Influence of presentation modes
on visual perceptions of daylit spaces

This work was realized at UCL, in the research group "Architecture et Climat" led by the Professor De Herde. Coralie Cauwerts was a research fellow of the Fonds de la Recherche Scientifique – FNRS.

Computational resources have been provided by the supercomputing facilities of the Université catholique de Louvain (UCL/SST/CISM) and the Consortium des Équipements de Calcul Intensif en Fédération Wallonie Bruxelles (CÉCI) funded by the Fond de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under convention 2.5020.11.

The following illustrations are from José Flémal (UCL/SST/LOCI): Figures I.A.1, I.B.3, I.B.5, I.B.7, III.A.2, IV.A.1, IV.A.2, IV.A.5, IV.A.6, IV.A.9, IV.A.12, IV.A.13.

Influence of presentation modes on visual perceptions of daylit spaces

Thesis submitted by

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in partial fulfillment of the requirements for the degree of

Docteur en Sciences de l'Ingénieur

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Louvain-la-Neuve, November 2013

“Even a room which must be dark needs at least a crack of light to know how dark it is. Architects in planning rooms today have forgotten their faith in natural light. Depending on the touch of a finger to a switch, they are satisfied with static light and forget the endlessly changing qualities of natural light, in which a room is a different room every second of the day.” Louis Kahn (1901-1974), architect.

LIST OF ABBREVIATIONS

AIC	Akaike information criterion
ANOVA	analysis of variance
CCT	correlated color temperature
DA	daylight autonomy
DF	daylight factor
DGP	daylight glare probability
ENTPE	Ecole Nationale des travaux publics de l'Etat
FOV	field of view
HDR	high dynamic range
IESNA	Illuminating Engineering Society of North America
INDSCAL	individual difference scaling
LDR	low dynamic range
LGCB	Laboratoire Génie Civil et Bâtiment
MCMC	Markov chain Monte Carlo
MCQ	multiple choice question
MRE	mean relative error
n.s.	non-significant
PCA	principal component analysis
QTVR	QuickTime Virtual Reality
SMB	semantic environment description
TMO	tone-mapping operator
UCL	Université catholique de Louvain
UDI	useful daylight illuminance

CONTENT

INTRODUCTION

"It is with light that we can bring soul and spirit back into architecture and perhaps find our soul in the process." Arthur Erickson (1924-2009), architect.

Context

Daylight has always been a preferred way for architects to reveal their architecture and create emotions. Part of the reason is definitely that vision is the first sense through which occupants experience architecture (Baker et al., 1993).

In the current context of sustainable development, the work of the architect has become highly complex. Regrettably, one of the current risks is to focus on building energy performance to the detriment of other important aspects participating in architectural quality, such as a suitable luminous ambience.

To avoid this type of misconduct, the willingness to define good lighting quality arose in the Eighties, in the artificial lighting context. After considerable debate, Veitch and Newsham proposed, in 1996, a convincing definition centered on occupants' needs (Veitch and Newsham, 1996). According to these authors, more than meet requirements linked to visual performances (a vision suited to the planned activities in the room), good lighting quality must meet requirements linked to post-visual performances (task performance and behavioral effects other than vision), social interactions, mood state, as well as health, safety, and aesthetic matters. In the ninth edition of the IESNA Lighting Handbook, this definition is completed in mentioning there should be a balance between occupants' needs, architecture, economics, and the environment (Rea, 2000).

Even if daylight is variable in intensity and color, and daylit spaces generally offer a view toward the outside, daylight is first and foremost a lighting source, similarly to artificial light. So, the definition proposed by Veitch et al. and completed in the IESNA Lighting Handbook seems to be a starting point for developing a more general definition also covering natural lighting. However, this definition does not take sufficient account of the design process of the architect, which, in our opinion, reveals the existing gap between lighting engineers and designers.

To account better for the architectural design process in the creation of high-quality daylit spaces, we propose to revisit this lighting quality definition in light of the Vitruvius triad.

According to Vitruvius, architectural quality is reached when three fundamental principles are satisfied: the aesthetic dimension (*venustas*), the functional aspects (*utilitas*) and the structural considerations (*firmitas*) (Vitruvius, - 25). As mentioned by Fernandez in Borillo and Goulette's book (2002), the Vitruvian triad has never been criticized, although the focus was on one or another dimension in function of the architectural styles, and the dimensions have sometimes been renamed. According to Chaabouni (2011), the triad also governs the design of luminous ambiances.

The lighting quality definition we propose is developed in a context of sustainable development i.e. in considering artificial lighting as a complement to daylighting and in better taking into account the occupant in the design process.

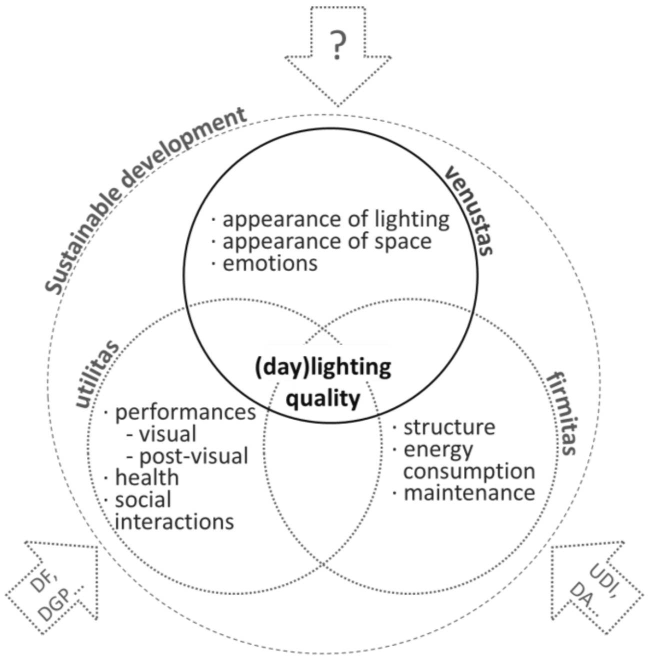


FIGURE 1
Lighting quality definition. Some performance indicators (DF, DGP, UDI, DA, and more) inform about the three dimensions of the design process.

In our definition (illustrated in Fig.1), the functional dimension of the Vitruvian triad (*utilitas*), which was originally centered on the convenience of the rooms and their distribution, now integrates comfort aspects and health matters. The structural dimension (*firmitas*), which originally only oriented on structural considerations, extends to more technical considerations of maintenance and reduction of energy consumption. At last, the aesthetic dimension (*venustas*) covers both the purely visual appearance and the creation of emotions. In comparison with the original definition of lighting quality proposed by Veitch and Newsham (1996), the aesthetics matters have become more important.

Figure 1 also identifies some current gaps in lighting research that should be filled to help the architect design high-quality luminous environments.

Most metrics developed and acknowledged in daylighting are task-driven performance indicators aiming at informing about the functional dimension (*utilitas*) such as the daylight factor DF (Moon and Spencer, 1942) or the daylight glare probability DGP (Wienold and Christoffersen, 2006).

In addition, current political, environmental and economic issues have also led to the development of energy-driven performance indicators such as the useful daylight illuminance UDI (Nabil and Mardaljevic, 2006) or the daylight autonomy DA (Reinhart et al., 2006), which inform about energy consumptions (*firmitas*) in taking into account the availability of daylight and its variability over the year.

Regrettably, to date, no appearance-driven performance indicator is currently acknowledged to assess the aesthetic dimension (*venustas*). Though, some studies have been led in this field. For instance, some researchers investigated lit room's appearance in studying occupant preferences and relating these preferences to luminance distribution (Tiller and Veitch, 1995, Newsham et al., 2003, Van Den Wymelenberg et al., 2010). Other researchers sought to categorize lit spaces on the basis of image analysis but without linking this objective assessment to subjective lighting evaluation (Demers, 2007, Rockcastle and Andersen, 2012).

Given that the aesthetic dimension is probably the main driving force of the architect when designing luminous ambiances, researches related to this dimension must continue and be intensified. They will complement the metrics or indicators currently in development for informing the two other dimensions. Moreover, these researches will allow reducing the existing gap between lighting engineers and designers.

Research question

A first step in the development of these tools related to aesthetics is the validation of the use of images for studying visual perceptions.

Indeed, if it was proved that virtual renderings faithfully represent the visual appearance of actual lit spaces, designers could use them to judge the visual quality of their architectural projects, and they could then be ensured that the designed space is what they seek to create in terms of visual appearance and emotions.

Despite the lack of works validating this hypothesis, this is what designers are already doing. Indeed, in the absence of tools informing about the aesthetic dimension, and also to facilitate better communication with clients, architects often resort to virtual renderings.

In research oriented on the visual appearance of lit environments, images are also increasingly used to improve understanding of the relationship between a lit environment and its visual appearance.

In these two fields (architecture and lighting research), money matters and efficiency are the main reasons for using images as a surrogate for the real world. Moreover, in daylighting research, images are also a way to overcome the uncontrollable variability of light encountered under natural sky and to ensure that all the participants of a survey assess the same scene. Given these advantages and the constantly increasing photo-realism of the computer-generated images, the confidence of the designer and the researcher in such images for judging visual quality is continually growing.

To our knowledge, only three major works have sought to determine whether images can be used as a surrogate for the real world in assessing the visual appearance of lit spaces: the works by Hendrick et al. (1977), Mahdavi and Eissa (2002) and Newsham et al. (2010). These three studies suggest there is a potential use for images, but the authors recommend further investigations. Given the increasing use of images in the architectural process and in the research field, there was an urgent need to pursue investigations to determine to what extent images can be used to assess the visual appearance of lit environments.

The present work aims at determining to what extent physically-based renderings, and more particularly Radiance renderings, can be used for assessing the perceived appearance of lighting and space in indoor daylit environments. The study also raises the question of the influence of the presentation modes of these images on these perceptions. Indeed, the recent advances of imaging and display technologies have developed some modes of presentation that produce increasingly immersive and "realistic" virtual environments which are potentially beneficial in assessing the visual appearance of daylit spaces. The potential of presentation modes such as 3D images, panoramic pictures, and HDR displays will be explored in the frame of the present work. These presentation modes have been chosen for their abilities to better approach some characteristics of the human vision (a binocular vision, a wide field of view and a large visible range of luminance). Our objective is to determine which dimensions characterizing a lit environment (e.g. perceived brightness, coloration, and more) may be studied with such a surrogate for the real world.

Structure

The first of the five parts of the thesis presents the state of the art and is divided in two chapters. The first chapter deals with methods commonly used in lighting research for measuring visual appearance of lit environments. The second chapter summarizes potential representation modes of the real world and focuses on images.

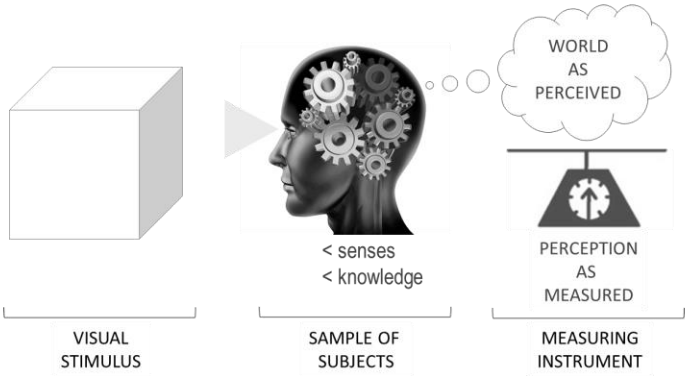
The second part of the work describes the objectives of the thesis and presents the experimental design implemented to respond to these objectives.

The third part of the thesis presents the first step of the experiment: the collection of visual perceptions experienced in the real world. The validation of the questionnaire used for collecting these perceptions is then discussed.

The fourth part of the thesis aims at evaluating the potential of several presentation modes of images for reproducing perceptions experienced in the real world. It first describes the creation of the photographs and presents the characteristics of the used display devices. The potential of each tested presentation modes is then analyzed.

Finally, the fifth part of the thesis discusses the reproduction of the experiment organized in the actual environments using virtual renderings (Radiance renderings). It presents first a comparison between classical physically-based renderings and image-based lighting rendering for replicating actual lit environments. The potential of Radiance renderings for replicating perceptions experienced in the actual lit environments is then discussed.

PART I
STATE OF THE ART



Psychology of perception aims at better understanding the relationship between a physical stimulus and the induced perception. Moreover, the measure of visual perceptions requires presentation of visual stimuli to subjects and collection of their visual perceptions using a measuring instrument.

This first part of the thesis:

- reviews categories of impressions affected by lighting and summarizes common methods encountered in the literature for measuring visual perceptions;
- reviews presentation modes commonly used in our context for measuring perceptions and presents potentially interesting technological advances.

CHAPTER I.A
PERCEIVED VISUAL APPEARANCE OF LIT ENVIRONMENTS

"(…) Daylight, the light on things, is so moving to me that I feel almost a spiritual quality. When the sun comes up in the morning – which I always find so marvelous… and casts its light on things, it doesn't feel as if it quite belongs in this world. I don't understand light. It gives me the feeling there's something beyond me, something beyond all understanding." Peter Zumthor (1943-), architect.

This chapter aims at determining categories of impressions affected by the lighting environment and at summarizing common methods encountered in the literature for measuring visual perceptions in global, artificial lighting, and daylight contexts. The most suitable method for assessing the appearance of lighting and space in the present study will be determined.

I.A.1. KÜLLER AND THE DESCRIPTION OF THE VISUAL ENVIRONMENT

In the seventies, Küller worked on the measurement and description of visual perceptions in the specific field of architecture. As a result of his work, he determined eight dimensions describing the visual environment and developed a standardized questionnaire for assessing visual appearance of built environments.

To reach his objectives, he used the following method. First, he conducted a series of studies in which he asked subjects to rate several kinds of environments (living rooms, housing area, landscape and working environments) using unipolar rating scales[1]. In total, he used about 200 descriptive words and he resorted several presentation modes (real world, full-scale model and color slides) to present the stimuli to the participants. Using factor analyses, Küller identified eight dimensions describing the environment: pleasantness, complexity, unity, enclosedness, potency, social status, affection, and originality (Küller, 1991). Finally,

[1] A unipolar scale is a rating scale whose only one end is anchored (for instance, the room is pleasant: slightly □□□□□□□ very). A bipolar scale is a rating scale whose the two extremes are anchored (for instance, the room is pleasant □□□□□□□ unpleasant).

he developed a standardized form composed of 36 seven-point unipolar adjective scales to assess visual perceptions in the built environment. His semantic environmental description form, often called SMB form[2], was translated into various languages. As presented in Table I.A.1, four adjectives composed each dimension, with the exception of the pleasantness dimension, which is composed of eight adjectives. For each dimension, a score can be calculated by averaging the scores of the scales constituting that dimension.

TABLE I.A.1
SMB form developed by Küller

Dimensions	Adjectives (seven-grade unipolar scales)
Pleasantness	Ugly (−), Stimulating (+), Secure (+), Boring (−), Idyllic (+), Good (+), Pleasant (+), Brutal (−)
Complexity	Motley (+), Subdued (−), Lively (+), Composite (+)
Unity	Functional (+), Of pure style (+), Consistent (+), Whole (+)
Enclosedness	Closed (+), Open (−), Demarcated (+), Airy (-)
Potency	Masculine (+), Fragile (−), Potent (+), Feminine (−)
Social status	Expensive (+), Well-kept (+), Simple (−), Lavish (+)
Affection	Modern (−), Timeless (+), Aged (+), New (−)
Originality	Curious (+), Ordinary (−), Surprising (+), Special (+)
The minus sign (−) indicates that the score of the item is reversed.	

During the following 40 years, Küller used this form to study, for instance the influence of the color of the walls on occupant perceptions. But the SMB form also makes it possible to study differences in perceptions between two groups of people (for instance, architects and non-architects).

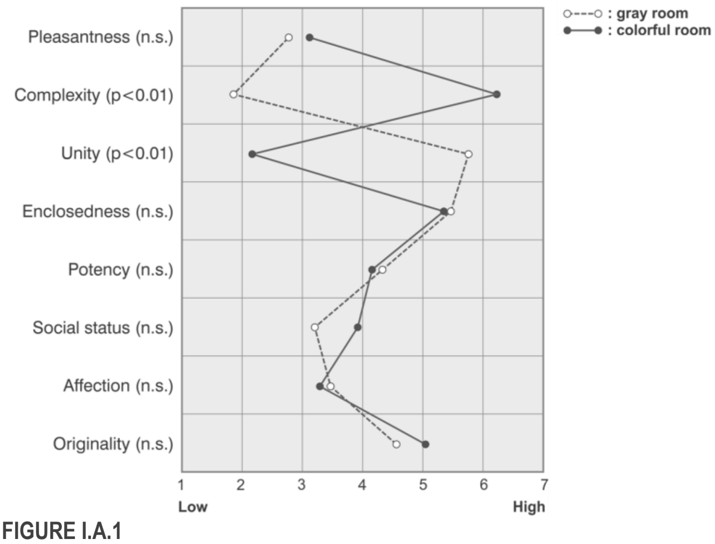


FIGURE I.A.1
Semantic profiles adapted from (Küller et al., 2009)

[2] Semantisk Miljo Beskrivning (Swedish)

As illustrated in Fig.I.A.1, on the basis of the mean score calculated for each dimension, semantic profiles can be built and a visual comparison can easily be done between the various tested conditions.

I.A.2. FLYNN AND THE ARTIFICIALLY LIT ENVIRONMENT

In parallel to the work done by Küller, during the same period Flynn et al. (1973) focused on the effect of artificial lighting on impressions. They studied a conference room in which only the artificial lighting arrangement varied. In the frame of this work, they investigated two rating techniques for better understanding how the lighting arrangements influenced occupant's impressions: semantic differential rating scales and multidimensional scaling. They also investigated the observation of the participants' overt behavior (comments and gestures) during the experiment.

The first rating technique investigated is the semantic differential measurement technique. It consisted of asking the subjects to rate six lighting arrangements using a series of 34 bipolar scales. Data were collected from 96 adults. Their educational and cultural backgrounds are not mentioned in the publication. Seventeen of the 34 rating scales presented significant differences between the various lighting arrangements. Regrettably, the authors did not clearly mention in their publication either the 34 scales or the 17 presenting differences between arrangements. Using a factor analysis, they identified three categories of impressions mainly affected by the lighting arrangements: evaluative impression, perceptual clarity, and spaciousness. The adjectives anchoring the seven-grade bipolar scales related to each of these categories are presented in Table I.A.2.

TABLE I.A.2
The three categories of impressions affected by the lighting arrangement in (Flynn et al., 1973) and the adjectives associated with the 18 seven-grade bipolar scales

Dimensions	Adjectives (bipolar rating scales)
Evaluative	pleasant/unpleasant; like/dislike; beautiful/ugly friendly/hostile; harmony/discord; satisfying/frustrating; sociable/unsociable; relaxed/tense; interesting/monotonous
Perceptual clarity	clear/hazy; bright/dim; faces clear/faces obscure; distinct/vague; focused/unfocused; radiant/dull
Spaciousness	large/small; long/short; spacious/cramped

As illustrated in Fig.I.A.2, similarly to Küller, Flynn et al. built semantic profiles for an easy visual comparison of the tested arrangements. But, contrary to Küller, they did not aggregate the scales of each dimension in a single score.

According to the study by Flynn et al., two among the eight dimensions identified by Küller as characterizing the visual appearance of a built environment are affected by the lighting arrangement: pleasantness (named evaluative impression in Flynn et al.'s work) and enclosedness (identified as spaciousness in Flynn et al.'s work). The perceptual clarity dimension, which is more particularly linked to the appearance of lighting, does not appear in the Küller SMB form, which was developed in a more general context.

The second technique investigated by Flynn et al. is multidimensional scaling. This technique aims at identifying similarities or dissimilarities in data. In Flynn et al.'s study, participants were asked to rate dissimilarities between pairs of lit scenes. The individual differences scaling (INDSCAL) analysis performed on collected judgments of dissimilarities was intended to identify some modes of lighting. The authors asked 46 participants to evaluate overall differences between successive pairs of lighting arrangements. Participants were asked to give for each pair (38 in total) a score between 0 and 10. The INDSCAL analysis identified three dimensions which the authors called "lighting modes": an "overhead/peripheral" mode, a "uniform/non-uniform" mode and a "bright/dim" mode. The first two dimensions appear to be linked to the distribution of light while the third, to the perceived brightness.

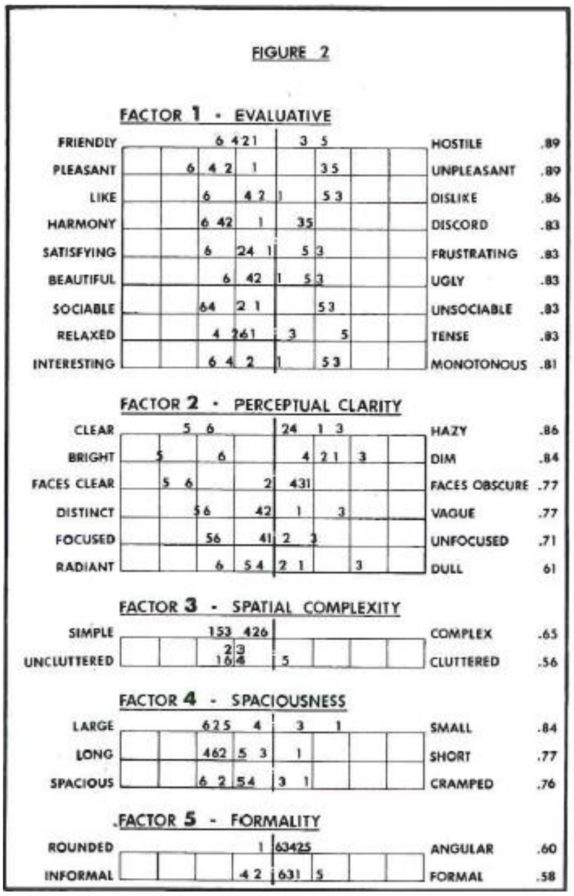


FIGURE I.A.2
Semantic profiles extracted from (Flynn et al., 1973)

Several years later, the same authors developed a standardized procedure for measuring subjective impressions in lighting (Flynn et al., 1979). Their objective was to make it possible to compare results from various researchers. Their paper aimed to present to the lighting community some methods for measuring perceptions. They clearly detailed steps for data collection and presented various methods to analyze data. But, while they were willing to standardize a procedure to collect and analyze data in order to facilitate comparison of works, they did not standardize the questionnaire. They argued that semantic differential rating scales should be selected according to the goal and context of the experiment, and so they just presented a non-exhaustive list of scales and gave no more details on how the scales were chosen than were provided in their previous paper (Flynn et al., 1973).

Despite the lack of information about the choice of the rating scales, many questionnaires on the appearance of lighting have been developed from Flynn's scales, such as in the studies by Boyce and Cuttle (1990), Newsham et al. (2003) and Han et al. (2005).

I.A.3. BÜLOW-HÜBE AND THE DAYLIT ENVIRONMENT

Most of the studies on the influence of light on human impressions have been conducted in the field of artificial lighting. To our knowledge, Bülow-Hübe is one of the first to have investigated daylit environments through her study on the impact of various coatings on the visual appearance of indoor daylit rooms (Bülow-Hübe, 1995).

In this work, she clearly made the distinction between the perception of the global indoor environment and the description of daylight in the environment. To assess global indoor environment, Bülow-Hübe used the SMB form developed by Küller (1991). To assess the appearance of the lighting, she developed a questionnaire based on the work of Liljefors and Ejhed, as cited in Bülow-Hübe (1995). According to these authors, seven dimensions characterize light in interiors: lighting level, light distribution, shadows, reflexes, glare, light color, and colors. To our knowledge, the work of Liljefors and Ejhed was not published in English, and we have no detail on how these dimensions were found. However these dimensions are similar to the parameters determining lighting ambience according to the European Standard EN 12464-1 on lighting of indoor workplaces: luminance distribution, illuminance, glare, directionality of light, color rendering and color of light, flickering, and daylighting (EN12464-1, 2002). Given that the objective of the questionnaire was to measure the influence of the coloration of a window on the perception of daylighting, Bülow-Hübe focuses more particularly on the color dimension and the view through the window. So, ten of the 29 questions in her questionnaire are related to the color dimension (see Table I.A.3).

Ninety-five subjects participated in her experiment and rated an experimental room furnished either as an office or as a bedroom. The statistical tests performed on the collected data identified that the type of window (standard or super-insulated) significantly influences two dimensions characterizing the visual appearance of the room: its pleasantness and its enclosedness. Concerning the appearance of the lighting, it is principally the brightness and the coloration dimension which were affected by the glazing type.

TABLE I.A.3
Lighting questionnaire developed in (Bülow-Hübe, 1995)

Question	Adjectives (7-grade bipolar scales)
How do you perceive the daylight in this room?	strong/weak
	pleasant/unpleasant
	warm/cold
	hard/soft
	tinted/clear
Do you perceive the room as a whole as light or dark?	light/dark
How well can you see in this light?	bad/good
How is the daylight distributed in the room?	varied/monotonous
How are the shadows on the sculpture?	diffuse/sharp
	soft/hard
How are the colors on the fruit poster?	clear/drab
	subdued/strong
	warm/cold
Are you disturbed by glare from the window?	much/little
Are you disturbed by glare from strongly lit surface?	much/little
How is the weather outdoors right now?	clear/hazy
	overcast/no clouds
	beautiful/dull
	grey/sunny
How is the light outdoors right now?	light/dark
	pleasant/unpleasant
	warm/cold
	glaring/mild
	natural/unnatural
How do you perceive the colors outside the window?	clear/drab
	subdued/strong
	warm/cold
	natural/unnatural

The questionnaire developed by Bülow-Hübe was adapted in a series of works carried out in reduced-scale models and conducted by Dubois to study the influence of glazing types on visual perceptions (Dubois et al., 2007, Pineault and Dubois, 2008, Pineault et al., 2008).

I.A.4. VOGELS AND THE DESCRIPTION OF THE ATMOSPHERE

While the previous works focused on purely visual perceptions, Vogels is particularly interested in the potential of luminous ambience to affect our emotional state (Vogels, 2008). According to Peter Zumthor, the famous Swiss architect who received the Pritzker Prize in 2009, this ability of an atmosphere to affect our emotional state participates actively in architectural quality (Zumthor, 2008).

In her work carried out in the artificial lighting context, Vogels focused on the construction of a questionnaire measuring this atmosphere (Vogels, 2008). While few details were given regarding the way the questionnaire by Flynn et al. (1973) was built, Vogels explained her methodology quite clearly. First, she identified the vocabulary used by people to describe an atmosphere. Forty-three people participated in her survey. They were asked to imagine a particular location (living room, shop, and so on) and to describe the atmosphere with as many words as possible. Then, they were asked to think of other terms that could be used to describe the atmosphere of an environment. Contrary to the approach of Küller (1991) and Flynn et al. (1973), who asked the participants to respond to a series of pre-determined semantic differentials, Vogels used open questions to collect vocabulary. One hundred eighty-four terms were so collected and split into three categories by the author:

- terms related to emotions (for instance, *terrified*)
- terms related to atmosphere (for instance, *cosy*)
- objective description of the environment (for instance, *clean* or *bright*)

Terms related to emotions were then transformed into atmosphere terms (for instance, *terrified* was transformed into *terrifying*) and terms related to objective description of the environment were deleted. Then, terms with similar meanings were grouped and a selection in each group was made to obtain a final 38 atmospheric adjectives anchoring 5-grade unipolar scales (see Table I.A.4).

TABLE I.A.4
The 38 atmospheric terms (translated from Dutch) anchoring the five-grade unipolar scales in the questionnaire developed in (Vogels, 2008)

Detached, terrifying, musty, threatening, cosy, oppressive, depressed, exciting, formal, hospitable, safe, pleasant, inspiring, intimate, chilly, cosy, cool, lively, luxurious, mysterious, uninhibited, uncomfortable, restless, relaxed, personal, romantic, spatial, tranquil, boring, lethargic, stimulating, accessible, hostile, cheerful, warm, business

Inspired by Vogels' work, van Erp developed a questionnaire to study the effects of some lighting characteristics (intensity, CCT, and directivity) on atmosphere perception in an experimental room (Van Erp, 2008). His questionnaire was divided into several parts. For studying the first impressions of the participants, he explored open questions. To study how lighting affects the emotional state of the observers, he used the atmosphere questionnaire developed by Vogels. However, he increased the number of gradations from five to seven. He then developed seven-point scales around preferences, light appearance, and application. So, in his study, he clearly made the distinction between several kinds of perceptions and judgments, and among others, between light appearance (bright/dim, uniform/non-uniform, warm/cold) and emotional response (Vogel's atmosphere questionnaire).

I.A.5. FERNANDEZ AND CONTEXTUALIZATION

In her recent PhD work on lighting in hotels, Fernandez stressed the importance of contextualization (Fernandez, 2012). As Veitch pointed out a few years ago in a comment on a paper by Loe (Loe et al., 2000), the participant is often considered as a spectator, while perceptions are complex phenomena influenced by the context.

Fernandez's approach aimed at better putting the observers in context in order to collect their impressions of the suitability of various lighting arrangements for several activities encountered in hotels. Her study was divided into three phases, all organized in a hotel. Through interviews, she first showed the importance attached by the occupant to the suitability of lighting according to the activity (work situation, leisure…). Through the visualization of computer-generated images organized in the bar of the hotel, the second phase aimed the selection of some lighting arrangements to investigate in the last phase of the work: the evaluation of the suitability of various lighting arrangements in an actual hotel room, equipped for the purposes of the study.

I.A.6. CONCLUSIONS

This chapter reviewed major works dealing with the measurement of visual perceptions in lit environments or more general contexts.

According to Küller's work, eight dimensions characterize the visual appearance of built environments: pleasantness, complexity, unity, enclosedness, potency, social status, affection, and originality. Among these eight dimensions, two appear to be affected by lighting: the room's pleasantness and its enclosedness (Flynn et al., 1973, Bülow-Hübe, 1995).

For its part, lighting in an indoor environment can be characterized through the following dimensions: brightness, light distribution, coloration of the lighting and the room, directivity of light (shadows), and glare.

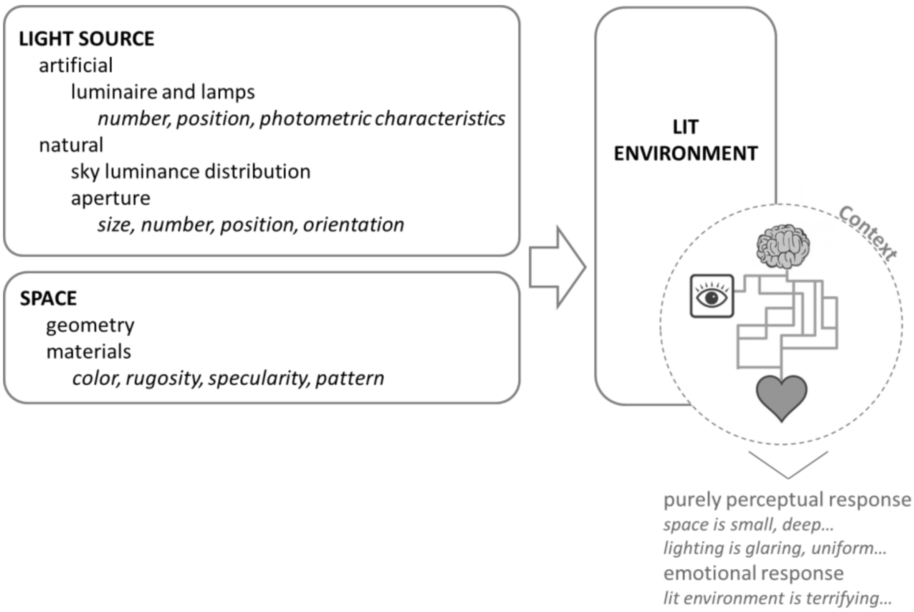


FIGURE I.A.3
Lit environments result from various characteristics of the space and the light source, and induce to the observer both purely a perceptual response and an emotional one.

This chapter also highlighted that the most commonly used technique for collecting perceptions in the field of lighting is the semantic differentials. And, as illustrated in Fig.I.A.3, Vogels' work (2008) pointed out the fact that more than producing a purely perceptual response, a luminous atmosphere gives rise to an emotional response. Last, the work by Fernandez (2012) stressed the importance of contextualization, too little addressed in the field of lighting.

CHAPTER I.B
REPRESENTATIONS OF THE REAL WORLD

Over the past four decades, many studies have highlighted the multiple influences of natural and artificial lighting on human beings. These impacts can be either purely visual (such as visibility, aesthetic judgment…) or non-visual (impact on chronobiology, mood, cognition…). While it does not seem feasible to study some of these impacts elsewhere than in the actual world, exploring matters of aesthetic judgments using surrogates for the real environment is a potential solution to take advantage of a lab context for reducing or avoiding some bias encountered in the real world.

This chapter aims at presenting an overview of the representations of the real world commonly encountered in the literature to study the visual appearance of indoor environments (see Fig.I.B.1). Among these representations, two main types can be distinguished: 3D reproductions such as mock-ups and reduced-scale models and 2D reproductions with images such as photographs (or movies) and virtual renderings (or animation pictures).

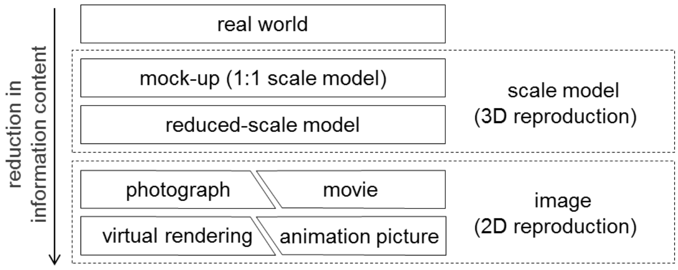


FIGURE I.B.1
Representations of the real world. This figure is inspired from Lau (1972).

Advantages and disadvantages of each of these types are discussed in the present chapter. Their ability to reduce some biases is also highlighted. Last, this chapter also reviews the works validating each of these representations of the real world, for visual appearance purpose.

I.B.1. 3D REPRODUCTION

I.B.1.1 MOCK-UPS

Among all the possible representation modes of the real world for studying perceptions, a mock-up – which is, by definition, a 1:1 scale model – is probably the surrogate which minimizes the loss of information content available in the real world.

The work carried out by Flynn et al. (1973) on the influence of artificial lighting on impressions (see Section I.A.2) was realized in this kind of experimental room. As explained by the authors, this type of environment presents, in comparison to actual rooms, the advantage of being equipped with systems for varying indoor luminous conditions without varying any other physical parameters.

To evaluate the influence of the lighting environment on people's impressions, Flynn et al. investigated two rating methods commonly used in the field of lighting for studying perceptions: direct evaluation (participants are asked to rate one condition at a time) and pairwise comparison (participants are asked to compare two conditions). To reduce the potential presentation order bias encountered with direct evaluations, Flynn et al. varied the luminous conditions in effect in the room when participants arrived, showed all the stimuli before asking the participants to rate each of them, and finally varied the presentation order of the stimuli. No detail is given in the publication regarding the strategy adopted to reduce the interval bias in the successive pairwise comparison implemented by the authors. However, as explained by Fotios and Cheal (2010), in successive pairwise comparisons, the two luminous conditions are presented to the participants successively, and the participants have to memorize the first stimulus to compare it to the second. Repeating the presentation of both stimuli as often as needed by the participants can be a way to reduce interval bias. And it is, in a sense, what is implemented in the mock-up experiment presented in the thesis by Charton (2002), also done in the context of artificial lighting. Contrary to Flynn et al., Charton worked in a pair of identical test rooms (see Fig.I.B.2). He implemented a pairwise comparison protocol in which the subject could not simultaneously see the pair of stimuli but could go from one room to the other as many times as he wanted, so reducing the interval bias.

FIGURE I.B.2
Pair of identical mock-ups in which Charton's experiment is carried out

In the field of daylighting also, mock-ups are used for studying perceptions. But, while in the field of artificial lighting, mock-ups are definitely an adequate environment for studying perceptions as they allow the minimization of the loss of information content available in the real world, in daylighting, working in such an environment – and so under natural sky – leads to uncontrollable variations in the luminous conditions between participants, as emphasized by Bülow-Hübe (1995). And these uncontrollable variations of light can introduce a problematic bias in experiments, where all the observers should rate similar conditions.

I.B.1.2 REDUCED-SCALE MODELS

Similarly to the mock-ups, reduced-scale models make it possible to easily control and to vary some parameters influencing the appearance of lighting and space, such as the color of the walls or the dimension of apertures. The major advantages of reduced-scale models, in comparison with mock-ups, are their efficiency (related to ease in varying the studied parameters) and their low cost. Another advantage is the possibility to work under an artificial sky in order to get rid of the variability of daylight encountered under natural sky and also to avoid problems related to meteorological conditions.

In 1972, Lau investigated the potential of reduced-scale models for studying perceptions in an artificial lighting context (Lau, 1972). He worked in a 1:6 scale model for matters of reproduction of textures and miniaturization of the artificial lighting components, and because 1:6 scale models are easily moveable and readily conceivable, according to Hopkinson, as cited by Lau (1972). Moreover, 1:6 to 1:20 scale models are the smallest models possible to study visual effects, due to limits of convergence and accommodation of human vision. Finally, for questions of accommodation, participants observed the model from within.

In order to determine whether reduced-scale models can be used as surrogates for the real world, for the purpose of studying visual perceptions, Lau explored various methods. In a first experiment, he implemented a pairwise comparison protocol and asked the participants to determine, between two lighting conditions, which was the gloomiest and which the most pleasant. He organized this experiment in a mock-up and in the corresponding reduced-scale model. He observed that the reduced-scale model and the mock-up were perceived as being similar. In a second experiment, he implemented a direct evaluation and asked the participants to rate eight luminous conditions using a 4-point scale (not gloomy/gloomy). Again he organized the experiment in a mock-up and in a reduced-scale model. Some of the observers were allowed to move in the mock-up while another group was stationary. Again, his results suggest that the reduced-scale model and the mock-up were perceived as being similar, but he also observed that inter-individual differences were significant when participants were allowed to move in the mock-up. In a third experiment, participants were asked to directly compare a mock-up and its corresponding reduced-scale model. In seven of eight tested luminous conditions, participants found the scale model more pleasant. Last, in a complementary experiment, Lau asked the participants to rate one lighting arrangement either in the mock-up or in the corresponding reduced-scale model, using semantic differentials (7-grade scales) covering various dimensions (see Fig.I.B.3).

Again, the results suggest that perceptions are similar between the two presentation modes and that the miniaturization beautified the space (the reduced-scale model was perceived as significantly more beautiful). Perceived brightness was also assessed significantly differently in the mock-up and in the reduced-scale model. And from these experiments, Lau concluded that perceptions experienced in the reduced-scale models do not differ significantly from those experienced in a full-scale experimental room and that reduced-scale models can be used to some extent as surrogates of the real world. However, he added that investigations should be pursued. He also noted that the degree of fidelity of the reduced-scale model with the real world should be defined according to the objective of the study and that, in a context of artificial lighting, the use of a highly detailed reduced-scale model did not reduce costs in comparison to the mock-up.

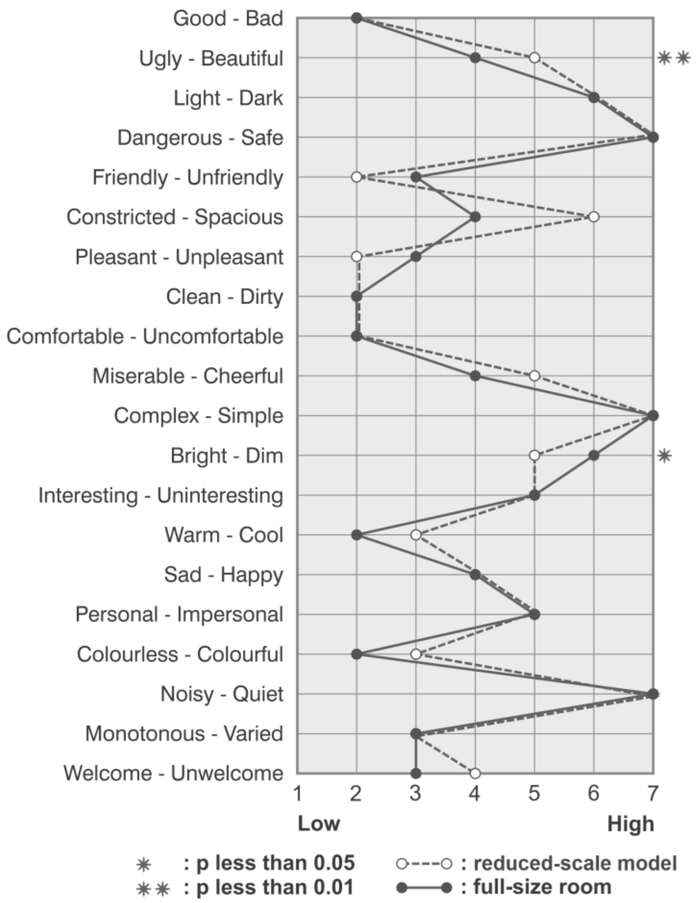


FIGURE I.B.3
Semantic profiles adapted from (Lau, 1972)

In the field of daylighting, Cowdroy's study, as cited by Dubois et al. (2007), explored, more specifically, the perception of glare and validated the use of reduced-scale models under natural sky for reproducing perceptions of glare experienced in mock-ups.

Based on these validation works, some researchers investigated reduced-scale models in a daylighting context, for instance for studying the influence of glazing types on the appearance of indoor rooms (Pineault et al., 2008, Pineault and Dubois, 2008, Dubois et al., 2007). In a first study, an experiment is realized under overcast sky conditions to ensure that the luminous conditions in the model remained constant (Dubois et al., 2007). In a second study, an experiment is realized under an artificial sky reproducing a CIE overcast sky, meaning the uncontrollable variability of daylight is no longer a problem (Pineault et al., 2008). To validate the results observed under artificial conditions, the authors reproduced the study under natural sky (Pineault and Dubois, 2008). The authors did not raise matters of uncontrolled variability of light but explained that the experiment was organized at a specific period of the day to avoid direct sun in the model. In a more recent work, also supervised by Dubois, and realized in a 1:4 scale model, matters of arousal and suitability of lighting for reading were added to luminous atmosphere consideration (Arsenault et al., 2012).

I.B.2. 2D REPRODUCTION

I.B.2.1 PHOTOGRAPHS

Interest in working with images for matters of efficiency and cost became apparent from the first investigations carried out by Flynn et al. (1973) on the influence of light on human impressions. So, a few years after their initial investigations in mock-ups, the same researchers replicated the experiment using photographic slides (Hendrick et al., 1977). The researchers had two motivations. They wanted to evaluate whether images can be used to reproduce results obtained in mock-up conditions, which could be interesting for reasons of efficiency and cost. But they were also interested in the following fundamental question: are some perceptions felt by people in a three-dimensional space reproduced using a two-dimensional surrogate of the real world?

