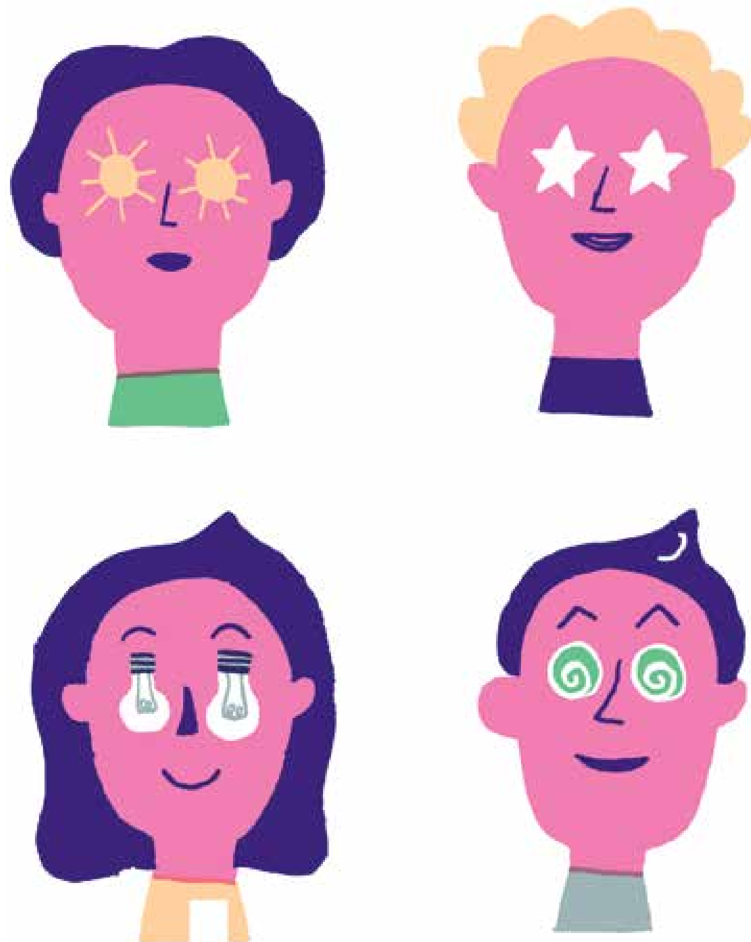
THE PHYSICAL ASPECT OF VISUAL COMFORT

In order to better define how visual comfort works, we need to understand what light actually is.
The sun, or an electric light bulb, emits energy in the form of propagating electromagnetic waves. Only a limited range of those waves, from infrared to ultraviolet wavelengths, is perceptible to the human eye as light. Ultraviolet (UV) waves are invisible (the wavelengths are too short for our eyes), but are responsible for colouring the human skin. The infrared (IR) are also invisible (the wavelengths are too long for our eyes), but are felt as heat.

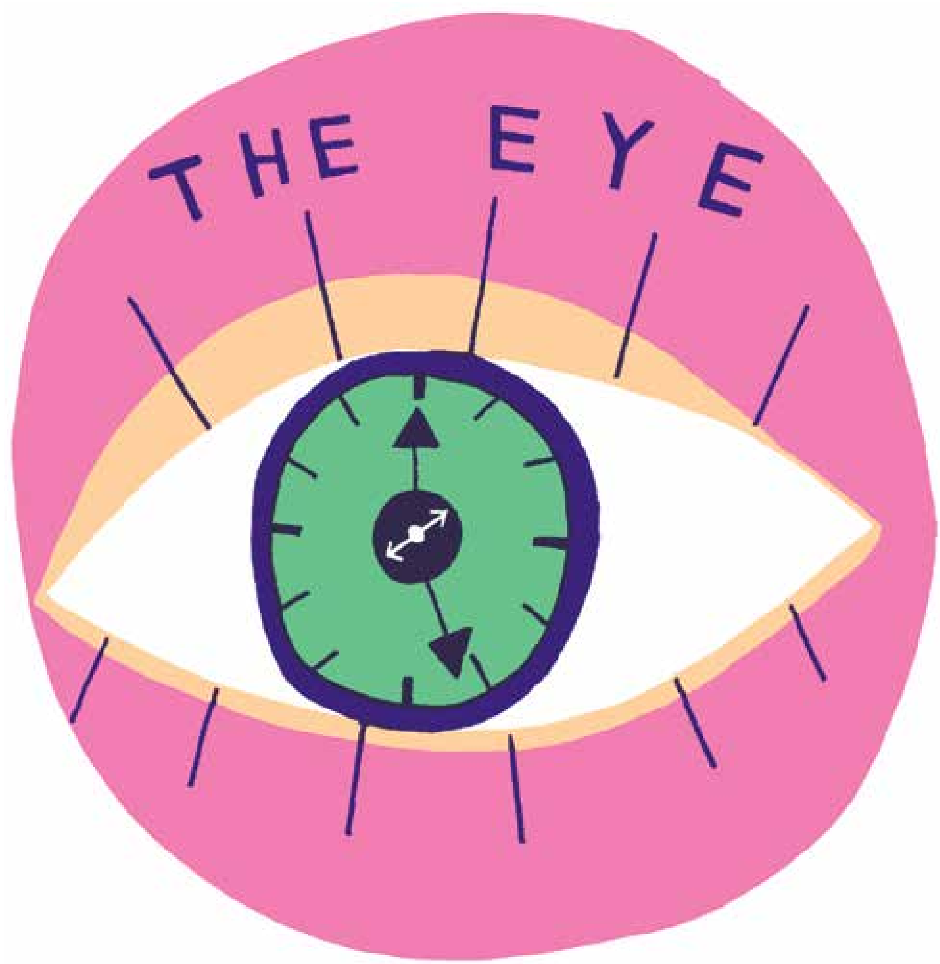
The most relevant physical quantities related to visual comfort are the illuminance and the luminance.

Illuminance (expressed in lux) is the luminous power coming from all directions and reaching a given point. This quantity allows mapping light distribution in a room independently from the observer.
Measuring illuminance on a surface is a good indicator for assessing visual comfort. Most of the norms in different countries impose a value of at least 500 lux on offices desks, which is a reasonable value for reading (e.g. newspaper, computer screen...). Metrics based on illuminance are useful to predict comfort with lower thresholds as in the former example and also, to assess discomfort, with upper limits.

Light sources and surfaces around us emit or reflect light with different luminous intensities per unit area, i.e. luminance levels (expressed in candela/m2). Measuring luminance allows us to appreciate light contrasts and, in extreme cases, glare effects. In other words it is a map of luminous power as we see it with our eyes. When watching a given scene, we can perceive different luminance levels coming from different directions, just as a photographic camera does. A luminance map shows the contrasts of light sources coming from different directions and so enables us to quantify glare. This kind of spatial map is crucial to understand whether the same amount of light is uniformly distributed around us or if it is coming only from a small glaring surface. Luminance is the quantity used to quantify the brightness of light sources, as for instance the brightness of a television.



IT IS THE INTERACTION OF A PHYSICAL PHENOMENON -LIGHT- WITH A BIOLOGICAL ORGAN -THE EYE- THAT ALLOWS US TO SEE.



OUR EYES CONTAIN CELLS THAT PLAY A ROLE IN THE SYNCHRONISATION OF OUR BIOLOGICAL CLOCK.

THE SOCIO-PSYCHOLOGICAL ASPECT OF VISUAL COMFORT

From sunlight flooding in through a window, to flickering candlelight over a romantic dinner or harsh neon lights in a supermarket, light has a profound effect on the way we feel and experience time and space, both consciously and unconsciously.

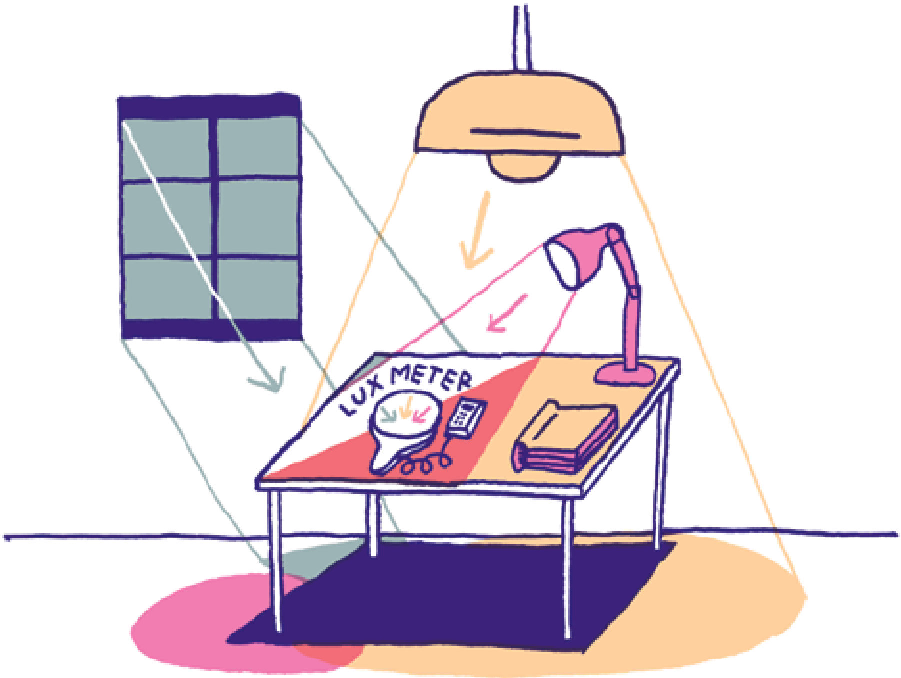
Our personal history and culture also shapes the way we appreciate light and visual environments. Extreme variations in preferred range of illuminance exist depending on age and culture. For instance, preferred light colours in Asia are quite different from those in Europe[32].

But whatever the nationality, age, gender or social category, light directly influences the mood and health of all humans. As mentioned previously, non-visual effects of light play an important role in this respect. Their discovery is fairly recent and they remain the subject of active scientific research, usually within the wider context of daylighting studies.

THE SPECIFICITIES OF NATURAL DAYLIGHT

Natural daylight is composed of direct sunlight and atmospheric light (sun radiation dispersed by water and dust). It is the reference illumination source to which our eyes are naturally adapted, so that we nearly always find it more comfortable and attractive than artificial lighting. When choosing a home, good natural light is often the 2nd most important criteria, after location.

There is clear scientific evidence demonstrating the benefits of daylight and associated external views in most building usages. For instance, in hospitals it has been observed that patients in rooms that are well daylit need up to 30% less pain-relief than others, that they recover faster and return home in much better spirits[33]. An extensive study in schools showed that children tended to be much more alert and learn more easily in comfortably daylit classrooms[34]. In office environments, several studies have indicated an overwhelming preference of occupants for daylight and views, and a corresponding increase in job-satisfaction and well-being when both were available. Today, evidence of higher productivity rates and lower absenteeism rates in well-daylit offices has been collected[35].



VISUAL COMFORT OR DISCOMFORT CAN BE ASSESSED BY MEASURING ILLUMINANCE LEVELS, I.E. ALL THE LUMINOUS POWER THAT REACHES IN A GIVEN POINT.

Daylight, by its variations in intensity and tint, also provides information about the hour of the day, the seasons, the weather, helping to maintain our psychological and social equilibrium. Spaces lit with daylight appear naturally beautiful and spacious, as daylight is composed of a broad electromagnetic spectrum with an excellent colour rendering quality. It plays a major role in defining the aesthetic quality of a space.

Sunlight also encapsulates a clean energy offering, which can both be transformed into electricity via photovoltaic cells, and warm a building by providing passive heat gain.

How can we currently assess visual comfort?

When assessing visual comfort in a building, three main indicators need to be taken into account:

1) the quantity of light,
2) the quality of light,
3) views to the outside.

Regarding the quantity of light, one needs to analyse both the illuminance levels for a given task and the spatial light distribution.
Regarding the quality of light, one needs to consider both the Daylight Autonomy (which is a percentage of annual daytime hours during which a given point in a space remains above a specified daylight illumination level) and the Useful Daylight Illuminance (which integrates both the evaluation of daylight levels and glare in one indicator).
Regarding views to the outside, one needs to study the ratio between the surface of the openings and the surface of the floors, but one needs also to take into account qualitative factors. A view onto a mountain lake will surely not bring the same comfort level as a view onto a busy motorway.

LIGHT SOURCES AND SURFACES AROUND US EMIT OR REFLECT LIGHT WITH DIFFERENT LUMINOUS INTENSITIES PER UNIT AREA, I.E. LUMINANCE LEVELS. MEASURING LUMINANCE ALLOWS US TO APPRECIATE LIGHT CONTRASTS AND, IN EXTREME CASES, GLARE EFFECTS.

LIGHTING CONDITIONS AFFECT MOOD AND HEALTH.

How do we build for visual comfort?