Several photographs of various lighting arrangements were made in the mock-up. The authors then chose those which best reproduced the scenes. Two of the three techniques investigated in (Flynn et al., 1973) to evaluate the impact of lighting arrangements on occupants' impressions were reproduced: rating scales and multidimensional scaling. Observation of overt behavior was abandoned. One hundred eighty-five people, in subgroups of 30 to 40, rated the photographic slides with the same semantic scales used in (Flynn et al., 1973). Participants were students in architecture and psychology, contrary to the reference experiment in which 96 adults (their educational background is not specified) rated the scenes. As in the reference study, participants first visualized the six lighting arrangements and then rated them one by one. Slides were presented in a dark room. Similarly to Flynn's study, it is unclear which 34 rating scales, were used as only 27 scales are presented in the figures. Moreover, in a note at the end of the paper, the authors explained that the number of gradations were not the same in the two studies (eight grades for the reference study against seven grades in this validation work). The authors realized a principal component analysis (PCA) on the collected data and observed a structure similar to that found in the reference study, as well as similar mean ratings. A second group of 45 students in psychology evaluated differences for 38 pairwise comparisons, similarly to what was also done in the reference study, and INDSCAL procedure was used to analyze data. Only one "lighting mode" was obtained (the "bright/dim" mode), contrary to the mock-up experiment, where three modes were found (two relative to distribution of light in the room and one related to perceived brightness).

Last, the authors observed that to reproduce results using slides, the semantic differential method should be used preferentially to multidimensional scaling, which did not reproduce results. Finally, they concluded that slides were promising, but that more work should be done.

Two years later, in a more general context, Danford and Willems assessed the potential of slides for studying human responses to physical environments (Danford and Willems, 1975). They highlight some common methodological shortcomings linked to the response instrument and to the procedure for presenting the scenes to the participants. Danford and Willems implemented an experimental protocol aiming at comparing the perceptions of participants visiting real-world scenes and perceptions of people visualizing slides of the same scenes. The originality of their study was to introduce in their protocol two control groups of participants. The first control group consisted of participants visualizing the slides without receiving information about the function or location of the assessed environment. The second control group did not visualize the slides or visit the real scenes, but received information about the function and location of the scenes. All the participants were asked to rate the scenes using 34 five-point descriptive and affective adjective scales. Participants to whom no visual stimulus was presented were asked to respond to the questionnaire according to their expectations.

Responses given by the four groups of participants were astonishingly similar. Danford and Willems concluded that the conventional method, consisting of comparing perceptions from real scenes and those from surrogates, is not sufficient, as responses can be influenced by the procedure for acquiring data. They suggested introducing into the experimental protocol some means to check potential instrument bias.

I.B.2.2 VIRTUAL RENDERINGS

Since the works carried out by Hendrick et al. (1977) and by Danford and Willems (1975), great leaps forward have been made in the area of imaging technologies. Currently, powerful rendering tools can provide hyper-realistic images. These renderings are particularly popular in the architectural process to judge the aesthetic qualities and appropriateness of designed spaces and to communicate with the client. This kind of image is also very interesting for subjective assessment of luminous ambiences, as a wide diversity of scenes can be created. Moreover, contrary to the photographs, virtual rendering requires neither actual buildings nor mock-ups or scale models.

Virtual renderings can be of two types: physically-based or photo-realistic. Contrary to physically-based renderings, photo-realistic images do not provide photometric data such as luminance. They only try to produce a visual response identical to that experienced in the actual scene. For matters of aesthetic judgment, working with physically-based renderings is probably not necessary. However, for architectural lighting quality research purpose, the chosen software should provide both realistic images and accurate photometric data to make it possible to link subjective assessments and physical measurements (a classical method in psychophysics to better understand perceptions).

Currently, the main simulation tools used for lighting analyses in the architectural context are: Radiance, Dialux, Relux, Mental Ray (used in 3D Studio Max Design), Inspirer, and Velux Daylight Visualizer (Ochoa et al., 2012). Despite the fact that the Radiance software does not offer a user-friendly interface, and requires a substantial period of time for training (Ubbelohde and Humann, 1998), it is widely used for daylighting research purpose as mentioned in (Villa, 2012). This is probably thanks to the fact that it offers a high level of flexibility and allows modeling complex geometries and materials. Moreover, contrary to other software, Radiance has also been the subject of numerous validation works as in (Mardaljevic, 1995, Jarvis and Donn, 1997, Reinhart and Walkenhorst, 2001, Galasiu and Atif, 2002, Reinhart and Andersen, 2006, Reinhart and Breton, 2009) where the accuracy of the program for predicting illuminance was checked. In (Houser et al., 1999), rather than analyzing illuminance, the authors compared simulated and measured luminances.

Most of the validation works carried out in the field of lighting simulations, such as those cited above, aimed at validating photometric data. Few studies have sought to determine whether the produced images replicate the appearance of the modeled environment. To our knowledge, only two major works have explored the extent to which physically-based renderings can be used to assess the impact of lighting on the appearance of indoor environments: Mahdavi and Eissa's study (2002) as well as Charton's thesis (2002). Both were conducted in the context of artificial lighting and using Lightscape, a software purchased by Autodesk in 1997 and discontinued as of 2003, in favor of 3D Studio Max Design. Contrary to Radiance which uses backward ray tracing, Lightscape is based on both ray tracing and radiosity. And, according to Maamari who studied the strengths and weaknesses of Lightscape 3.2 against the CIE 171:2006 test cases, Lightscape presents a high level of accuracy with artificially lit environments while it is not recommended for studying daylit spaces (Maamari et al., 2006).

Mahdavi and Eissa (2002) compared perceptions experienced by 50 people in five actual lighting situations to those experienced by 50 other people visualizing, on a conventional display, computationally rendered scenes. In order to reduce the bias linked to the viewpoint, a vantage point was predefined and was identical for the assessment in the actual environment and those using the renderings. Participants were asked to rate each lighting situations using ten rating scales covering the following categories: psychological impression, perceptual clarity, spaciousness, light distribution, complexity, formality, thermal, acoustic, and haptic associations. According to the authors, the high level of correlation between the actual environment ratings and the image ratings suggested that the use of renderings is reliable for the tested dimensions. However, the Kolmogorov–Smirnov non-parametric test highlighted significant differences between some of the tested actual scenes and their virtual reproduction. The differences were observed for the following scales (related dimension is indicated in parentheses): dim/bright (perceptual clarity), non-uniform/uniform (light distribution), boring/interesting (psychological impression), private/public (formality), small/large (spaciousness), unpleasant/pleasant (psychological impression). Only the following scales did not present significant differences: simple/complex (spatial complexity), dull/shiny (psychological impression), cool/warm (thermal association), somber/cheerful (psychological impression).

The authors concluded that the images reproduce some aspects of the lighting environment. But they also stressed the importance of conducting further research using other semantic differentials, investigating multiple room types in terms of activity, using other samples of participants (most of their participants were architecture students), and testing the potential interest of a non-static experience.

The second study investigating the potential of virtual renderings is Charton's work (2002). Rather than working with semantic differentials for collecting perceptions as Mahdavi and Eissa did, Charton used a pairwise comparison protocol. Three phases were organized: a first experiment in mock-ups, a second experiment using photographs, and a last one using renderings. Forty people participated in each phase, but part of the group which participated in the real-world phase was recruited for the photographs phase. Forty new participants were recruited for the renderings phase. In each phase, participants were asked to determine, between two lighting situations, which was the brightest, the most uniform, the most glaring, the most intimate, and the most pleasant. In the mock-up, participants could move, while for the visualization of images, they had two vantage points of the rooms. To increase their "realism", the images were presented on a 3D display.

According to Charton, the tendencies observed in the mock-ups were reproduced using the renderings. However, only the question related to brightness presented a high correlation between the actual environments and the virtual renderings. Differences in ratings between photographs and renderings were almost non-existent for questions linked to brightness, uniformity, intimacy, and glare. Charton concluded his work in suggesting the use of devices displaying a wider range of luminance and covering a broader visual range to minimize differences between the actual and virtual environments. Similarly to Mahdavi and Eissa, he also suggested experiencing the virtual environment in a more dynamic way. Last, he stressed the importance of constructing a questionnaire that is understandable and that makes sense to the observer.

So, both studies emphasized the need for further validation work and for exploring alternative dimensions or methods to collect data. They also questioned the use of static images and the choice of vantage points.

Despite the fact that little work has been done to validate their usage, virtual renderings are increasingly used for assessing visual perceptions. For instance, Oi used computationally-based renderings to study differences of perceptions of artificially lit environments between generations (Oi, 2005). Villa, in her thesis, used V-Ray renderings to investigate the self-reported suitability of various luminous atmospheres for work or perceived intimacy (Villa, 2012). Fernandez used the same type of renderings to assess the self-reported preferred luminous environments in hotel rooms, for several kinds of activities (Fernandez, 2012). In these two studies, global appreciation is assessed in a direct way: the observer himself determined his evaluation criteria. On the other hand, in the more poetic work of Lo and Steemers (2009), global appreciation is not assessed but the authors focused on how perceptions of sacredness and poetry in architecture can be influenced by the size, number and shape of the apertures. The authors used renderings realized in Radiance software but they investigated little on the relationship between photometric descriptors and perceptions. Last, rather than using images to explore the luminous atmosphere, other researchers used renderings to assess, more specifically, spatial perceptions of a room. For instance, Oberfeld studied the influence of lightness of walls on perceived room height using renderings created with the Vizard software (Oberfeld et al., 2010), and Tai and Inanici assessed the influence of luminance contrast on depth perception with Radiance renderings (Tai and Inanici, 2010).

I.B.2.3 NEW TECHNOLOGIES FOR IMPROVING REALISM OF IMAGES

Although the field of exploration offered by images is narrower than that offered by scale models, the area of investigation of the researches cited above is varied and emphasizes the fact that validation work should be pursued to evaluate the extent to which images can be used as a psychological substitute for the real world in studies on the appearance of lighting and space.

Moreover, the image, whether photographic or computationally-based, can be presented in various ways. Indeed, images can be static or dynamic, such as in the case of movies which appeared at the end of the 19th century. They can be presented in various sizes. And can be displayed in black and white or, since the Fifties, in colors.

Besides, recent advances in high dynamic range (HDR) imaging technology make it possible to further increase physical realism, in displaying ranges of luminance similar to those encountered in the real world. In parallel to advances in HDR imaging, other imaging and display technologies are continuously developed to consistently improve virtual reality providing images increasingly immersive such as 3D and panoramic pictures (see Fig.I.B.4). Regrettably, while imaging technologies have been strongly developed, little validation work has been done.

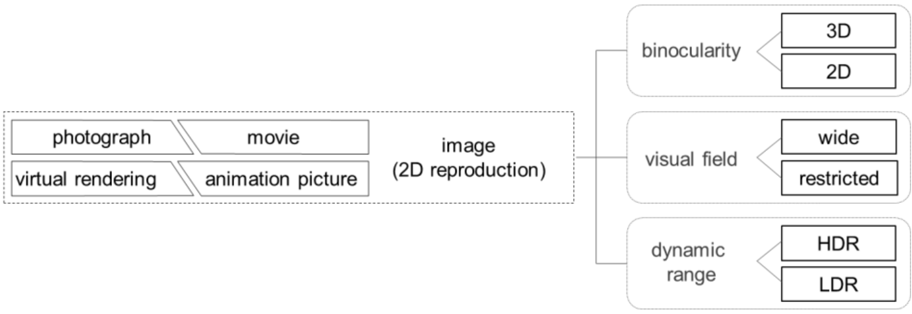


FIGURE I.B.4
Various technologies are developped for increasing the "realism" of the images

The following sections point out some technologies which could present an interest for studying the appearance of lighting and space as they have been developed to better approach three particular characteristics of human vision: the human binocular vision, the field of view and the visible range of luminances. Works validating their use for lighting purposes are also presented.

I.B.2.3.1 TECHNOLOGIES MIMICKING BINOCULAR VISION

There are various ways to create the illusion of depth. Many artists have explored this area in developing linear perspective, treatment of shadows or atmospheric perspective, such as for instance the *sfumato*[1] technique in the Renaissance. But depth is also perceived as a result of cues such as interposition of objects or size constancy.

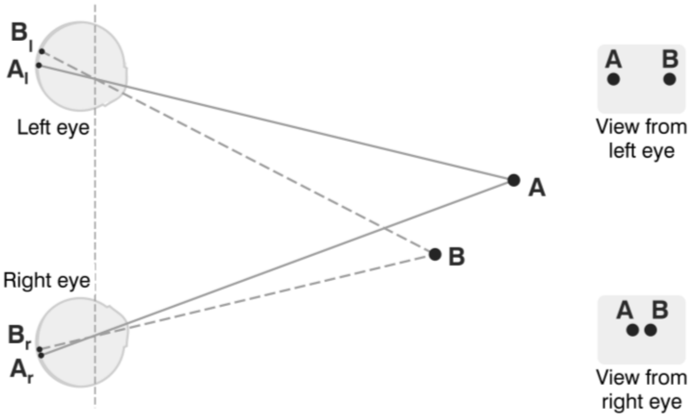


FIGURE I.B.5
Principle of binocular vision

[1] *Sfumato* literally means "gone up in smoke".

Stereoscopy, also called 3D imaging and developed in the twenties, make it possible to increase illusion of depth in creating the third dimension on a two-dimensional medium. This method is based on the fact that human beings have binocular vision and each eye does not receive identical information. Indeed, two slightly different images are formed on the eyes' retinas, and these differences participate in the appreciation of depth and the assessment of distances (see Fig.I.B.5).

The principle of stereoscopy is based on binocular vision: a first image is delivered to the left eye and another one, slightly different, to the right eye. Disparities (differences) between the two images create the illusion of depth.

Currently, various methods of 3D visualization exist, as illustrated in Fig.I.B.6: stereoscope, 3D projection system (active or passive), 3D monitors (active or passive), or more immersive systems, such as 3D headsets. The principle which is common to all these technologies is to deliver a slightly different image to each eye.

FIGURE I.B.6
Three kinds of stereoscopic technologies: a) the famous View-Master, a stereoscope commercialized in the 1930s[2]; b) 3D passive projection[3]; c) 3D active monitor[4]; d) 3D headset[5]

Although some studies exploring perceptions of lit environments have been carried out using such methods of visualization, the potential of 3D technology – which is currently expanding – has not yet been tested in detail for lighting purposes.

In a preliminary study (Cauwerts and Bodart, 2011), we compared some visual perceptions experienced in actual daylit rooms with those experienced in visualizing 2D and 3D projections of photographs of the same spaces. The study demonstrated that some scenes were judged to be more realistic with the 3D projection than with the 2D projection. However, this perception of realism did not influence subjective ratings for lighting: differences between 2D and 3D projections were not significant.

I.B.2.3.2 TECHNOLOGIES INCREASING THE COVERED FIELD OF VIEW

The human visual field covers a horizontal field of view (FOV) of about 180°, while the vertical FOV is about 140°. A large part of the visual information captured

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2 http://lacourderecre.files.wordpress.com/2011/09/visionneuse-view-master.jpg
3 http://www.pixelution.co.uk/wp-content/uploads/mini3dprojector-300x260.jpg
4 http://cdn.idealo.com/folder/Product/2908/7/2908707/s4_produktbild_gross/asus-vg278h.png
5 http://gadgets.sysblog.info/images/2011/12/2011_12_22_smartgoogles.jpg

by the observer in the actual world is also the result of his ability to move his eye, his head, and his body.

A traditional picture (realized using a 50 mm "normal" focal length lens) covers a much smaller area than the one covered by our two eyes, as illustrated in Fig.I.B.7. However, these traditional pictures largely cover the ergorama, responsible for the distinction of forms.

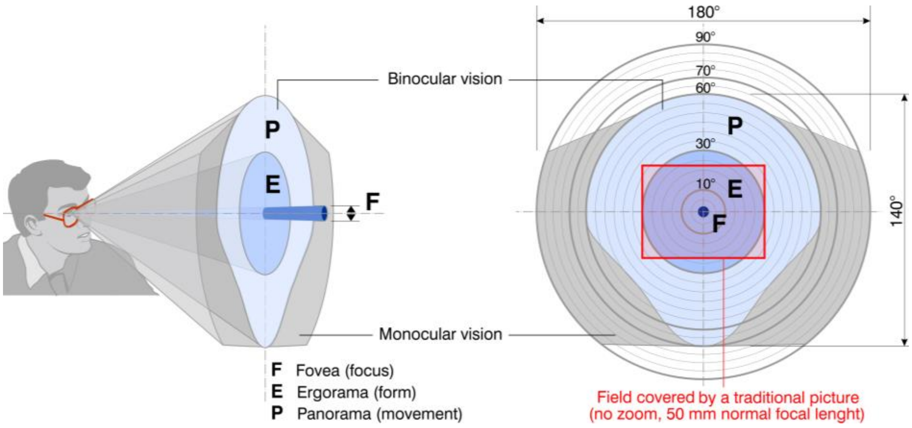

FIGURE I.B.7
Human field of view

To offer images covering a wider part of the environment than traditional photographs do, acquisition techniques, image formats, and display devices such as panoramic displays (see Fig.I.B.8) are continuously developed. In a work aiming at exploring the relationship between features and perception of the environment, Franz et al. (2005) used a spherical display to improve participants' immersion in the virtual environment. They did not mention any study having demonstrated that such a display better reproduces the perceptions experienced in the actual environment.

FIGURE I.B.8
Three kinds of panoramic displays: a) curved display[6] b) spherical display[7] c) cubic room[8]

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6 http://images.gizmag.com/hero/hhi_time_panoramic_screen.jpg
7 http://truthpluslies.com/wp-content/plugins/imgsize/resize/600/wp-content/photos/visionstation.jpg&sg=1
8 http://www2.cnrs.fr/sites/journal/image/2007n01048hd.jpg

QuickTime Virtual Reality (QTVR) panoramic images also respond to the need to cover a wider part of the environment. This kind of image format allows the visualization of panoramic images that cover up to 360° without distorting it, contrary to a fisheye picture (see Fig.I.B.1).

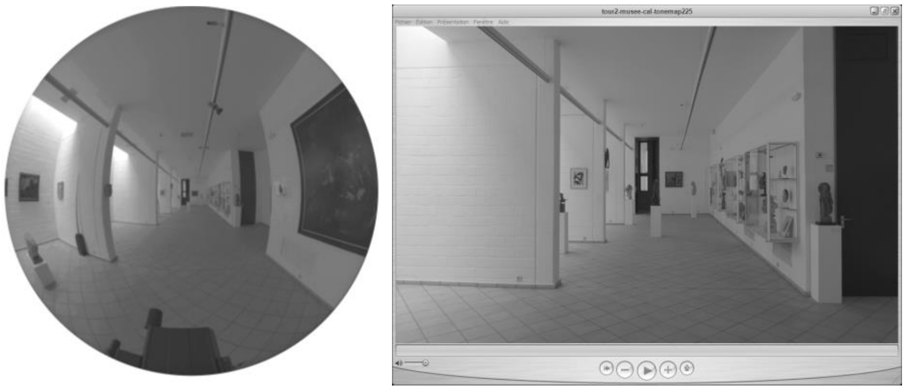


FIGURE I.B.9
Distorted and undistorted panorama: a) fisheye picture; b) QTVR panorama

Moreover, in QTVR panorama, contrary to a movie, the vantage point is fixed, but the observer can explore the environment by virtually pivoting his head and zooming on areas of interest.

Regrettably, their visualization on a 3D monitor or a HDR display needs a high level of post-processing for correcting luminance and geometrical disparities simultaneously to the exploration of the image by the observer. But their visualization on a conventional display device presents the advantage of reducing the investment in time and money, which makes these images a promising tool.

I.B.2.3.3 TECHNOLOGIES INCREASING DISPLAYED LUMINANCE RANGE

As illustrated in Fig.I.B.10, the range of luminance present in the natural world varies from 10^{-4} cd/m² (starless night sky) to 10^{10} cd/m² (lightning flash), and the human eye can detect luminance from 10^{-4} cd/m² to 10^{6} cd/m² (a brief exposure to luminance higher than 10^{6} cd/m² can cause eye damage). The range of luminance perceivable by human eye is thus quite wide in comparison to luminances displayable on a conventional monitor (from 0.5 to 100–250 cd/m²). However, simultaneously, the human eye cannot perceive so wide a range of luminance, but it can adjust its sensitivity to accommodate to a range of five orders of magnitude through a process called adaptation. This process which covers changes in pupil size, but also neural and photochemical adaptations lead to three types of vision which are function of the ambient light conditions: scotopic vision (luminances < 0.001 cd/m²), mesopic vision (luminances between 0.001 and 3 cd/m²) and photopic vision (luminances > 3 cd/m²).

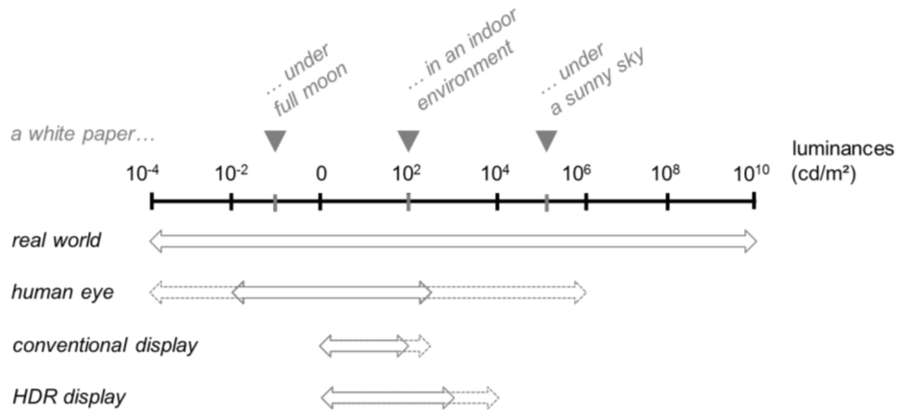


FIGURE I.B.10
Dynamic range of the visual system

Until recently, the range of luminosity captured using photographic techniques was also reduced due to encoding. But thanks to the development of high dynamic range (HDR) image encodings, it is nowadays possible, using a conventional camera, to capture the wider range of luminance existing in actual indoor and outdoor environments and so, to avoid the under-exposed or over-exposed areas often encountered in the picture when conventional photographic techniques are used.

Regrettably, conventional devices are not able to display such HDR images. To adapt the range of luminance of these pictures to the lower dynamic range of printing devices or conventional display devices, tone-mapping operators have been developed (Reinhard et al., 2006). In parallel to the development of these tone-mapping operators, HDR display devices have also been developed to accurately display these images without losing information. This new kind of displays aims at overcoming limitations of conventional devices for displaying luminances and contrasts encountered in the real world. They are able to display luminances up to 8000 cd/m² (Seetzen et al., 2004). Since 2011, a French research laboratory is working on a HDR display capable of displaying both larger pictures and higher luminances than the existing devices, with the objective of assessing risks of glare using images (Gatel, 2011).

Over the last ten years, the potential of HDR display device for assessing lighting quality have been studied at NRC's Institute for Research in Construction (Newsham et al., 2002, Newsham et al., 2010). This research team is, to our knowledge, the first to address the validation of such display devices for assessing the visual appearance of lit environments. In (Newsham et al., 2010), they tested the hypothesis that HDR images presented on HDR display are perceived as more realistic than conventional images in asking 39 participants to rate six rooms (mixing artificial lighting and daylight) using four semantic differentials (unpleasant/pleasant, dim/bright, non-uniform/uniform, glaring/not glaring). Three presentation modes (real world, conventional display, HDR display) were tested. From this experiment, the authors concluded that HDR images displayed on a HDR device are not worse than conventional images for studying perceived space appearance. They also observed that this type of image is better than conventional images for scenes presenting large areas of high luminances (luminances superior to 2000 cd/m²).

Regrettably, while HDR monitors seem promising for studying daylit scenes as they often present high luminances, few of them are commercialized and no display combining HDR imaging and 3D technology currently exists, to our knowledge.

I.B.3. CONCLUSIONS

As presented in this chapter, actual lit environments can be reproduced in various ways (see Fig.I.B.11). While mock-ups minimize the loss of information content available in the real-world and make possible a wider field of exploration, virtual renderings, and more particularly computationally-based renderings, offer some non-negligible advantages. Indeed, they make possible the minimization of costs, a better control of the investigated variables, and the reduction of some biases encountered in the real world whose the biases linked to the uncontrollable variation of daylight. These advantages make virtual renderings a clearly promising tool to assess the visual appearance of lit environments, both in an architectural process and in a lighting research context.

First investigations of photographs and virtual renderings carried out by Hendrick et al. (1977), Mahdavi and Eissa (2002) and Charton (2002) indicated that, using semantic differentials, images are promising for studying influence of light on human impressions. Since these investigations, as pointed out in this chapter, lots of technologies of images have been developed to better approach three particular characteristics of human vision: the human binocular vision, the field of view and the visible range of luminances. Currently, as illustrated in Fig.I.B.11, images can be presented in various ways. They can be displayed on a conventional LDR monitor, or on a HDR one. They can cover a restricted field of view (traditional picture) or a wider one. And finally, they can be visualized in 2D or in 3D.

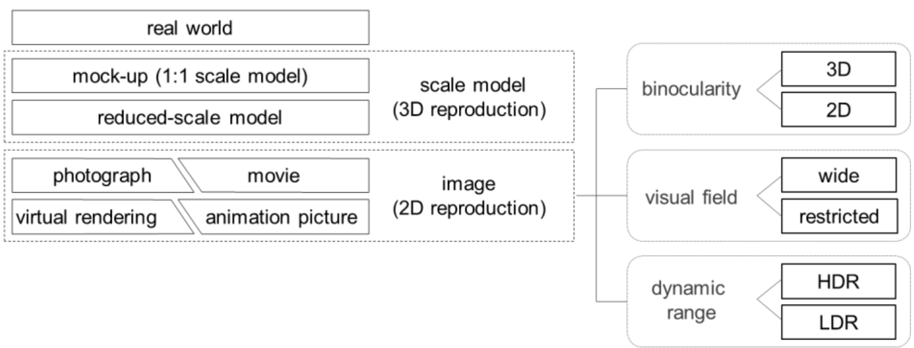


FIGURE I.B. 11
Representations of the real world and presentation modes of images

Regrettably, as raised in the present chapter and detailed in Table I.B.1, combining these technologies is not always possible because of display limitations. In addition, some cumbersome post-processing also questioned the interest of some combinations.

TABLE I.B.1
Feasibility of combining the various technologies

Combination	Variable #1: Binocularity	Variable #2: Visual field	Variable #3: Dynamic range	Feasibility
1	2D	Restricted	LDR	✓
2	2D	Restricted	HDR	✓
3	2D	Wide	LDR	✓
4	2D	Wide	HDR	*
5	3D	Restricted	LDR	✓
6	3D	Restricted	HDR	**
7	3D	Wide	LDR	***
8	3D	Wide	HDR	**

* panoramic HDR displays do not exist currently and combining HDR technologies and QTVR format is technically cumbersome due to luminance disparities

** displays combining 3D and HDR technologies do not exist currently

*** panoramic 3D displays do not exist currently and combining 3D technologies and QTVR format is technically cumbersome due to geometrical disparities

Moreover, some technologies presented in this chapter are very expensive for acquisition by the architect (for instance, the 3D headset). And, among the solutions for increasing the covered field of view, only the QTVR panoramas present a good price-quality ratio. Among the 3D solutions, active LCD monitors present a reduced price-quality ratio and are suitable when the number of spectators is inferior to three (Michel, 2011). Last, the few HDR displays currently commercialized are very expensive.

PART II

OBJECTIVES AND EXPERIMENTAL DESIGN

The first chapter below describes the specific objectives of the thesis. The second chapter is dedicated to the choice of an experimental design to respond to these objectives.

CHAPTER II.A
OBJECTIVES

Images are particularly popular in the architectural process to judge the aesthetic qualities and the appropriateness of designed spaces, and also to communicate with clients. Due to their numerous advantages in comparison to other media, they are also increasingly used in lighting quality research for assessing visual perceptions. However, little work has been done to validate their use.

The present PhD work aimed at determining to what extent these images (photographs and virtual renderings) can be used for assessing the perceived appearance of lighting and space in indoor daylit environments. It also investigated the influence of the presentation mode of these images on the observer's perceptions.

In consequence, the study raised the question of the measure of perceptions and, more particularly, the measure of perceived visual appearance of indoor lit environments. In Chapter I.A, we summarized common methods encountered in the literature for assessing this kind of perceptions. We also determined the dimensions characterizing a lit space affected by lighting. It appeared from this chapter that among the eight dimensions identified by Küller (1991) for characterizing the visual appearance of a built environment (pleasantness, complexity, unity, enclosedness, potency, social status, affection and originality), two are influenced by the lighting: the pleasantness and the enclosedness. Besides, lighting can also be characterized by a series of dimensions: brightness, distribution of light, coloration, directivity and glare. This chapter also highlighted that the most commonly used technique for collecting perceptions in the field of lighting is the semantic differentials.

Following this state of the art, it seemed interesting to us to not only test the hypothesis that the dimensions characterizing the lighting are perceived similarly when visualizing images than in the actual environments but also to study the two dimensions characterizing a built environment influenced by the lighting – the pleasantness and the enclosedness – which are two dimensions of great interest for architects. We chose to focus on the purely perceptual response, even if as pointed out by Vogels (2008) more than producing a purely visual response, a luminous atmosphere gives rise to an emotional response. This emotional response could be investigated in additional research. Last, semantic differentials were used for measuring perceptions. But a series of non-conventional questions based on blank sketches were also developed to link objectives maps (luminance-based maps) with subjective maps (participant sketches). Last, in response to Danford and Willems' observations, some mean to check potential procedure or instrument bias was included in the experimental protocol. This is an uncommon practice in subjective lighting quality research.

Chapter I.B reviewed the more often used media to study human impressions, in the field of lighting. The non-negligible advantages of images, and more particularly of virtual renderings, were pointed out: this type of medium allows the reduction of the cost, an easy control of the investigated parameters influencing the luminous ambience, and the control of the variations of daylighting encountered in actual environments.This chapter also highlighted the fact that images can be presented in several ways thanks to various imaging technologies developed in the last twenty years to better approach some characteristics of the human vision (the human binocular vision, the field of view and the visible range of luminance). The advantages of 3D, panoramic and HDR technologies for studying daylit environments were emphasized.

Given this review, it seemed to us interesting to pursue the validation of photographs. To avoid under and over-exposed areas in the pictures, HDR imaging techniques were used when capturing the scenes. Tone-mapping operators were then applied to the picture for adapting the image to the display device. It seemed also interesting to us to investigate the potential of Radiance virtual renderings which offer the opportunity to link human visual perceptions to physical stimuli (Radiance software is a validated physically-based software widely used and acknowledged in lighting simulation context).

As explained in Chapter I.B, various imaging and display technologies were recently developed for improving the realism of images. Three presentation modes have particularly caught our attention. First, among the technologies mimicking binocular vision, the active 3D displays are an interesting technology financially affordable for the architects. Secondly, among the technologies increasing the covered visual field of view, QuickTime Virtual Reality (QTVR) panoramas appeared also to be a promising technology. Indeed, this type of image covers a wider field of view than traditional picture (without introducing distortion) and introduces a certain dynamic in the visualization as the observer can virtually turn his head to discover the environment. Contrary to movies, which can also cover a wide field, this type of images does not require lots of post-processing. Moreover, contrary to immersive rooms, QTVR images do not require high-tech monitors as they can be displayed on conventional displays. Thirdly, over the last decade, a few laboratories throughout the world developed HDR devices that could display higher luminances than conventional monitors. According to the study carried out by Newsham et al. (2010), this type of monitor could be a valuable tool for subjective lighting quality evaluation when the assessed scenes present some large areas of high luminances such as daylit scenes do. If, as expected by Veitch (2009), industry pursues the development of HDR display devices, this technology could become an interesting tool to assist the designer in his architectural process, and could help the creation of high quality daylit spaces. Regrettably, as explained in Chapter I.B, these three presentation modes (active 3D display, QTVR panoramas and HDR display) cannot be combined. They were thus be studied separately to determine whether they are benefit for studying the appearance of lighting and space in comparison to traditional 2D images presented on a conventional low dynamic range (LDR) display.

To summarize, the main objectives of this thesis were as follows:

- **determining to what extent some presentation modes of images replicate the perceptions of the appearance of lighting and space measured in actual daylit environments – four modes were tested:**
    - **2D pictures displayed on a conventional low dynamic range (LDR) monitor – a complementary objective was to determine whether the other modes of presentation tested better reproduce the visual perceptions experienced in the actual environment than this traditional mode of presentation**
    - **3D displays that could help study the perception of depth and the rendering of the textures (interplay between light and material)**
    - **QTVR panoramic pictures that could favor immersion in the image by increasing the visual field covered by the picture without deforming it, and by offering the opportunity to turn the head virtually**
    - **high dynamic range (HDR) displays that could aid in the study on the perception of glare**
- **determining whether virtual rendering is an image type that can be used as a surrogate for the real world to study the perceptions of the appearance of lighting and space (Radiance software was used to create the virtual renderings)**

CHAPTER II.B
EXPERIMENTAL DESIGN

The first objective of the present study was thus to determine to what extent various presentation modes of images can be used as a surrogate for the real world when studying visual perceptions of lighting and space.

As explained in Chapter I.B, 3D, panoramic and HDR technologies cannot always be combined due to display limitations or cumbersome post-processing. Only four combinations are feasible. As presented in Table II.B.1, the present study tested the perceptual equivalence between actual daylit environments and these four modes of presentation in comparing visual perceptions experienced in the real world to those produced by visualizing images of the same spaces. To minimize differences with the real world, photographs were used rather than virtual renderings.

TABLE II.B.1
The first objective of the study aims at determining to what extent four presentation modes of images can be used as a surrogate for the real world when studying visual perceptions.

Medium	Type of image	Mode of presentation		
		Variable #1: Binocularity	Variable #2: Visual field	Variable #3: Dynamic range
real world (reference)	-	-	-	-
2D mode (traditional mode)	Photograph	2D	Restricted	LDR
HDR mode	Photograph	2D	Restricted	*HDR*
QTVR mode	Photograph	2D	*Wide*	LDR
3D mode	Photograph	*3D*	Restricted	LDR

Note: For each high-tech medium (HDR, QTVR and 3D), the only variable which differs with the traditional 2D mode is printed in italics.

As presented in Table II.B.1, only one variable differs between the traditional 2D mode and each other presentation mode of image (HDR mode, QTVR mode and 3D mode). More than determining whether each presentation mode of image replicates visual perceptions experienced in the real world, we aimed at determining whether the high-tech presentation modes (HDR mode, QTVR mode and 3D mode) are benefit in comparison to the traditional 2D mode.

Our second objective aimed at determining whether virtual renderings replicate visual perceptions experienced in actual daylit environments.

As illustrated in Table II.B.2, actual daylit environments, QTVR photographs and QTVR virtual renderings were compared.

The use of photographs sought to determine whether differences between virtual renderings and real world are due to the switch to images or to the virtualization of the images.

TABLE II.B.2
The second objective of the study aims at determining to what extent virtual renderings can be used as a surrogate for the real world when studying visual perceptions.

Medium	Image type	Mode of presentation		
		Variable #1: Binocularity	Variable #2: Visual field	Variable #3: Dynamic range
real world (reference)	-	-	-	-
QTVR mode	Photograph	2D	Wide	LDR
SIMU mode	*Virtual rendering*	2D	Wide	LDR

Note: The only variable which differs between SIMU mode and QTVR mode is the image type. It is printed in italics.

As presented in Table II.B.2, only the image type variable differs between QTVR mode and SIMU mode.

II.B.1. REPEATED-MEASURE DESIGN OR BETWEEN-GROUP DESIGN

In the present study, the effect of the image type and the influence of the presentation mode of these images on the way participants rated the visual appearance of various daylit rooms was of primary interest. Five media were tested (2D mode, QTVR mode, 3D mode, HDR mode and SIMU mode) and compared to actual daylit environments (real world).

Two designs were envisaged: a repeated-measure design, as implemented by Newsham et al. (2010), and a between-group design, as implemented by Danford and Willems (1975) and by Mahdavi and Eissa (2002). As illustrated in Fig.II.B.1, repeated-measure designs require the same subjects in every condition of the experiment while between-group designs build separate samples of subjects for each treatment condition.

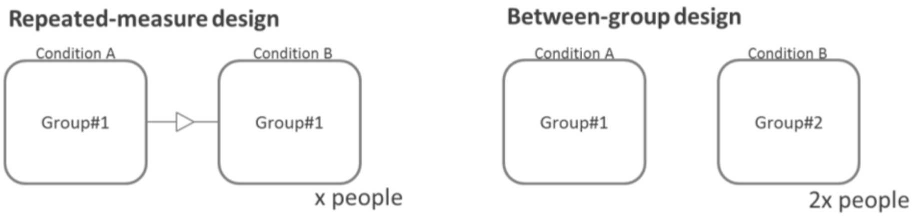


FIGURE II.B.1
Envisaged experimental design a) Repeated-measure design b) Between-group design

Each of these designs presents some advantages and disadvantages.

The main interest of repeated-measure design is the control of inter-individual variations. Indeed, as all the subjects participate in each condition, the differences between the conditions cannot be due to inter-individual differences. The other main advantage of this type of design is the reduced requested number of participants. But this kind of design also presents some disadvantages: as each participant takes part in each condition, he often guesses the objective of the study. This is a problem due to the social desirability bias: most people try to do what they think the experimenter expects. Repeated-measure designs also introduce order effects, but this bias can be easily reduced in counterbalancing the conditions as illustrated in Fig.II.B.2.

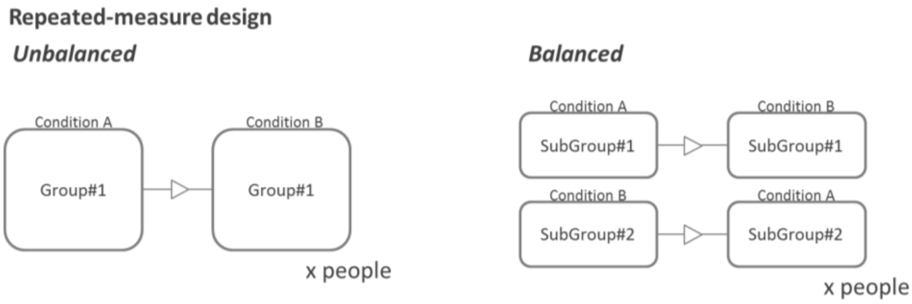


FIGURE II.B.2
To reduce the order bias encountered in repeated-measure designs, the conditions can be balanced: half the participants visualize first Condition A while the other participants visualize first Condition B.

While the risk that participants get bored or tired is high in repeated-measure designs, this fatigue effect is reduced in between-group designs as each subject participates in only one condition. Moreover, participants have more difficulty guessing the purpose of the study. The major disadvantage of this design comes from the lack of control of inter-individual differences.

As summarized in Table II.B.3, the disadvantages of a design correspond often to the advantages of the other design.

TABLE II.B.3
Advantages and disadvantages of two possible experimental designs

	Advantages	Disadvantages
Balanced repeated-measure design	Control of inter-individual differences Small sample size	Fatigue effect Social desirability bias
Between-group design	No fatigue effect No social desirability bias	No control of inter-individual differences Large sample size

We decided to work a between-group design for three reasons.

The first reason is the uncontrollable variability of daylighting encountered in the actual environments. Indeed, this uncontrollable variation is the main difficulty when organizing an experiment in real world. One validation study we identified was organized in such environments: the investigation of HDR display for lighting purpose carried out by Newsham et al. (2010). In this study, a balanced repeated-measure design was implemented. As the images required a lot of post-processing, the authors took the pictures some weeks before the visits of the actual rooms by the subjects. In our experiment, we aimed at minimizing differences between the luminous conditions experienced by people in the actual rooms and the conditions in the rooms when pictures were taken. One way to do that was to take pictures the day of the experiment in the actual environments. But that required realizing the experiment in the actual environments first, which made it impossible to balance the conditions not to introduce an order bias.

The second reason for choosing a between group design is the large number of modes of presentation tested in the present work: actual environments, 2D images, QTVR pictures, HDR display, 3D images, physically-based renderings. Due to this high number of conditions – six media – the fatigue effect would not be negligible if a repeated-measure design was implemented.

Last, the third reason for choosing a between group design is that we do not have an HDR display in our laboratory. And, given that this design does not require the same subjects for each treatment condition, HDR mode experiment can be organized in a French laboratory which is currently developing such a display.

Additional advantage of this between-group design is the opportunity to pursue the investigation on other media in the future (for instance, to study the influence of being an architect, or the influence of the number of gradation of the rating scales).

II.B.2. INTRODUCING A CONTROL GROUP

Based on Danford and Willems' work (1975), a control group was added in the design to check that participants' responses were not constrained by the measuring instrument. This group of participants was invited to respond to the developed questionnaire on the basis of blank sketches and without visiting the real-world spaces or visualizing pictures.

TABLE II.B.4
The validation of the real world experiment is a first preliminary step

Name	Type of image	Mode of presentation		
		Variable #1: Binocularity	Variable #2: Visual field	Variable #3: Dynamic range
real world (reference)	-	-	-	-
control	Blank sketches	-	-	-

Control group responses were compared to responses of the real-world group of participants to determine whether the luminous stimuli really influenced the responses (see Table II.B.4).

II.B.3. SAMPLE OF SUBJECTS

Based on Flynn et al.'s recommendations (Flynn et al., 1979) and common practice in subjective lighting evaluations (Charton, 2002, Newsham et al., 2010), a group of 40 people was recruited for each tested medium. These distinct groups of participants presented similar characteristics in terms of educational background, gender, and age because of potential influences of these characteristics on perceptions as discussed in (Baron et al., 1992, Knez, 1995, Oi, 2005).

II.B.3.1. POTENTIAL INFLUENCE OF NATIONALITY

While sharing a same language (French), the recruited participants did not share a same nationality as part of the experiment was organized in France and another part in Belgium. To evaluate whether differences in perception of the two samples of subjects were significant, an experiment organized in Belgium (3Db mode) was reproduced in France (see Table II.B.5).

TABLE II.B.5
Assessing the influence of the nationality of the participants is the second preliminary step

Name	Type of image	Mode of presentation			Nationality
		Variable #1: Binocularity	Variable #2: Visual field	Variable #3: Dynamic range	
3Db mode	Photograph	3D	Restricted	LDR	Belgian
3Df mode	Photograph	3D	Restricted	LDR	*French*

Note: The only variable which differs between 3Db and 3Df mode is the nationality (printed in italics).

As presented in Table II.B.5, only the nationality variable differs between these two experiments.

II.B.3.2. THE USE OF STUDENTS IN PSYCHOLOGICAL RESEARCHES

To find the 320 participants required (8 groups of 40 people), university students aged between 18 and 25 years were recruited. Students in architecture were excluded from the recruitment because differences in perceptions and preferences exist between the architects and the non-architects, as emphasized in the Devlin and Nasar's work cited by Walsh et al. (2000).

Students are often recruited for psychological research, mainly for their accessibility and availability. But, their use is controversial because, while their homogeneity makes possible a better control of the noise, their profile (unfinished personalities, higher cognitive abilities…) could introduce biases (Butori and Parguel, 2010). In consumer research, as highlighted by Peterson (2001), the generalization of the results to a non-student population is questioned. In lighting quality research, on the other hand, Lau (1972) observed some proofs that subjective lighting assessment does not differ significantly between students and housewives aged between 22 and 36 years.

II.B.4. VISUAL STIMULI

Four spaces were chosen among the university buildings in Louvain-la-Neuve (see Fig.II.B.3). These four daylit rooms were located in three distinct buildings. They were chosen for several reasons.

First, these four rooms shared the same function: they were all corridors. Corridors were chosen for the aesthetic dimension. Moreover, corridors present the advantage that participants, during the experiment, feel as much as possible in a real context of use which satisfies the contextualization stressed by Fernandez (2012).

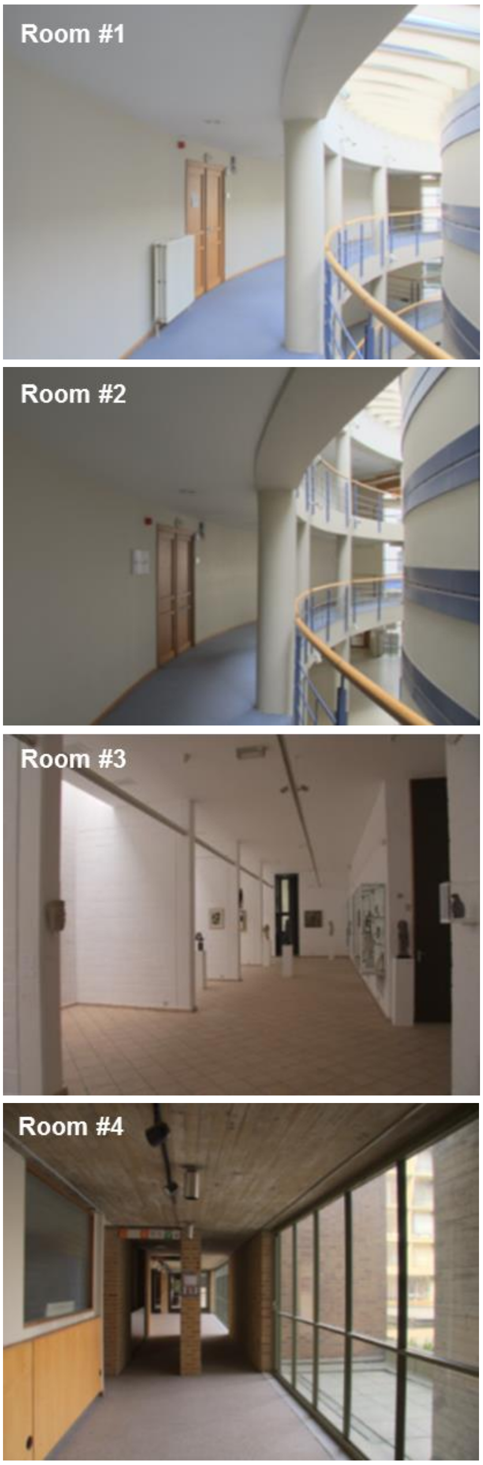


FIGURE II.B.3
The four rated rooms

The four rooms were also selected to maximize visual appearance differences. Last, particular attention was paid to some practical reasons like accessibility, cleanliness, and calm during the visit.

II.B.5. MEASURING INSTRUMENT

The questionnaire developed for this study deals with the visual appearance of lighting and space. As described in the following sections, two kinds of questions were developed in this research: conventional questions (rating scales and multiple choice questions) and non-conventional questions (based on blank sketches). Original questions were in French, but for publication purposes, they have been translated into English. An original questionnaire is presented in Appendix II.

II.B.5.1. CONVENTIONAL QUESTIONS: RATING SCALES

II.B.5.1.1. *VISUAL APPEARANCE OF SPACE*

As presented in Chapter I.A, eight dimensions characterize the visual appearance of a built environment: pleasantness, complexity, unity, enclosedness, potency, social status, affection, and originality (Küller, 1991). And two of these dimensions are mainly affected by the lighting: the pleasantness and the enclosedness (Flynn et al., 1973, Bülow-Hübe, 1995). Only these two dimensions were assessed in our study, using Küller's SMB scales.

The pleasantness dimension, as in the SMB form detailed in Chapter I.A, consists of the following items: ugly*[1], stimulating, secure, boring*, idyllic, good, pleasant, and brutal*. The enclosedness adjectives are close, open*, demarcated, and airy* (see Table II.B.6).

TABLE II.B.6
The visual appearance of the space was assessed through two Küller's dimensions

Environmental factor	Ref.		Question	Rating scale
Pleasantness	P0	P0.1	The corridor is ugly: slightly – very	1-6
		P0.2	The corridor is stimulating: slightly – very	1-6
		P0.3	The corridor is secure: slightly – very	1-6
		P0.4	The corridor is boring: slightly – very	1-6
		P0.5	The corridor is idyllic: slightly – very	1-6
		P0.6	The corridor is good: slightly – very	1-6
		P0.7	The corridor is pleasant: slightly – very	1-6
		P0.8	The corridor is brutal: slightly – very	1-6
Enclosedness	E0	E0.1	The corridor is closed: slightly – very	1-6
		E0.2	The corridor is open: slightly – very	1-6
		E0.3	The corridor is demarcated: slightly – very	1-6
		E0.4	The corridor is airy: slightly – very	1-6

[1] The asterisk (*) indicates that the score of the item is reversed.

For each dimension, the scores of the different items are added to obtain a single score for the factor. As recommended by Fotios and Houser (2009), to reduce the potential contraction bias encountered with scales presenting an obvious center, six-grade scales were used instead of the commonly used seven-grade scales planned by Küller for the SMB form.

Last, the French questionnaire presented in Appendix II is inspired from the French translation proposed by Küller (1991) but some terms were modified for matters of understandability.

To focus on the pleasantness of lighting and the impact of lighting on spaciousness, we complemented the form with additional questions (see Table II.B.7) linked to the visual appearance of the space, a field of great interest for architects and researchers, as illustrated by Tai and Inanici's study (2010) or Matusiak's work (2006).

TABLE II.B.7
Additional questions on the appearance of the space

Environmental factor	Ref.	Question	Rating scale
Pleasantness	P1	Light in the corridor is: pleasant – unpleasant	1–6
Enclosedness	E1	The corridor is spacious : slightly – very	1–6
	E2	The corridor is narrow : slightly – very	1–6
	E3	The corridor is deep : slightly – very	1–6
	E4	The corridor is tall : slightly – very	1–6

II.B.5.1.2. *VISUAL APPEARANCE OF LIGHTING*

Questions developed to assess the visual appearance of lighting were adapted from Bülow-Hübe's work (1995). They were developed around the following dimensions characterizing the lighting: perceived brightness, coloration, distribution of light, directivity of light, glare, and contrast. Contrast, which does not appear as a dimension in the work by Liljefors and Ejhed as cited by Bülow-Hübe (1995), was added for its potential ability to synthetize distribution, directivity and glare dimensions.

Table II.B.8 presents the bipolar rating scales composing the lighting questionnaire, grouped by lighting dimensions.

Contrary to the questionnaire developed by Bülow-Hübe, our lighting questionnaire does not focus on a particular dimension as the objective of the work is to determine whether some modes of presentation are better appropriated to study some lighting dimensions.

Two types of judgments are assessed: descriptive judgments, on six-point rating scales, and judgments of appreciation, on five-point rating scales. Scales of appreciation were reduced to five grades to offer the opportunity to the participant to have no opinion.

TABLE II.B.8
Lighting questionnaire

Lighting dimension	Ref.	Question	Rating scale
Brightness	D11	Corridor is dim – bright	1–6
	D12	You are in the dark – in the light	1–6
	A11	You would prefer the corridor to be more bright – less bright	1–5
Coloration	D21	Corridor is neutral – colorful	1–6
	D22	Corridor is visually cold – warm	1–6
	D23	Light is neutral – colorful	1–6
	A21	You would prefer the corridor to be more colorful – less colorful	1–5
Contrast	D31	Contrast in the corridor is high – low	1–6
	A31	You would prefer the corridor presenting a contrast higher – lower	1–5
Distribution	D41	Distribution of light in the corridor is various – monotonous	1–6
Directivity	D51	Shadows are sharp – blurry	1–6
	D52	Textures are sharp – blurry	1–6
Glare	D61	Corridor is comfortable – glaring	1–6
	D62	You are disturbed by glare from the windows little – much	1–6
	D63	You are disturbed by glare from a surface little – much	1–6

Note: D : descriptive judgment
A : judgment of appreciation

II.B.5.2. CONVENTIONAL QUESTIONS: MULTIPLE CHOICE QUESTIONS

Although it presents advantages such as the quantification of the perception, the rating scales require the participants to choose a response that does not always exactly match their perceptions.

TABLE II.B.9
Multiple choice questions

Factor	Ref.	Question
Pleasantness	MCQ1a	Among the four corridors, which did you find the most pleasant?
	MCQ1b	Among the four corridors, which did you find the least pleasant?
Enclosedness	MCQ2a	Among the four corridors, which did you find the most enclosed?
	MCQ2b	Among the four corridors, which did you find the least enclosed?
	MCQ3a	Among the four corridors, which did you find the most spacious?
	MCQ3b	Among the four corridors, which did you find the least spacious?
Brightness	MCQ4a	Among the four corridors, which did you find the brightest?
	MCQ4b	Among the four corridors, which did you find the least bright?
Coloration	MCQ5a	Among the four corridors, which did you find the most colorful?
	MCQ5b	Among the four corridors, which did you find the least colorful?
Contrast	MCQ6a	Among the four corridors, which did you find presenting the highest contrast?
	MCQ6b	Among the four corridors, which did you find presenting the lowest contrast?

In order to check the consistency with the responses to the rating scales, participants were also asked at the end of the experiment to respond to a series of multiple choice questions (MCQ) (see Table II.B.9).

II.B.5.3. NON-CONVENTIONAL QUESTIONS

To complement information collected using conventional questions (rating scales and multiple choice questions), a series of questions based on blank sketches were developed.

Recently, there has been development of HDR imaging techniques and powerful physically-based renderings, making it possible to produce maps of luminances. These maps, as explained by Howlett et al. (2007), are full of interesting data for developing new metrics to quantify and qualify daylight. If the spatial dimension is conserved, these new luminance-based metrics will probably be more appreciated by the architects than current indicators based on illuminance.

Two kinds of questions based on sketches were investigated. These questions were developed to link objectives maps (luminance-based maps) with subjective maps (participant sketches). The aim of these questions was to evaluate the ability of the observer to detect some zones in his visual field as well as his ability to distinguish among surfaces of different brightness, roughness, or uniformity in a built environment (in context).

Participants were first asked to compare pairs of walls for brightness, uniformity, and roughness, on 5-point rating scales. They were also asked to classify three punctual zones of the scene, for brightness, on a continuous scale. Figure II.B.4 illustrates the pairs of walls and the punctual zones to be compared.

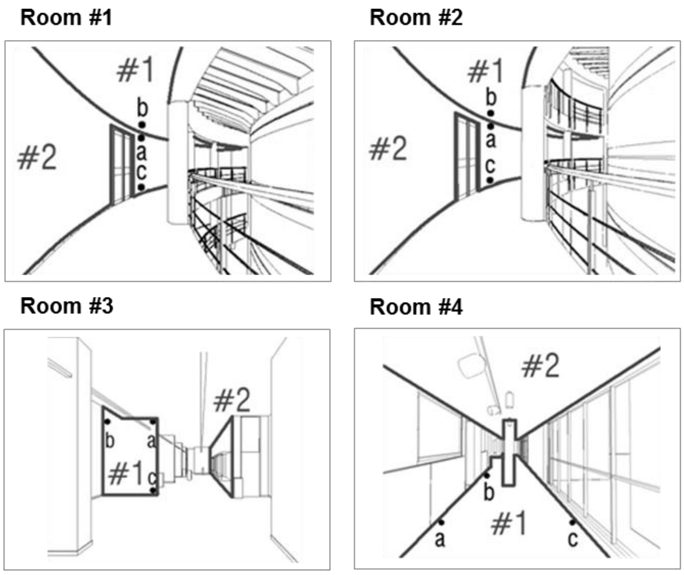


FIGURE II.B.4
Walls (#1, #2) and punctual zones (a, b, and c) to be compared

Participants were then asked to circle, on blank sketches (see Fig.II.B.5), the areas they judged attractive as well as the materials emphasized by light.

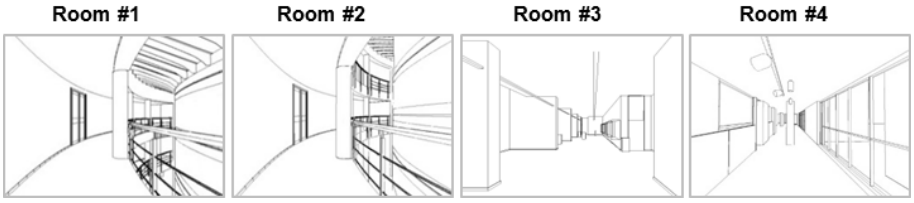


FIGURE II.B.5
Blank sketches

Finally, they were asked to color with a red pencil the brightest zones of the scene, and with a blue pencil, the dimmest areas.

II.B.5.4. COMMENTS

At the end of the questionnaire, participants were invited to make comments if they wished.

II.B.6. SUMMARY OF THE EXPERIMENTAL DESIGN

The present chapter described the experimental protocol implemented to respond to the two main objectives of the thesis.

To test the perceptual equivalence between actual daylit environments and various types of images, visual perceptions experienced in actual rooms were compared to those produced by visualizing images of the same spaces. A group of 40 people was recruited for each tested medium. Participants of each group were invited to viewed the same daylit scenes (see Section II.B.4), presented in various ways, and to fill in an identical questionnaire (see Section II.B.5).

The first preliminary step consisted in realizing the experiment in the real world and validating it in comparing responses of this group to responses of a control group (see Table II.B.10). Responses were also compared to physical measurements.

TABLE II.B.10
Overview of the experiment. Each tested medium required a new sample of 40 participants.

Medium		Image type	Presentation mode			Nationality	Prelim. Step #1	Prelim. Step #2	Obj. #1	Obj. #2
#	Name		Var. #1	Var. #2	Var. #3					
1	real world	-	-	-	-	Belgian	×		×	×
2	control	Sketches	-	-	-	Belgian	×			
3	2D mode	Photograph	2D	Restricted	LDR	French			×	
4	HDR mode	Photograph	2D	Restricted	HDR	French			×	
5	QTVR mode	Photograph	2D	Wide	LDR	Belgian			×	×
6	3Db mode	Photograph	3D	Restricted	LDR	Belgian		×	×	
7	3Df mode	Photograph	3D	Restricted	LDR	French		×	×	
8	SIMU mode	Rendering	2D	Wide	LDR	Belgian				×

Note : Var. : variable, Prelim. Step : preliminary step, Obj. : objective

The second preliminary step consisted in comparing responses of a Belgian and a French population visualizing a same type of image to evaluate whether differences in perception of these two populations are significant (3Db mode was compared to 3Df mode as presented in Table II.B.10).

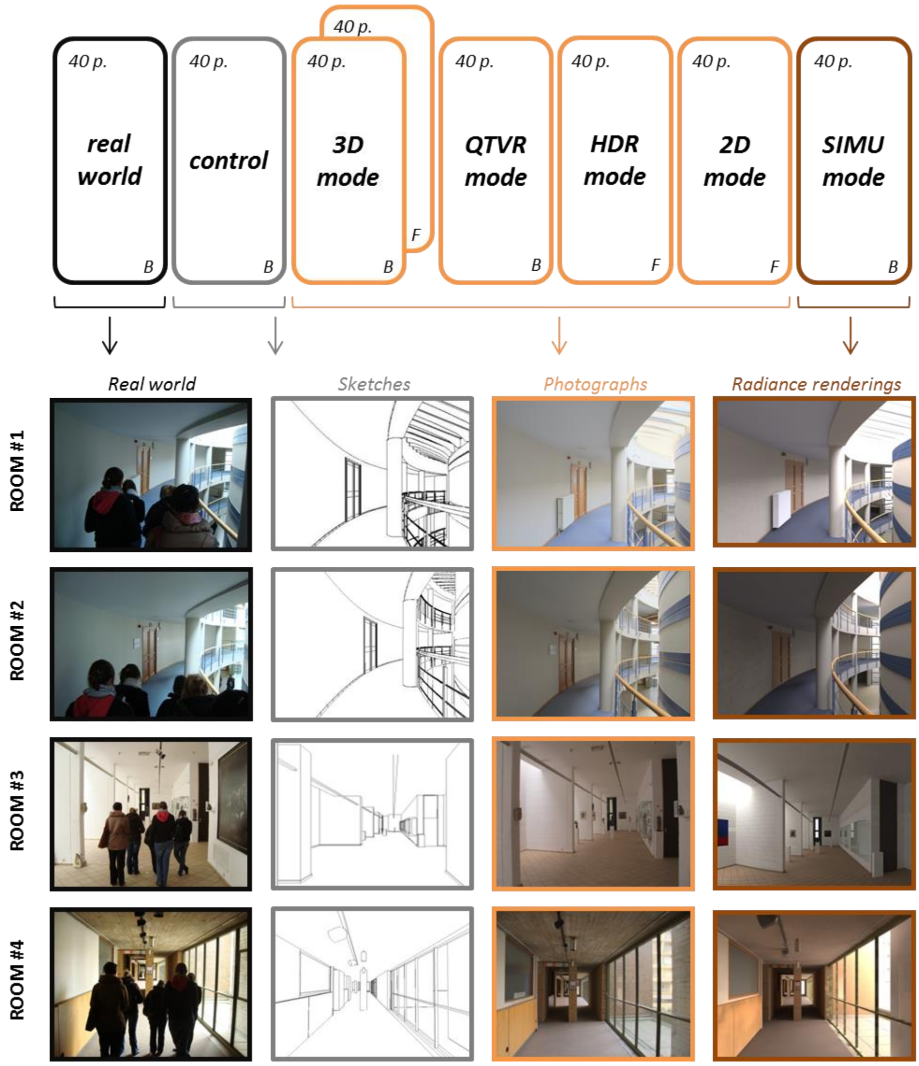


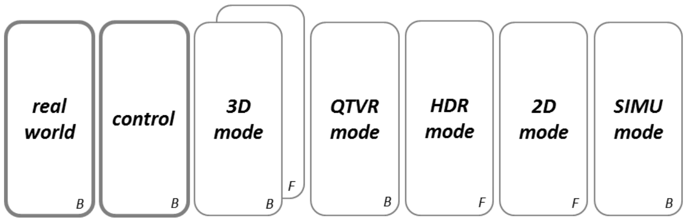
FIGURE II.B.6
To respond to the objectives of the thesis, eight groups of 40 participants (40 p.) were recruited in Belgium (B) or in France (F). They viewed four daylit corridors (Room #1, Room #2, Room #3, Room #4) and filled in a questionnaire about the appearance of lighting and space. The corridors were presented in several ways: a first group of participants visited the actual rooms while the other groups visualized their reproduction in sketches, photographs or virtual renderings.

Then, for responding to our first objective – determining to what extent some presentation modes of images replicate the visual perceptions experienced in actual environments, perceptions produced by visualizing various types of images (2D, HDR, QTVR, 3D modes) were statistically compared to the perceptions experienced by the participants in the actual environment (real world) (see Table II.B.10). Then, we analyzed results and determined whether HDR, QTVR and 3D modes are benefit for studying visual perceptions experienced in the real world in comparison to the more traditional 2D mode.

Last, to respond to our second objective – determining whether virtual rendering is an image type that can be used as a surrogate for the real world, perceptions produced by visualizing photographs and virtual renderings (QTVR and SIMU modes) were statistically compared to the perceptions experienced by the participants in the actual environment (real world) (see Table II.B.10).

Figure II.B.6 summarizes the ways the corridors were presented to each group of participants: a first group of participants visited the actual rooms while the other groups visualized their reproduction in sketches, photographs or virtual renderings. The creation of photographs is described in Chapter IV.A while the creation of Radiance virtual renderings is discussed in Chapter V.A.

PART III
ASSESSING AND VALIDATING REAL-WORLD PERCEPTIONS



As explained in the objectives of the work (see Chapter II.A), we tested the hypothesis that perceptions of the visual appearance of lighting and space experienced in actual environments are replicated when visualizing various reproductions of the spaces in images.

This part of the thesis presents the first step of our validation work: the collect of visual perceptions experienced by people visiting actual daylit rooms (Chapter III.A) as well as the validation of these measurements (Chapter III.B). The experiment in the real world was also organized with the objective to capture daylit scenes and sky conditions to reproduce the experiment using images.

CHAPTER III.A
ASSESSING VISUAL PERCEPTIONS IN THE ACTUAL LIT ENVIRONMENTS

This chapter presents the procedure implemented to collect visual perceptions experienced by subjects in actual daylit environments, which is the first step of our experiment (see Fig.III.A.1).

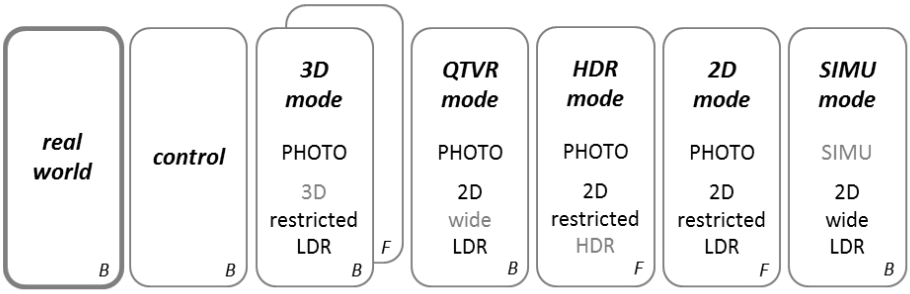


FIGURE III.A.1
The first step of the experiment consisted in collecting perceptions in the actual daylit environments (four corridors)

Some metrological qualities of the questionnaire developed to evaluate the visual appearance of lighting and space are then discussed: the sensitivity of the questions, the reliability of responses, and the responses' consistency between various types of questions.

III.A.1. MATERIAL AND METHOD

III.A.1.1. PROCEDURE

A group of forty-three participants (real-world group) visited the four daylit scenes presented in Chapter II.B and responded to the questionnaire (also presented in Chapter II.B), dealing with the appearance of lighting and space. The visit took place in Louvain-la-Neuve (Belgium) on March 9th, 2012 around solar noon to minimize daylight variations linked to the sun's position. As it was not possible to visit the room in a single and large group, participants visited the rooms in groups of five to seven. The first group of participants started the visit at 11.00 am while the last group finished at 14.20 pm. On average, the visit took 45 minutes by subgroup of participants. A unique order of visit was fixed to minimize the duration of the visit in each room and so ensure that all the participants visit the rooms under similar luminous conditions. The bias linked to the order in which the stimuli (in this case, the rooms) are presented to the participants is assumed and implied.

Before the visit to the real rooms, participants received instructions and questionnaire booklets. Unclear vocabulary was defined. As the rooms were located in several buildings, each group of participants was led from room to room by a guide. Participants were asked to walk across the corridor and stop at the level of the mark indicated on the ground. They should look straight ahead as they crossed the corridor, and they should not turn around.

In order to reduce the potential bias between the real-world experiment and its reproduction using images, pictures of the scenes were made in each room during the visit by the participants. Pictures of the sky were made simultaneously to realize Radiance renderings. Because pictures of the sky were taken outside with photographic material, it could not rain or drizzle during the experiment. Three dates were fixed for the experiment in the real world. According to the weather, the participants received a text messaging on their mobile phone the morning of the experiment notifying whether the visit would take place.

The overall procedure implemented in the real world is illustrated in Fig.III.A.2.

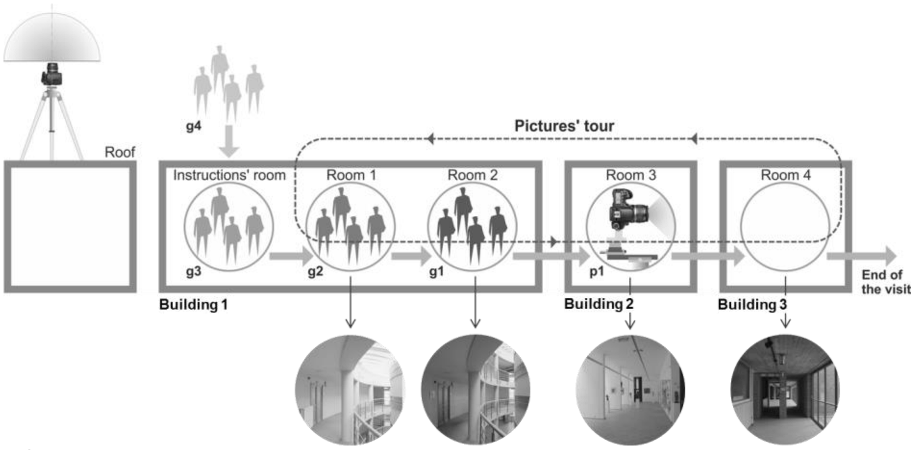


FIGURE III.A.2
Each subgroup of participants (g1…8) received instructions and visited the rooms successively. Pictures of the rooms (p1…3) and pictures of the sky were realized parallel to the visit.

As illustrated in this figure, the four assessed corridors were located in three distinct buildings. And participants went outside between Rooms #2 and #3 as well as between Rooms #3 and #4.

III.A.1.2. PARTICIPANTS

The fact that some students could be absent the day of the experiment was anticipated, and to ensure a minimum of 40 people, 60 participants (50% women, 50% men) were recruited. As expected, all the participants were not there the day of the experiment, only 43 were present (60% women, 40% men). All of them were students at the Université catholique de Louvain and were between 18 and 25 years old (mean age +/- standard deviation: 21.8 +/- 1.7). Their first language was French. They had a self-reported normal or corrected-to-normal vision. Participants were paid 25 euros for participating in this experiment.

III.A.1.3. RESPONSE INSTRUMENT

Participants were asked to respond to the questionnaire presented in Chapter II.B which consisted of an A5 printed booklet. After immersion in the room for 30 seconds, they were asked to answer without going back to the questionnaire.

III.A.2. RESULTS

Statistical tests were performed using R software (R Development Core Team, 2010). Detailed descriptive results (means and standard deviations) are presented in Appendix III. The reader is invited to consult the Appendix IV to get a better idea of the distribution of responses to the rating scales, for the real-world experiment.

III.A.2.1. SENSITIVITY OF THE RATING SCALES

The sensitivity of the rating scales (its ability to highlight differences between the rooms) was tested in performing one-way repeated measures ANOVA and multiple comparison tests.

Even though many researchers use parametric tests such as ANOVA on data collected using rating scales (Knez, 1995, Boyce and Cuttle, 1990, Bülow-Hübe, 1995), the controversy on the use of parametric tests on rating scales is still relevant. So, before realizing a statistical test, we checked that the participants considered the rating scales as continuous scales, and that parametric tests can be performed. To verify this, we used the successive interval method (Villa, 2012). ANOVA normality assumption was then checked graphically. The assumption of homogeneity of variance was checked by Levene's test ($p<0.01$). Even if ANOVA is quite robust and thus valid under moderate departures from these two assumptions, when homogeneity of variances assumption was violated, a logarithmic transformation was applied to the data. The sphericity assumption was checked using Mauchly's test, and Huynh-Feldt's correction was applied if necessary. P-values for significance were adjusted for multiple comparisons using a Bonferroni correction.

III.A.2.1.1. *VISUAL APPEARANCE OF SPACE*

As explained in Chapter II.B., visual appearance of the space was assessed using the SMB form developed by Küller (1991), but only two dimensions were addressed: the pleasantness and the enclosedness. Rather than using seven-point scales as initially planned (Küller, 1991), the number of gradations of the scales constituting these dimensions was reduced from seven to six. Moreover, the terms were translated into French. Internal consistency of these two dimensions was measured using the Cronbach's alpha coefficient. The coefficients of 0.91 for pleasantness subscales and 0.72 for enclosedness subscales indicated a high level of consistency in the two dimensions. So, despite the translation and the reduction of the number of gradations, the items still measured the same underlying construct.

Figure III.A.3 illustrates the mean ratings given by the participants of the real-world group for pleasantness and enclosedness. This figure also indicates the grouping of rooms resulting from the statistical analysis. For each dimension (pleasantness and enclosedness), rooms sharing a same color do not differ significantly.

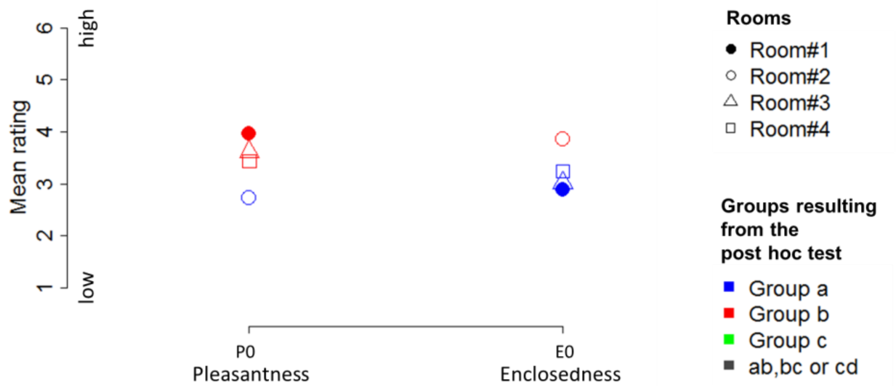


FIGURE III.A.3
Mean ratings for pleasantness (P0) and enclosedness E0). In each dimension, rooms sharing a same color do not differ significantly.

With one-way repeated-measure ANOVA, we found a significant effect of the room on the perception of pleasantness (for P0, $F(2.37,99.54)=12.01$, $p=3.98E-07$). As illustrated in Fig.III.A.3, the pairwise comparison revealed that Room #2 differs significantly from the others: it is perceived as less pleasant. Moreover, on average, Room #1 is the room perceived as the most pleasant.

A significant effect of the room on the perception of enclosedness was also observed ($F(2.67,112.14)=12.766$, $p=9.68E-07$). Again, Room #2 differs significantly from the other rooms: it is perceived as more enclosed.

As illustrated in Fig.II.B.3, Room #1 and Room #2 are very similar in terms of geometry but differ in their lighting. Fig.III.A.3 illustrates that these two rooms are perceived as significantly different in terms of pleasantness and enclosedness. From this observation, we can suppose that the lighting and the location of the apertures influence the perception of pleasantness and enclosedness.

To complement previous information, the subjects were asked more specific questions regarding the pleasantness of the lighting and the spaciousness of the room. Mean ratings to these five rating scales are presented in Fig.III.A.4.

There was a significant effect of the room on the perception of the pleasantness of the light (for P1, $F(2.4,108)= 13.755$, $p=1.21E-06$). Three groups of rooms are formed. The first room is perceived as the most pleasant regarding light, and the second is less pleasant.

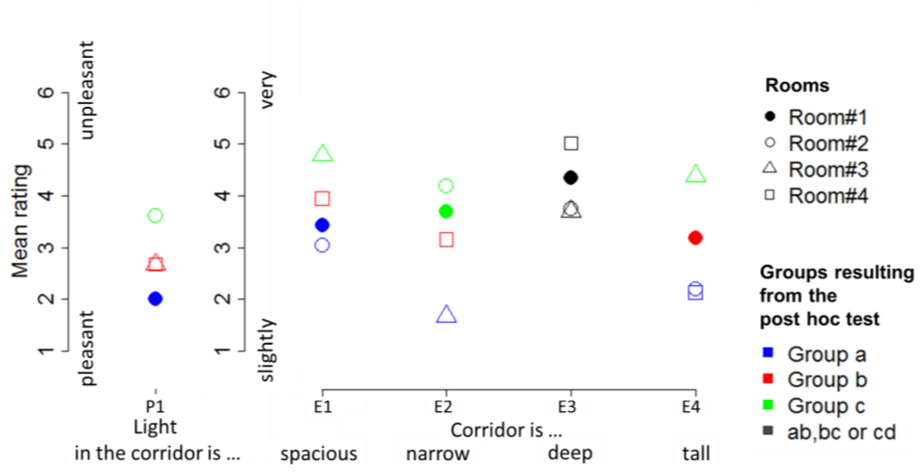


FIGURE III.A.4
Mean ratings of additional questions on the appearance of the space. For each scale, rooms sharing the same color do not differ significantly.

There was a significant effect of the room on the perception of the spaciousness (for E1: F(3,126)= 29.51, p=1.93E-14), the narrowness (for E2: F(3,126)= 69.89, p=2.20E-16), and the room height (for E4: F(2.67,112.14)= 30.87, p=1.31E-13). ANOVA was not performed on the question related to the depth of the room (E3) because the homogeneity of variances is not assumed even after a log-transformation of the data. However, the mean scores indicate that Room #2 and Room #3 are perceived as the least deep while Room #4 is perceived as the deepest. Last, participants reported the ambiguity of the slightly/very tall scale in the first two rooms due to the fact that these corridors overlook the lobby mezzanine. Confusion arose between the ceiling height and the floor height as shown in Fig.III.A.4: Rooms #1 and #2 are perceived differently while their ceiling height is similar. This question won't be addressed in the next steps of the experiment.

III.A.2.1.2. *VISUAL APPEARANCE OF LIGHTING*

As illustrated in Fig.III.A.5, which presents mean ratings and results of the multiple comparison tests for rating scales relative to the appearance of the lighting, most of the questions make the differentiation of the rooms possible. A log-transformation of the data was applied to two rating scales (D12 and D23) in order to meet the variance homogeneity assumption required for ANOVA.

According to the ANOVA results, two scales among the three related to glare (D61 and D63) do not present significant differences between rooms (p>0.05). The third rating scale related to glare (D62) indicates that the fourth room is perceived as presenting a surface a bit more glaring than the three other rooms (F(3,126)= 10.557, p=3.05E-06).

D11 (related to light level), D22 (related to coloration), and D51 (related to shadows) are the most discriminating scales: three or four groups of rooms are formed.

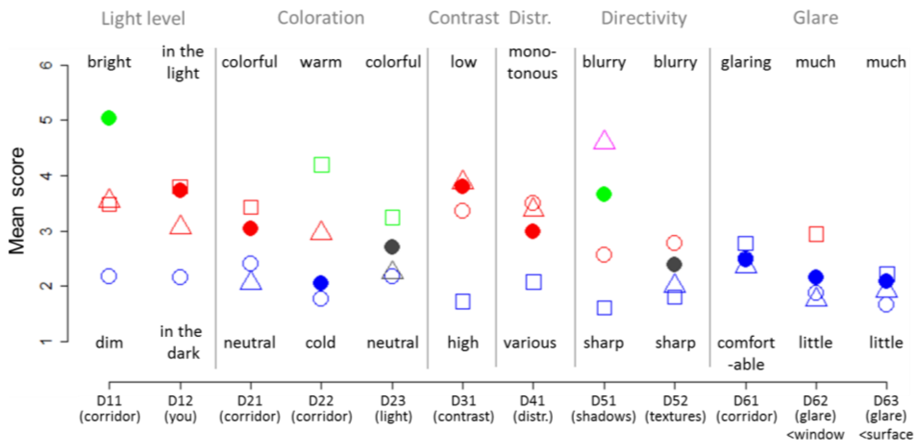


FIGURE III.A.5
Mean ratings for descriptive scales related to the appearance of the lighting. For each scale, rooms sharing a same color do not differ significantly (Rooms : ●Room #1, ○Room #2, △Room #3, □Room #4, Post hoc test: ■ Group a, ■ Group b, ■ Group c, ■ Group ab, bc or cd)

As shown in Fig.III.A.6, participants would prefer brighter and more colorful rooms. They do not have a clear preference concerning the contrast.

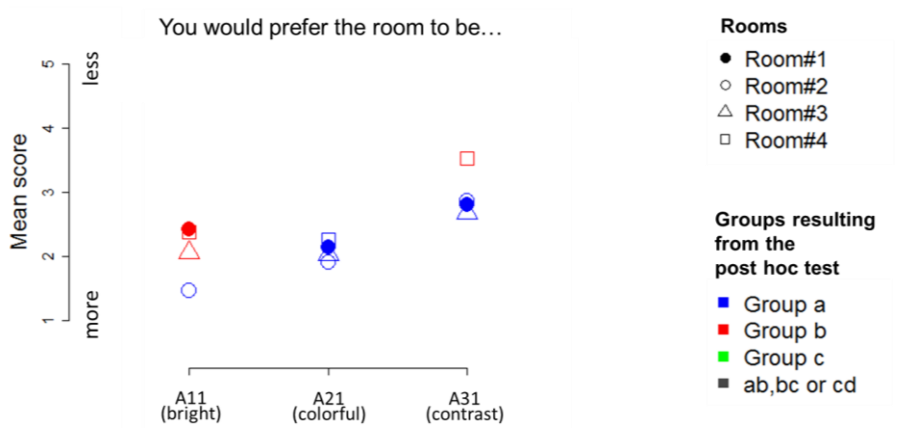


FIGURE III.A.6
Mean ratings for scales of appreciation related to the appearance of the lighting. For each scale, rooms sharing a same color do not differ significantly.

Ranges of scores are between 0.3 and 1.0 for appreciation scales while they are between 0.4 and 2.9 for the descriptive scales. The three appreciation scales are less discriminating than the descriptive ones: only one or two groups of rooms are formed. A21 does not discriminate between the rooms (p>0.05).

III.A.2.2. RELIABILITY OF THE RATING SCALES

To test the within-group agreement similarly to what was done in (Danford and Willems, 1975), the real-world group was divided in two subgroups of participants (Subgroup #1 and Subgroup #2) identically balanced in terms of gender and time of the visit. Figure III.A.7 illustrates the observed similarity between responses of the two subgroups of participants for the scale "Corridor is: dim – bright (D11)".

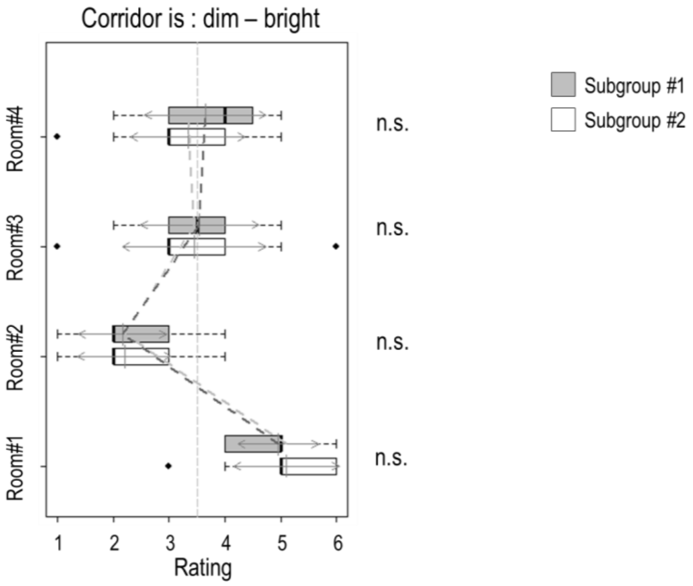


FIGURE III.A.7
Light level (D11). Mean ratings for the two subgroups of participants. The analysis of variance revealed non-significant (n.s.) differences between the two subgroups.

Whatever the question, the analysis of variance revealed no significant difference between the two subgroups. The results of this analysis suggest a high within-group agreement.

III.A.2.3. CONSISTENCY BETWEEN RATING SCALES RESPONSES AND MCQ ANSWERS

To check participants' responses consistency, rating scales were compared to multiple choice questions dealing with the same concept.

A chi-squared test was first performed on each multiple choice question to determine if the observed frequency distribution (see Table III.A.1) differed from the expected one. A post-hoc multiple comparison was then performed to determine, for each question, which room was perceived as the most and the least pleasant, enclosed, spacious, bright, colorful, and presenting the highest and the lowest contrast. P-values were adjusted for multiple comparisons using the Bonferroni correction.

TABLE III.A.1
Frequency of responses to the multiple choice questions (MCQ) and statistical significance resulting from the multiple comparison tests (chi-squared tests)

MCQ			Room			
			#1	#2	#3	#4
Pleasant	the most	MCQ1a	**24***	0***	10	9
	the least	MCQ1b	2**	**24***	7	10
Enclosed	the most	MCQ2a	1**	**26***	7	9
	the least	MCQ2b	15	0***	**19***	9
Spacious	the most	MCQ3a	7	0***	**31***	5
	the least	MCQ3b	1**	**36***	2**	4
Bright	the most	MCQ4a	**31***	0***	2**	10
	the least	MCQ4b	0***	**23***	10	10
Colorful	the most	MCQ5a	9	0***	3*	**31***
	the least	MCQ5b	5	13	**23***	2**
Contrast	the highest	MCQ6a	3*	0***	2**	**38***
	the lowest	MCQ6b	11	9	**22***	0***

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

According to the analysis, Room #1 is the most enclosed and the brightest. Room #2 is the least pleasant, the most enclosed, the least spacious, and the least bright. Room #3 is the least enclosed, the most spacious, the least colorful, and the one presenting the lowest contrast. Room #4 is the most colorful and the one presenting the highest contrast.

Results of this analysis conformed to the conclusions of the rating scales. Fig.III.A.9 to 14 illustrate this comparison. Fig.III.A.8 presents the boxplot legend for the reading of these figures.

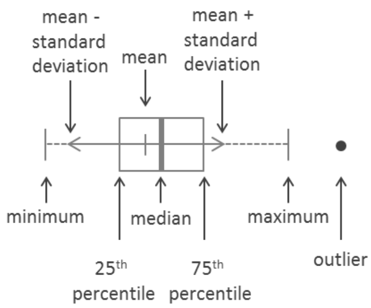


FIGURE III.A. 8
Boxplot key

Concerning the pleasantness of the room (see Fig.III.A.9), while statistical analyses performed on multiple choice questions made it possible to determine that one room was perceived as the most pleasant (Room #1) and another as the least pleasant (Room #2), statistical analyses performed on this dimension did not make it possible to differentiate Rooms #1, #3, and #4. Indeed, according to ANOVAs performed on this dimension, these three rooms are perceived as the most pleasant but do not differ significantly. But mean scores indicate that Room #1 is the most pleasant and that Room #2 is perceived as the least pleasant, which matches the MCQ.