Until 20 years ago, most of the research on lighting was focused on how to provide enough artificial lighting to perform certain tasks. Since then, new demands for energy efficiency in buildings and questions about the impact of light on health and comfort have stimulated research on natural daylight, leading us to reconsider the way we build for visual comfort.

It is now commonly accepted that the key to visual comfort in buildings is based on:

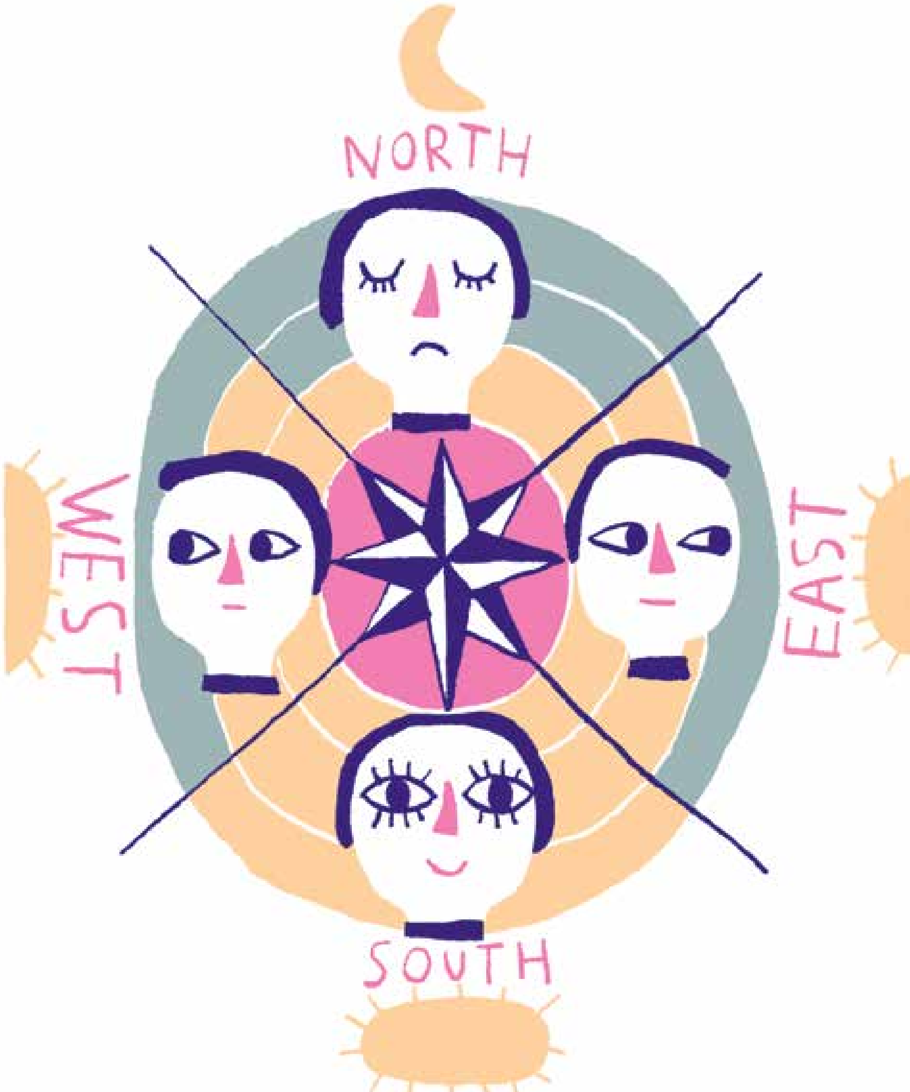
- access to views/the outdoors,
- daylight provision
  - in sufficient quantity,
  - distributed homogeneously throughout the space (no dark areas or flickering),
  - in good combination with artificial light, adapted to the visual task and allowing a good colour rendering,
  - controlled to ensure the absence of glare and high contrasts,
- in an aesthetically pleasing space[36].

Building design and choice of materials and equipment obviously play a decisive role. Because natural light varies all the time, ensuring a constant quality of light involves controlling its intensity. This can mean either reducing too much incoming light by shading, or compensating for low light levels with artificial light. Increasingly sophisticated control systems are able to manage all these variables, and help achieve a successful balance in the combined use of artificial light and daylight.

DESIGNING FOR VISUAL COMFORT

When designing a building, predicting the internal visual atmosphere is key, but often difficult to achieve accurately. One of the reasons is that so far there is no formal, universally accepted definition and way of measuring visual comfort.

Another reason is that while the notion of visual comfort is relative to building use and the tasks to be performed, most of the academic work and building regulations in this area are based on office environments and related to the use of artificial lighting alone.
Basic visual needs are therefore commonly measured through illuminance levels. Standard recommended values are 300 lux to 500 lux on the desktop, based on reading tests[37]. However, these recommendations might not always be adequate for other activities. For instance, a recent scientific study has shown that children tend to be more creative in spaces with lower lighting levels. A dim lighting atmosphere can elicit a feeling of being free from constraints and trigger a more explorative thinking style[38].



DAYLIGHT IS THE REFERENCE LIGHTING SOURCE.

For artificial lighting, glare and colour are also commonly evaluated.

Specific metrics are needed for natural light since it is dynamic, has a larger intensity range, and is responsible for several non-visual effects. Currently, there are two kinds of competing metrics for natural light:

- Static metrics: which allow a quick assessment but do not take into consideration either location or orientation (for example Daylight Factor %);
- Dynamic metrics (climate-based): which rely on the calculation of illuminances for each hour of the year in a certain location (for example Daylight Autonomy %)[39].

Glare from natural light is particularly hard to predict as it involves contrast between competing sources, is influenced by many variables and can be quite subjective. There are on-going scientific efforts to understand and measure it efficiently[40].
Content of a view is usually described qualitatively, though first metrics are under development[41].

Some standardisation work is under development at European level. Future recommendations will probably be extended to non-visual criteria (health and general well-being)[42]. Correlation with real performances and people's perception will be needed.

BUILDING REGULATIONS FOR VISUAL COMFORT

Although access to natural light was first regulated by the Romans, modern day regulations appeared in the 1900s. In the first half of the 20th century, focus was on visual comfort when performing a task. Increasing provisions were made for minimum requirements for daylight openings in factories and workspaces. In the development of office lighting, artificial lighting for activity purposes was given priority.

Recently, more attention was paid to well-being and health. The importance of daylight openings was recognised, not only for providing daylight but also a necessary contact with the outside world.
Today's environmental certifications (BREEAM, LEED, etc.) all integrate visual comfort. Daylight Factor remains the main evaluation parameter, but climate-based dynamic metrics are beginning to appear in some labels, e.g. LEED v.4. These metrics will probably become more important in future standards.