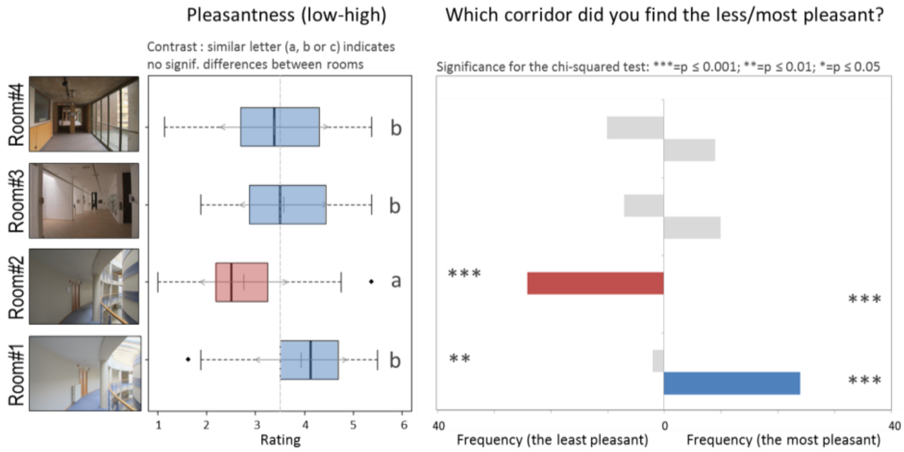


FIGURE III.A.9

Comparison between rating scales (P0) and multiple choice questions (MCQ1a and MCQ1b) for pleasantness. Red coloration indicates the rooms that are perceived as the least pleasant and blue coloration as the most pleasant, according to the statistical tests. (Similar letter indicates that the rooms do not differ significantly. Significance: * = p< 0.05; ** = p< 0.01; *** = p< 0.001).

As illustrated in Fig.III.A.10, the most enclosed room is Room #2 according to MCQ. The least enclosed is Room #3. That matches with ANOVA results, but rating scales did not make it possible to distinguish between the three least enclosed rooms (Rooms #1, #3, and #4), and according to mean scores, the first room is the least enclosed.

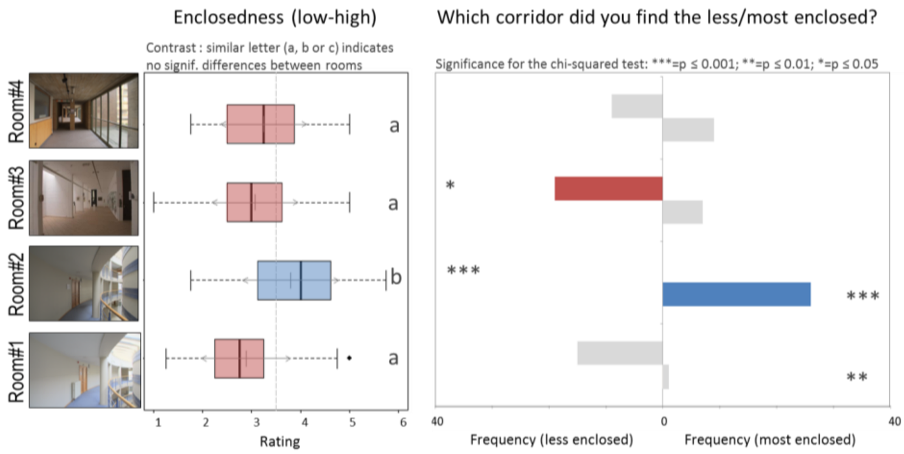


FIGURE III.A.10

Comparison between rating scales (E0) and multiple choice questions (MCQ2a and MCQ2b) for enclosedness (Similar letter indicates that the rooms do not differ significantly. Significance: * = p< 0.05; ** = p< 0.01; *** = p< 0.001).

Figure III.A.11 illustrates results for the perception of the spaciousness. Room #3 is the one perceived as the most spacious according to MCQ. This same room is perceived as the most spacious according to the mean scores of the rating scale. (No ANOVA was performed because the homogeneity assumption is not assumed.) Room #2 is the one perceived as the least spacious according to MCQ and the least spacious according to the mean score of the rating scale.

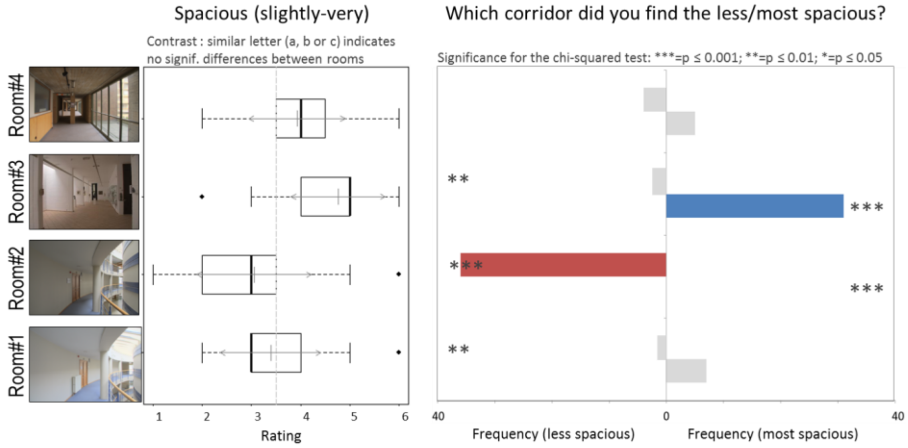


FIGURE III.A.11
Comparison between rating scales (E1) and multiple choice questions (MCQ3a and MCQ3b) for spaciousness (Similar letter indicates that the rooms do not differ significantly. Significance: * = p< 0.05; ** = p< 0.01; *** = p< 0.001).

As illustrated in Fig.III.A.12, according to MCQ, the brightest room is the first one and the dimmest is the second one. These observations match the rating scales.

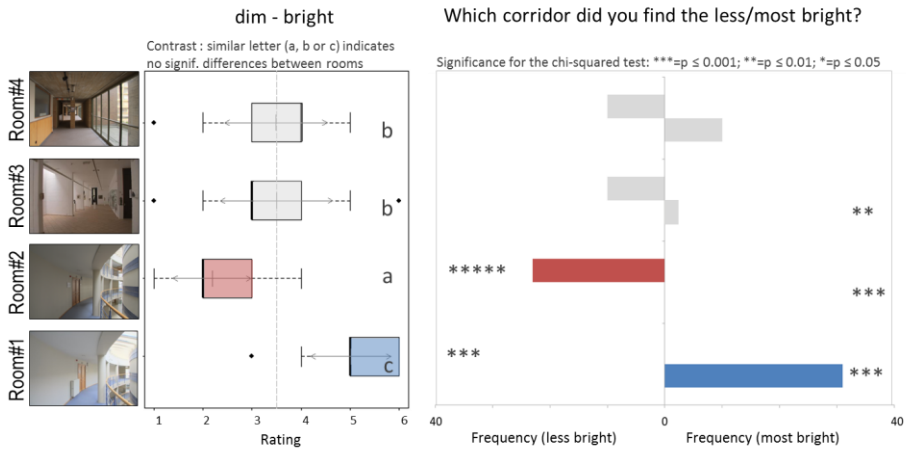


FIGURE III.A.12
Comparison between rating scales (D11) and multiple choice questions (MCQ4a and MCQ4b) for brightness (Similar letter indicates that the rooms do not differ significantly. Significance: * = p< 0.05; ** = p< 0.01; *** = p< 0.001).

Figure III.A.13 presents results related to coloration of rooms. Room #4 is perceived as the most colorful according to multiple choice questions while Room #3 is the least colorful. That matches the mean scores to the rating scale related to coloration of the room. However, ANOVA results do not make it possible to differentiate between Rooms #1 and #4 or Rooms #2 and #3.

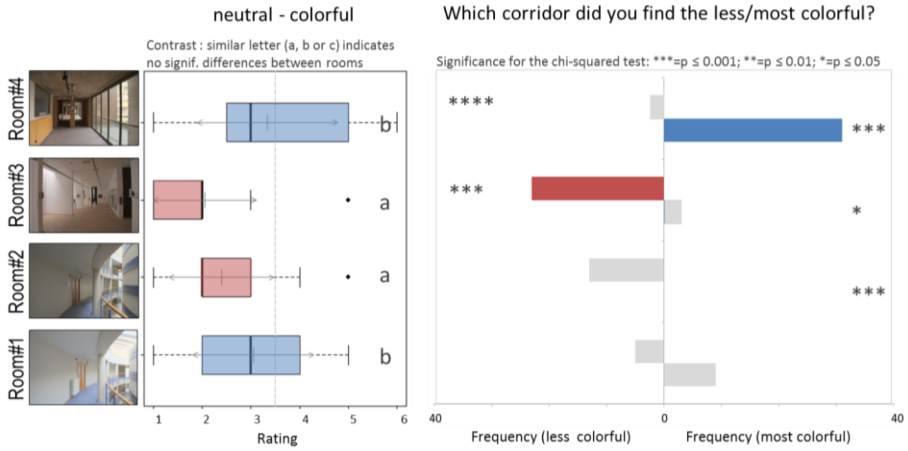


FIGURE III.A.13

Comparison between rating scales (D21) and multiple choice questions (MCQ5a and MCQ5b) for coloration (Similar letter indicates that the rooms do not differ significantly. Significance: * = p< 0.05; ** = p< 0.01; *** = p< 0.001).

Figure III.A.14 presents the results concerning the perception of contrast. The room presenting the highest contrast is Room #4, according to MCQ and the rating scale (D31). The room presenting the lowest contrast is the third one according to MCQ, which matches with mean score. However, ANOVA results do not distinguish the three rooms presenting the lowest contrast.

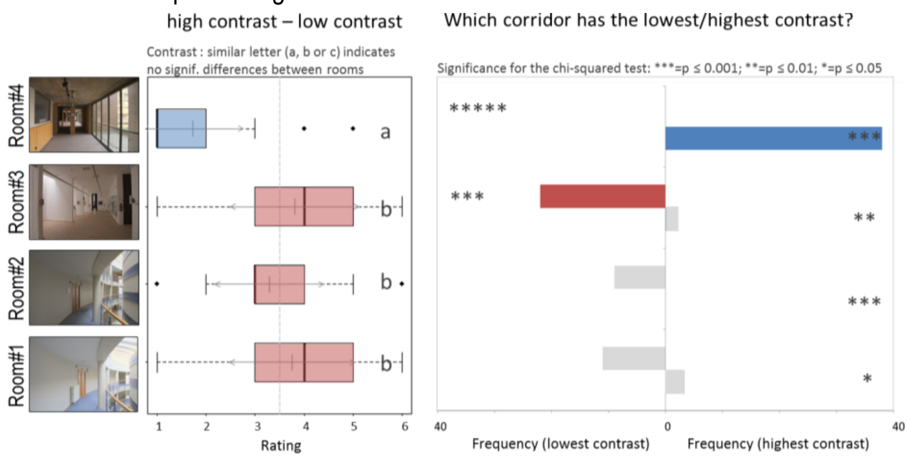


FIGURE III.A.14

Comparison between rating scales (D31) and multiple choice questions (MCQ6a and MCQ6b) for contrast (Similar letter indicates that the rooms do not differ significantly. Significance: * = p< 0.05; ** = p< 0.01; *** = p< 0.001).

The comparison between the multiple choice questions (MCQ) and the rating scales show that the results are consistent but that MCQs make possible the distinction between some rooms that rating scales did not.

III.A.2.4. SENSITIVITY OF THE NON-CONVENTIONAL QUESTIONS

As explained in Chapter II.B, participants were also asked to respond to a series of non-conventional questions based on blank sketches.

III.A.2.4.1. *PAIRED COMPARISON OF WALLS*

Participants were asked to compare, on a five-point rating scale, two walls for brightness, uniformity, and roughness (see Fig. III.A.15).

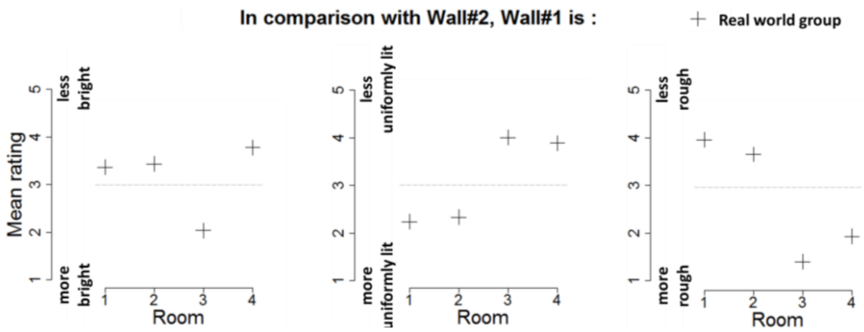


FIGURE III.A.15
Comparison of two walls for brightness, uniformity and roughness.

As illustrated in Fig.III.A.15, participants have the ability to distinguish the two walls for brightness, uniformity and roughness.

III.A.2.4.2. *ABILITY TO CLASSIFY PUNCTUAL ZONES FOR BRIGHTNESS*

Fig.III.A.16 presents graphically how the subjects of the real-world group classified points a, b, and c in each room. While the order of the points is similar in the first, the second and the fourth room, it differs in the third room. Moreover, even if they are classified in the same order in three rooms, the ratings differ. Participants seem thus to have the ability to classify points for brightness.

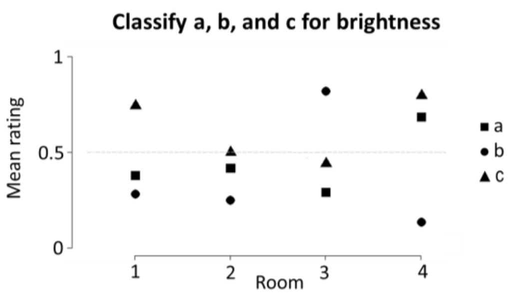


FIGURE III.A.16
Classification of the points a, b, and c for brightness

III.A.2.4.3. *ABILITY TO DISTINGUISH SOME AREAS IN THE SCENES*

Finally, participants were asked to circle, on blank sketches, attractive zones and materials emphasized by light. They were also asked to color in red the brightest zones of their visual field, and in blue, the dimmest zones.

The analysis of the sketches in which the participants were asked to circle some zones of interest (attractive zones or materials emphasized by light) requested a fairly substantial work of encoding. Participants' responses were first encoded using the Gimp software, resulting in black and white maps as those presented in Fig.III.A.17. These images were then imported in Matlab software, and the percentage of participants having circled various zones of the room was calculated. Finally, maps of frequency in false colors were created (see Fig.III.A.17c).

FIGURE III.A.17
Transformation of the sketches to black and white maps and finally to maps of frequency

The encoding of the second kind of sketches (colored in red and blue) was faster. As illustrated by Fig.III.A.18, sketches were first scanned into JPEG format. Using a Matlab script, RGB data were read. Each sketch was decomposed into two matrices: one matrix containing the red information and another containing the blue information. Finally, maps in false colors were created to easily determine which zones were more frequently colored by the subjects.

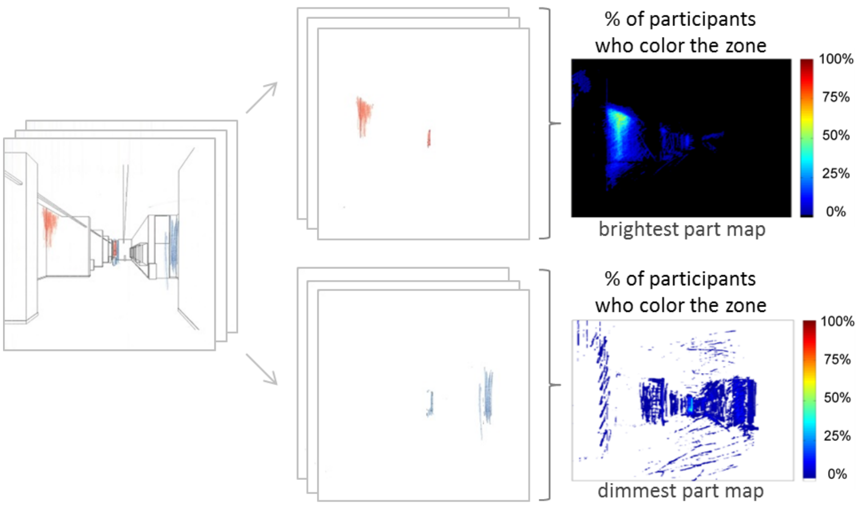
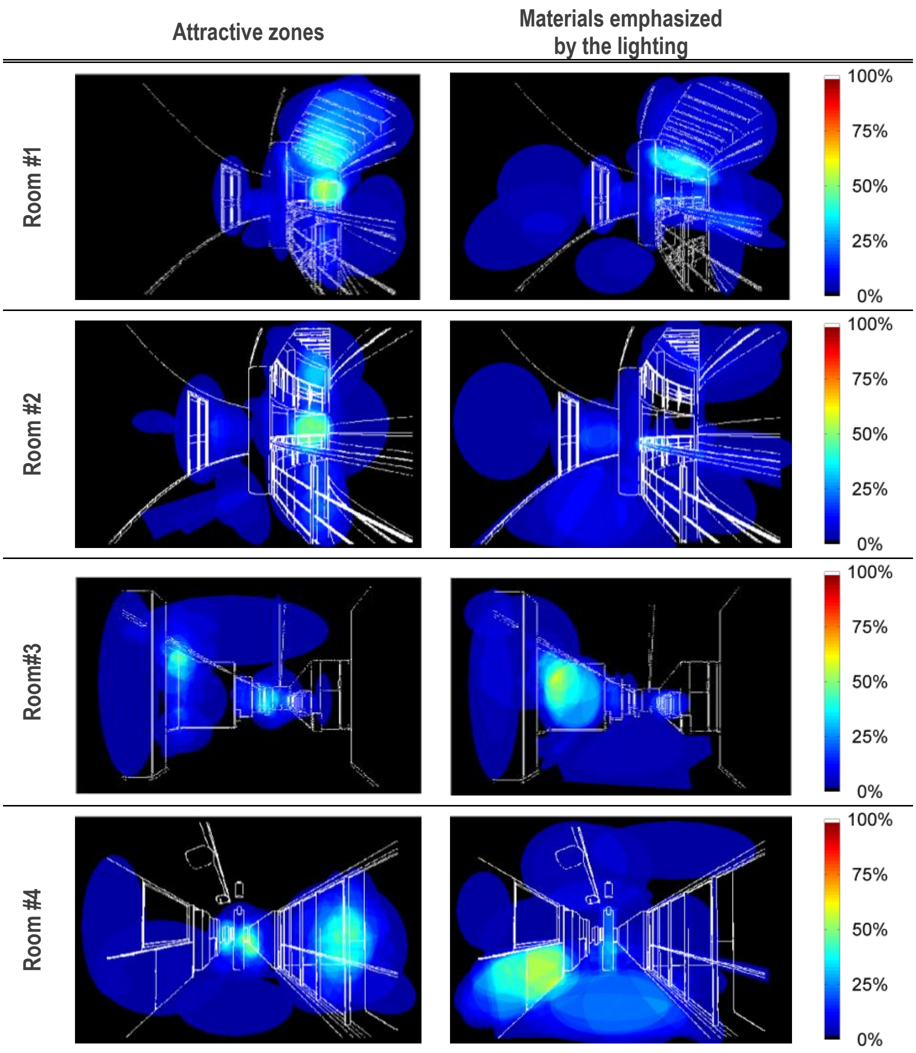


FIGURE III.A.18
Transformation of the colored sketches to two maps of frequency presenting the zones perceived as the brightest and as the dimmest

Tables III.A.2 and 3 present the maps of frequency realized following these methods.

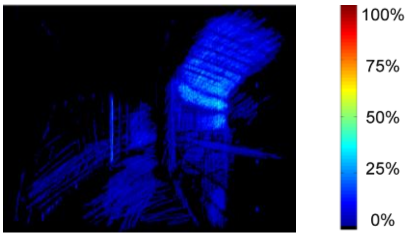
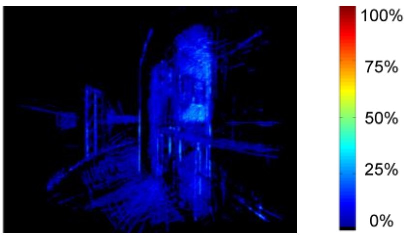
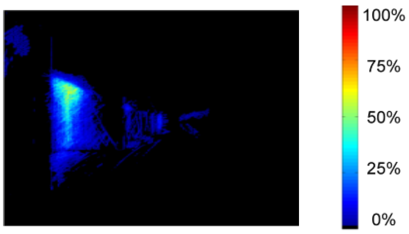
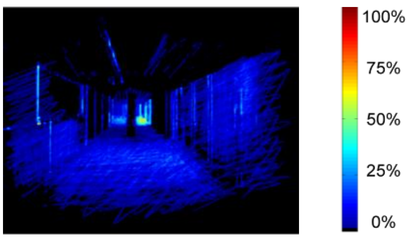
TABLE III.A.2
Percentage of participants who perceived some areas of the rooms as attractive, and some materials as emphasized by the lighting



As illustrated in Table III.A.2, some zones of the scenes are perceived attractive by at least 50% of the participants. Some materials also appeared emphasized by the lighting.

Table III.A.3 presents the areas colored by the participants as the brightest or the dimmest areas of the room.

TABLE III.A.3
Percentage of participants who perceived the area as the brightest or the dimmest part of the room.

	Brightest parts	Dimmest parts
Room #1		
Room #2		
Room#3		
Room #4		

These sketches suggest that the participants have the ability to locate the brightest and dimmest parts of the scenes. The consensus between the participants is higher in the third and in the fourth room.

III.A.3. DISCUSSION

III.A.3.1. SENSITIVITY OF THE RATING SCALES

ANOVA performed on the data made it possible, for most of the rating scales, to create groups of rooms that differ significantly. Three rating scales (D61, D63, A21) do not present a high level of sensitivity: they did not create distinct groups of rooms. The comparison with physical measurements in the next chapter will determine whether the question is sensitive enough or whether the risk of glare is reduced.

Moreover, two other scales did not highlight acute differences between rooms: the scale related to the color of light (D23) and the one related to the perception of material textures (D52). Even if post hoc test distinguished two groups of rooms, some rooms belong to the two groups. We suspect that participants had difficulty answering these questions. To help them, colorful and textured objects such as a poster of fruits or a sculpture could be placed in the rooms.

Last, the analysis of the sensitivity of the rating scales showed that scales of appreciation are less discriminating than descriptive rating scales and that people are, on average, satisfied with their lit environment.

III.A.3.2. RELIABILITY OF THE RATING SCALES

In dividing our sample of participants in two subgroups, we aimed at checking the reliability of the rating scales similarly to what was done in (Danford and Willems, 1975). The analysis of variance performed on the responses revealed no significant difference between the two subgroups suggesting a high within-group agreement.

III.A.3.3. PARTICIPANTS' RESPONSES CONSISTENCY

Results from the MCQ are consistent with those obtained using rating scales. However, statistical analyses performed on the MCQ make possible the distinction between some rooms that statistical analyses performed on the rating scales do not. In forcing people to choose, the MCQ provides additional information to the rating scales.

III.A.3.4. SENSITIVITY OF THE NON-CONVENTIONAL QUESTIONS

The analysis of sketches suggests that participants have the ability to detect attractive zones and materials emphasized by the lighting and also, to locate the brightest and dimmest parts of the scenes

Moreover, participants appreciated the fact that the questionnaire has various kinds of questions, and they appreciated the non-conventional questions that they found less boring and less difficult.

CHAPTER III.B
VALIDATING THE MEASURED PERCEPTIONS

To check potential instrument or procedure bias, a control group of participants was asked to respond to the questionnaire without receiving the luminous stimuli (neither actual scenes nor colored pictures) but only on the basis of the blank sketches of the scenes. This chapter presents first a comparison between real-world group and control group responses. The analysis of the luminous conditions encountered in the actual environments during the experiment presented in the previous chapter is then presented. This analysis is based on the physical measurements and the HDR pictures taken in the rooms on the day of the visit. Last, visual perceptions of the real-world group are compared to this "objective" analysis.

III.B.1. COMPARISON BETWEEN REAL-WORLD AND CONTROL GROUPS

As explained in Chapter II.B, the work carried out by Danford and Willems (1975) highlighted the possible bias linked to the response instrument. Indeed, the authors observed that responses given by the groups of participants receiving a visual stimulus versus those not receiving one were astonishingly similar. Based on this observation, we introduced in our experimental protocol a control group to check the potential instrument bias (see Fig.III.B.1). A second group of forty-two participants (the control group) was asked to respond to the same questionnaire without visualizing the luminous stimuli (neither actual scenes nor colored pictures) but only on the basis of the blank sketches of the scenes present in the questionnaire. Participants were instructed to imagine themselves walking across the corridors.

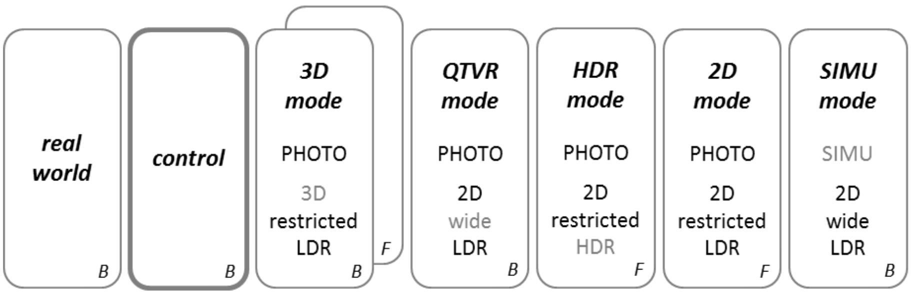


FIGURE III.B.1
A group of participants (control group) was asked to respond to the questionnaire without receiving the luminous stimuli (neither actual scenes nor colored pictures) but only on the basis of the blank sketches of the scenes

Forty-two participants presenting characteristics similar to the real-world group in terms of age, gender and educational background composed thus the control group (mean age +/- standard deviation: 21.5 +/- 1.7).

III.B.1.1. VALIDITY OF THE RATING SCALES

Responses given by the participants who visited the actual rooms were compared to those of this control group. Figures III.B.2 to 4 present mean scores of the control group (C) and the real-world group (R).

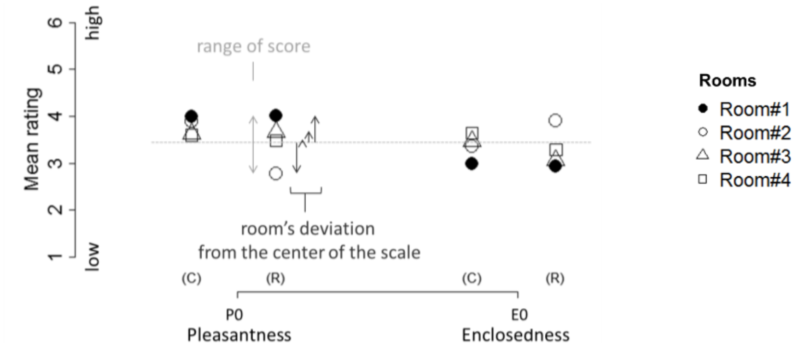


FIGURE III.B.2
Mean ratings of pleasantness and enclosedness for the control group (C) and the real-world group (R).

As illustrated in Fig.III.B.2, the range of scores was calculated for each dimension and each group of participants (control group and real-world group). Mean score deviation from the center of the scale was also determined for each room.

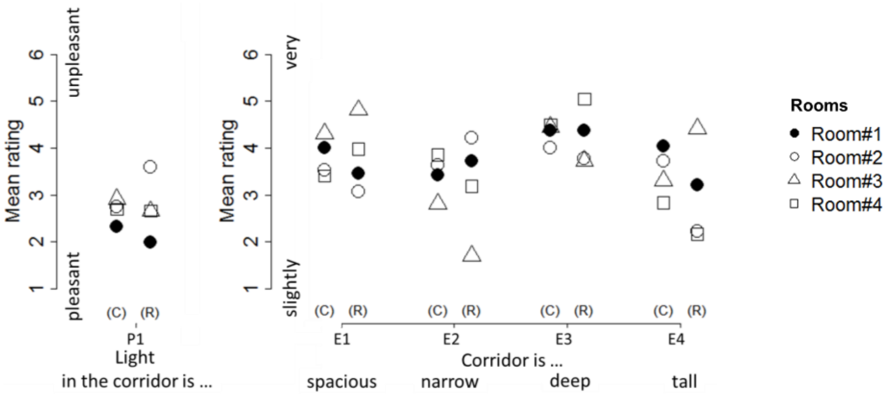


FIGURE III.B.3
Additional questions linked to the spaciousness of the space: comparison between the mean ratings for the control group (C) who did not receive the luminous stimuli, and the real-world group (R).

Regardless of the scales, the range of scores of the control group is inferior to that of the real-world group except for the three scales related to the perception of glare (D61, D62, D63) (see Fig.III.B.4). However, the calculation of the deviation of the mean scores from the center of the scale indicated that these three scales are more deviated from the center when the participants receive the luminous stimuli (real-world group) than when they do not (control group).

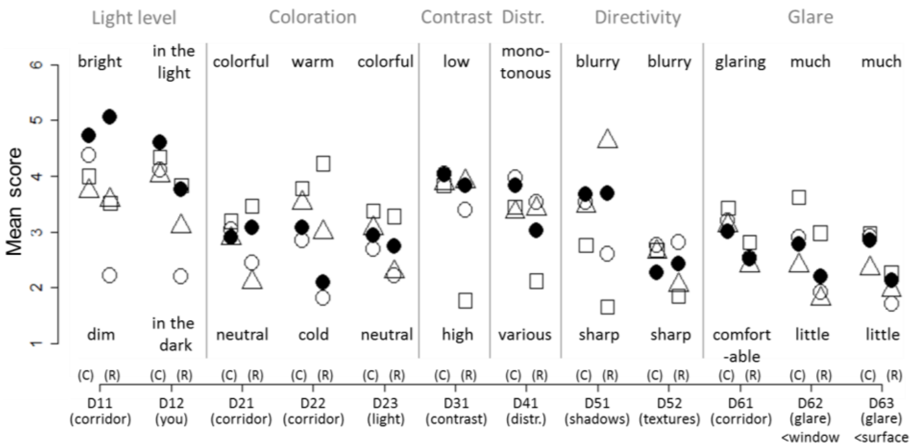


FIGURE III.B.4
Appearance of the lighting: comparison between the mean ratings for the control group (C) who did not receive the luminous stimuli, and the real-world group (R) (● Room #1, ○ Room #2, △ Room #3, □ Room #4).

The comparison between the responses to the rating scales given by the real-world group and the control group proves that the luminous stimuli actually influences the way the participants perceived the appearance of the rooms.

III.B.1.2. VALIDITY OF THE NON-CONVENTIONAL QUESTIONS

Participants were also asked to respond to a series of non-conventional questions based on sketches.

III.B.1.2.1. *PAIRED COMPARISON OF WALLS*

Participants were asked to compare, on a five-point rating scale, two walls for brightness, uniformity, and roughness (see Fig. III.B.5).

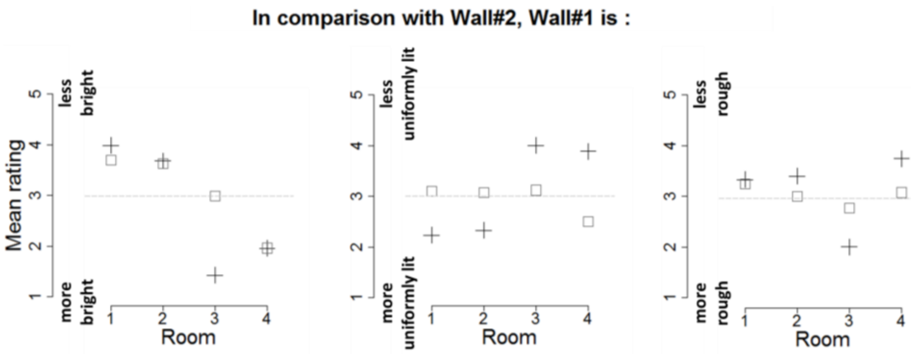


FIGURE III.B.5
Comparison of two walls for brightness, uniformity and roughness (+ Real world, □ Control)

Whatever the question and the room, deviations from the center of the scale are always higher for the group receiving the luminous stimuli than for the other (see Fig.III.B.5).

However, Fig.III.B.5a also shows that when comparing the brightness of the walls, responses from the control group are quite similar to those of the real-world group, except in the third room. This room is the least known by the participants and it is also the room where it is the most difficult to determine the location of the windows on the basis of the sketches.

III.B.1.2.2. *ABILITY TO CLASSIFY PUNCTUAL ZONES FOR BRIGHTNESS*

Fig.III.B.6 presents graphically how the subjects of the real-world group and those of the control group classified points a, b, and c in each room.

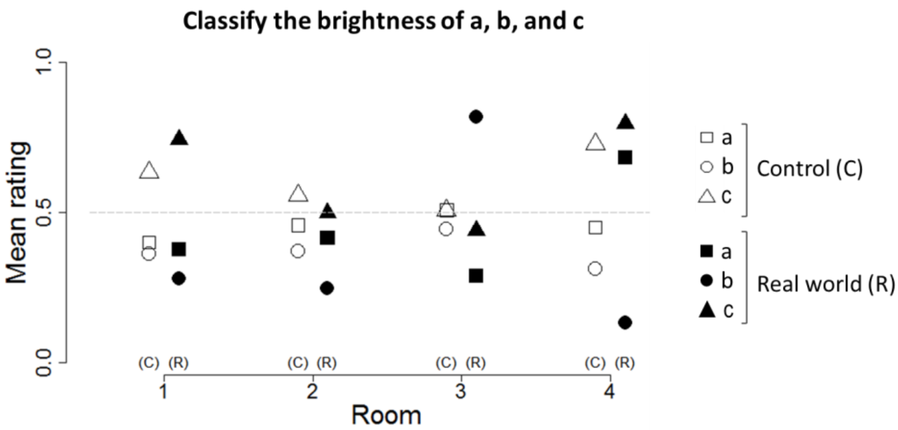


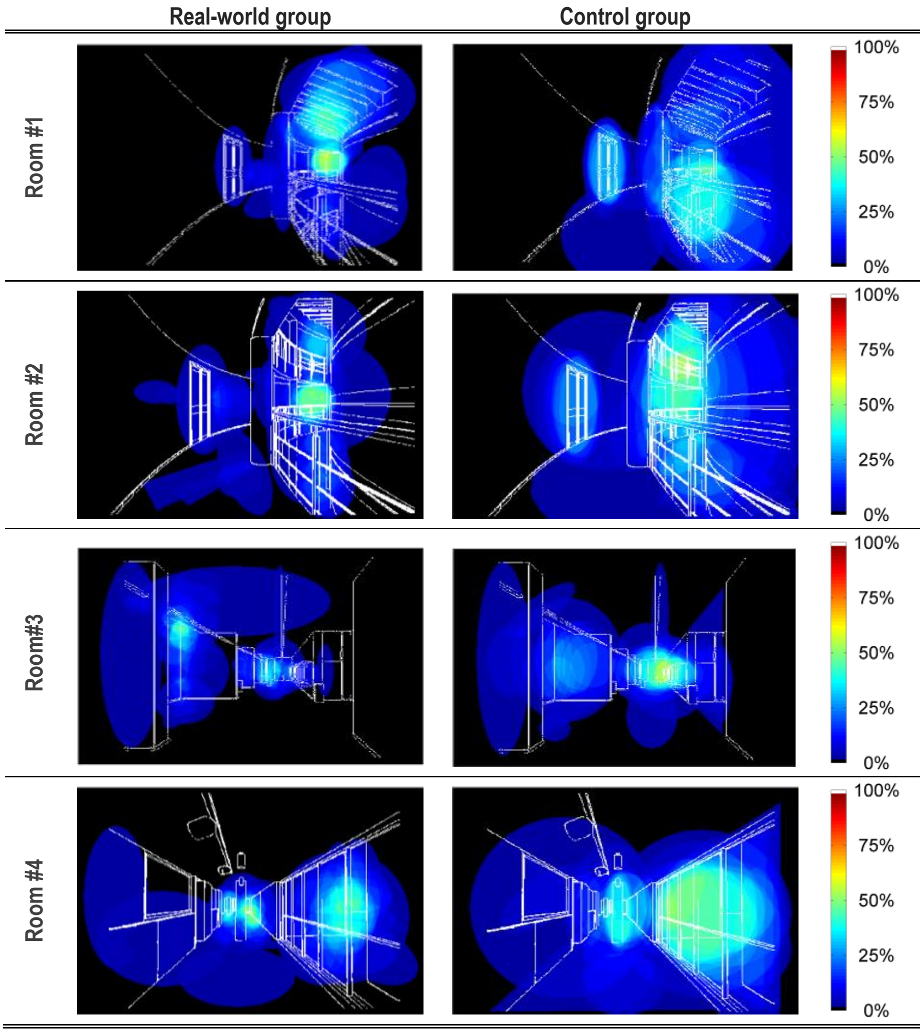
FIGURE III.B. 6
Classification of three points for brightness

In the first, the second, and the fourth room, the three points are classified in the same order by the real-world group and by the control group.

III.B.1.2.3. *ABILITY TO DISTINGUISH SOME AREAS IN THE SCENES*

Tables III.B.1 to 4 compared sketches realized by the participants of the real-world group to those realized by the participants of the control group.

TABLE III.B.1
Percentage of participants who perceived some areas of the rooms as attractive



As illustrated in Table III.B.1, some parts of the scenes are distinguished by the two groups of participants (real-world group or control group). The circled areas are not identical in the two groups. Moreover, these areas are wider (less precise) in the control group than in the real-world group.

In this second question (see Table III.B.2), the participants were asked to circle the materials emphasized by the lighting. Some zones are distinguished by the real-world group while no area is distinguished by the control group.

TABLE III.B.2
Percentage of participants who perceived some materials as emphasized by the lighting

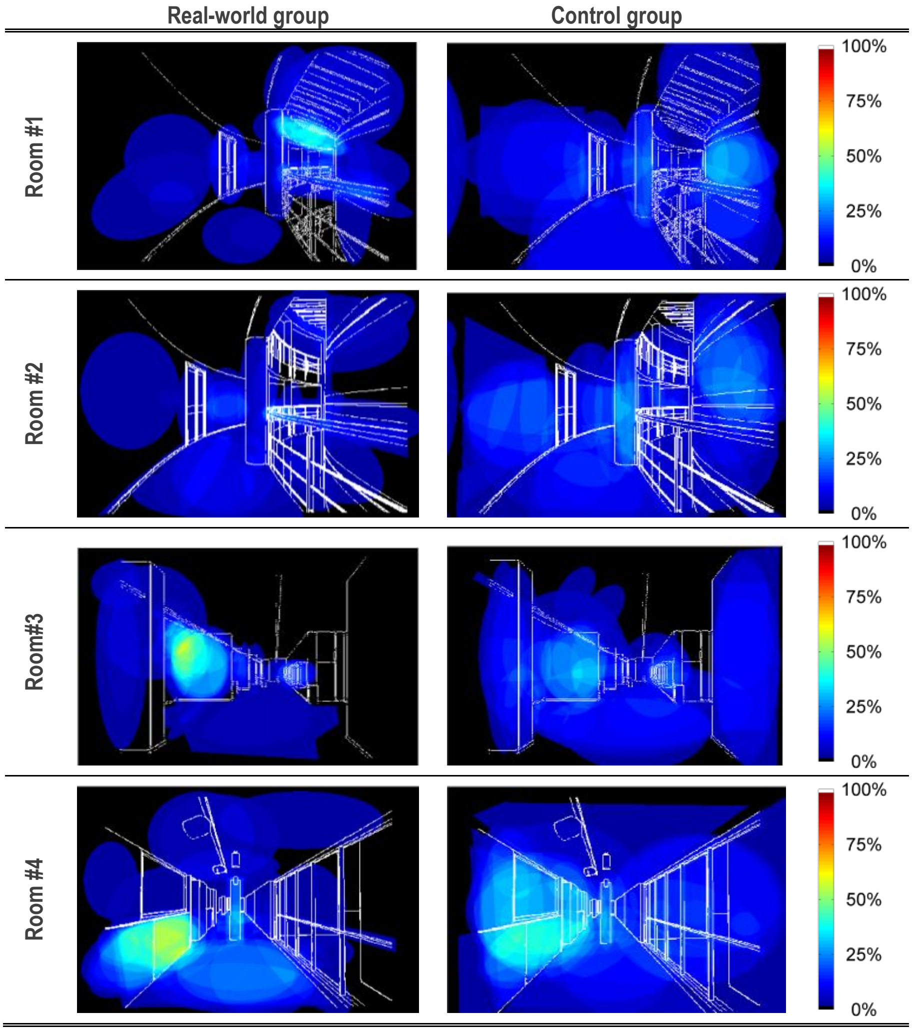
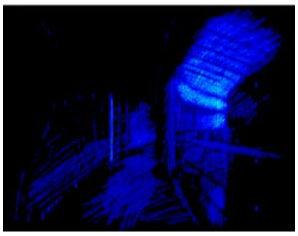
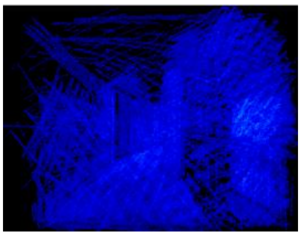
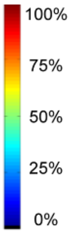
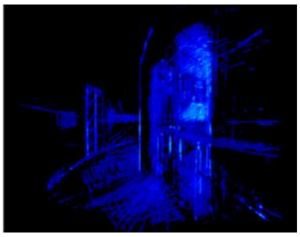
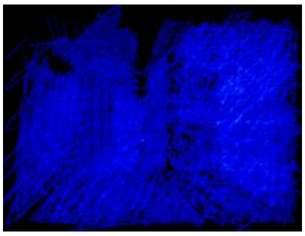
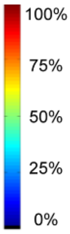
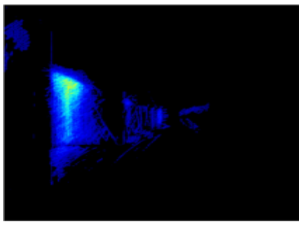
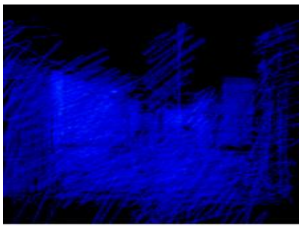
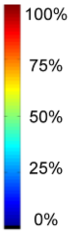
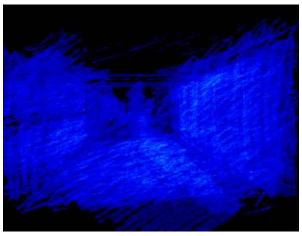
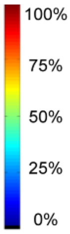


Table III.B.3 presents the areas colored by the participants as the brightest areas of the room.

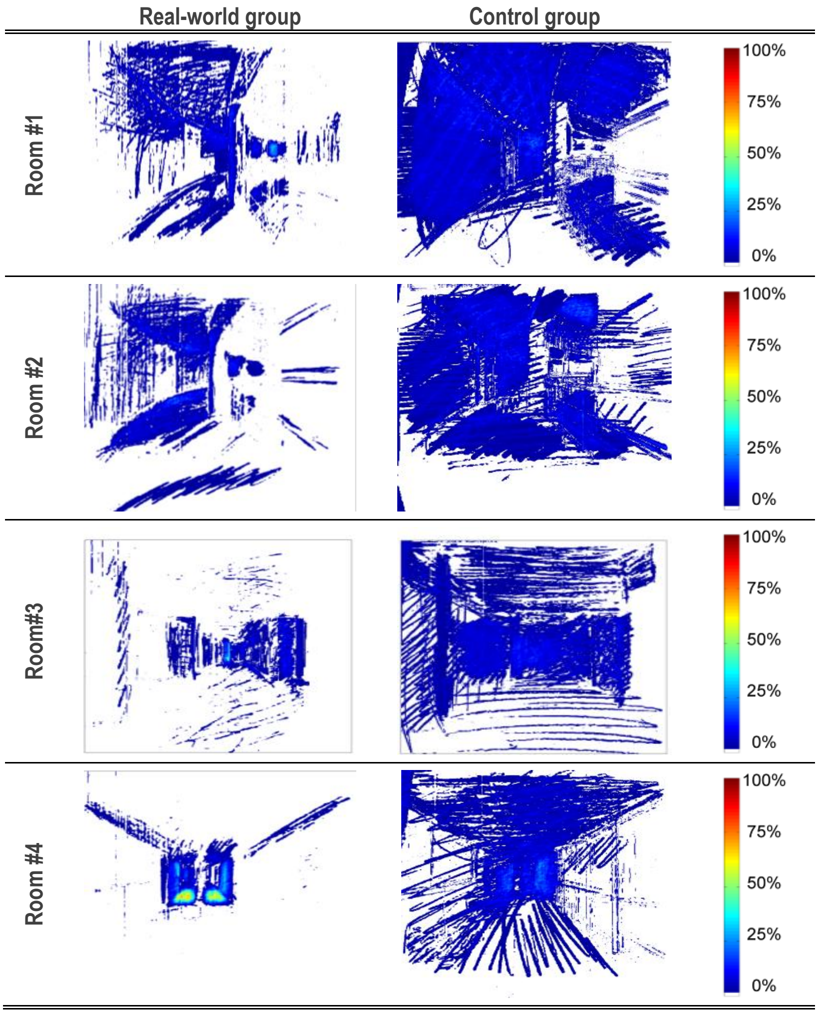
TABLE III.B.3
Percentage of participants who perceived the area as the brightest part of the room

	Real-world group	Control group	
Room #1			
Room #2			
Room#3			
Room #4			

Clearly, the subjects do not have the ability to determine the brightest areas of the rooms when they do not receive the luminous stimuli (control group).

The conclusion is similar for the dimmest areas of the rooms (see Table III.B.4).

TABLE III.B.4
Percentage of participants who perceived the area as the dimmest part of the room



III.B.2. COMPARISON WITH REAL-WORLD MEASUREMENTS

During the participants' visit to the rooms, illuminance and luminance measurements as well as HDR pictures were done in the indoor spaces. Three series of pictures and measurements were realized in each room. A first series was realized just before the visit of the first participants (Tour #1), a second series halfway through (Tour #2), and a third series just after the visit of the last group of participants (Tour #3). Sky luminance and illuminance measurements were done every five minutes.

Figure III.B.7 illustrates that during the real-world experiment, outdoor illuminances varied widely: the sky was partly cloudy during the first two-thirds of the experiment and became overcast in the last part.

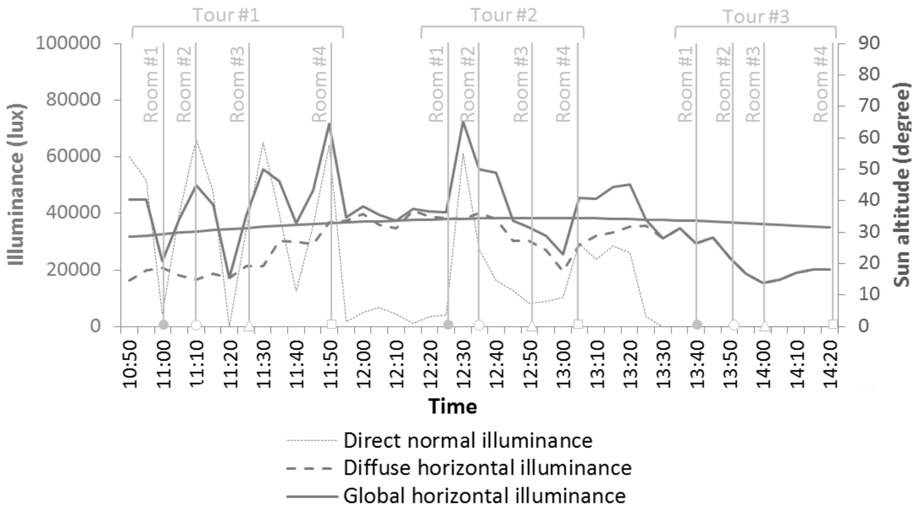


FIGURE III.B.7
Variation of the sky conditions during the experiment in the real world

This section analyzes the impact of these outdoor variations on the indoor lighting conditions.

III.B.2.1. METHOD

To objectively describe the lighting conditions in the rooms, some indicators of performance were chosen in the literature and were calculated on the basis of the measurements made the day of the experiment in the actual spaces. They illustrate the following dimensions characterizing lighting in interiors: perceived brightness, distribution of light, luminance contrast, directivity of light, risk of glare, and coloration. A brief justification for the choice of each indicator is presented below. Some of these indicators were calculated in Matlab (The MathWorks, 2009) using luminances extracted from the calibrated HDR pictures.

III.B.2.1.1. *BRIGHTNESS*

Brightness was first evaluated through the horizontal and vertical illuminances at eye level, respectively denoted by Eh_eye and Ev_eye in Tables III.B.5 to 8. They were measured with a Hagner EC1-X lux meter.

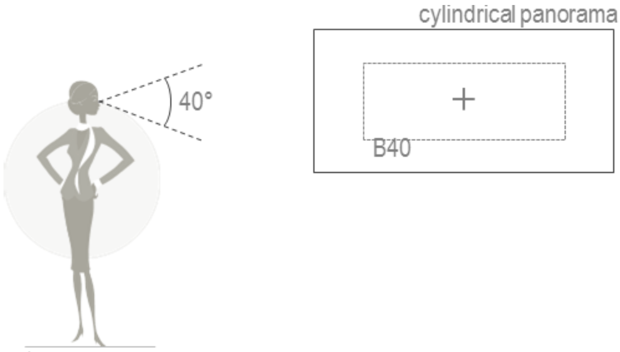


FIGURE III.B.8
40° vertical 90° horizontal B40 band

Average luminance in a 40° vertical 90° horizontal band was then extracted from the HDR pictures (Lmean_B40 in Tables III.B.5 to 8). According to Loe et al. (2000), this indicator can be used to describe the brightness of a scene.

III.B.2.1.2. *DISTRIBUTION OF LIGHT*

Distribution of light in the room was first studied through maps of luminances. Mean luminance in several parts of the visual field were then calculated in order to compare the four rooms more easily. Based on the literature, two other indicators were calculated: the logarithm of the ratio of maximum to minimum luminance, in a 40° horizontal band (correlated with the perceived non-uniformity) (Loe et al., 1994), and the ratio of luminances of the 75th to 25th percentile pixels, normalized by mean luminance (which decreases when the uniformity of the scene increases) (Newsham et al., 2010).

III.B.2.1.3. *LUMINANCE CONTRAST*

Luminance contrast is defined as the difference between the luminance of an object and the luminance of its background, normalized by the luminance of the background (Rea, 2000). Depending on what is considered the background, several luminance contrasts can be calculated.

A first luminance contrast, identified as global contrast, was calculated as the difference between the luminance of each pixel of the HDR picture and the mean luminance of the scene as in Equation III.B.1.

$$C_g(x,y) = \frac{\left| L(x,y) - L_{mean} \right|}{L_{mean}}$$

EQUATION III.B.1
Cg_x,y is the global contrast of the pixel positioned at (x,y); L_x,y is the luminance of this same pixel ; and L_mean is the mean luminance of the scene.

Maps of global contrast were created in order to detect zones of the scenes presenting a high contrast. For easy comparison of rooms, the mean global contrast of each scene was also calculated.

III.B.2.1.4. *DIRECTIVITY*

To assess the directivity of light, the vertical to horizontal illuminance ratio was calculated. According to the work of Cuttle et al. and Love and Navvab (as cited by Cantin (2008)), a ratio between 1.2 and 1.8 is desired. Satisfaction decreases for a ratio under 1, and a ratio above 2.2 is unacceptable for daylit rooms. This first indicator of directivity was complemented by the creation of a map of local contrast, calculated as in Equation III.B.2.

$$C_l(x,y) = \frac{\left|L(x,y) - L_{background}(x,y)\right|}{L_{background}(x,y)}$$

EQUATION III.B.2
Cl_x,y is the local contrast of the pixel positioned at (x,y) ; L_x,y is the luminance of this same pixel ; and L_ background_x,y is the mean luminance of the eight pixels surrounding the pixel positioned at (x,y).

Once again, for easy comparison of rooms, the mean local contrast of each scene was also calculated.

III.B.2.1.5. *GLARE*

The European Standard EN 12665 defines glare as the "condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrasts" (EN12665, 2002).

Most of the existing glare indices have been developed in an artificial lighting context. Few indices exist to assess risk of glare caused by a large source such as windows. These few indicators include the daylight glare index DGI developed in the Seventies, and the more recent daylight glare probability DGP (Wienold and Christoffersen, 2006) informing the percentage of people disturbed by a glare source. Contrary to the DGI which was developed under artificial lighting conditions, the DGP is based on and validated by daylighting. And, DGP presents a stronger correlation with user's perception of glare than DGI, in the case of daylit scenes.

DGP was developed in an office environment and is currently not validated for values under 20%. In the absence of other reliable index for assessing glare in environments other than offices, DGP was chosen in the present study for informing about risks of glare. We will keep in mind that, by using DGP, we may overestimate the perceived risks of glare given that, in a corridor context, people are probably less affected by glare than in an office environment because of their mobility and their activity (specific tasks realized in an office (writing, reading…) are definitely more constraining than walking in a corridor).

In this study, DGP was calculated based on the HDR pictures taken in the actual environments and vertical eye illuminance measurement, using the *evalglare* program in Radiance.

III.B.2.1.6. *COLOR*

To analyze the color dimension of the indoor environment, CIELAB color space was used. The three coordinates of this color space are L*, a*, and b*. L* represent the lightness of the color while a* and b* represent green-red and blue-yellow axes, respectively. (a*,b*) chromaticity diagrams were created on the basis of RGB values extracted from HDR pictures. +a* indicates the red direction; -a*, the green direction; +b*, the yellow; and -b*, the blue direction. The warm colors are thus situated in the right part of the diagram while cold colors are on the left. Points located close to the origin (0;0) are less saturated.

III.B.2.2. RESULTS

Results of the analysis, by rooms, are presented in Tables III.B.5 to 8.

III.B.2.2.1. *ANALYSIS OF THE LUMINOUS CONDITIONS IN THE ROOMS*

III.B.2.2.1.1. DAYLIGHT VARIABILITY IN EACH ROOM

Some variability of the luminous conditions in Room #1 was detected on the basis of this objective analysis. Indeed, as shown in Table III.B.5, the first room was darker during the first series of measurements (Tour #1) and brighter during the third series (Tour #3). Even though Tour #1 is darker, maximum luminances are found for this series of measurements due to a sun spot near the zenithal window. Maps of luminances indicate that light in this room comes from the top right, and DGP index indicates no risk of glare.

In Room #2 (see Table III.B.6), the variation of brightness is lower than in Room #1. Global contrast is higher in Tour #1 than in the two other tours.

The luminous conditions in Room #3 during Tour #1 were clearly darker than in the two other tours (see Table III.B.7). However, maps of contrast did not vary much even if uniformity was higher for the first tour. In this room, a shift of color from red-blue to red-yellow was also observed in the CIE a* b* diagrams. The maps of luminances show that contrary to the two previous rooms, the light comes from the left. This room is also the one presenting less global contrast.

Contrary to the other rooms, Room #4 presented the highest luminances during the first series of measurements and it is then darkened (see Table III.B.8). In this room, the vertical to horizontal illuminance ratio was higher than 2.2 and thus unacceptable, as cited in (Cantin, 2008). This room presents the highest global contrast.

TABLE III.B.5
Room #1

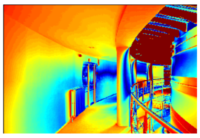
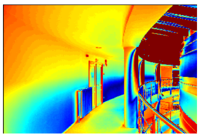
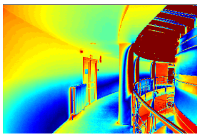
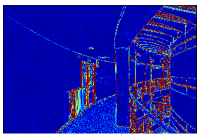
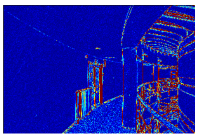
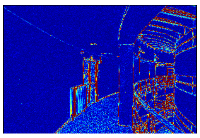
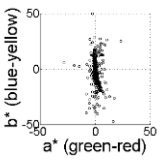
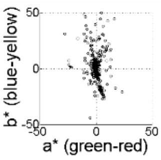
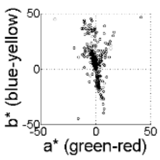
	TOUR #1	TOUR #2	TOUR #3	
Tone-mapped HDR picture				
		Brightness		
Eh_eye	240	378	578	(lux)
Ev_eye	215	312	343	(lux)
Lmean_B40	81	103	125	(cd/m²)
		Distribution		
[Lmin-Lmax]_B40	[2.3-7775]	[3.5-1791]	[4.5-1206]	(cd/m²)
Mean luminances by zone of the visual field				200 cd/m² 100 0
Log(max/min)_B40	3.5	2.7	2.4	(-)
(75p:25p)/Lmean_B40	0.03	0.02	0.02	(-)
		Contrast		
Map of global contrast				1 0
Mean global contrast	0.93	0.91	0.80	(-)
		Directivity		
Ev_eye /Eh_eye	0.90	0.83	0.59	(-)
Map of local contrast				0.1 0
Mean local contrast	0.031	0.028	0.029	(-)
		Glare		
DGP	<20	<20	<20	%
		Color		
CIE a*b* diagram				(-)

TABLE III.B.6
Room #2

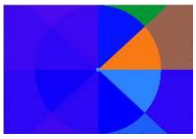
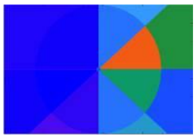
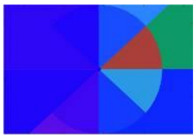
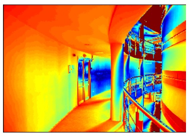
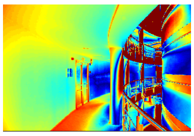
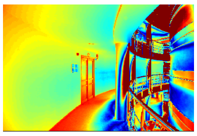
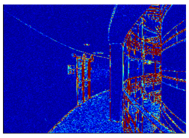
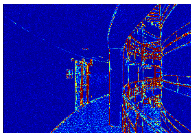
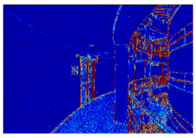
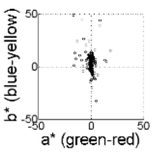
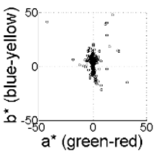
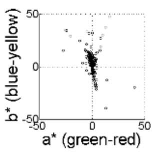
	TOUR #1	TOUR #2	TOUR #3	
Tone-mapped HDR picture				
Brightness				
Eh_eye	60	94	75	(lux)
Ev_eye	100	113	85	(lux)
Lmean_B40	43	49	39	(cd/m²)
Distribution				
[Lmin-Lmax]_B40	1.3-7755	1.6-2470	1.2-1210	(cd/m²)
Mean luminances by zone of the visual field				200 cd/m² 100 0
Log(max/min)_B40	3.8	3.2	3	(-)
(75p:25p)/Lmean_B40	0.05	0.03	0.04	(-)
Contrast				
Map of global contrast				1 0
Mean global contrast	1.06	0.81	0.86	(-)
Directivity				
Ev_eye /Eh_eye	1.67	1.20	1.13	(-)
Map of local contrast				0.1 0
Mean local contrast	0.032	0.029	0.030	(-)
Glare				
DGP	<20	<20	<20	%
Color				
CIE a*b* diagram				(-)

TABLE III.B.7
Room #3

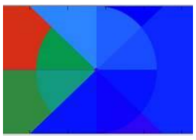
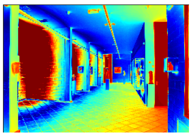
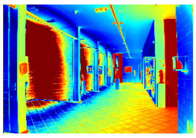
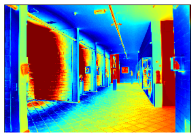
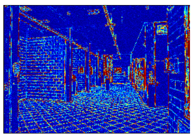
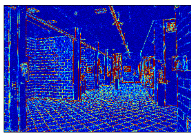
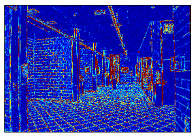
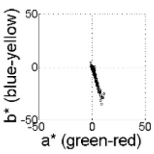
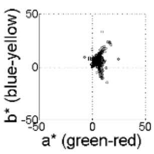
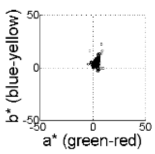
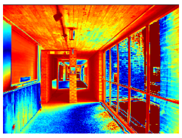
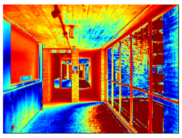
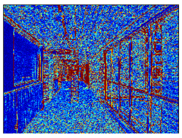
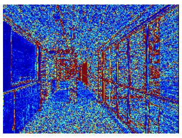
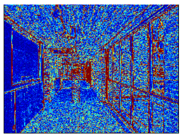
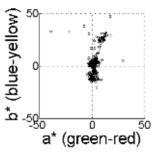
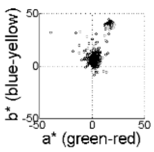
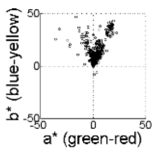
	TOUR #1	TOUR #2	TOUR #3	
Tone-mapped HDR picture				
		Brightness		
Eh_eye	40	167	92	(lux)
Ev_eye	38	150	88	(lux)
Lmean_B40	15	67	42	(cd/m²)
		Distribution		
[Lmin-Lmax]_B40	0.3-130	1.2-607	0.8-342	(cd/m²)
Mean luminances by zone of the visual field				200 cd/m² 100 0
Log(max/min)_B40	2.6	2.7	2.6	(-)
(75p:25p)/Lmean_B40	0.20	0.05	0.07	(-)
		Contrast		
Map of global contrast				1 0
Mean global contrast	0.65	0.65	0.62	(-)
		Directivity		
Ev_eye /Eh_eye	0.95	0.90	0.96	(-)
Map of local contrast				0.1 0
Mean local contrast	0.032	0.032	0.031	(-)
		Glare		
DGP	<20	<20	<20	%
		Color		
CIE a*b* diagram				(-)

TABLE III.B.8
Room #4

	TOUR #1	TOUR #2	TOUR #3	
Tone-mapped HDR picture				
		Brightness		
Eh_eye	120	70	44	(lux)
Ev_eye	388	250	168	(lux)
Lmean_B40	87	79	50	(cd/m²)
		Distribution		
[Lmin-Lmax]_B40	0.3-4281	0.4-887	0.6-762	(cd/m²)
Mean luminances by zone of the visual field				200 cd/m² 100 0
Log(max/min)_B40	4.3	4.7	3.1	(-)
(75p:25p)/Lmean_B40	0.16	0.11	0.13	(-)
		Contrast		
Map of global contrast				
Mean global contrast	1.11	0.90	0.81	(-)
		Directivity		
Ev_eye /Eh_eye	3.23	3.57	3.82	(-)
Map of local contrast				0.1 0
Mean local contrast	0.058	0.059	0.054	(-)
		Glare		
DGP	<20	<20	<20	%
		Color		
CIE a*b* diagram				(-)

III.B.2.2.1.2. COMPARISON BETWEEN THE FOUR ROOMS

It appears from this analysis that the brightest room is Room #1 and the least uniform is Room #4 (which also presents the highest directivity). Maps of mean luminances show that the brightest part of Room #2 is the right part while in Room #3, it is the left part. No risk of glare is predicted according to the calculated DGP value, regardless of the room. a*b* chromaticity diagrams show that Room #3 is the most neutral room while Room #4 presents a wider variety of colors (two groups of points are observed). Room #1 seems to be the warmer room (yellowish) and the most saturated (points are further apart to the origin).

III.B.2.2.2. *COMPARISON WITH SUBJECTIVE SCORES*

The analysis based on the objective indicators of performance was compared to perceptions presented in the previous chapter (see Chapter III.A).

As presented in Table III.B.9, no contradiction is observed between the responses to the rating scales and the analysis based on the physical measurements.

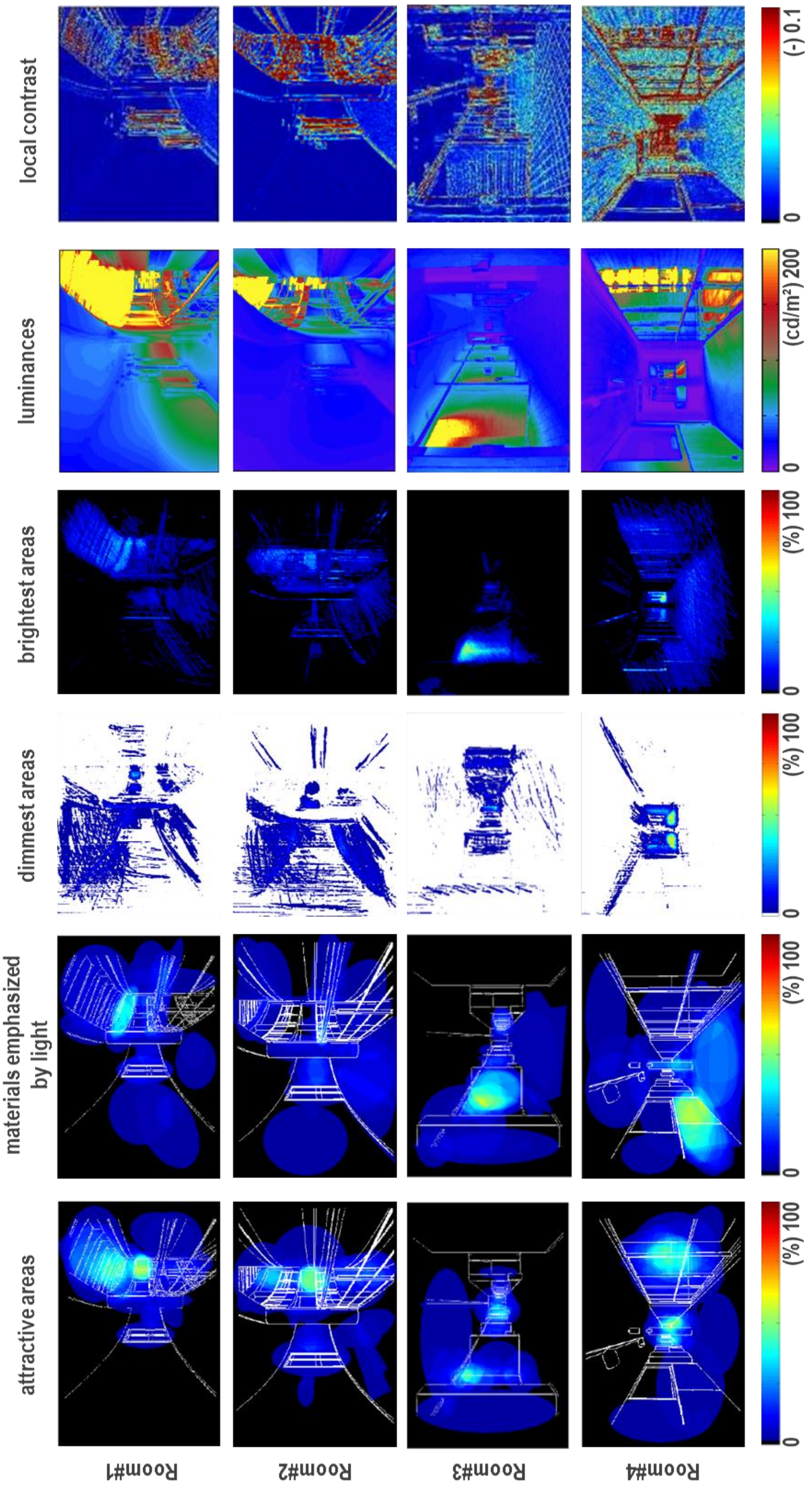
TABLE III.B.9
Comparison of the objective assessment based on physical measurements and the participants' responses to the rating scales.

		Objective assessment	Rating scales
Brightness	**The brightest**	#1	#1
	The dimmest	-	#2
Coloration	**The most colored**	#4	#1, 4
	The least colored	#3	#2, 3
	The warmest	#4	#4
	The coldest	#1	#1,2
Contrast	**The most**	-	#4
	The least	-	#1, 2, 3
Distribution	**The most uniform**	-	#1, 2, 3
	The least uniform	#4	#4
Directivity	**The most**	#4	#4
	The least	-	#3
Glare	**The most**	-	#4
	The least	#1, 2, 3, 4	#1, 2, 3

However, while the rating scales make possible the identification of some rooms for each dimension, the objective analysis did not always differentiate the rooms. For instance, we identified neither the dimmest room nor the room presenting the lowest directivity.

Subjective sketches were also compared to maps of luminances (see Table III.B.10). The parts of the rooms judged by the participants as attractive seem to be those presenting the highest contrast. Materials perceived as emphasized by light seem to be the most lit materials. The areas colored as the brightest and the dimmest match with zones presenting the highest and the lowest luminances.

TABLE III.B.10
Comparison between subjective sketches and maps of luminances.



Maps of luminances and maps of local contrast do not contradict the responses of the subjects when asked to compare two walls (see Fig.III.B.9).

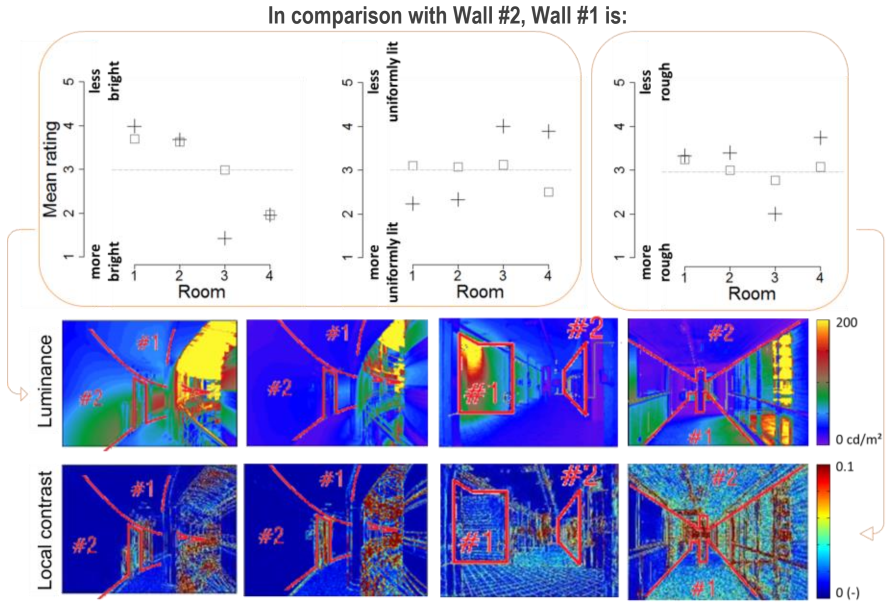


FIGURE III.B.9
Comparison between subjective scores (+ Real-world group □ Control group) and objective maps of luminances and local contrast

The luminance of points a, b, and c were extracted from the HDR pictures and compared to the participants' responses. The classification order of the three points is respected, as illustrated in Fig.III.B.10.

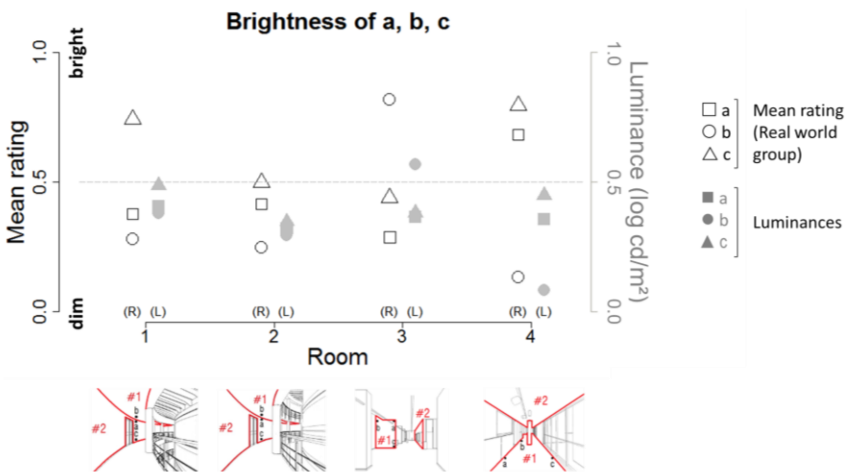


FIGURE III.B.10
Classification of three points for brightness – comparison between subjective and objective classification

III.B.3. Discussion

III.B.3.1. Comparison between real-world group and control group

Contrary to the study by Danford and Willems (1975), we observed some differences between the control group and the real-world group. Our results suggest that the presence of the luminous stimuli influenced the way participants responded to the questionnaire. The comparison of walls and of punctual zones for brightness suggests that the participants of the control group have the ability, on the basis of sketches, to analyze where daylight comes from and to guess how it is distributed. And it seems that participants remember that the ceiling in a room is generally less bright than the other walls in daylit rooms. Indeed, in the three rooms where the subjects can locate the windows (Rooms #1, #2 and #4), responses to the comparison of walls for brightness are identical whether the group receives the luminous stimuli (real-world group) or does not receive it (control group). Moreover, for these rooms, the three points are classified in the same order by the real-world group and by the control group. However, in the control group, the deviation from the center of the scale is reduced in comparison to the real-world group. At last, in visually comparing sketches of the real-world group and those of the control group, we observed that participants are clearly influenced by the luminous stimulus and that some areas of the rooms are determined as attractive by more than 50% of people or that some materials are perceived as emphasized by light. We also observed that people have the ability to distinguish the brightest and the dimmest areas of the scenes.

III.B.3.2. Comparison with real-world measurements

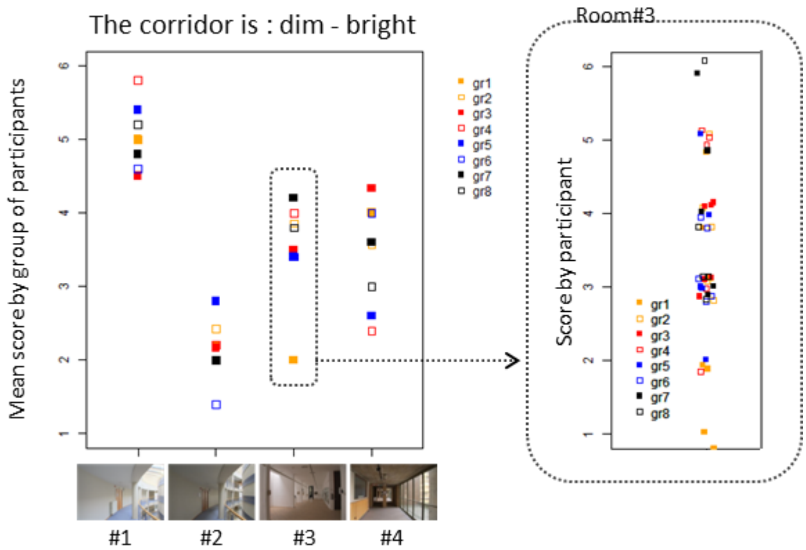


FIGURE III.B.11
Mean score by group of participants regarding question D11 and score by participant regarding the same question for Room #3.

The analysis showed that participants' responses do not contradict the objective analysis based on physical measurements. However, the objective analysis revealed some variations of the lighting conditions in the rooms during the visit by the participants. And a large variation of brightness was detected in Room #3. In order to evaluate whether this variation of the lighting level was detected by the participants, we analyzed the mean score given by each group of participants to question D11 (corridor is dim/bright). As illustrated in Fig.III.B.11, the mean ratings to this question on the perceived lighting level revealed that participants of the first group (gr1) rated Room #3 as particularly dim in comparison to the other groups of participants, which is accordance with physical measurements.

In response to this observation, we decided to pursue the experiment (visualization of images) using the three series of pictures realized in each room. Each subgroup of participants was first assigned to a series of measurements as illustrated in Fig.III.B.12. And, in the following steps of the experiment (visualization of images), rather than asking all the subjects to rate the same images, a part of the participants (28%) visualized the first series of pictures; 49% visualized the second series; and the remaining 23% visualized the third series of pictures.

In taking pictures the day of the real-world experiment, we aimed at reducing the difference, encountered in Newsham et al.'s study (2010), between the luminous conditions experienced by the participants visiting the real spaces and the conditions in the environments when pictures were taken (several weeks before the real-world experiment).In working with the three series of pictures taken in each room the day of the real-world experiment, we hope to balance the variations encountered during the visit of the real-world and to further reduce the bias between the real-world experiment and its reproduction using images.

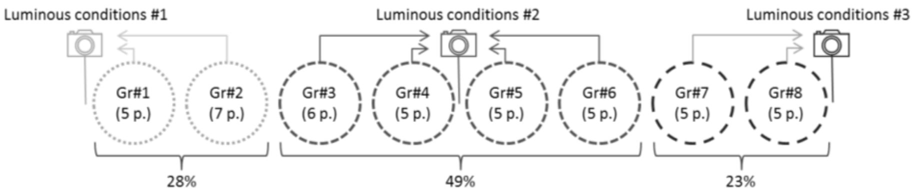


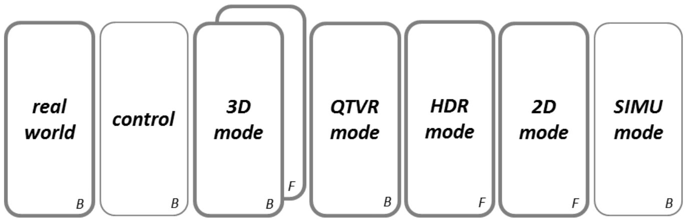
FIGURE III.B.12
Each subgroup of participants was assigned to a series of measurements.

Last, the calculation of the DGP revealed no risk of glare regardless of the room, which concurs with participants' responses. The rating scales related to glare will be nevertheless used in the next steps of the experiment to determine if monitors – specifically, the HDR display – increase the risk of glare, as expected.

Finally, based on the observations presented in Chapter III.A, neither scales of appreciation (which do not highlighted sharp differences between rooms) nor sketches in which participants are asked to circle some areas of interest (they require too much time for encoding) will be used in the next steps of the experiment.

PART IV

ON THE INFLUENCE OF THE PRESENTATION MODE OF IMAGES WHEN ASSESSING VISUAL PERCEPTIONS



This part of the thesis presents the second step of the work: the reproduction of the real-world experiment using photographs. Our objective is to determine whether some presentation modes of images better reproduce the visual perceptions experienced in the real world than traditional 2D images presented on a low dynamic range (LDR) display.

The first chapter describes the creation of the photographs (2D pictures, 3D pictures, panoramic pictures) and characterizes the devices on which these images were displayed – i.e. a conventional LDR display and a high dynamic range (HDR) display.

As explained in Chapter II.B, part of the experiment was organized in France. Before using the real-world experiment carried out in Belgium as the reference for determining whether perceptions are reproduced with images, we first checked that our two populations perceived similarly the appearance of lighting and space. We compared perceptions experienced by Belgian participants visualizing 3D pictures on a LDR display to the perceptions experienced by French participants visualizing the same pictures. The second chapter below presents the results of this comparison.

At last, the third chapter presents the comparison between the perceptions experienced in the actual environment and those produced by visualizing various types of photographs.

CHAPTER IV.A
CREATION OF PHOTOGRAPHS

Various kinds of photographs were realized in the frame of the present work: 2D, 3D and QTVR panoramic pictures. All of them were taken using HDR techniques to capture luminances of the real world while avoiding over or underexposed scenes.

This chapter describes first how these photographs were taken in the actual environments, on the day of the experiment. Then, the capabilities of the two devices on which the pictures were displayed are presented (a conventional low dynamic range (LDR) display device and a high dynamic range (HDR) display device). The need and the choice of a tone-mapping operator for displaying the pictures on the conventional LDR display is also discussed.

IV.A.1. CREATION OF THE IMAGE FILES

One of the objectives of this PhD work was to determine whether some presentation modes of images better reproduce visual perceptions experienced in the real world in comparison to traditional 2D images presented on a conventional LDR display. For the reasons exposed in Chapter I.B, it was decided to investigate more particularly 3D images and QTVR panoramas as well as the potential of HDR display devices.

During the real-world experiment (see Chapter III.A), 2D pictures, 3D pictures and QTVR panoramic pictures were taken in each room on three occasions: just before the visit of the first group of participants, between the third and the fifth group, and just after the visit of the last group. Pictures were taken to create surrogates for the real world but also to capture real-world luminances. HDR imaging techniques were used: a series of LDR pictures were taken varying the exposure time but keeping constant the aperture of the camera. For easy and automatic bracketing, the camera was controlled from a computer using a USB cable thanks to the DSLR Remote Pro software. Pictures were taken with a Canon EFS 17-85mm IS lens mounted on a Canon 40D camera. A tripod was used to avoid camera shakes and get sharp HDR pictures. Moreover, a double axis bubble level was placed on the camera to ensure that the device was level. A Manfrotto 303 panoramic head, with two sliding plates and the possibility to mount the camera in portrait or landscape orientation was used.

Pictures were taken at 160cm from the floor which corresponds to the Belgian average eye height (Motmans, 2005). Pictures' points of view were similar to those of the participants evaluating the actual scenes and were chosen to obtain pleasant 3D pictures to look at. Indeed, the framing of the picture is really important in 3D, as highlighted in our previous study (Cauwerts and Bodart, 2011).

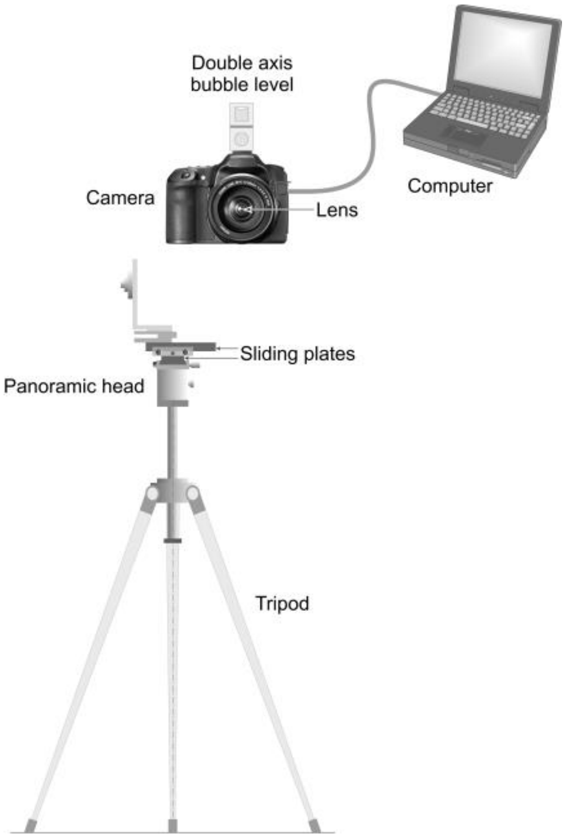


FIGURE IV.A.1
Material required for taking pictures in the real rooms

Pictures were taken with the settings presented in Table IV.A.1. The lowest sensitivity (ISO100) was chosen to reduce the noise in the HDR picture (Inanici, 2006). To calibrate the pictures, luminance of several objects in the room was simultaneously measured with a luminance meter (Minolta LS100).

TABLE IV.A.1
Camera settings

Parameters	Mode
White balance	Daylight
Sensitivity	ISO100
Metering mode	Spot
Image size	3888 pixels * 2592 pixels
Number of f-stops	2
Number of shots	7
Focal length	17mm

The following sections describe the process of creation of 3D, 2D and QTVR pictures.

IV.A.1.1. 3D PICTURES

3D pictures were taken using the material described in Fig.IV.A.1. No zoom was used and the camera was mounted in landscape orientation. The field of view covered was about 66 degrees horizontal and 47 degrees vertical (see Fig.IV.A.2).

FIGURE IV.A.2
Shooting of 3D pictures

As explained in Chapter I.B, the principle of 3D stereoscopic vision is to create illusion of depth in presenting to each eye a slightly different image. The scene should thus be captured twice. Following the recommendations given in (Michel, 2011), the cha-cha method, a very common technique in stereoscopy, was chosen to capture 3D pictures. This method consists in taking a first picture for the left eye and then moving the camera horizontally about 6.5cm to take a second picture for the right eye. This method gives good results with immobile subjects (buildings, objects, and so on). To ensure a perfectly horizontal camera movement, the panoramic head was mounted on the tripod and the horizontality was checked with the bubble level. The camera was moved 6.5cm using the sliding plates, as fast as possible to reduce the time lapse between the two pictures. Instead of taking a single picture for each eye, a series of pictures at various exposure times was taken to recompose HDR picture.

As illustrated in Fig.IV.A.3, the first step in the creation of 3D pictures was the capture of the two series of LDR pictures.

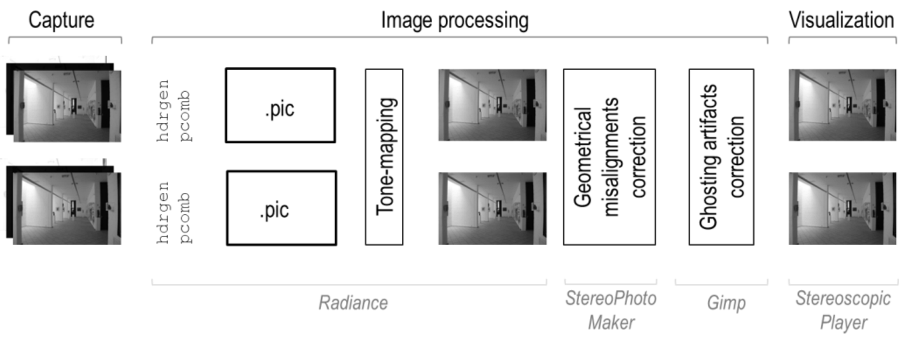


FIGURE IV.A. 3
Process of creation of 3D pictures

The two HDR images (one for each eye) were then recomposed using *hdrgen* program in Radiance and calibrated with *pcomb* using the luminances measured in the real rooms with a luminance meter (Minolta LS100).

3D photographs were intended to be displayed on a conventional LDR display. To adapt the dynamic range of the HDR picture to the range of the conventional monitor, a tone-mapping operator was applied to the picture (tone-mapping operators are discussed in Section IV.A.2.2.). Then, in StereoPhotoMaker, a stereo image editor, some geometrical disparities (barrel distortion and alignment of left and right pictures) were corrected. Finally, ghosting artifacts due to people passing through the corridor during the process of capturing pictures were deleted in Gimp. And, finally, pictures were displayed on a monitor supporting active 3D using Stereoscopic Player, a 3D movie player.