THE FUTURE

The desire to reduce energy consumption, combined with a better understanding of visual comfort, has brought daylight to the forefront of building design. In today's well-insulated buildings lighting is one of the main consumers of energy, so the reduction of artificial lighting is crucial.
Using natural daylight, however, implies finding the balance in a continual dance between natural and artificial sources, whereby the benefits of daylighting are not outweighed by the problems of overheating and glare. Hence the role of the lighting designer is changing considerably, from a profession specifying artificial lighting to one that understands natural light – a very different subject. Control systems for levels of natural daylight or balancing between natural and artificial is a particular area of research and investment[43].

As our living and working habits continue to change, so will our lighting needs and what we consider to be visually comfortable. For instance, if reading e-books rather than print becomes standard, the way we light places to read – offices, sitting-rooms, bedrooms – will have to change as well. As we feel the effects of global warming, so we are likely to experience a growing need to shade ourselves from rising temperatures. Alternative solutions may then have to be developed to mitigate the lack of exposure to sunlight. Equally, increase in smog and cloud formation may have an effect on the quality of daylight, resulting in the need for compensatory artificial lighting solutions.
Also, as we gain a better scientific understanding of the non-visual effects of light, we will have to adjust lighting design principles to better take into account the way light influences our health and well-being.

THE KEY TO VISUAL COMFORT IN BUILDINGS IS BASED ON SEVERAL FACTORS.

AS OUR LIVING HABITS CONTINUE TO CHANGE SO WILL OUR LIGHTING NEEDS AND WHAT WE CONSIDER TO BE VISUALLY COMFORTABLE.

How can Saint-Gobain contribute?

Visual comfort in a building can be managed through the size and positions of the openings, the orientation of the facades, the consideration of shade-casting or view-blocking obstructions close to the building, solar protection devices, the reflectance of the surfaces, the layout of furniture and the overall aesthetics of indoor space.
Saint-Gobain offers several product categories that have a direct impact on visual comfort and aesthetics:

- transparent products, such as glass, films or architectural membranes, which allow access to daylight and views through windows, doors, partitions;
- translucent products that allow daylight while preserving privacy;
- active glazings that help manage glare, overheating or privacy;
- opaque interior products, such as wall coverings, ceiling or flooring products, which can contribute to the distribution of daylight and to the aesthetic of the space;
- lighting materials, such as lighting textiles or ceiling tiles, which can be excellent complementary light sources, especially in glare management;
- opaque exterior products, which can help to throw natural light in to brighten dark spaces in cities.

INDOOR AIR QUALITY

Air is a vital requirement for humans: we can live 30 days without eating, three days without drinking, but only three minutes without breathing. The importance of good air quality in a building has long been recognised for general health and well-being. In the first century BC, Vitruvius wrote about air quality as the primary consideration in ensuring a comfortable indoor environment. By the Middle Ages, when contagious diseases were repeatedly killing thousands, the need for 'good air' in buildings was recognised as essential. And so began discussions on how much ventilation was required to prevent the spread of disease and provide comfort – subjects which remain an active preoccupation to this day.

Most people feel that air quality is important to their day-to-day well-being. In a recent Danish survey, when questioned on the words that describe factors contributing to comfort, 21% of responses related to 'fresh/clean air and smell', just after 'light, sun' (46%) and 'temperature, warmth' (35 %)[44].

Over the next few pages we will look at today's thinking on how best to ensure the quality of the indoor air that we spend most of our lifetime breathing[45].

WE SPEND 90% OF OUR LIFE BREATHING INDOOR AIR.

AIR IS A GAS THAT IS MAINLY COMPOSED OF OXYGEN (21%) & NITROGEN (78%) THE REMAINING 1% CAN CONCENTRATE A NUMBER OF POLLUTANTS.

What is indoor air quality and why is it important?

When talking about 'fresh, clean air', images that come to mind are often nature-related: an Alpine landscape, a seaside breeze, a forest after the rain. So how does this translate when inside a building today?

Over the last couple of centuries, industry has developed, mechanical services have been introduced into buildings, synthetic materials have been invented, motorised transport has become standard and human activity has densified around the world's growing cities. The quality of air, both outdoors and indoors, has changed accordingly.

As pollution levels have grown, attention has been given to understanding and managing the threats of outdoor air pollution on human health and the environment. However, it was only in the last few decades that any attention was paid to indoor air quality in terms of its effects on health and well-being.

Air is a gas that is mainly composed of oxygen (21%) and nitrogen (78%). The remaining 1% can concentrate a number of pollutants. Historically, good air quality was assimilated to the absence of pollutants that could affect the health of the occupant. However, today other parameters appear that are also important for the occupants' comfort and well-being: absence of bad or overly intense smells, sensory irritations, and stuffiness.

The sources of indoor pollution are multiple and can be divided into the following categories:

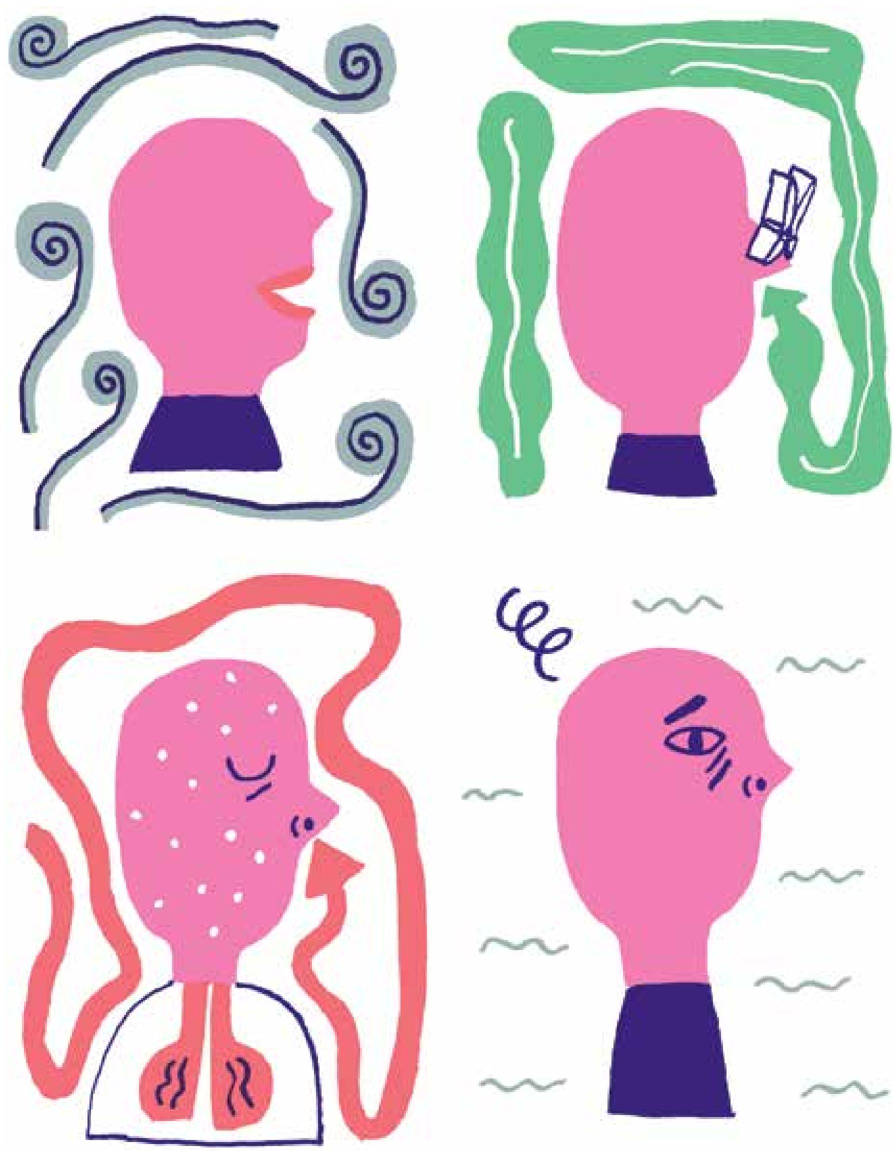
- outdoor sources (traffic and industry),
- occupant-related activities and products (tobacco smoke, cleaning products, personal care, printers, etc.),
- building materials and furnishings (plywood, paint, furniture, floor/wall coverings, etc.),
- ventilation system components (filtres, ducts, humidifiers, etc.).

In sufficient concentration, pollutants can have a direct influence on our health (carbon monoxide fumes, for example, can be lethal), and a sometimes less quantifiable effect on our well-being (discomfort from bad odours, stuffiness, fatigue, etc.).

The majority of air pollution complaints are odour related. The usual factors influencing these complaints are frequency of occurrence, intensity, duration of exposure, perceived level of unpleasantness and location. Building materials, furniture, human activities or bio-effluents from people and pets may all be at the origin of odours. Odours are generally generated by volatile molecules or a combination of different ones in such a concentration (Volatile Organic Compounds) that they can be perceived by the human nose. Some are considered pleasant, others less so, but the distinction is usually quite personal.In any case, the level of detection of several odorous VOCs is very low. Although there is no evidence that unpleasant odours per se are linked to adverse health effects, scientific evidence shows that they can cause mental distraction and may have a negative impact on mood and stress levels[46].

VOCs are also at the origin of sensory irritations, which are characterized by sensations of burning, itching, pain, scratching and stinging in eyes, nose and the upper airways. In most cases, the threshold for sensory irritation is several orders of magnitude higher (i.e. lower sensitivity) than the threshold for odour perception[47].
The sensation of stuffiness results from the overall pollution load. Many different pollutants, which include odorous VOCs, products of incomplete combustion and bio-effluents, are present at very low concentrations, but in combination can affect occupant well-being.

IN SUFFICIENT CONCENTRATION POLLUTANTS CAN HAVE A DIRECT IMPACT ON OUR HEALTH AND SOMETIMES AN EFFECT ON OUR WELL-BEING.



GOOD AIR QUALITY IS SYNONYMOUS WITH THE ABSENCE OF POLLUTANTS, BAD ODOURS, IRRITATIONS AND STUFFINESS.

How does indoor air quality work?

THE PHYSIOLOGICAL ASPECT OF INDOOR AIR QUALITY

We inhale and exhale an average of 12,000 litres of air per day. Our ability to assess the quality of this air generally involves two senses:

- olfaction (smell),
- the common chemical sense (the ability to sense irritants).

The human nose is a sophisticated organ. In each nostril two types of nerve fibres – the olfactory sense and the trigeminal nerve – are embedded, with millions of receptor cells over a 5cm2 areav. While the olfactory tissue senses smell, the trigeminal nerve endings sense irritant aspects of chemicals in the air. When stimulated by pollutants, both olfactory and trigeminal nerve endings send information to the brain for interpretation. The olfactory bulb communicates with several regions in the brain, such as the cortex, where conscious perception is formed, but also the limbic system, which controls unconscious mood and emotions.
The result of this process is our sensory evaluation of air. Human olfaction is a protective sense, creating a natural aversion to bad smells and irritants.

Testing instruments are being developed to replicate the human nose in evaluating air quality. Some successful, others less so, because of incomplete understanding of the way the brain processes information, the high sensitivity of the human nose, and the fact that one smell can be created by different means – by one specific compound or a combination of several of them.

THE PHYSICAL ASPECT OF INDOOR AIR QUALITY

A marked change in approach came in the 1990s with the understanding that the occupants of a building were not its main source of internal pollution, and that good air quality was not simply a question of appropriate ventilation.

The different indoor pollutants can be classified into two main categories:

- physico-chemical pollutants: gases and vapours (inorganic and organic such as carbon dioxide, carbon monoxide, ozone, VOCs), dust (micro-particles, fibres, etc.),
- biological pollutants: micro-organisms (such as viruses, bacteria, mould) and materials of biological origin (such as pollens, particles from pets, birds, from mites or insects) that can be a source for allergens or toxins.