IV.A.1.2. 2D PICTURES

2D pictures were created using the series of LDR pictures captured for the left eye. These pictures were intended to be displayed on a LDR display but also on a HDR display.

For the visualization on the LDR display, similarly to what was done with 3D pictures, a tone-mapping operator was applied in order to adapt the range of luminance of the picture to those of the monitor. As explained in Section IV.A.2.2, tone-mapping parameters for 2D images were different to those used for 3D pictures.

2D pictures to be displayed on the HDR display went, for their part, through a series of transformations described in Section IV.A.3.2.

IV.A.1.3. QTVR PANORAMIC PICTURES

The interest of panoramic pictures is to cover a larger field of view than a traditional picture does, while also displaying an undistorted image (see Chapter I.B). QuickTime Virtual Reality (QTVR) is an image file format which makes it possible. Indeed, contrary to fisheye lens pictures or other panoramic pictures which present high distortions, QTVR creates an immersive virtual environment in which the observer can explore the environment by virtually pivoting his head.

To realize QTVR panoramic images, pictures can be taken using any lens. Using a fisheye lens and an appropriate camera's sensor size, it is possible in one shot to capture the entire human field of view. And, in two shots, it is possible to capture an entire scene (a 360-degree field of view).

Some tests were realized using a Sigma 4.5 mm fisheye lens. It was observed that the resolution of the captured image was not high enough and involved poor quality panoramic pictures (see Fig.IV.A.4a). As the quality of the images presented to the participants is of the utmost importance in this work studying visual perceptions, panoramic pictures were created using a conventional lens, which requires several shots but which results in a panoramic picture of higher quality (see Fig.IV.A.4b).

FIGURE IV.A.4
The quality of the panoramic image varies according to the lens used for shooting (a) Sigma 4.5 mm fisheye lens (b) Canon 17-85mm conventional lens

To maximize the field of view covered vertically, the camera was positioned vertically and was rotated each 30 degrees to be sure that pictures overlap (see Fig.IV.A.5).

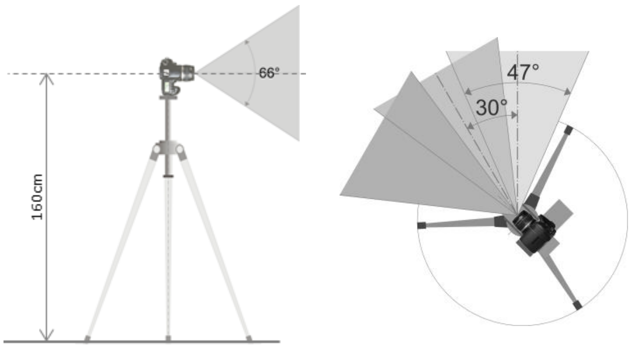


FIGURE IV.A.5
To cover a wider field of view the camera is rotated each 30° around its entrance point

To minimize the disparities between the various pictures composing the panoramic view, the camera was rotated around its entrance point. A method to determine the position of the entrance point of the camera consists in adjusting the camera using the two sliding plates of the panoramic head to find a position that keeps the foreground and background objects aligned when rotating the camera (see Fig.IV.A.6).

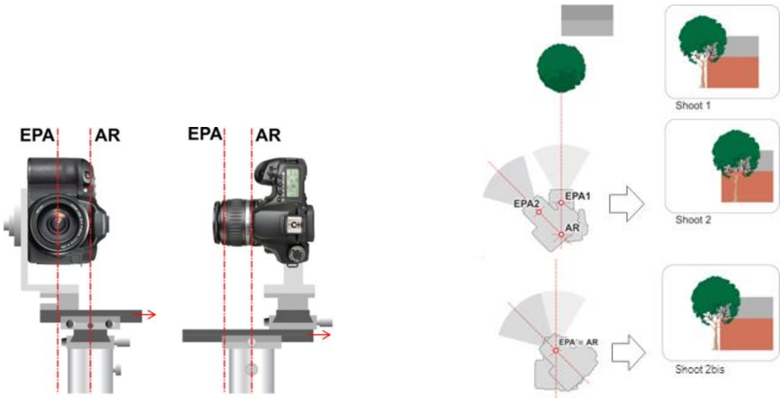


FIGURE IV.A.6
Alignment between the entrance pupil axis (EPA) and the axis of rotation (AR)

Regrettably, due to an inability of the software to merge some adjacent pictures, it was not possible to cover the same visual field in the narrow corridors (Room#1 and Room #2). Table IV.A.2 presents the field of view (FOV) covered by the 2D and 3D pictures and those covered by the panoramic pictures. In the third room, the point of view for the 2D and 3D pictures is slightly different from the panoramic picture vantage point for framing questions. This table also mentions for each picture, its vertical and horizontal FOV.

TABLE IV.A.2
Field of view covered by 2D, 3D and panoramic pictures, in each room

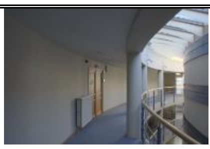
	2D and 3D pictures	Panoramic pictures
Room #1	 *47° × 66°*	 *66°× 100°*
Room #2	 *47° × 66°*	 *66°× 100°*
Room #3	 *47° × 66°*	 *66°× 180°*
Room #4	 *47° × 66°*	 *66°× 140°*

Figure IV.A.7 summarizes the process for creating QTVR panoramic pictures. The scenes were first captured as explained here above. For each exposure time, multiple images then were stitched into several LDR panoramas in PTguiPro.

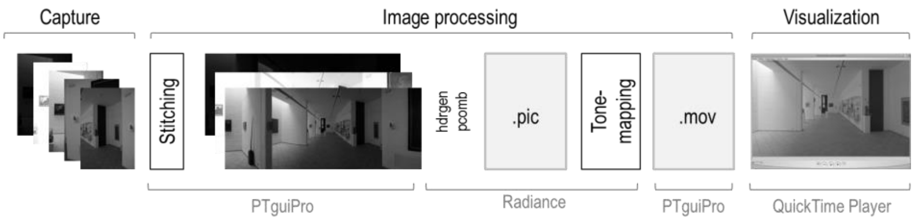


FIGURE IV.A.7
Process for creating panoramic pictures

The LDR panoramas were then merged into a HDR panorama using Radiance software and were calibrated using the luminances measured in the actual environments with the luminance meter. At last, as QTVR panoramic pictures were intended to be displayed on a conventional display, pictures were tone-mapped. They were finally converted into a QTVR panoramic picture (.mov) in PTguiPro software.

IV.A.2. DISPLAYING PICTURES

To be visualized by the participants, image files were displayed on two types of devices: a conventional LDR monitor and a HDR device capable of displaying a wide range of luminances. This section presents first the performances of the conventional LDR monitor. The necessity and the choice of a tone-mapping operator for displaying the pictures on this display are then discussed. Finally, the HDR display device is characterized and some improvements of the system are presented.

IV.A.2.1. PERFORMANCES OF THE CONVENTIONAL LDR DISPLAY

Except for the HDR mode, the images were displayed on a Samsung SyncMaster 2233RZ which is a LDR monitor offering the possibility to visualize in 2D or in 3D thanks to its 120Hz refresh rate and a Nvidia 3D Vision Kit. Table IV.A.3 presents the geometrical characteristics of the monitor.

TABLE IV.A.3
Geometrical characteristic of the Samsung SyncMaster 2233RZ

Parameter	Mode
Diagonal	22 inches (56cm)
Resolution	1680*1050 pixels
Aspect ratio	16:10

IV.A.2.1.1. *LUMINOSITY*

The range of luminances displayable with the Samsung monitor was determined using HDR imaging techniques coupled with physical luminance measurements. In

2D mode, range of displayable luminances varies between 2.5cd/m² (black pixel) to 200cd/m² (white pixel). Performances in 3D modes are not identical due to the wearing of active glasses which cause about 50% loss of luminances (Michel, 2011).

IV.A.2.1.2. *GAMMA CURVE*

The gamma curve which is another important characteristic of the monitor was also determined (it was not specified in the documentation of the monitor). The gamma is a power function describing the relation between the input RGB and the output luminance as following:

$$Lum_{out} = RGB^{gamma}$$

EQUATION IV.A.1
Determination of the gamma of the monitor. Lum$_{out}$ is the output luminance and RGB is the input RGB value.

To determine the gamma curve of the monitor, five shades of gray were displayed in 2D mode and in 3D mode and their luminance was measured. As illustrated in Fig.IV.A.8, the relation between the input RGB and the displayed luminances varies according to the mode of the monitor (2D mode or 3D mode). A gamma of 2.2 is founded for 2D mode while a gamma of 1.7 is determined for 3D mode.

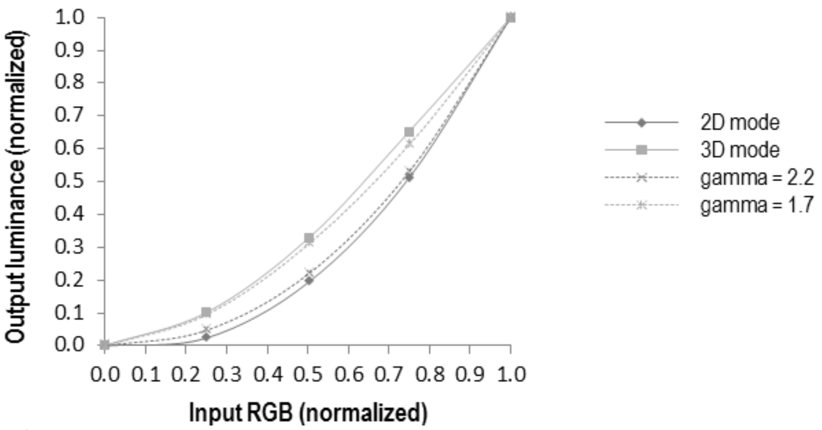


FIGURE IV.A.8
Gamma curve of the Samsung monitor in 2D and 3D modes

Table IV.A.4 summarizes the luminance performances of the monitor.

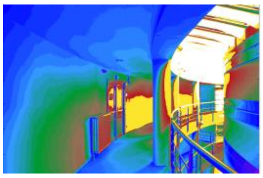
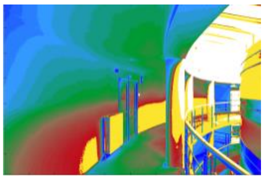
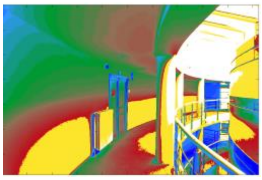
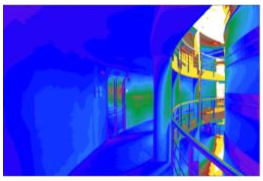
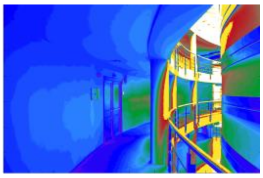
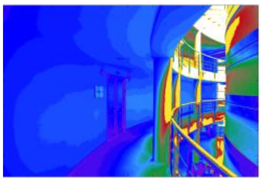
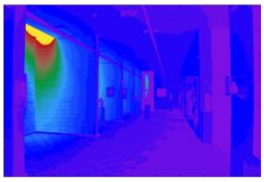
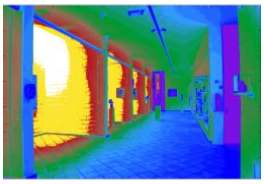
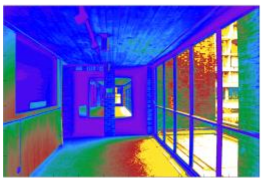
TABLE IV.A.4
Luminance performances of the Samsung display

	2D mode	3D mode + active glasses
Lwhite_mean	200 cd/m²	100 cd/m²
Lblack_mean	2.5 cd/m²	1.25 cd/m²
Gamma	2.2	1.7

IV.A.2.2. Choice of a tone-mapping operator

Pictures were realized using HDR imaging techniques to capture luminances of the actual environments and avoid over or underexposed scenes. However, current conventional monitors are not able to display accurately most of these pictures because the range of luminances encountered in the real world does not match with the range of luminances displayable by the monitor. Indeed, the range of luminances displayable with our conventional display varies between 2.5 and 200cd/m² in 2D mode and 1.25 and 100cd/m² in 3D mode, while the range of luminances captured in the visited room varies between about 0 and 7700 cd/m² (see Table IV.A.5). And, even if, as illustrated, the major part of the pictures presents luminances under 100cd/m², some areas have higher luminances which cannot be displayed by the conventional display.

TABLE IV.A.5
Parts of the pictures are saturated when displayed on the conventional display (yellow and white areas in 3D mode and white areas in 2D mode).

	TOUR #1	TOUR #2	TOUR #3	
Room #1				
	2.1 - 7 132 cd/m²	3.1 - 3 288 cd/m²	4 - 3 220 cd/m²	
Room #2				
	1.3 - 7 632 cd/m²	1.5 – 3 679 cd/m²	1.15 – 1 274 cd/m²	
Room #3				
	0.3 - 135 cd/m²	1.2 - 653 cd/m²	0.8 - 369 cd/m²	
Room #4				
	0.02 - 4 296 cd/m²	0.4 - 891 cd/m²	0.5 - 853 cd/m²	

Hopefully, in parallel to the development of HDR devices for displaying HDR files, tone-mapping operators (TMO) were developed for visualizing the HDR content on conventional LDR monitors. As illustrated in Fig.IV.A.9, these algorithms aim at adapting the large range of luminances of the actual scene (contained in the HDR file) to those of the display device while reproducing the visual impressions experienced in the actual environment (Reinhard et al., 2006).

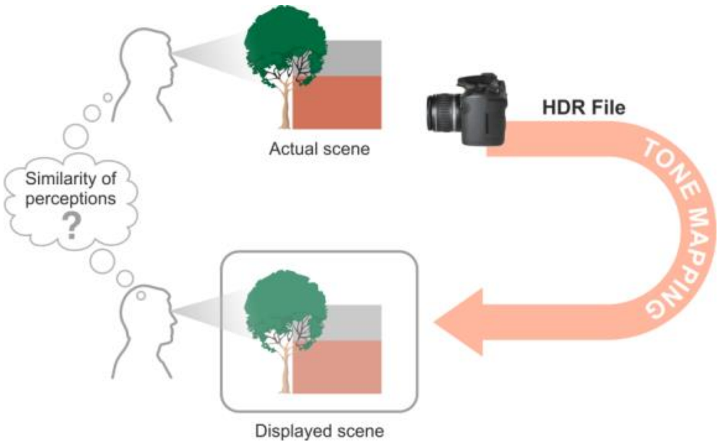


FIGURE IV.A. 9
Tone-mapping process

TMO can be classified in two main categories: global operators and local operators. Global operators apply an identical curve to the entire image which can lead to a loss of visibility or contrast. Local operators try to tackle this problem in applying a curve adjusted according to the neighboring of each pixel. As illustrated in Fig.IV.A.10, the choice of the operator greatly influences the rendering of the picture.

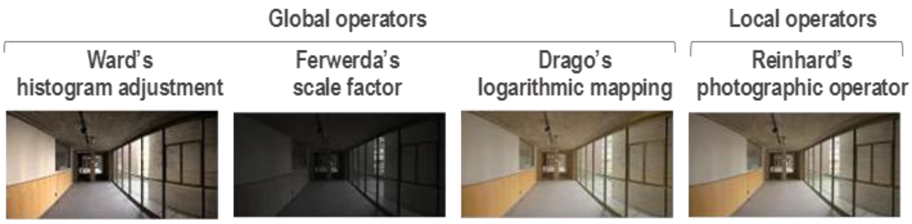


FIGURE IV.A.10
A same scene tone-mapped using various operators (default parameters are used).

Lots of studies carried out on the quality of TMO have compared several operators between them (Drago et al., 2003) or with pictures displayed on HDR displays (Ledda et al., 2005). Few studies attempted to compare tone-mapped pictures to real-world scenes as did Yoshida et al. (2005). In this study, the authors evaluated seven TMO in conducting direct comparison between real-world scenes and tone-mapped images presented on a LDR display. Participants rated naturalness, contrast, brightness, details reproduction in bright and dark scenes in taking real-world scene as the reference. The authors tested four global tone-mapping operators (linear mapping, Ward's histogram adjustment, Pattanaik TMO and Drago logarithmic mapping) and three local operators (Reinhard's photographic operator, Ashikhmin TMO and bilateral filtering). The study highlighted differences between local and global operators: images tone-mapped using a global operator were perceived as brighter and presenting a higher contrast while local operators seems to preserve details in bright regions. Moreover, Yoshida et al. observed that naturalness was better reproduced with Ward, Reinhard and Drago operators.

On the basis of this study, and after some pre-tests on our scenes, we decided to work with the Reinhard photographic operator, similarly to Tai and Inanici (2010) did for studying space perception and luminance contrast using virtual renderings. Indeed, this operator preserves both naturalness and details in bright regions. However, even if this algorithm gives satisfying results, it leaves to the appreciation of the user the setting of some important parameters whose the key value, a parameter which greatly affects the overall luminosity of the picture as illustrated in Fig.IV.A.11. And while lots of studies have been carried out on the comparison between the various TMO, few have questioned the setting of the parameters influencing the final rendering.

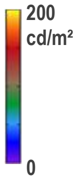
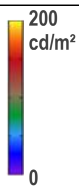
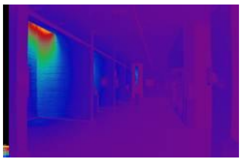
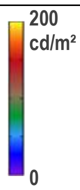
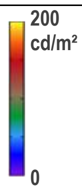
FIGURE IV.A.11
Influence of the key value parameter on the final rendering (a) key = 0.09 (b) key = 0.18 (default) (c) key = 0.36

As a result of a pilot test realized using default parameter, a key value minimizing the relative error between real-world luminances and luminances extracted from the tone-mapped image was preferred. Indeed, we observed that the use of the default key value minimized the differences of brightness between the rooms, as presented in (Cauwerts, 2013). To determine the optimized key values for each scene, mean maximum luminance and mean minimum luminance of the monitor were used (tone-mapping parameters are thus different for 2D pictures and 3D pictures). On the basis of these values, theoretical luminances of the tone-mapped image were calculated. Relative error between real-world luminances and tone-mapped luminances was determined at each pixel. Finally mean relative error (MRE) for the entire picture was calculated. The key value minimizing this error was determined using an iterative process.

As illustrated in Table IV.A.6, the general luminosity of the image tone-mapped with the optimized key is more similar to the real world than the image tone-mapped with the default key value.

TABLE IV.A.6

Comparison between luminances captured in the actual rooms and luminances of the pictures tone-mapped with the default key value or the optimized one (2D pictures – Tour #1)

	Real world	Default key value	Optimized key value	
ROOM #1				
		Key value = 0.18 MRE = 14.3%	Key value = 0.19125 MRE = 13.1%	
ROOM #2				
		Key value = 0.18 MRE = 92.1%	Key value = 0.0675 MRE = 12.6%	
ROOM #3				
		Key value = 0.18 MRE = 285%	Key value = 0.03375 MRE = 41.4%	
ROOM #4				
		Key value = 0.18 MRE = 89%	Key value = 0.07875 MRE = 26.7%	

MRE : mean relative error with the real-world map as the reference

IV.A.2.3. PERFORMANCE OF THE HDR DISPLAY SYSTEM

As illustrated in Table IV.A.5, some parts of the pictures are out of the range of luminances displayable by the Samsung monitor. There is thus an interest in using a HDR display device for displaying the pictures to the participants. In order to evaluate the potential of this kind of display for studying the appearance of daylit spaces, I spent six months in the LGCB laboratory at ENTPE in France, which has developed a HDR display since 2011.

This section presents first the HDR display device originally developed at LGCB for displaying both higher luminances and larger pictures than the few existing HDR displays (Aubry, 2011). Improvements made to the system in the frame of this PhD work are then described.

IV.A.2.3.1. *DESCRIPTION OF THE AVAILABLE HDR DISPLAY SYSTEM*

As explained by Aubry (2011), the display device developed at ENTPE consists of a rear projection system with dual projectors to which bitmap image files are sent. In order to cover a large range of luminances, the two projectors do not present the same characteristics in terms of luminosity, as described in Table IV.A.7.

TABLE IV.A.7
Characteristics of the two projectors

	Projector #1	Projector #2
Model	Christie LX1500	Hitachi CP-SX635
Flux	15 000 lumen	4 000 lumen
Resolution (pixels)	1024 pixels*768 pixels	1400 pixels*1050 pixels
Aspect ratio	4:3	4:3

As expected, Aubry observed that the luminances displayed on the screen vary according to the distance between the screen and the projectors and according to the position of the observer in front of the screen. He also observed that the projection on the non-lambertian screen leads to a high non-uniformity of the displayed luminances and the presence of two hotspots (see Fig.IV.A.12).

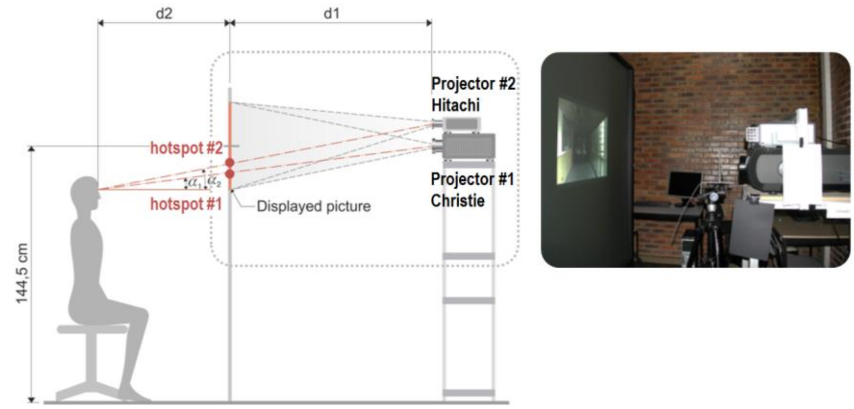


FIGURE IV.A.12
Parameters influencing the displayed luminances and the location of the hotspot

Aubry determined the position of the screen (130cm from the projectors) to have a larger picture than the existing HDR displays while keeping high luminances. He also fixed the position of observation at 200cm from the screen and 120cm high. The result is a picture of 49inches (see Fig.IV.A.13). When the two projectors display a white blank screen, luminance at the center of the screen is about 18000cd/m². It is reduced to 4000cd/m² at the left border. When the two projectors display a black blank screen, luminance at the center is 14cd/m², and, at the left border, 5cd/m².

Aubry determined that, in comparison with the first projector (Christie), the second one displays luminances weaker by a factor of about 7.

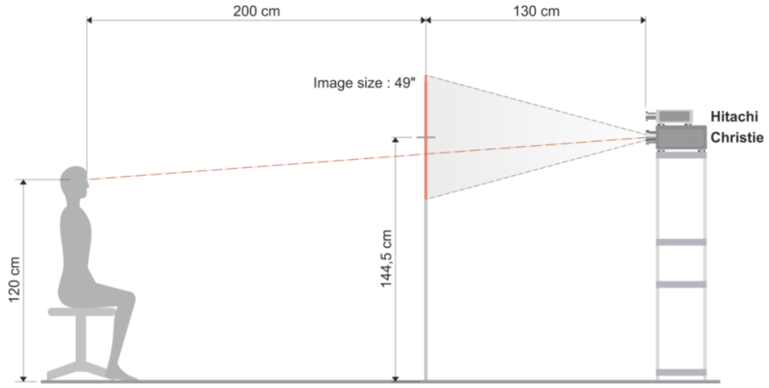


FIGURE IV.A.13
Aubry's configuration

In order to display actual luminances contained in the HDR file, Aubry's approach is the following. Firstly and similarly to what we did in a previous work (Cauwerts and Bodart, 2010), a correction is applied to the HDR picture file to counter the non-uniformity of the luminances displayed on the screen. This correction also integrates the gamma curve of each projector. Then, the HDR picture file is converted into a file format readable by the projectors (a bitmap file format). This conversion leads to a loss of information that can cause the apparition of halos in the picture, as illustrated in Fig.IV.A.14.

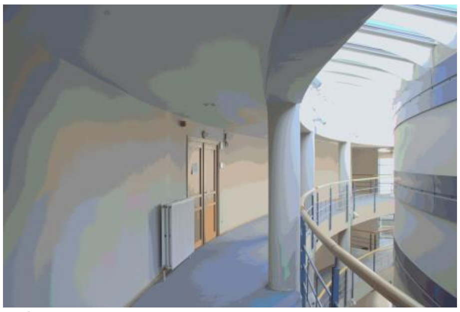


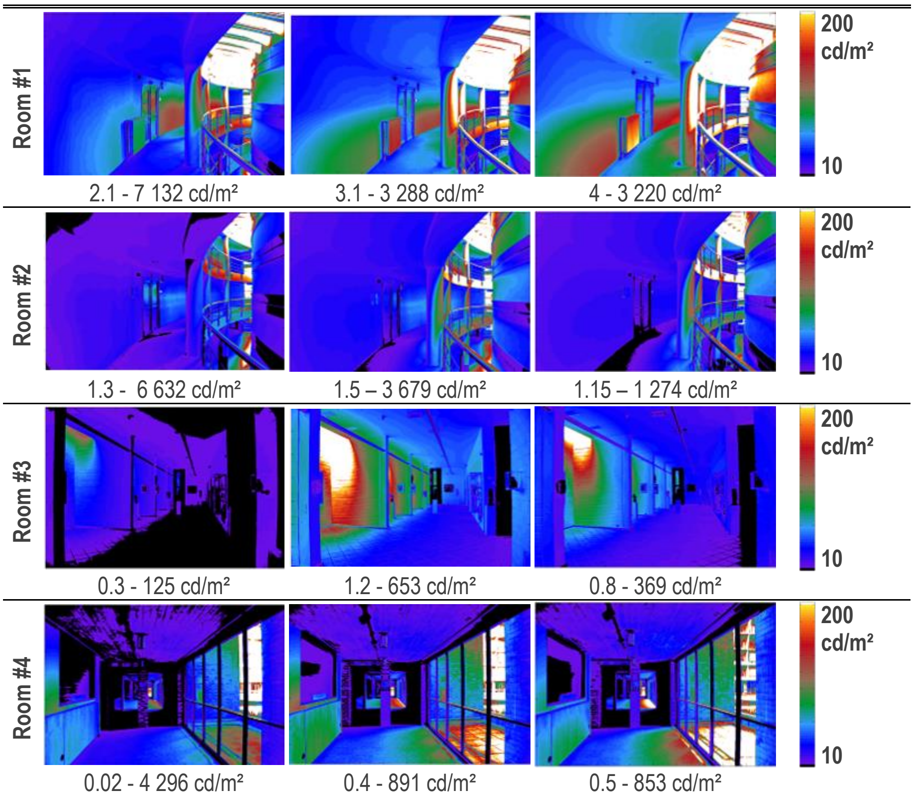
FIGURE IV.A.14
Illustration of the types of halos that can be caused by the compression of the HDR picture into a LDR file format

This RGB picture file is then displayed by the most powerful projector (Christie projector). The second projector (Hitachi projector) was planned to be used to minimize the halos. However, a perfect alignment between the two pictures projected by the two devices was not reached, and in most of the projections currently carried out at ENTPE, only the most powerful projector is used, as in Gatel's study (2011) and Villa's work (2012).

IV.A.2.3.2. *IMPROVEMENT OF THE HDR DISPLAY SYSTEM*

Our 2D pictures captured in the actual environments were first projected using the Aubry's approach. But lots of halos were caused by the conversion from HDR to LDR file format. Moreover, as illustrated in Table IV.A.8, important parts of Room #3 and Room #4 present luminances inferior to 10cd/m² that cannot be displayed by the device in this configuration (zones colored in black).

TABLE IV.A.8
Luminances captured in the actual environments the day of the experiment



An approach different from the Aubry's approach was adopted to display luminances lower than 10cd/m², and to increase the dynamic range of the device (quite low in comparison with existing display devices, as presented in Table IV.A.9).

TABLE IV.A.9
Comparison of the luminosity performances of various displays

Name	Max. lum.	Dynamic range	Size
Samsung SyncMaster 2233rz (2D mode)	200 cd/m²	80:1	22inches (56cm)
SunnyBrook/Brightside (Seetzen et al., 2004)	2700 cd/m²	54000:1	15inches (38cm)
Sim2 (SIM2)	4000 cd/m²	1000000:1	47inches (119cm)
ENTPE (Aubry, 2011)	18000 cd/m²	300:1	49inches (124cm)

To reduce the halo effect, the idea was to display the low luminances of the picture with the second projector (Hitachi projector) and to display high luminances with the first projector (Christie projector) which is capable to generate high luminosities. The position of the observer (viewing height at 144.5cm from the ceiling and viewing distance at 75cm from the screen) was determined to cover the same field of view than the one covered with the Samsung conventional display (see Fig.IV.A.15).

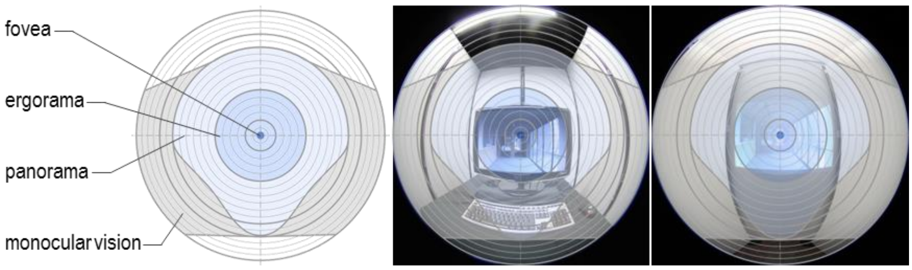


FIGURE IV.A.15
A similar field of view is covered by the two devices: (a) Human field of view (b) Field of view covered by the Samsung display (c) Field of view covered by the HDR display device

The position of the screen (115cm from the projectors) was then determined to reach the maximum luminances of the scenes with the most powerful projector (Christie). This configuration results in an image of 33'' and the luminances illustrated in Fig.IV.A.17. To ensure both high luminances with the first projector and low luminances with the second one, a tinted glass (light transmittance of 13%), was placed in front of the second projector to reduce displayable luminances (see Fig.IV.A.16).

FIGURE IV.A.16
The tinted glass placed in front of the second projector to reduce displayable luminances

As illustrated in Fig.IV.A.17, placing this tinted glass in front of the second projector makes it possible to cover a wider range of luminances with the two projectors (from 7 to 26000cd/m² instead of 56 to 26000cd/m², at the center of the screen). The dynamic range of our device increases so from about 1:460 to 1:3700.

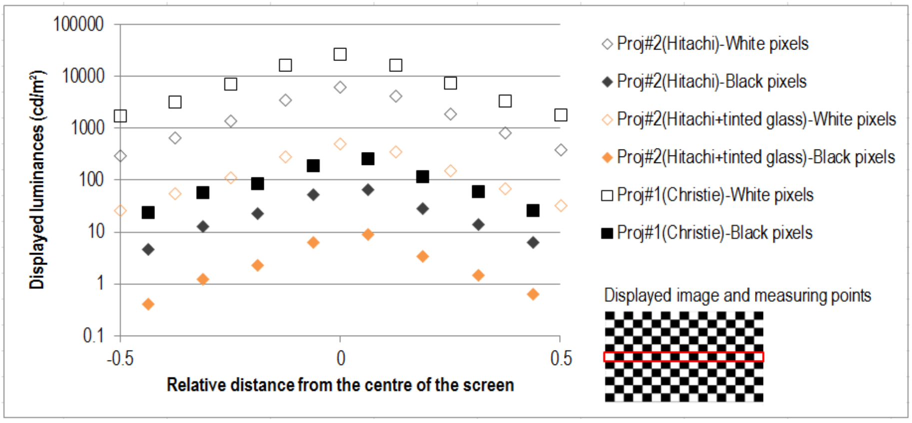


FIGURE IV.A.17
Range of luminances displayable by each device

Thanks to this configuration, the major part of the picture can be displayed with the second projector whose range of luminance varies between 7 and 470cd/m², at the center of the screen, and between 0.2 and 24 at the left border. Pixels of the scenes whose the luminance is higher than the capabilities of this projector are displayed using the first projector (see Fig.IV.A.18).

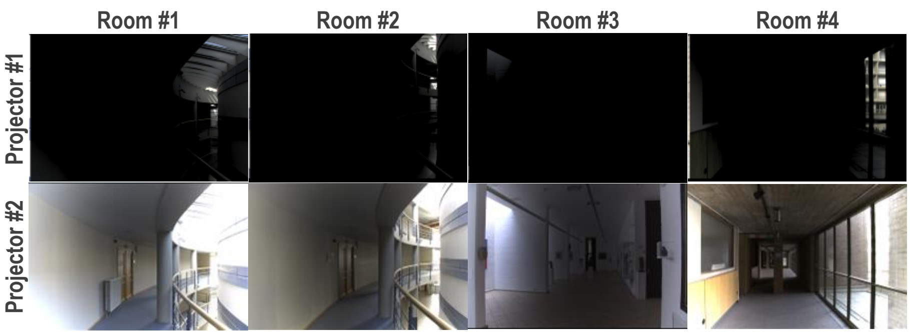


FIGURE IV.A.18
Picture projected by each projector

This configuration made it possible to reduce the artifacts due to the compression of the pictures from HDR to LDR file format. However, this configuration does not settle the problem of the residual light as a black pixel still emits about 7cd/m² at the center of the screen (see Fig.IV.A.17). For very dark scenes, this residual light is a problem as illustrated in Fig.IV.A.19.

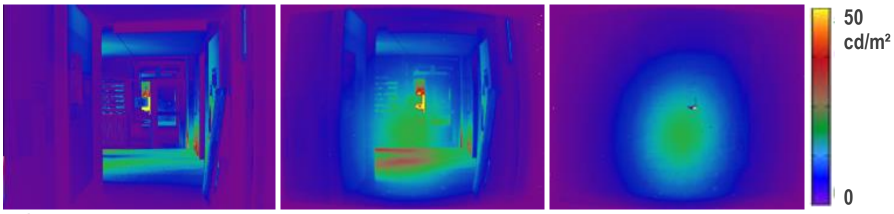


FIGURE IV.A.19
(a) Luminances to be displayed; (b) Displayed luminances; (c) Residual light

To tackle the problem, black masks were designed to block the residual light coming from the first projector (see Fig.IV.A.20).

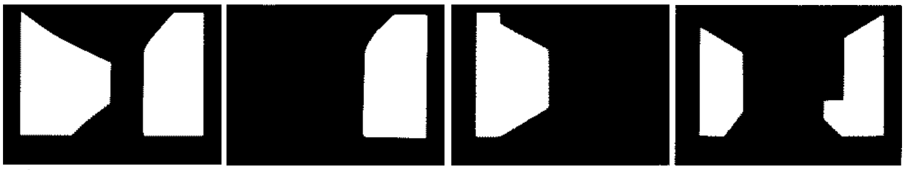


FIGURE IV.A.20
Black masks for (a) Room #1 (b) Room #2 (c) Room #3 (d) Room #4

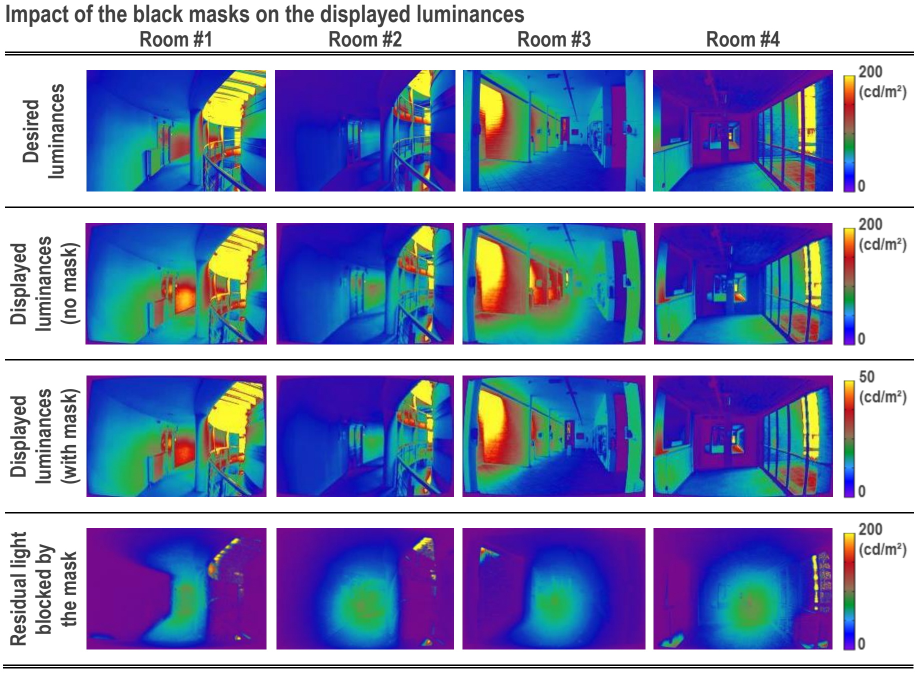
These masks cut out of black cardboard and were placed in front of the first projector, as illustrated in Fig.IV.A.21.


FIGURE IV.A.21
Masks placed in front of the first projector

To check that desired luminances were accurately displayed, HDR pictures of the screen were realized using HDR imaging techniques. Table IV.A.10 compares desired luminances, displayed luminances without the mask and displayed luminances when the mask is placed in front of the first projector. Residual light catched by the mask is presented in the last row.

TABLE IV.A.10

Impact of the black masks on the displayed luminances



Thanks to the mask, differences between displayed luminances and desired luminances are reduced.

IV.A.3. Conclusion

This chapter first presented the way pictures visualized by the participants were created. Display devices were then described.

Special care was taken to ensure the similitude between the actual lit environments and the photographic pictures. We tried to create images reproducing at best the lighting ambience. We used HDR imaging techniques to avoid over or underexposed scenes. We observed that the post-processing needed to achieve high quality 3D and QTVR pictures in which artifacts are reduced is non-negligible.

Visualizing HDR pictures on a conventional LDR display necessitates the use of a tone-mapping operator (TMO). The fact that the setting of important TMO parameters influencing the appearance of the lighting is left to the appreciation of the user was highlighted. At last, before realizing the HDR mode, some changes had to be brought to the system available at ENTPE to avoid artifacts and to display accurately luminances experienced in the real world.

CHAPTER IV.B
PERCEPTUAL DIFFERENCES BETWEEN BELGIAN AND FRENCH PEOPLE

This chapter presents the comparison between a phase of the experiment (3D phase) organized in Belgium and then replicated in France (see Fig.IV.B.1).

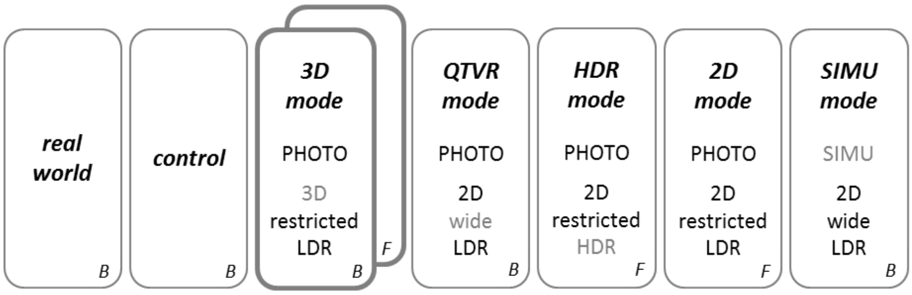


FIGURE IV.B.1
A same phase was organized in Belgium (B) and in France (F) to determine potential differences of perceptions between the two samples of participants

The objective of this analysis is to determine whether differences of perception exist between the two samples of participants. If no difference is observed, the real-world experiment organized in Belgium will be used as the reference to evaluate whether perceptions experienced in the actual environment are reproduced when visualizing pictures. The modes tested in France (HDR and 2D modes) will be compared to the real-world experiment. If the results observed in Belgium are not replicated in France, QTVR and $3D_{belgium}$ modes will be compared to the real-world experiment carried out also in Belgium and $3D_{france}$ and HDR modes tested in France will be compared to the 2D mode also tested in France.

IV.B.1. MATERIAL AND METHOD

The experiment realized in the actual environment and presented in Chapter III.A (real world experiment) was first reproduced in Belgium using 3D pictures, during April 2012. The experiment was then organized in France, in November 2012. The visualization of the pictures was done on a same monitor (a Samsung 2233rz display device whose the characteristics are presented in Chapter IV.A). Participants were invited to visualize the pictures in a black room for improving the immersion into virtual scenes and for avoiding the flickering experienced with 3D displays, in lit rooms (see Fig.IV.B.2).

The visualization of the pictures was individual and took between 45 and 60 minutes by participants. As explained in Chapter III.B, to reduce the bias between the real-world experiment and its reproduction using images, 28% of participants visualized the first series of pictures, 49% the second series and 23% the last series.

Before visualizing pictures and during about ten minutes, participants received the instructions (always given by the same person).

FIGURE IV.B.2
Experimental conditions for the visualization of 3D pictures (a) in Belgium and (b) in France

Similarly to what was organized in Newsham et al.'s experiment (2010), before visualizing the first scene and between each scene, a blank background screen was displayed for 30 seconds. Its luminance corresponded to the mean luminance of the four assessed scenes (42cd/m² for the first series of pictures; 66cd/m² for the second series of pictures and 64cd/m² for the last one). After these 30 seconds, the scene was displayed on the screen and the participant was invited to immerse in it for 30 seconds. After this minute of adaptation, the participant was asked to respond to the questionnaire. When he finished, he pursued with the next scene. The rooms were presented in the same order than the visit of the actual environments to minimize the bias between the experiment in the real world and its reproduction using pictures.

IV.B.1.1. PARTICIPANTS

Two samples of participants presenting similar characteristics in terms of language, age, gender and educational background as participants of the real-world group were built (see Table IV.B.1). Participants were recruited by e-mails and were paid 15 euros.

TABLE IV.B.1
Characteristics of the samples of participants

Phase	Real world	$3D_{belgium}$	$3D_{france}$
Location	Belgium	Belgium	France
Number of participants (women, men)	43 (26, 17)	40 (23,17)	40 (23,17)
Native language	French	French	French
Educational background	Students at UCL	Students at UCL	Students at ENTPE
Age (mean +/- standard deviation)	21.8 +/- 1.7	21.7 +/- 1.8	21.2 +/- 1

In Belgium, participants were students at UCL. In France, students were recruited at ENTPE and were exclusively students in engineering.

IV.B.1.2. QUESTIONNAIRE

Participants were asked to respond to the same questionnaire than the one used in the real-world experiment. To not introduce a bias linked to the modification of the protocol, the participants responded on a printed questionnaire, similarly to what was done in the real-world phase.

IV.B.2. RESULTS

IV.B.2.1. RATING SCALES

Rather than performing repeated-measure ANOVA's on the rating scales as in Chapter III.A, a linear mixed model was used to improve the statistical analysis. Indeed, linear mixed models present the advantages over more traditional repeated-measure analyses of variance to reduce the loss of data due to missing observations.

The following approach, illustrated in Fig.IV.B.3, was used to determine whether perceptions of the Belgian participants were different to those of the French group. Each rating scale was analyzed separately.