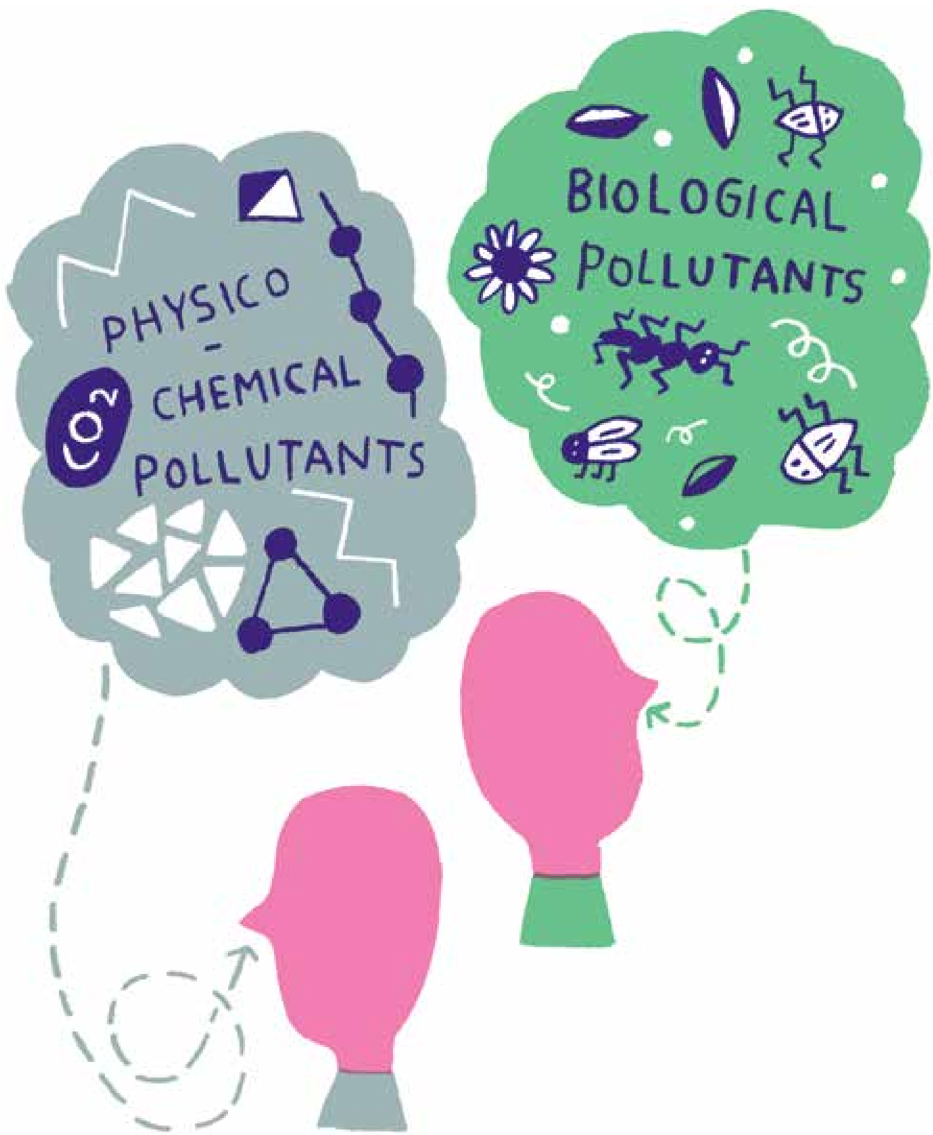
A product can emit substances (particles and/or gases) that originate from the product itself (primary emissions), that are caused by the product coming into contact with other products, or that arise during the in-use phase of the product itself (secondary emissions).

The effects of indoor air pollutants on perceived air quality and health is influenced by indoor environmental parameters such as ventilation rate, air velocity, temperature, relative humidity, the activities taking place, and the frequency and duration of exposure.

THE SOCIO-PSYCHOLOGICAL ASPECT OF INDOOR AIR QUALITY

Several industries, such as the food, cosmetics and automobile industries, have devoted considerable resources to the scientific understanding of the socio-psychological dimension of air and odour perception. With regards to the building industry, most of the effort to date has been focused on pollutants and unpleasant odours, mainly with regards to their impact on people's performance at work or at school. A lot of investigation is yet to be carried out[49].

THE OLFACTORY BULB COMMUNICATES WITH SEVERAL REGIONS IN THE BRAIN, INCLUDING THE CORTEX BUT ALSO THE LIMBIC SYSTEM, WHICH CONTROLS UNCONSCIOUS MOODS & EMOTIONS.



THE DIFFERENT INDOOR POLLUTANTS CAN BE CLASSIFIED IN TWO MAIN CATEGORIES.

How can we currently assess indoor air quality?

When assessing indoor air quality in a building, one needs to consider the level of stuffiness, of pollutants, of particulate matter and of odours.
Evaluating stuffiness is usually done by measuring the level of CO2, which is considered as comfortable when below 600 ppm.
Evaluating the level of pollutants requires measuring the total content of VOCs (TVOC) in the air, with concentrations below 1000 µg/m3 being considered as comfortable.
Evaluating particulate matter involves analyzing two categories of particles:

1) Respirable Suspended Particles (with a diameter of 10µm or less) the concentration of which should not exceed 20 µg/m3 to be comfortable;
2) Fine particles (with a diameter of 2,5µm or less) the concentration of which should not exceed 10 µg/m3 to be comfortable.

Evaluating odours requires the analysis of their concentration, their intensity and their hedonic assessment (i.e. how these odours are considered on a scale ranging from extremely pleasant to extremely unpleasant).

MANY FACTORS INFLUENCE OUR PERCEPTION OF INDOOR AIR QUALITY.

How can we build for indoor air quality?

As the comfort associated with indoor air quality cannot be restricted to the presence, or absence, of a limited number of pollutants, the best way of improving it is to work to reduce pollution from source, while improving ventilation, and purifying the air.

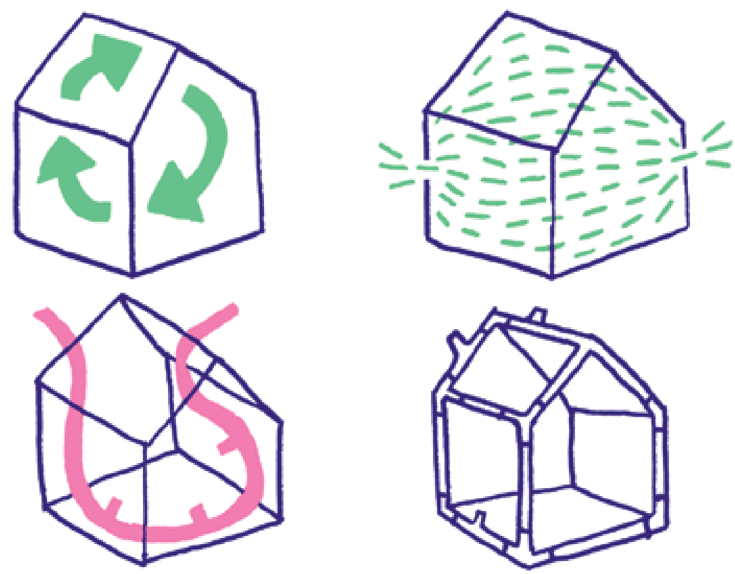
DESIGNING FOR INDOOR AIR QUALITY

The first step in controlling indoor air pollution is in removing or minimising emissions of primary and secondary pollutants at source. Careful specification of non-polluting materials and equipment is required. However, it is not always economic, practical or even possible to avoid such materials.
After the maximum has been done to treat the problem at source, the other factors to be dealt with are:
Ventilation: A certain number of air changes per hour are necessary within a given spatial volume. The appropriate extraction and replacement of air is dependent on several factors, including levels of occupancy, activity, etc.
Air purification: By filtering incoming and outgoing air, particulate matter can be removed. However, these filters need to be maintained to prevent the ventilation system itself from becoming a source of pollution, rather than a solution. Active scavenging materials can also contribute to removing pollutants from indoor air.