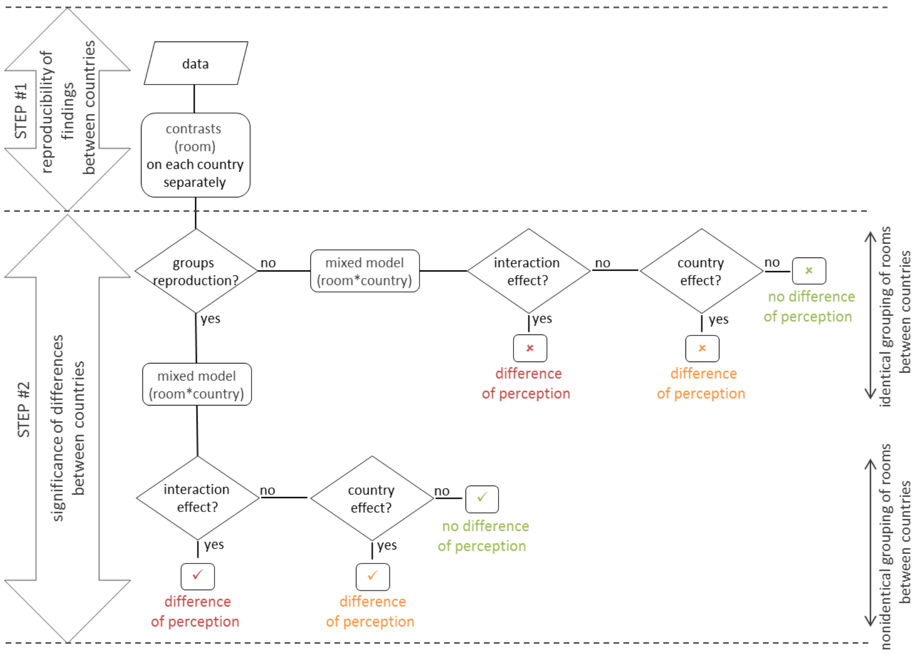


FIGURE IV.B.3
Illustration of the approach used to determine whether perceptions of the Belgian participants are different to those of the French group.

The first step of the analysis consisted in performing a contrast analysis on each group of participants separately (Belgian or French group) to evaluate the reproducibility of the findings. This contrast analysis (an equivalent of post hoc tests) allowed the determination of groups of rooms which do not present significant differences. In this analysis, the fixed effect was the room and a random variance among subjects was introduced in the model to better take into account the fact that several observations were made by a same subject (each subject rated four rooms). Assumptions of linear regression (linearity, independence, homoscedasticity and normality) were tested graphically. If necessary, a log-transformation was applied to the scale to assume the linearity.

The second step of the analysis consisted in performing a mixed model analysis on the whole data set to determine whether differences of visual perceptions between Belgian participants and French participants were significant. In this model, the fixed effects were the country (Belgium or France) and the room. The subjects were set as random effect. The Akaike information criterion (AIC) which is a measure of the quality of a statistical model was used to judge whether adding interaction between country factor and room factor improves the model. Between the model with room-country interaction and the model without interaction, the preference was for the model presenting the smaller AIC, and thus a better fit of the model to the data. Then, to interpret the country-room interaction, contrasts were tested. The rooms presenting significant differences between the two groups of participants were finally determined.

As illustrated in Fig.IV.B.3, at the end of the analysis made on each rating scale separately, if neither interaction nor country effect was detected (✓/×), perceptions of the two populations are judged as not different and the real-world experiment is used as the reference for the following steps of the experiment.

Statistical analyses were performed using R software. Descriptive results are presented in Appendix III.

IV.B.2.1.1. *VISUAL APPEARANCE OF SPACE*

Fig.IV.B.4 compares the mean ratings given by each group of participants (Belgian or French subjects) for pleasantness and enclosedness dimensions. This figure also illustrates the results of the first step of our analysis: the reproducibility of the findings of the Belgian experiment ($3D_{Belgium}$ group) with the French population ($3D_{France}$ group).

For each dimension (pleasantness-P0 and enclosedness-E0), a linear mixed model was performed on each group of participants separately ($3D_{belgium}$ and $3D_{france}$). The contrast analysis made possible the determination of the groups of rooms which do not differ significantly, in each country. As a result of this analysis, Fig.IV.B.4 indicates by a color these groups of rooms (in each country, the rooms sharing a same color do not differ significantly).

As shown in Fig.IV.B.4, the range of scores for the pleasantness dimension varies between 3.1 and 4.4 for $3D_{belgium}$ group and 3 and 3.9 for $3D_{france}$ group. For the enclosedness dimension, the ranges are also similar between the two samples of participants and vary between 2.6 and 3.7 for $3D_{belgium}$ group and 2.8 to 4.1 for $3D_{france}$ group. Regardless of the sample of participants, on average, Room #1 is perceived as being the most pleasant and Room #4 as the least pleasant. The most enclosed room is Room #4 and the least enclosed is Room #1.

The contrast analysis shows that while the rooms are ordered in an identical way regardless of the country, groupings resulting from the contrasts analysis are different (see Fig.IV.B.4).

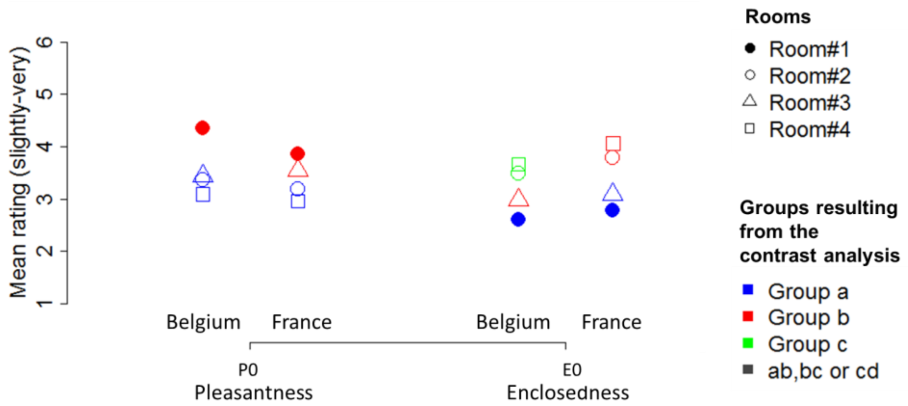


FIGURE IV.B.4
Visual appearance of the space - reproducibility of findings. Rooms sharing a same color do not differ significantly.

The second step of the analysis consisted in performing a mixed model analysis on the whole data set to determine whether differences observed between the two groups of participants were significant or not. The smaller the AIC, the better the fit, the preference is, as presented in Table IV.B.2, for the model without interaction whatever the dimension (pleasantness or enclosedness).

TABLE IV.B. 2
Visual appearance of the space – statistical differences between phases

Factor		**AIC** without interaction	**AIC** with interaction	**MCMC mean**	**p-value**	**Signif.**
Pleasantness	**P0**	816.28	818.13	-0.15	0.11	-
Enclosedness	**E0**	848.51	853.06	0.27	0.05	*
Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.						

As shown in Table IV.B.2, no effect of country is observed for pleasantness dimension but a small effect is detected for the enclosedness dimension: the French participants perceived, on average by 0.27 points on the scale, the scenes as significantly more enclosed.

Figure IV.B.5 illustrates mean ratings to the additional questions related to the perception of the space.

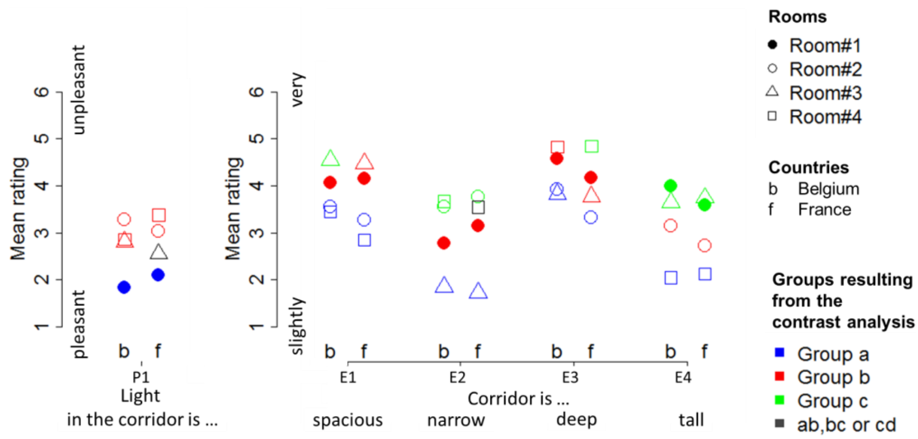


FIGURE IV.B.5
Visual appearance of the space (additional questions) - reproducibility of findings. Rooms sharing a same color do not differ significantly.

To determine the presence of an effect of the country, a mixed model analysis was performed on the whole data set. The smaller the AIC, the better the fit, the preference is for the model without interaction regardless of the scale (see Table IV.B.3).

TABLE IV.B.3
Visual appearance of the space (additional questions) – statistical differences between phases

Factor		AIC without interaction	AIC with interaction	MCMC mean	p-value	Signif.
Pleasantness	P1	1025.0	1025.5	0.0743	0.58	-
Enclosedness	E1	1009.6	1012.2	0.2167	0.12	-
	E2	908.68	908.82	0.0874	0.58	-
	E3	974.90	975.63	-0.2550	0.12	-

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

No significant effect is detected between the Belgian sample and the French one as presented in Table IV.B.3.

The comparison of the two populations only revealed a significant effect of the country on the enclosedness dimension (P0): the French participants perceived the rooms as more enclosed than the Belgian ones.

IV.B.2.1.2. *VISUAL APPEARANCE OF LIGHTING*

The result of the first step of our analysis (contrast analysis) on the scales related to the appearance of lighting is presented in Fig.IV.B.6.

As a result of this analysis, we observed that the grouping of rooms is identical, regardless of the country, for four of the 12 rating scales related to the appearance of lighting: D12, D31, D51 and D63 (see Fig.IV.B.6).

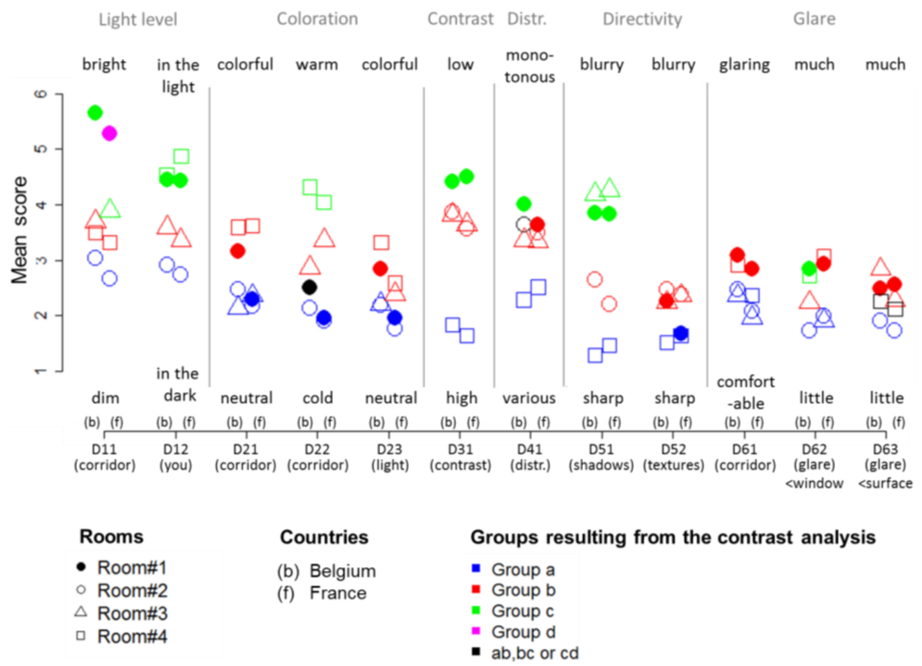


FIGURE IV.B.6
Visual appearance of the lighting - reproducibility of findings

As presented in Table IV.B.4, according to the AIC criterion, adding the interaction between the country and the room factor improves the model for the three questions related to coloration (D21, D22, D23) and one related to the directivity (D52). The presence of these interactions indicates that, for these ratings, the country effect varies according to the level of the room factor. For the other scales, no interaction effect was detected and only the country effect is analyzed (see Table IV.B.4).

As shown in this table, Room #1 is perceived as being least colorful and colder by the French sample of participants than by the Belgian one (see D21, D22 and D23). Moreover this room is perceived by the French sample similarly to Room #2 while the Belgian sample did a differentiation between the two spaces. Room #3 is perceived as warmer by the French sample and the lighting in Room #4 as less colorful. Textures in Room #1 are also perceived as sharper by the French group (see D52).

TABLE IV.B.4
Visual appearance of the lighting – statistical differences between phases

Factor	Ref.	AIC without interaction	AIC with interaction	Room	MCMC mean	p-value	Signif.
Brightness	D11	976.17	978.16		-0.1796	0.21	-
	D12	1025.6	1028.4		-0.0185	0.94	-
Coloration	D21	1020.2	1016.2	#1	-0.8651	0.0011	**
				#2	-0.3162	0.24	
				#3	0.2199	0.39	
				#4	0.0275	0.92	
	D22	972.73	967.05	#1	-0.5543	0.03	*
				#2	-0.2285	0.35	
				#3	0.5036	0.04	*
				#4	-0.2741	0.26	
	D23	997.21	990.89	#1	-0.8775	0.0008	***
				#2	-0.4333	0.09	
				#3	0.1779	0.50	
				#4	-0.7295	0.0011	**
Contrast	D31	981.41	985.77		-0.144	0.36	-
Distribution	D41	1114.1	1117.8		-0.0781	0.67	-
Directivity	D51	986.02	988.11		-0.0514	0.73	-
	D52	977.15	971.56	#1	-0.3044	0.007	**
				#2	-0.0419	0.70	-
				#3	0.1120	0.31	-
				#4	0.0685	0.53	-
Glare	D61	904.32	909.25		-0.3974	0.01	*
	D62	1055.2	1057.0		0.0965	0.61	-
	D63	1003.7	1005.6		-0.2005	0.33	-

Significance: *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$.

At last, this table also shows that Belgian participants responded significantly differently to French participants to the question D61 related to the perception of glare: the scenes were perceived as less glaring by the French sample of participants than by the Belgian one.

The comparison between the two countries highlighted significant differences of perceptions of the lighting: coloration, directivity of light and glare are perceived differently by the two populations.

IV.B.2.2. NON-CONVENTIONAL QUESTIONS

IV.B.2.2.1. *PAIRED COMPARISON OF WALLS (#1, #2)*

The paired-comparisons of walls have shown in Chapter III.B that some responses of the control group were identical to the responses of the real-world group. In three rooms (Rooms #1, #2 and #4), the control group rated the difference of brightness between two walls similarly than the real-world group. As a consequence of this observation, only the responses in Room #3 were validated.

Figure IV.B.7 presents the responses given by $3D_{belgium}$ and $3D_{france}$ participants in this third room.

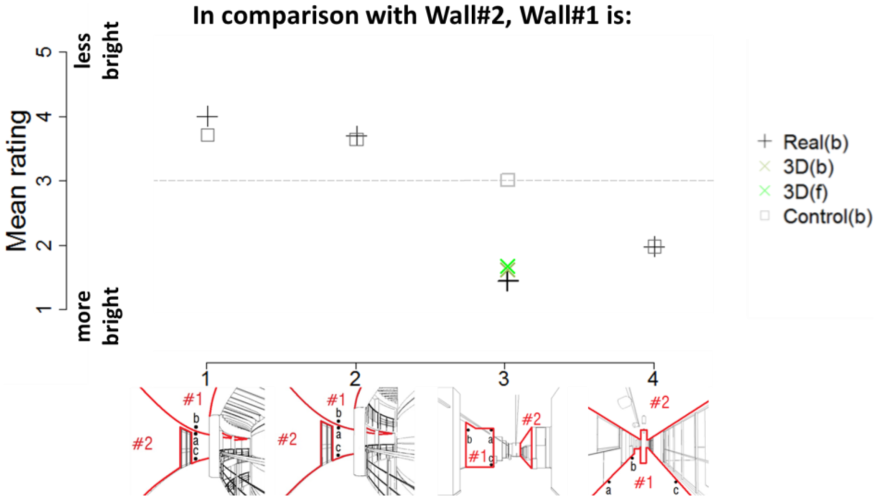


FIGURE IV.B.7
Comparison of two walls for brightness (C1) – mean ratings

A linear mixed model analysis was performed on these data. No significant difference was detected between the two samples (MCMCmean=-0.13, pvalue=0.1212).

Figure IV.B.8 presents the mean ratings for the comparison of the uniformity of the pairs of walls. Differences of uniformity are more pronounced for the French group than for the Belgian participants (the deviation of scores from the center of the scale is higher for the French group than for the Belgian one).

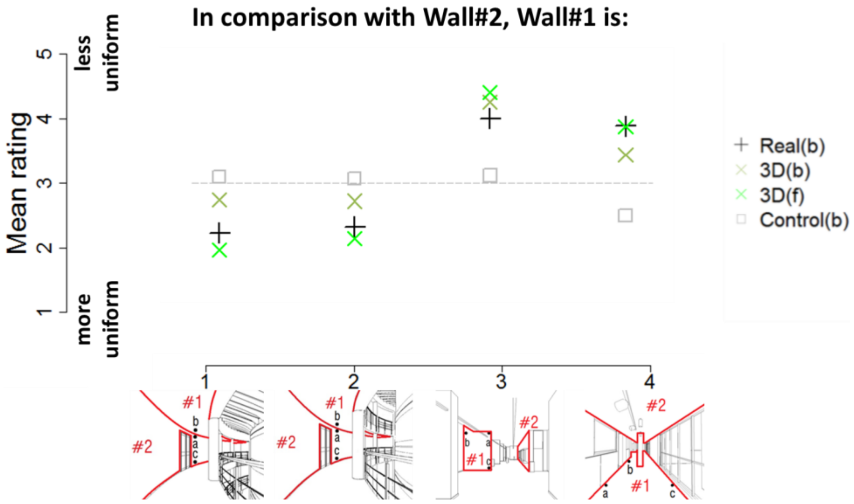


FIGURE IV.B.8
Comparison of two walls for uniformity (C2) – mean ratings

A linear mixed model analysis was performed on these data. The smaller the AIC, the better the fit, the preference is, as presented in Table IV.B.5, for the model with interaction. This presence of interaction indicates that the phase effect varies according to the level of room factor. This phase effect is significant in three rooms. It confirms our observation: differences of uniformity are significantly more pronounced for the French group than for the Belgian participants.

TABLE IV.B.5
Comparison of the uniformity of two walls - statistical differences between phases

Ref.	**AIC** without interaction,	**AIC** with interaction,	**Room**	**MCMC mean**	**p-value**	**Signif.**
Uniformity - C2	926.65	912.85	#1	-0.7757	0.0006	***
			#2	-0.5739	0.01	**
			#3	0.1404	0.52	
			#4	0.4404	0.05	*

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Figure IV.B.9 presents the results for the comparison of roughness. Results observed on the $3D_{belgium}$ group are replicated with the $3D_{france}$ group. A linear mixed model analysis was performed on these data. The smaller the AIC, the better the fit, the preference is for the model without interaction.

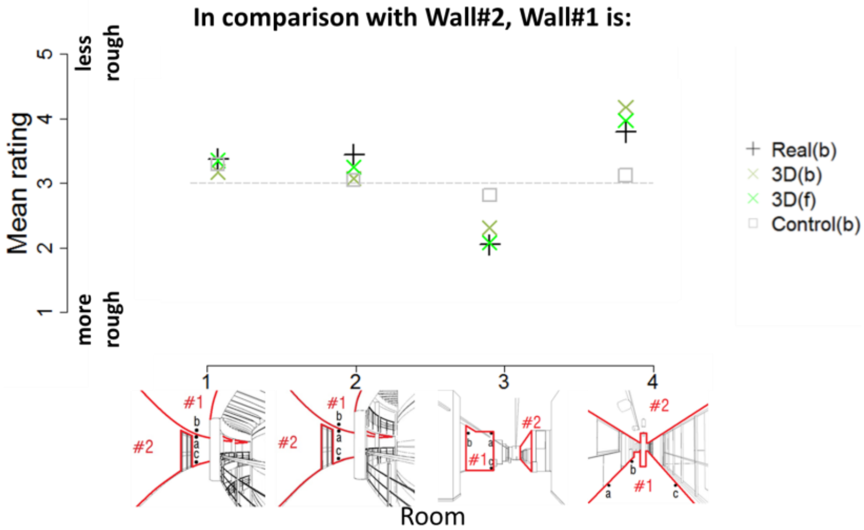


FIGURE IV.B.9
Comparison of two walls for roughness (C3) – mean ratings

As shown in Table IV.B.6, no effect of the country is detected. Perception of roughness is similar for the two samples of participants.

TABLE IV.B.6
Comparison of the roughness of two walls - statistical differences between phases

Ref.	AIC without interaction	AIC with interaction	MCMC mean	p-value	Signif.
Roughness - C3	852.46	854.66	-0.0207	0.8409	-

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

IV.B.2.2.2. *CLASSIFICATION OF PUNCTUAL ZONES FOR BRIGHTNESS*

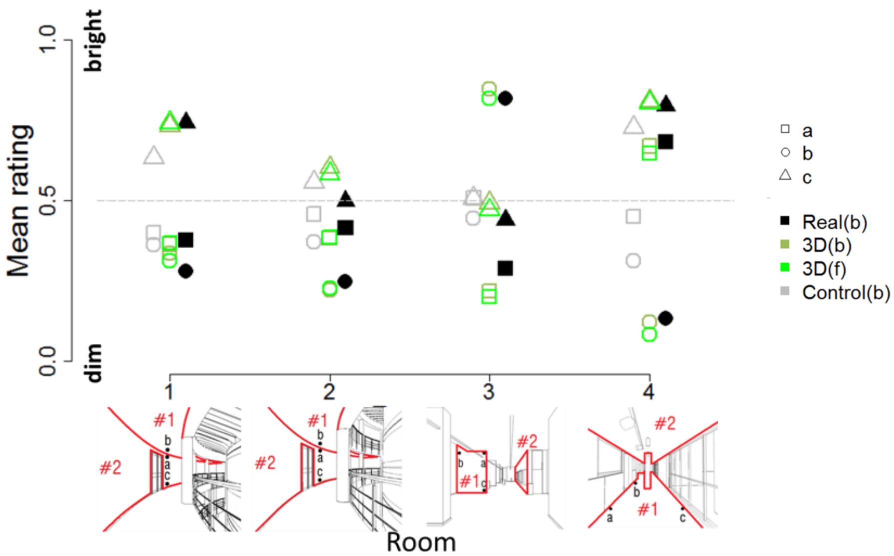


FIGURE IV.B.10
Classification of three points for brightness

Figure IV.B.10 illustrates the similarity of the responses done by the two groups of participants when they are asked to classify three points for brightness, in each room.

The participants of the two populations (3Dbelgium and 3Dfrance groups) give similar responses for the paired-comparison of walls except for the perception of uniformity. In comparison with the real-world phase, 3Dbelgium group minimized differences between the two walls. 3Dfrance group gives similar responses than the real-world group. No divergence was observed between the two populations for the classification of punctual zones for brightness.

IV.B.2.2.3. *DETERMINATION OF ZONES FOR BRIGHTNESS*

Table IV.B.7 illustrates the fact that similar areas are judged by the two groups of participants (Belgian and French people) as the brightest parts of the rooms.

TABLE IV.B.7
Brightest part maps (the color scale indicates the percentage of participants who identified the areas as the brightest part of the scene)

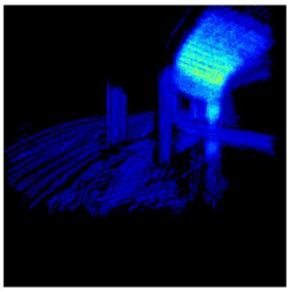
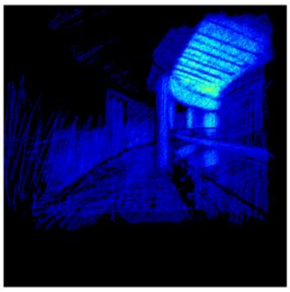
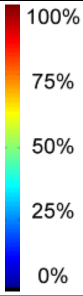
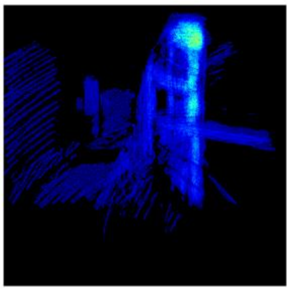
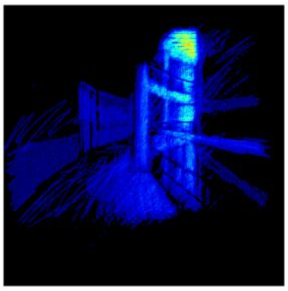
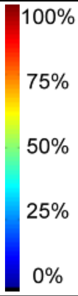
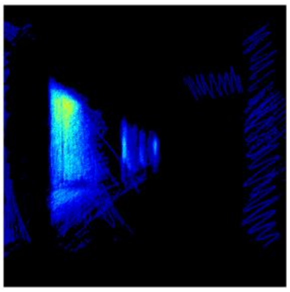
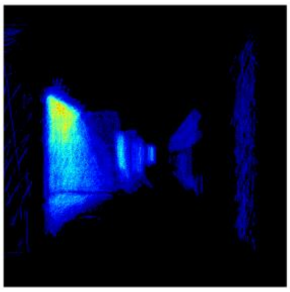
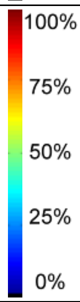
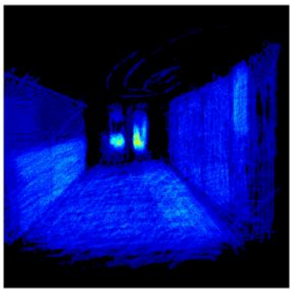
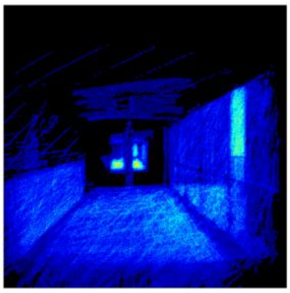
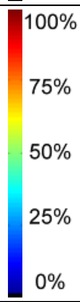
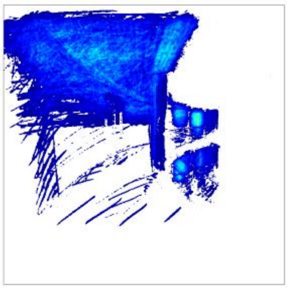
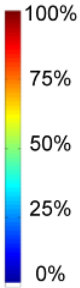
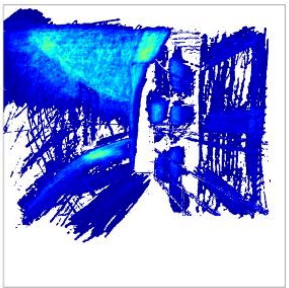
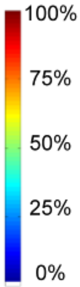
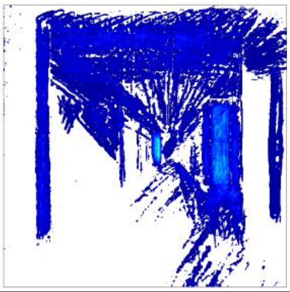
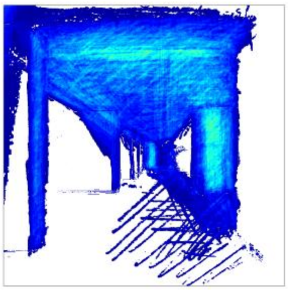
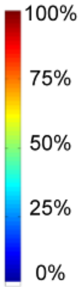
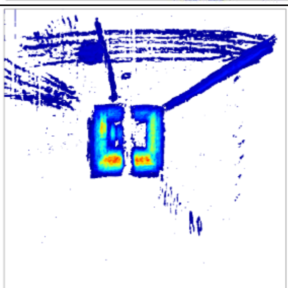
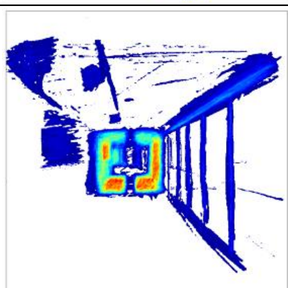
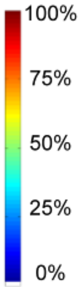
	$3D_{belgium}$ group	$3D_{france}$ group	
Room #1			
Room #2			
Room#3			
Room #4			

Table IV.B.8 illustrates the parts of the scenes perceived as the dimmest.

TABLE IV.B.8
Dimmest part maps (the color scale indicates the percentage of participants who identified the areas as the dimmest part of the scene)

	$3D_{belgium}$ group	$3D_{france}$ group	
Room #1			
Room #2			
Room#3			
Room #4			

In three rooms (Room #1, Room #2 and Room #3), the ceiling is identified as the dimmest part of the scene by a larger percentage of French participants than Belgian ones.

IV.B.3. Discussion

The first objective of this PhD work was testing the hypothesis that some presentation modes of images better reproduce the perceptions experienced in the actual environment than 2D pictures displayed on a conventional LDR monitor.

As part of the experiment was carried out in France, before comparing the modes tested carried out in this country to the real-world experiment organized in Belgium, we sought to determine whether the cultural background (the fact that the participants are Belgian or French) has an influence on the perception of the appearance of lighting and space. A same mode (the visualization of 3D pictures) was carried out in each of the two countries.

Some differences of perceptions were observed between the two populations for the following dimensions: enclosedness, coloration, directivity, and glare.

Table IV.B.9 summarizes the results of the two-step analysis realized on the rating scales. According to Fig.IV.B.3, we considered that there is no difference between the two populations and that the real-world experiment can be used as the reference in the next analyses if neither interaction effect nor country effect is detected (✓/×).

TABLE IV.B.9
Summary of the comparison between $3D_{belgium}$ and $3D_{france}$ groups

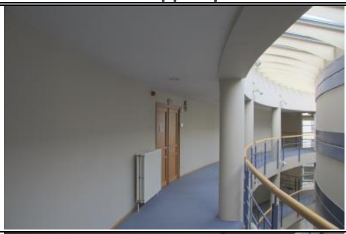
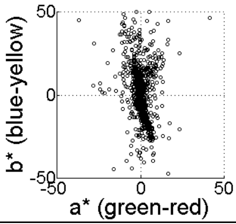
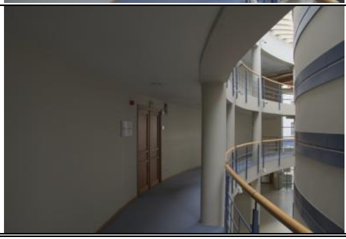
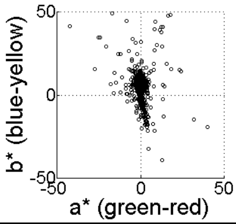
Factor	Ref.	Question	$3D_{belgium}$ vs. $3D_{france}$
Pleasantness	**P0**	Pleasantness is: low-high	×
	P1	(light) pleasant-unpleasant	×
Enclosedness	**E0**	Enclosedness is: low-high	×
	E1	(corridor) slightly-very spacious	×
	E2	(corridor) slightly-very narrow	✓
	E3	(corridor) slightly-very deep	×
Brightness	**D11**	(corridor) dim – bright	×
	D12	(you) in the dark – light	✓
Coloration	**D21**	(corridor) neutral – colorful	×
	D22	(corridor) cold – warm	×
	D23	(light) neutral – colorful	×
Contrast	**D31**	(corridor) high – low contrast	✓
Distribution	**D41**	(distribution) varied – monotonous	×
Directivity	**D51**	(shadow) sharp – blurry	✓
	D52	(textures) sharp – blurry	×
Glare	**D61**	(corridor) comfortable – glaring	×
	D62	(you) little – much disturbed < window	×
	D63	(you) little – much disturbed < surface	✓

Grouping of rooms: ✓ reproduced, × not reproduced
Country effect or interaction: ✓/ × interactions, ✓/× country effect, ✓/× no country effect

As a result of the analysis on the rating scales, a significant difference of perception of enclosedness was first detected: French people rated the rooms as more enclosed than Belgian people. This difference could be due to architectural differences between the two countries. French people could be accustomed to less enclosed spaces.

The coloration of the lighting and the space was also perceived differently by the two populations. French participants perceived the coloration in Room #1 similarly to Room #2 while Belgian people perceived the two rooms differently. As illustrated in Table IV.B.10, the CIE a* b* diagrams indicate that the coloration in the two rooms is bluish. The points are further apart from the origin in Room #1, indicating that the colors are more saturated than in Room #2. However, the architectural materials in Room #1 are similar to those in Room #2.

TABLE IV.B.10
Comparison of the coloration in Room #1 and Room #2

	Tone-mapped picture	CIE a* b* diagram
Room #1		
Room #2		

The difference of perception between the two populations could be due to a lack of precision in the question rather than a difference of perception. The term "colorful"[1] is probably not precise enough and can be understood as "varied in colors" or "presenting vivid (saturated) colors". Figure IV.B.11 illustrates the ambiguity of the term.

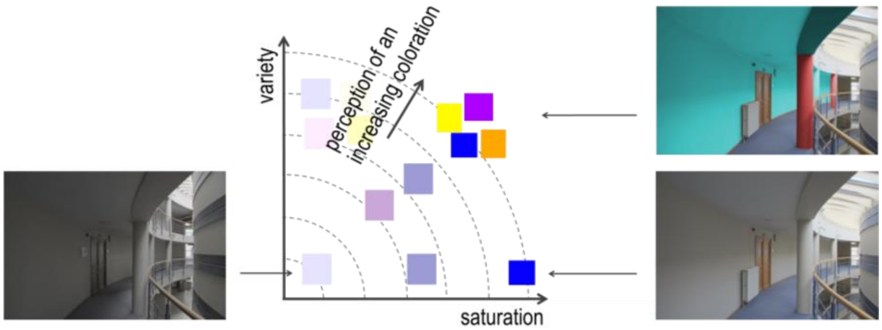


FIGURE IV.B.11
Illustration of the ambiguity of the term colorful

[1] "coloré" in French.

This ambiguity could explain the differences in the responses of the two samples of participants and highlights the importance of the precision of the terms used in the questionnaire.

The analysis of the rating scales also revealed a difference in the perception of the textures in Room #1: French participants perceived the textures as sharper than Belgians did. Again, this difference could be explained by a difficulty understanding the term "texture"[2]: one fourth of the participants reported having difficulty in understanding this rating scale.

Finally, the analysis of the scales revealed that French participants perceived the rooms as significantly less glaring than did Belgian respondents. Our hypothesis is that people are influenced by the weather to which they are accustomed. The weather is sunnier in Lyon than in Louvain-la-Neuve as illustrated by the hours of sun per year (2000 hours for Lyon and 1500 hours for Brussels which is next to Louvain-la-Neuve). This observation is interesting, because it suggests the threshold of glare acceptability varies according to the location, even within a country.

Non-conventional questions based on sketches also highlighted some differences of perceptions between the two populations. The paired-comparison of walls revealed that French participants accentuated the difference of uniformity in comparison with the Belgian group. Moreover, the ratings of the brightest and dimmest parts maps indicated that a larger percentage of French participants rated the ceilings as the dimmest part of the room.

As a consequence of these observations, in the next step of the analysis, the real-world experiment will be the reference group except for the questions presenting a difference between the two populations (perception of enclosedness, coloration, textures, and glare).

[2] Also "texture" in French.

CHAPTER IV.C
BENEFIT OF VARIOUS PRESENTATION MODES OF IMAGES

This chapter aims at comparing participants' ratings collected in the actual environment to the ratings collected when the participants visualized 3D pictures (3D mode), QTVR panoramas (QTVR mode) and 2D pictures displayed on a conventional LDR display (2D mode) or on a HDR display (HDR mode) (see Fig.IV.C.).

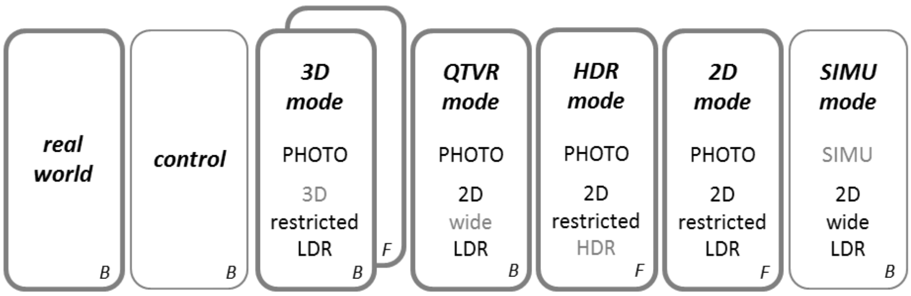


FIGURE IV.C.1
Comparison between various presentation modes of images tested in Belgium (B) and in France (F)

The previous chapter has shown that the real-world experiment can be used as the reference except for the enclosedness dimension, as well as one rating scale related to the perception of textures (D52), another one linked to glare (D61) and the three rating scales related to the coloration of the lighting and the space (D21, D22, D23). For these questions, QTVR and $3D_{belgium}$ modes will be compared to the real-world experiment while HDR and $3D_{france}$ modes will be compared to the 2D mode.

IV.C.1. MATERIAL AND METHOD

The experiment realized in the real world and presented in Chapter II.A was reproduced using several types of images: QTVR panoramas (QTVR mode tested in April 2012), 2D pictures presented on a conventional display (2D mode tested in January 2013), and 2D pictures presented on a HDR display (HDR mode tested in March 2013). A procedure of visualization similar than the one implemented for testing 3D mode was followed (see Chapter IV.B). Regardless of the mode, the visualization was organized in a black room. To not introduce a bias between the new presentation modes and the 3D mode (which required working in the darkness as explained in the previous chapter), we pursued the experiment in a dark room. As illustrated in Fig.IV.C.2, only the HDR experiment was conducted on another device than the conventional Samsung SyncMaster 2233rz monitor whose the characteristics are presented in Chapter IV.A.

FIGURE IV.C.2
Experimental conditions: (a) Visualization on a conventional LDR display of QTVR panoramas and 3D pictures in Belgium (b) Visualization on the same conventional LDR display of 2D and 3D pictures in France (c) Visualization of 2D pictures on the HDR display in France.

Table IV.C.1 presents the characteristics of the samples of participants recruited for the QTVR, 2D and HDR modes. These samples present similar characteristics than the real-world group in terms of language, age, gender and educational background.

TABLE IV.C.1
Characteristics of the samples of participants

Medium	Real world	$3D_{belgium}$	$3D_{france}$	QTVR	HDR	2D
Location	Belgium	Belgium	France	Belgium	France	France
Number of participants (women, men)	43 (26, 17)	40 (23,17)	40 (23,17)	39 (23,16)	37 (18,19)	40 (22,18)
Native language	French	French	French	French	French	French
Educational background	Students at UCL	Students at UCL	Students at ENTPE	Students at UCL	Students at ENTPE	Students at ENTPE
Age (mean +/- standard deviation)	21.8 +/- 1.7	21.7 +/- 1.8	21.2 +/- 1	21.5 +/- 1.3	22.1 +/- 1.3	21.3 +/- 1.1

IV.C.2. RESULTS

IV.C.2.1. RATING SCALES

As illustrated in Fig.IV.C.3, an approach similar to the one implemented to determine the potential differences of perceptions between Belgian and French populations was adopted to compare the various modes of presentation.

Each medium was first analyzed separately and groups of rooms resulting from the contrasts analysis were compared to the real-world experiment to determine whether the results of the real-world experiment were replicated with each surrogate.

A mixed model analysis was then performed on the whole set of data (real-world, QTVR mode, $3D_{belgium}$ mode, $3D_{france}$ mode, HDR mode and 2D mode). The fixed effects were the presentation mode and the room while the subject was set as random effect. The AIC criterion was used to judge whether adding interaction between mode and room factors improves the model. For reasons of clarity, only MCMCmean differences (difference between each presentation mode tested and the real world) and p-values are presented.

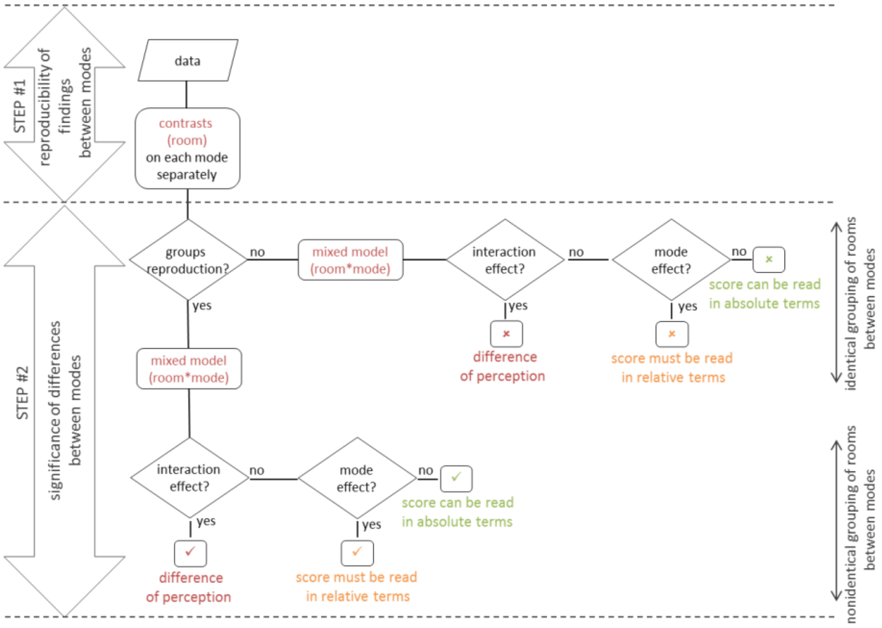


FIGURE IV.C.3
Illustration of the approach used to determine whether perceptions experienced when visualizing various types of pictures are similar to those experienced in the real world

As a result of this two-step analysis, for each presentation mode of images, the rating scales replicating the perceptions experienced in the real world are determined. As illustrated in Fig.IV.C.3, results are considered as replicated if no mode-room interaction is detected. If no presentation mode effect is observed (✓/×), the score can be read in absolute terms. If a presentation mode effect is detected (✓/×), the score must be read in relative terms.

Statistical analyses were performed using R software. Descriptive results are presented in Appendix III.

IV.C.2.1.1. VISUAL APPEARANCE OF SPACE

IV.C.2.1.1.1. *PLEASANTNESS*

Perception of pleasantness was first analyzed. Figure IV.C.4 illustrates mean scores obtained with each presentation mode and results of the contrasts analysis. For each presentation mode, rooms sharing a same color do not differ significantly.

As shown in this figure, the four assessed rooms are ordered in an identical way in the QTVR and 2D modes and in the real-world experiment. However, contrasts analyses revealed that, whatever the mode, groupings of rooms are not identical to the real-world grouping. Moreover, in two modes ($3D_{belgium}$ and HDR), Room #4 is perceived on average as the least pleasant room rather than Room #2 as observed with the other media.