VENTILATION

Ventilation systems may be mechanical, natural or, increasingly, hybrid. The basic requirements of any system are:
- high air-change efficiency,
- clean air supplied to the right places.

A first step in ventilation is to introduce detectors to control when ventilation is actually required. This may be done manually by occupants, or may be mechanically controlled by timers or pollutant detectors, for example sensors of CO_2 levels. Automated systems are the most efficient, but personal control in itself can help to provide a feeling of comfort[50].
Ventilation can be a source of noise pollution – by allowing external noise in or by generating noise itself. A balance is to be found to reach the optimum solution.



THE BEST WAY TO IMPROVE INDOOR AIR QUALITY IS TO REDUCE POLLUTION AT SOURCE WHILE IMPROVING VENTILATION AND PURIFYING THE AIR.

Natural ventilation removes the need for mechanical plant and ducting, with initial cost savings, lower running costs and health benefits. It also affords the psychological benefits of providing user control and associated contact with the outside world – hearing birdsong, experiencing the seasons...
However, the benefits of natural ventilation depend on what the natural world in the immediate vicinity consists of: obviously it is not the right solution for a building next to a busy motorway.
Another potential problem with natural ventilation is that it brings in air at external temperatures, so that, depending on the season or time of the day or night, incoming air may need to be heated or cooled, filtered, humidified or de-humidified.

An idea gaining ground is for hybrid ventilation: typically, natural ventilation in mid-season and mechanical in cold and warm seasons.

BUILDING REGULATIONS/STANDARDS FOR INDOOR AIR QUALITY

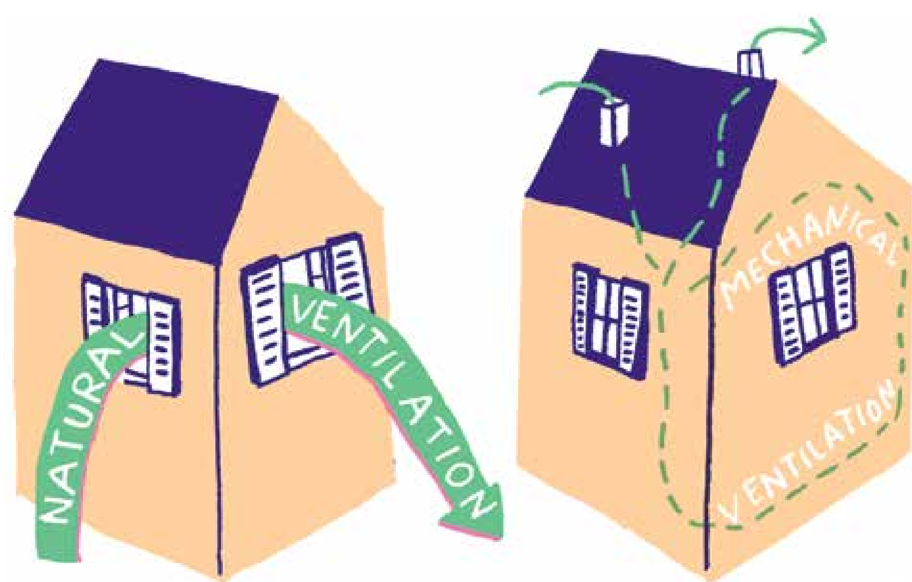
Traditionally, the air quality of an environment is assessed by measuring the concentration of the chemical pollutants found in it. Threshold values have been defined under which human beings can safely evolve, work, live. These values were set up with regards to the impact of each given compound on health.

On this basis, a list of guideline values was proposed by the World Health Organization (WHO), which concerns a wide spectrum of air pollutants[51]. Some of these have been introduced into International and/or National standards (ISO 16000) and regulations.

Several product-labelling schemes rate building products according to their impact on indoor air quality, and Green building labelling schemes such as BREEAM or LEED also include indoor air quality in their assessment criteria.

However, supplying guidelines of permissible concentrations is sometimes of uncertain value given our lack of clear understanding of indoor chemistry.

Standards, labels and regulations for ventilation tend to be more comprehensive.



AN IDEA GAINING GROUND IS FOR HYBRID VENTILATION.

ULTIMATELY IN ORDER TO REDUCE FUEL CONSUMPTION AND THEREFORE USE OF MECHANICAL SYSTEMS WE WILL NEED TO ADAPT OUR EXPECTATIONS REGARDING CONDITIONED INDOOR CLIMATES.

THE FUTURE

Our indoor air quality needs will probably remain the same, but two important aspects are likely to change in the future: our understanding of indoor chemistry and our need to reduce our energy consumption.
As discussed previously, scientific evidence shows that regarding air quality, discomfort may arise at levels well below the sanitary threshold. Detection and interpretation of the thousands of indoor pollutants and their respective interactions (indoor chemistry), is still evasive but will surely improve in the coming years.
Ultimately, in order to reduce fuel consumption and, therefore, use of mechanical systems, we will need to change our expectations of maintaining a conditioned indoor climate all year round and either learn again to open a window, put on a jumper or sweat a bit, or find new passive means of renewing air efficiently to maintain a comfortable thermal environment.

How can Saint-Gobain contribute?

Saint-Gobain offers several product categories that have a direct impact on indoor air quality:

- **products with the lowest possible emissivity possible of VOCs and odorous compounds** (insulation, dry lining, facade, wall or floor covering);
- **products contributing to the performance of ventilation systems,** such as high-performance windows, doors, and technical insulation;
- **products that help purify indoor air** by scavenging certain VOCs (namely Aldehydes) or by using photo catalysis to degrade VOCs and NOx;
- **intelligent membranes that assist vapour dissipation** at the relevant moment, improving both indoor air quality (when combined with ventilation) and safety of building structures by preventing lasting condensation within.

CONCLUSION

CONCLUSION

As most people in the urbanized western world today spend the vast majority of their lifetime indoors, ensuring comfortable and healthy interior environments has become more crucial than ever.

This handbook focusses on the four main factors related to the built environment that actually affect people's perceptions of comfort. However, it cannot be stressed enough that while thermal, acoustic, visual, and air quality comfort is vital, it is only a part of what is needed to ensure healthy and pleasant indoor environments. Safety, security, adequate provision of space, aesthetics, ease of maintenance, modularity and connectivity are some of the other major parameters that need to be taken into account when building or renovating.

Adapting indoor environments to the activities and needs of their occupants, both at individual and collective levels, should not be taken lightly. Beyond the building industry or medical profession, there is only limited awareness of the complex impacts of buildings on our health and well-being. Building owners, designers, constructors, facility managers, together with building product manufacturers and distributors such as Saint-Gobain, all have a responsibility to ensure these issues are taken seriously throughout the industry. But occupants should also have a much greater say in this important matter. Awareness of these issues should grow as recent advances in sensor technology, the Internet of Things and the rise of Big Data are enabling people to gain new insight into their surroundings, their day-to-day habits, and their physical requirements.

In light of all this, Saint-Gobain is always looking at how to further contribute to the development of buildings that are healthier, more sustainable and more comfortable for all.

GLOSSARY

Adaptive model
The Adaptive model is used to assess thermal comfort, often in buildings where no mechanical ventilation systems have been installed. Unlike the Predicted Mean Vote model, it is based on the idea that occupants dynamically interact with their thermal environment, for instance by means of clothing, operable windows, fans, personal heaters and sun shades.

Air temperature stratification
Air temperature stratification is the difference of temperature between head and feet. Discomfort is likely to be experienced if this difference is greater than 2°C.

Air Velocity
Air velocity is the movement of air, measured in meters per second (m/s). Unwanted draughts are a source of local discomfort, and are likely to be considered as such when air velocity is above 0.15 m/s during the cold season, and 0.25 m/s during the warm season.

Daylight Autonomy (DA)
Daylight Autonomy is a 'dynamic daylight metric', in the sense that it is climate based. It is represented as a percentage of annual daytime hours for which a given point in a space registers illumination levels above a specified level.

Glare
Glare occurs when one experiences important changes in light levels or sharp contrast. It can cause stress and fatigue as the human eye is permanently adapting to light levels.

Hygrothermal comfort zone
Hygrothermal comfort zones are determined by the relationship between the temperature of the air and its relative humidity. They vary according to climate zones, but also to the type of activity performed in a given building. Air temperature has an impact on the amount of energy the human body needs to transfer to keep a balanced temperature, while humidity levels influence skin evaporation. If the air is too humid, skin evaporation is slow and uncomfortable. Conversely, if the air is too dry, skin and respiratory tissues evaporate too quickly.

Illuminance
Illuminance (expressed in lux) is the luminous power coming from all directions and reaching a given point. This quantity allows mapping light distribution in a room independently from the observer. Most of

the norms in different countries impose a value of at least 500 lux on offices desks, which is a reasonable value for reading (e.g. newspaper, computer screen...). Metrics based on illuminance levels are useful to predict comfort with lower thresholds and also, to assess discomfort, with upper limits.

Luminance
Luminance levels, expressed in candela/m2, are the different luminous intensities per unit area emitted or reflected by light sources and surfaces. Measuring luminance allows us to appreciate light contrasts and, in extreme cases, glare effects. Luminance is the quantity used to quantify the brightness of light sources, as for instance the brightness of a television.

Operative temperature
The operative temperature is the temperature felt by the human body. It integrates several measurements: the mean wall radiation temperature, the ambient air temperature and the air movement. When designing for thermal comfort, a given operative temperature will be targeted for a given type of activity in a given type of building within a given climate.

Particulate matter
Particulate matter is microscopic solid or liquid matter suspended in the atmosphere. It can be divided into two main categories: 1) Respirable Suspended Particles with a diameter of 10µm or less; 2) fine particles with a diameter of 2,5µm or less.

Predicted Mean Vote (PMV)
Statistics enable an estimation of the percentage of people who will be satisfied or dissatisfied with their thermal environment. The Predicted Mean Vote (PMV) model is used to assess thermal comfort. It was developed using principles of heat balance and experimental data collected in a controlled climate chamber under steady state conditions. Unlike the adaptive model, it is often applied to air conditioned buildings.[52]

Radiant asymmetry
Radiant asymmetry is when one side of your body receives more heat radiation than the other. It is a source of local discomfort when this asymmetry is above 5°C during the cold season, and 14°C during the hot season.

Reverberance
Reverberance is linked to the speed at which sound energy disappears in a room. An unfurnished room with hard surfaces, such as a church, is perceived as being more reverberant than a well-furnished living room.

Reverberation Time (Tr)
The reverberation time is the time that it takes for the sound level to decrease after the source of sound has been turned off. It is usually defined as the time it takes for sound to decrease by 60 dB, and is expressed in seconds.

Spatial Decay
The sound level decreases as the distance from the sound source increases. Spatial decay describes the extent to which the sound decreases when the distance is doubled. This parameter, designated DL2 and measured in dB, determines the slope of the sound propagation curve. The design of the room (shape, furnishing, surface finish, etc.) influences the extent to which the sound level decreases along the distance.

Speech Transmission Index (STI)
Speech clarity concerns the quality of speech transfer to the listeners. In a reverberant room with disturbing background noise, it can be difficult to pick up speech. In the case of poor speech transmission, variations in speech are perceived less well. Factors that impair speech transmission, thus contributing to a lower STI index, are, for instance, background noise, long reverberation and echoes. When speech transmission is perfect, STI = 1. In a normal-sized classroom, STI should be greater than 0.75.

Useful Daylight Illuminance (UDI)
Useful Daylight Illuminance integrates the evaluation of daylight levels and glare in one indicator. It is defined as the annual occurrence of illuminances across the work plane that are within a range considered “useful” by occupants.
It couples Daylight Autonomy (DA) and Maximum Daylight Autonomy (maxDA).

Volatile Organic Compound (VOC)
Volatile Organic Compounds are organic chemicals that are present in the air. They are numerous, varied and omnipresent. They include both human-made and naturally occurring chemical compounds. Most scents or odours are of VOCs. They play an important role in the communication between plants, and between plants and animals. However, some are dangerous to human health or cause harm to the environment. Depending on their nature and concentration, they can be at the origin of sensory irritations, which are characterized by sensations of burning, itching, pain, scratching and stinging in eyes, nose and the upper airways.

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