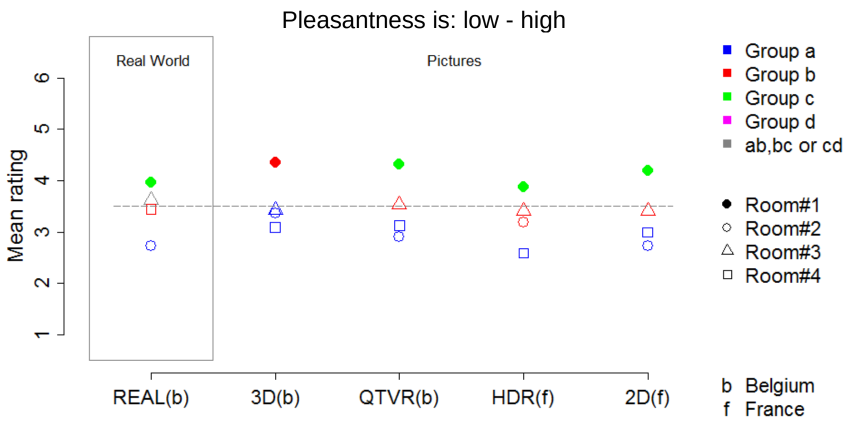


FIGURE IV.C. 4
Pleasantness dimension (P0) – Reproducibility of the findings

A mixed model analysis was then performed on the whole set of data. The fixed effects were the mode and the room. The subject was set as random effect. The AIC criterion was used to judge whether adding interaction between mode and room improves the model. The smaller the AIC, the better the fit, the preference is for the model with interaction. Tested contrasts are presented in Table IV.C.2. For reasons of clarity, only MCMCmean differences (difference between each presentation mode and the real-world experiment) and p-values are presented.

TABLE IV.C.2
Pleasantness dimension (P0) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	**AIC** without interaction	**AIC** with interaction	**Room**	**$3D_{belgium}$ vs. real world**	**QTVR vs. real world**	**HDR vs. real world**	**2D vs. real world**
P0	2519.4	<u>2503.7</u>	**#1**	0.38, 0.06	0.34, 0.08	-0.095, 0.64	0.21, 0.27
			#2	0.63, 0.00***	0.18, 0.35	0.47, 0.02*	-0.003, 1.00
			#3	-0.18, 0.35	-0.09, 0.65	-0.21, 0.29	-0.20, 0.30
			#4	-0.49, 0.08	-0.35, 0.11	-1.24, 0.00***	-0.83, 0.02*

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

There is no significant difference between the images and the real world in Rooms #1 and #3. In Room #2, a significant difference between the real-word experiment and the 3D and HDR modes was detected. No significant difference is detected between the QTVR mode and the real world, whatever the room.

QTVR mode is the presentation mode which best replicates the perception of pleasantness experienced in the real world. Note that differences between the QTVR mode and the 2D mode are not significant (MCMCmean=0.14, p-value=0.24).

Figure IV.C.5 shows that the pleasantness of the light is similarly perceived with images than in the real world except with HDR mode. Indeed, while Room #2, the dimmest room, is perceived with all the media as the most unpleasant, with the HDR mode, it is Room #4 which is perceived as the most unpleasant.

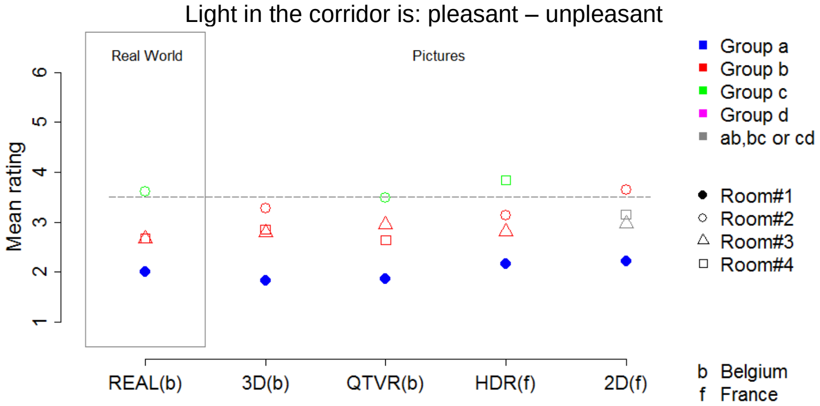


FIGURE IV.C.5
Pleasantness of the light (P1) – Reproducibility of the findings

The contrasts analysis confirms this observation, as presented in Table IV.C.3: Room #4 is rated with the HDR mode as significantly more unpleasant than in the real-world experiment.

TABLE IV.C.3
Pleasantness of the light (P1) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	**AIC** without interaction	**AIC** with interaction	**Room**	**3D$_{belgium}$ vs. real world**	**QTVR vs. real world**	**HDR vs. real world**	**2D vs. real world**
P1	3054.7	3048.2	**#1**	-0.18, 0.50	-0.13, 0.62	0.16, 0.54	0.23, 0.39
			#2	-0.32, 0.22	-0.12, 0.65	-0.47, 0.07	0.04, 0.86
			#3	0.13, 0.63	0.27, 0.29	0.14, 0.61	0.30, 0.25
			#4	0.17, 0.50	-0.03, 0.90	1.16, 0.00***	0.48, 0.07

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

The perception of the pleasantness of the light is not reproduced with the HDR display in Room #4.

IV.C.2.1.1.2. *ENCLOSEDNESS*

Figure IV.C.6 presents mean scores for enclosedness and groups of rooms resulting from the contrasts analysis.

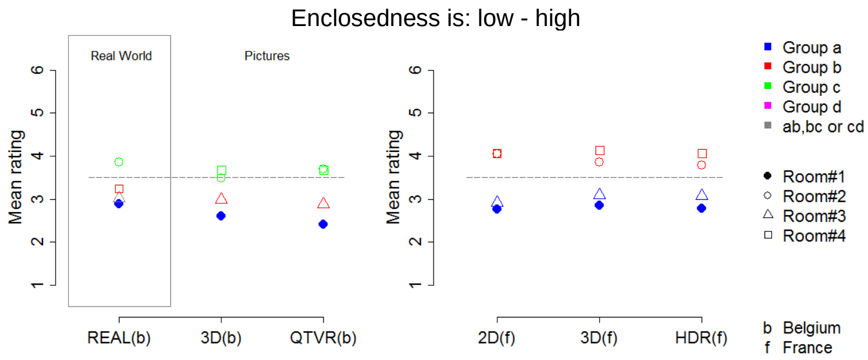


FIGURE IV.C.6
Enclosedness dimension (E0) – Reproducibility of the findings

This figure shows that real-world experiment results are not identically replicated with pictures. However, the two kinds of visualization carried out in Belgium (QTVR and $3D_{belgium}$ modes) produced identical groups of rooms. And, the three experiments organized in France ($3D_{france}$, HDR and 2D modes) also produce identical groups of rooms even if different from the Belgian group. Regardless of the presentation mode, Room #4 was perceived as similarly enclosed than Room #2 while it was perceived in the real world as significantly more enclosed than Room #4.

In the previous chapter (Chapter IV.B), a slight difference of perception of enclosedness was detected between Belgian and French participants. As a consequence of this observation, contrasts were tested in taking the real world as the reference level for analyzing QTVR and $3D_{belgium}$ modes while the 2D mode was taken as the reference for the experiments organized in France ($3D_{france}$ and HDR modes). According to the results presented in Table IV.C.4, Room #4 is perceived as significantly more enclosed when visualized in picture. In France, no difference of perception of the enclosedness was found between the three presentation modes.

TABLE IV.C.4
Enclosedness dimension (E0) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level for experiments carried out in Belgium while 2D mode is the reference for experiments carried out in France

Ref.	**AIC** without interaction	**AIC** with interaction	**Room**	**$3D_{belgium}$ vs. real world**	**QTVR vs. real world**	**$3D_{france}$ vs. 2D**	**HDR vs. 2D**
E0	2529.8	<u>2523.4</u>	**#1**	-0.27, 0.18	-0.47, 0.02*	0.03, 0.87	0.10, 0.63
			#2	-0.39, 0.06	-0.16, 0.43	-0.26,0.21	-0.20, 0.34
			#3	-0.04, 0.84	-0.14, 0.49	0.16, 0.45	0.17, 0.42
			#4	0.43, 0.03*	0.43, 0.03*	0.05, 0.81	0.08, 0.73

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Differences between the perceptions of enclosedness experienced in the real world and those experienced when visualizing the space in pictures were detected. This distortion is similar regardless of the presentation mode. One room in particular (Room #4) appears more enclosed when visualized in image than in the real world. Information content is thus probably lost between the real world and images.

As shown in Fig.IV.C.7, regardless of the presentation mode, Rooms #1 and #4 are perceived as being respectively more and less spacious than in the real world.

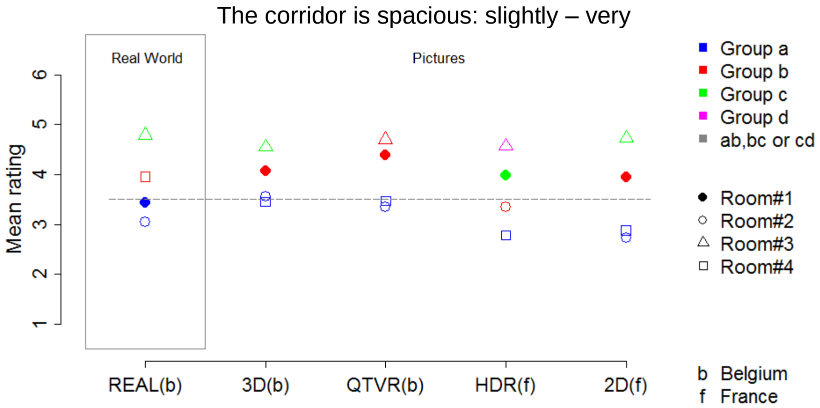


FIGURE IV.C.7
Spaciousness of the corridor (E1) – Reproducibility of the findings

This observation is confirmed with the contrasts analysis (see Table IV.C.5).

TABLE IV.C.5
Spaciousness of the corridor (E1) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	**AIC** without interaction	**AIC** with interaction	**Room**	**3D$_{belgium}$ vs. real world**	**QTVR vs. real world**	**HDR vs. real world**	**2D vs. real world**
E1	2857.3	2818.0	**#1**	0.65, 0.005**	0.96, 0.00***	0.55, 0.023*	0.52, 0.03*
			#2	0.50, 0.03*	0.30, 0.20	0.31, 0.20	-0.32, 1.17
			#3	-0.24, 0.30	-0.10, 0.70	-0.23, 0.34	-0.065, 0.78
			#4	-0.50, 0.03*	-0.48, 0.04*	-1.17, 0.0001***	-1.08, 0.0001***

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

The perception of the spaciousness experienced in the real world is not reproduced using images. However, all the presentation modes produce similar mean profiles. Again, we hypothesize that information content is lost between the real world and the pictures.

As shown in Fig.IV.C.8, the pictures do not reproduce the perceptions of narrowness experienced in the real world. However, it appears that perception of narrowness is similar between all the presentation modes. On the basis of pictures, Room #4 is perceived similarly narrow than Room #2 while in the real world, they were perceived as significantly different.

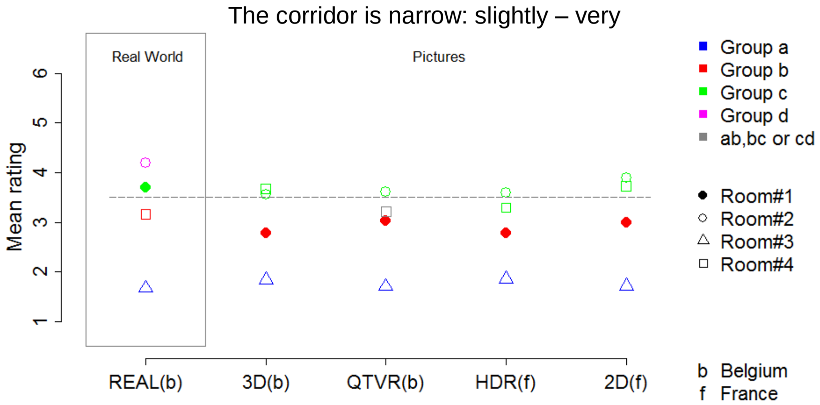


FIGURE IV.C.8
Narrowness of the corridor (E2) – Reproducibility of the findings

As presented in Table IV.C.6, Room #1 is perceived as significantly narrower on the basis of pictures than in the real world. Room #3 which is perceived as the narrowest room in the real world is still the narrowest room with the other media.

TABLE IV.C.6
Narrowness of the corridor (E2) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	AIC without interaction	AIC with interaction	Room	$3D_{belgium}$ vs. real world	QTVR vs. real world	HDR vs. real world	2D vs. real world
E2	2928.2	2921.7	#1	-0.92,0.00***	-0.67,0.008**	-0.91,0.0003***	-0.70,0.005**
			#2	-0.64,0.01**	-0.58,0.02*	-0.60,0.02*	-0.29,0.25
			#3	0.17,0.48	0.04, 0.89	0.19,0.45	0.05,0.84
			#4	0.51,0.04*	0.05, 0.85	0.13,0.60	0.56,0.02*

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Differences between the perceptions of narrowness experienced in the real world and those experienced when visualizing the space in pictures were detected. The perceptions experienced when visualizing pictures appears to be shared regardless of the presentation mode of image.

As illustrated in Fig.IV.C.9, whatever the medium, the corridors are perceived as being rather deep. And only the 2D mode reproduced the groups of rooms observed in the real world.

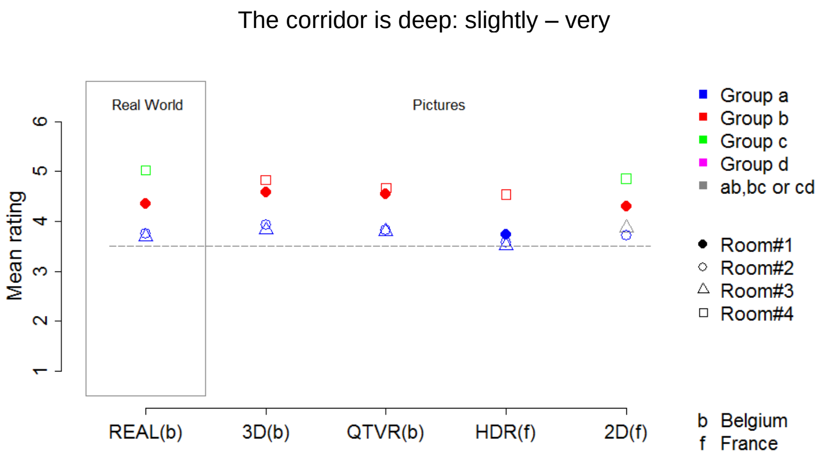


FIGURE IV.C.9
Depth of the corridor (E3) – Reproducibility of the findings

No medium-room interaction was observed. A significant medium effect was detected for the HDR mode (see Table IV.C.7). This effect could be due to the fact that the participant was positioned close to the screen, to cover a similar field of view than the one covered by the Samsung display. Most of the participants of this mode felt an artificial situation.

TABLE IV.C.7
Depth of the corridor (E3) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	**AIC** without interaction	**AIC** with interaction	**3D$_{belgium}$** **vs. real world**	**QTVR** **vs. real world**	**HDR** **vs. real world**	**2D** **vs. real world**
E3	2971.7	2987.2	0.005,0.97	0.09,0.62	-0.37,0.03*	-0.015,0.92
Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.						

Only the HDR mode introduces a distortion of the perception of depth.

IV.C.2.1.2. VISUAL APPEARANCE OF LIGHTING

IV.C.2.1.2.1. *BRIGHTNESS*

Figure IV.C.10 shows that, for the first question related to the perceived brightness (D11), the rooms are ordered identically regardless of the medium. The grouping of rooms is identical for all the media except the HDR mode. With this mode, Room #4 is perceived as dim as Room #2 while with the other media, Room #4 is perceived as bright as Room #3.

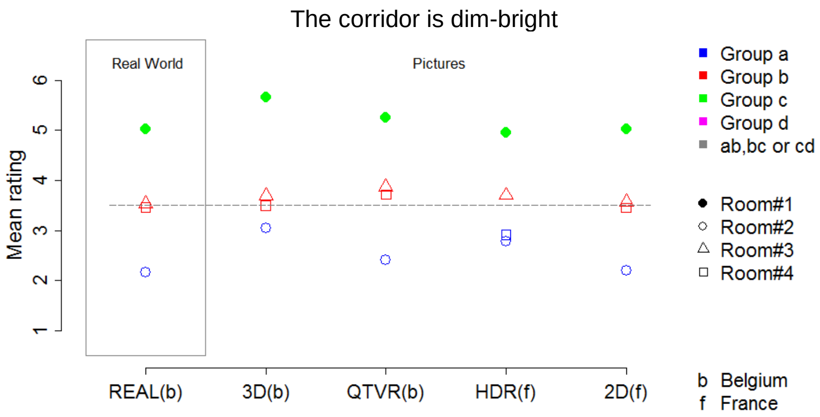


FIGURE IV.C.10
Brightness (D11) - Reproducibility of the findings

No interaction effect between presentation mode and room factors was detected. The contrasts analysis shows that rooms are, in average, rated as significantly brighter in QTVR and $3D_{belgium}$ modes (see Table IV.C.8). 2D and HDR modes do not present significant differences with the real world but, in average the rooms are perceived as slightly brighter in images than in the real world. In Chapter III.B, we observed a mean difference of 0.18 between $3D_{belgium}$ and $3D_{france}$ modes: in average, the French participants rated the rooms as dimmer than the Belgian sample but the difference was not significant. For this rating scale, the absence of significance between the real world and the two modes carried out in France is probably linked to the fact that we carried out the experiments on two different populations.

TABLE IV.C.8
Brightness (D11) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	AIC without interaction	AIC with interaction	$3D_{belgium}$ vs. real world	QTVR vs. real world	HDR vs. real world	2D vs. real world
D11	2838.1	2839.4	0.43,0.0003***	0.27,0.02*	0.04,0.73	0.02,0.89

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Figure IV.C.11 presents mean ratings and groups of room for the second question related to the perceived brightness (D12). Again, the order of rooms and the groupings are identical for all the modes except HDR display. With this presentation mode, difference between Room #3 and Room #2 is reduced in comparison with the other media.

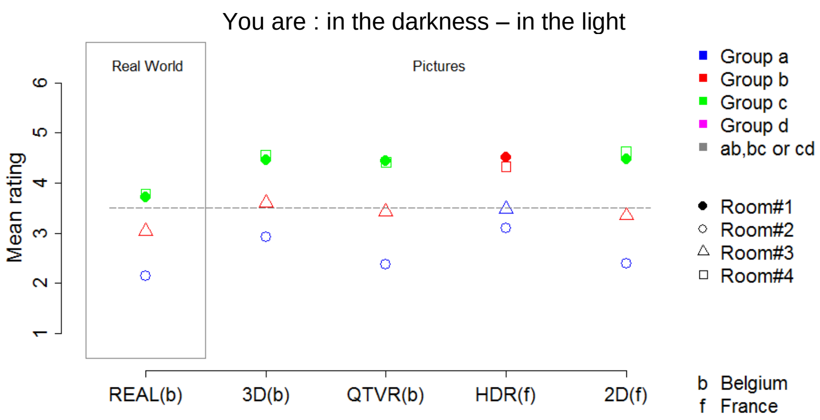


FIGURE IV.C.11
Brightness (D12) - Reproducibility of the findings

The analysis of variance presented in Table IV.C.9 reveals that the participants felt to be significantly more into the light and less in the darkness when visualizing pictures than in the real world.

TABLE IV.C.9
Brightness (D12) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	**AIC** without interaction	**AIC** with interaction	**$3D_{belgium}$ vs. real world**	**QTVR vs. real world**	**HDR vs. real world**	**2D vs. real world**
D12	3013.5	3023.4	0.71, 0.00***	0.49, 0.01**	0.68, 0.00***	0.71, 0.00***

Significance: *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$.

Whatever the mode, perceived brightness is overestimated when visualizing pictures on a display device. However, except the HDR display, images make possible the same grouping of rooms. Rating scores must be read in relative.

IV.C.2.1.2.2. *Coloration*

In Chapter III.B, we observed that the Belgian and the French participants perceived differently the coloration of the lighting and the space. Figure IV.C.12 shows that, this observation, made in the previous chapter, is reproduced in the additional experiments carried out in France: the first room is perceived differently by the French and the Belgian population. While Belgian participants perceived significantly differently Room #1 and Room #2, French population does not make any significant distinction between the two rooms. As illustrated in Fig.IV.C.12, groupings of rooms in the real world, $3D_{belgium}$ and QTVR modes (the three modes tested in Belgium) are identical. And, groupings in 2D, $3D_{france}$ and HDR modes (the three modes tested in France) are also identical but different from the Belgian groupings.

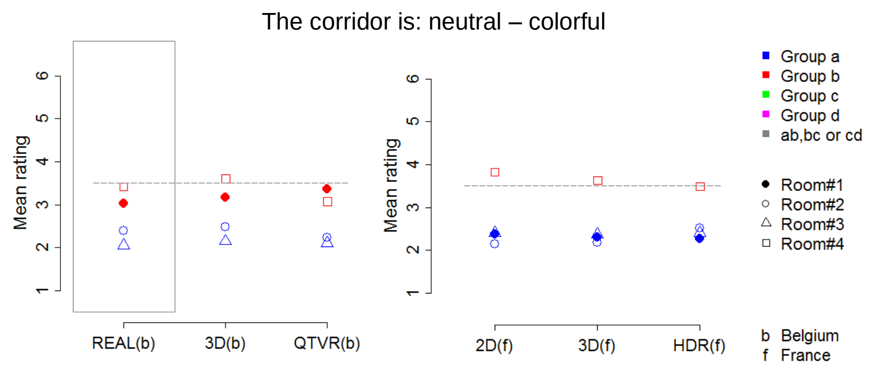


FIGURE IV.C.12
Coloration (D21) - Reproducibility of the findings

Contrasts analysis was done in taking the real-world experiment as the reference for the modes tested in Belgium. 2D mode was taken as the reference for the modes tested in France. No significant difference was detected as in Table IV.C.10.

TABLE IV.C.10
Coloration (D21) - Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level for modes tested in Belgium while 2D mode is the reference for modes tested in France.

Ref.	AIC without interaction	AIC with interaction	Room	$3D_{belgium}$ vs. real world	QTVR vs. real world	$3D_{france}$ vs. 2D	HDR vs. 2D
D21	3092.2	<u>3072.1</u>	**#1**	0.15, 0.57	0.33, 0.21	-0.07, 0.79	-0.11, 0.70
			#2	0.09, 0.76	-0.17, 0.54	0.02, 0.93	0.36, 0.19
			#3	0.11, 0.70	0.06, 0.83	-0.03, 0.93	0.008, 0.98
			#4	0.18, 0.49	-0.34, 0.20	-0.20, 0.46	-0.34, 0.22

Significance: *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$.

Perception of color temperature is similar whatever the medium (see Fig.IV.C.13). Groups formed in $3D_{belgium}$, 2D and $3D_{france}$ modes are identical to the real world.

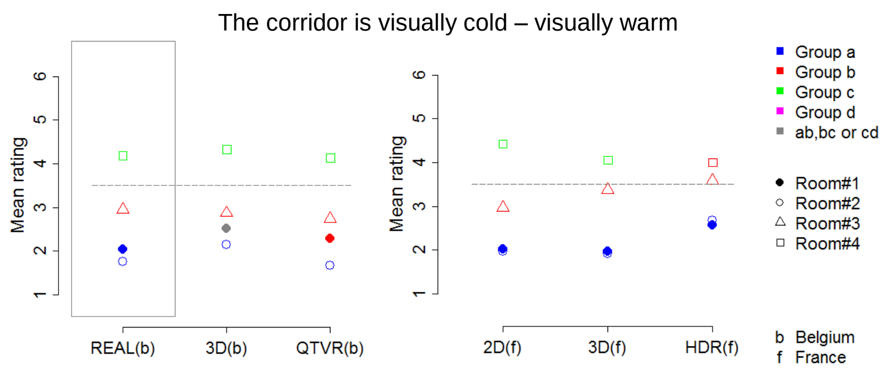


FIGURE IV.C.13
Coloration (D22) - Reproducibility of the findings

Contrasts analysis detected significant differences between the 2D mode and the HDR mode revealing a distortion of coloration with the HDR display system: three rooms are perceived as being warmer on the HDR display. The range of score for this mode is moreover widely reduced (see Table IV.C.11).

TABLE IV.C.11
Coloration (D22) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	AIC without interaction	AIC with interaction	Room	$3D_{belgium}$ vs. real world	QTVR vs. real world	$3D_{france}$ vs. 2D	HDR vs. 2D
D22	2956.9	2953.4	#1	0.48, 0.05	0.24, 0.35	-0.05, 0.83	0.54, 0.04*
			#2	0.39, 0.12	-0.1, 0.71	-0.05, 0.84	0.70, 0.01**
			#3	-0.08, 0.75	-0.21, 0.40	0.40, 0.11	0.62, 0.02*
			#4	0.13, 0.58	-0.06, 0.82	-0.37, 0.14	-0.42, 0.10

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

As shown in Fig.IV.C.14, light is perceived as being neutral regardless of the medium.

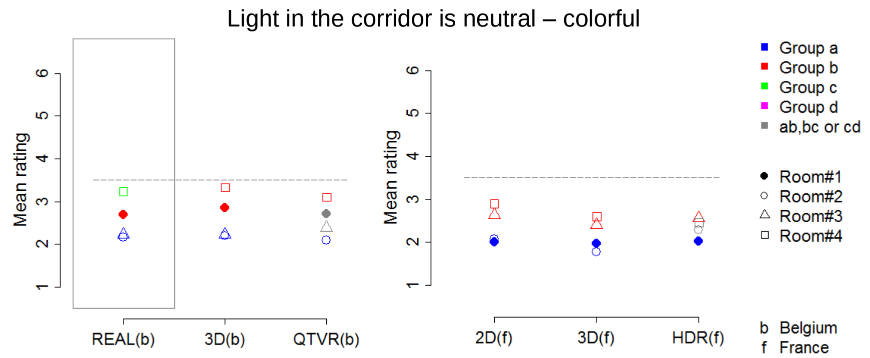


FIGURE IV.C.14
Coloration (D23) - Reproducibility of the findings

No significant difference was detected either between the real world and the QTVR or $3D_{belgium}$ modes or between the 2D mode and the $3D_{france}$ or HDR modes (see Table IV.C.12).

TABLE IV.C.12
Coloration (D23) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	AIC without interaction	AIC with interaction	Room	$3D_{belgium}$ vs. real world	QTVR vs. real world	$3D_{france}$ vs. 2D	HDR vs. 2D
D23	2977.0	2965.5	#1	0.16, 0.55	0.02, 0.94	-0.03, 0.90	0.03, 0.92
			#2	0.05, 0.84	-0.06, 0.81	-0.30, 0.25	0.22, 0.40
			#3	-0.01, 0.98	0.16, 0.53	-0.24,0.39	-0.06, 0.82
			#4	0.09, 0.72	-0.13, 0.61	-0.30, 0.25	-0.44, 0.10

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

The difference in the perception of coloration between the two populations (Belgian and French people), observed in the previous chapter, is replicated regardless of the presentation mode: Room #1 is perceived, by the Belgian group, significantly differently to Room #2 while these two rooms are perceived similarly by the French group. Moreover, our results revealed a color shift from a colder temperature to a warmer one with the HDR display.

IV.C.2.1.2.3. *CONTRAST*

As illustrated in Fig.IV.C.15, Rooms #1 and #3 are perceived as presenting a similar contrast in the real world, while with $3D_{belgium}$, 2D and HDR modes, Room #1 is perceived as the room presenting the lowest contrast. Whatever the medium, Room #4 presents the highest contrast.

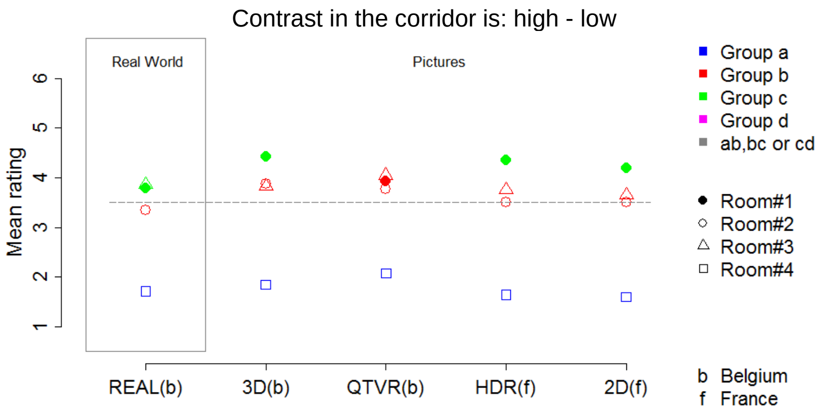


FIGURE IV.C.15
Contrast (D31) – Reproducibility of the findings

Mixed model analysis revealed that the contrast perceived with $3D_{belgium}$ mode was significantly lower than in the real world (see Table IV.C.13).

TABLE IV.C.13
Contrast (D31) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	**AIC** without interaction	**AIC** with interaction	**$3D_{belgium}$ vs. real world**	**QTVR vs. real world**	**HDR vs. real world**	**2D vs. real world**
D31	3004.5	3015.2	0.31, 0.03*	0.28, 0.06	0.14, 0.35	0.06, 0.69

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Contrast is perceived as lower when the scenes are displayed in 3D.

IV.C.2.1.2.4. *DISTRIBUTION*

The participants rated Room #4 as the room presenting the most varied distribution regardless of the medium (see Fig.IV.C.16).

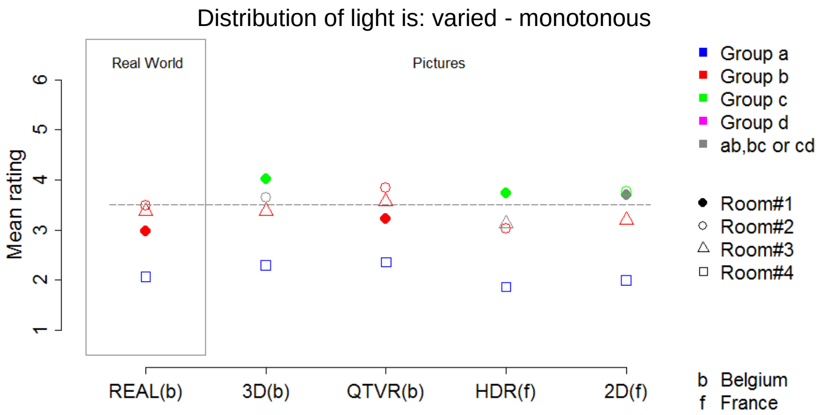


FIGURE IV.C.16
Distribution (D41) – Reproducibility of the findings

Contrast analysis (see Table IV.C.14) revealed that Room #1 was perceived significantly most monotonous in images than in the real world except with QTVR panoramas which is the only mode of presentation which does not present differences with the actual scenes.

TABLE IV.C.14
Distribution (D41) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	**AIC** without interaction	**AIC** with interaction	**Room**	**3D$_{belgium}$ vs. real world**	**QTVR vs. real world**	**HDR vs. real world**	**2D vs. real world**
D41	3373.1	3367.0	**#1**	1.04, 0.0008***	0.26, 0.42	0.75, 0.02*	0.71, 0.02*
			#2	0.15, 0.65	0.36, 0.25	-0.46, 0.15	0.28, 0.36
			#3	0.004, 0.99	0.19, 0.54	-0.24, 0.45	-0.17, 0.58
			#4	0.22, 0.46	0.29, 0.36	-0.21, 0.52	-0.07, 0.82

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

QTVR mode is the only presentation mode of images which does not distort the perception of the distribution of light experienced in the real world.

IV.C.2.1.2.5. *DIRECTIVITY*

Figure IV.C.17 illustrates that the classification order encountered with the actual rooms is replicated with all the modes of presentation. Rooms are grouped similarly regardless of the mode except the 3D$_{belgium}$ mode in which no significant difference is detected between Rooms #3 and #1.

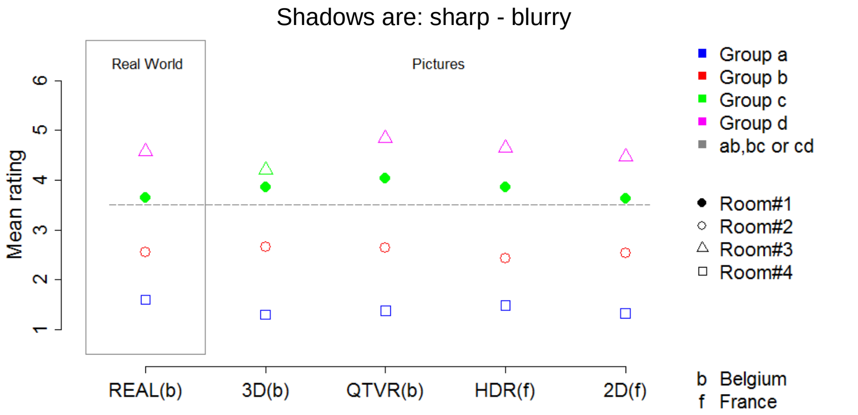


FIGURE IV.C.17
Directivity (D51) - Reproducibility of the findings

Mixed model analysis revealed no significant difference between the real world and its reproduction using image (see Table IV.C.15).

TABLE IV.C.15
Directivity (D51) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	**AIC** without interaction	**AIC** with interaction	**3D$_{belgium}$ vs. real world**	**QTVR vs. real world**	**HDR vs. real world**	**2D vs. real world**
D51	2925.6	2941.1	-0.10, 0.51	0.13, 0.40	0.008, 0.95	-0.11, 0.46

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Figure IV.C.18 shows that textures are perceived as being rather sharp regardless of the medium. But the rooms are grouped differently according to the mode: with QTVR and 2D modes, only Room #2 is distinguished from the other rooms. With 3D and HDR modes, only Room #4 is distinguished from the three others rooms. Mean profiles observed in QTVR and 2D are similar to the real world.

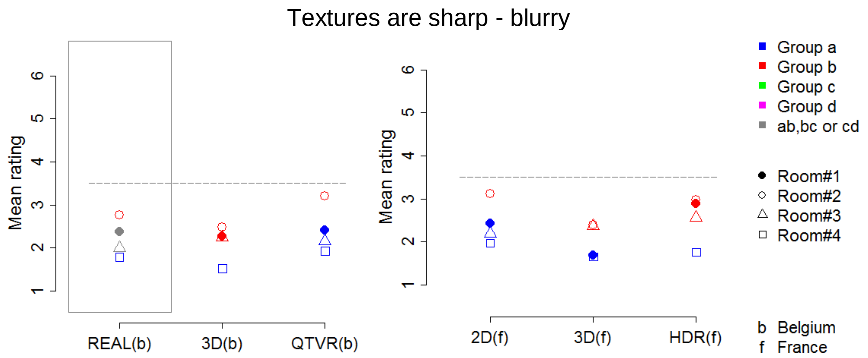


FIGURE IV.C.18
Directivity (D52) - Reproducibility of the findings

The analysis of variance revealed that textures were perceived by the French participants as sharper when visualized in 3D than in 2D (see Table IV.C.16).

TABLE IV.C. 16
Directivity (D52) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level for the modes tested in Belgium while 2D mode is the reference for the modes tested in France

Ref.	AIC without interaction	AIC with interaction	$3D_{belgium}$ vs. real world	QTVR vs. real world	$3D_{france}$ vs. 2D	HDR vs. 2D
D52	3024.5	3030.1	-0.10, 0.43	0.19, 0.14	-0.40, 0.002**	0.12, 0.39
Significance: *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$.						

Directivity of light is well reproduced using images. Textures are perceived as sharper in 3D than in 2D. QTVR and 2D modes best replicate the mean profiles observed in the real world.

IV.C.2.1.2.6. *Glare*

In Chapter III.B, we observed that glare was perceived significantly differently by our two populations of participants: Belgian people rated the four rooms as slightly more glaring than the French participants. As in the real world, with the QTVR mode, the four rooms do not differ significantly and only one group of room is created. But with $3D_{belgium}$, 2D, $3D_{france}$ and HDR mode, the rooms are grouped differently (see Fig.IV.C.19).

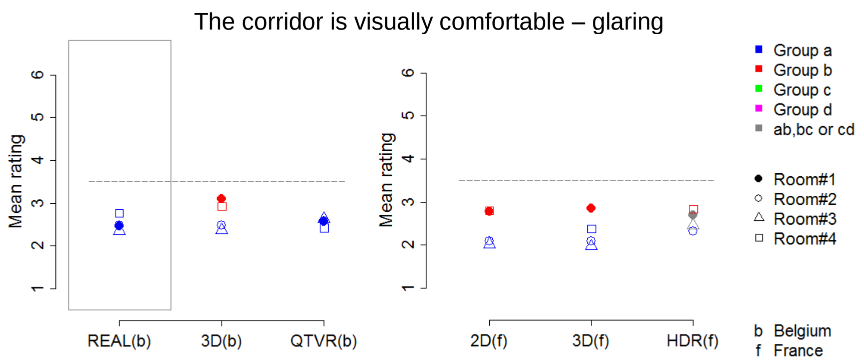


FIGURE IV.C.19
Glare (D61) - Reproducibility of the findings

Contrasts analysis revealed that Room #1 is perceived as more glaring when visualized in 3D than in the actual environment (see Table IV.C.17).

TABLE IV.C.17
Glare (D61) - Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level for the modes tested in Belgium while 2D mode is the reference for the modes tested in France

Ref.	AIC without interaction	AIC with interaction	Room	$3D_{belgium}$ vs. real world	QTVR vs. real world	$3D_{france}$ vs. 2D	HDR vs. 2D
D61	2742.9	2740.2	#1	0.64, 0.01*	0.10 ,0.67	0.07, 0.79	-0.07, 0.76
			#2	-0.006, 0.99	0.10, 0.66	0.004,1	0.22, 0.34
			#3	0.03, 0.91	0.29, 0.20	-0.05, 0.83	0.44, 0.07
			#4	0.15, 0.49	-0.34, 0.14	-0.42, 0.07	0.04, 0.87

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Figure IV.C.20 presents mean ratings for the question related to the risk of glare caused by a window. Only the HDR mode replicates the order and the groups of rooms observed in the real world.

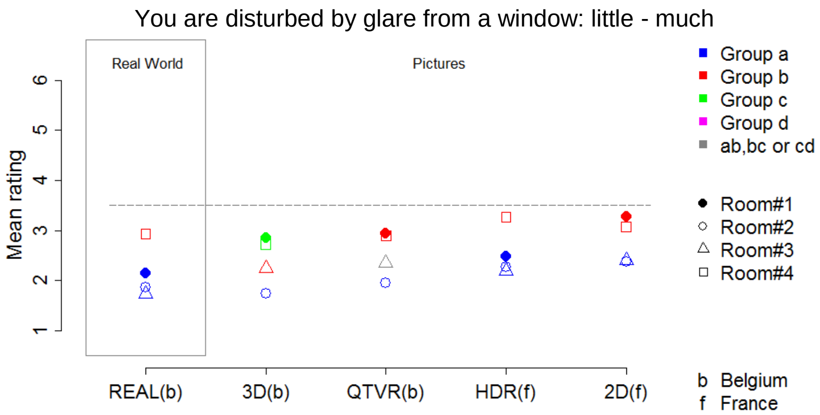


FIGURE IV.C.20
Glare (D62) - Reproducibility of the findings

The contrasts analysis revealed that only the HDR mode does not present significant difference with the real world (see Table IV.C.18).

TABLE IV.C.18
Glare (D62) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	AIC without interaction	AIC with interaction	Room	$3D_{belgium}$ vs. real world	QTVR vs. real world	HDR vs. real world	2D vs. real world
D62	3245.3	3237.1	#1	0.71, 0.02*	0.81, 0.006**	0.35, 0.25	1.14, 0.0001***
			#2	-0.13, 0.68	0.08, 0.76	0.40, 0.17	0.51, 0.08
			#3	0.51, 0.08	0.62, 0.04*	0.45, 0.14	0.66, 0.03
			#4	-0.20, 0.48	-0.04, 0.91	0.34, 0.26	0.14, 0.62

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Figure IV.C.21 presents the mean ratings to the question related to the potential risk of glare caused by a bright surface. In the real world, no difference was detected between the four rooms (perceived as not glaring). When visualized in images, Room #3 presents a surface slightly more glaring.

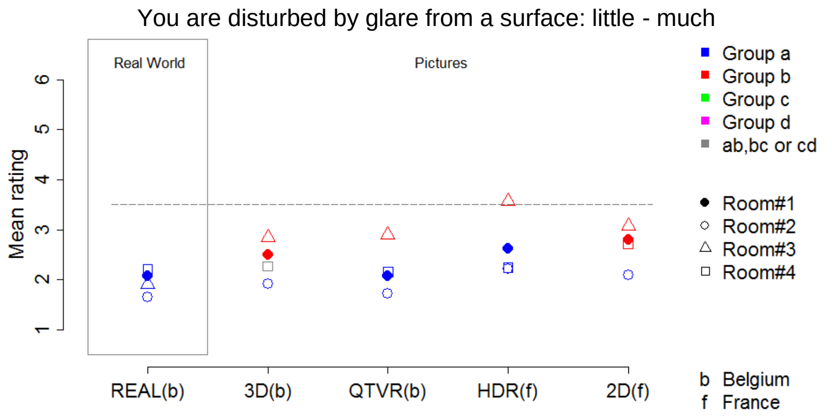


FIGURE IV.C.21
Glare (D63) - Reproducibility of the findings

This observation is confirmed by the contrasts analysis which detects in this room a significant difference between the pictures and the real world (see Table IV.C.19).

TABLE IV.C.19
Glare (D63) – Results of the contrasts analysis (MCMCmean and p-value). Real-world experiment is taken as the reference level.

Ref.	AIC without interaction	AIC with interaction	Room	$3D_{belgium}$ vs. real world	QTVR vs. real world	HDR vs. real world	2D vs. real world
D63	3152.5	3148.2	#1	0.43,0.13	0.008,0.98	0.55,0.06	0.73,0.01**
			#2	0.26,0.37	0.066,0.82	0.56,0.05	0.45,0.12
			#3	0.94,0.00***	0.99,0.00***	1.65,0.00***	1.16,0.00***
			#4	0.07,0.82	-0.06,0.85	0.03,0.91	0.52,0.07

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Regardless of the presentation mode of images, the rooms are assessed as not glaring similarly to what is observed in the real world. However, glare from window is better replicated with the HDR display. Glare caused by a bright surface is overestimated in Room #3 when the scene is assessed on the basis of images, whatever the mode of presentation.

IV.C.2.2. NON-CONVENTIONAL QUESTIONS

IV.C.2.2.1. PAIRED COMPARISON OF WALLS (#1, #2)

As shown in Fig.IV.C.22, responses given by the participants visualizing in image Room #3 are similar to those given by the participants in the real world.

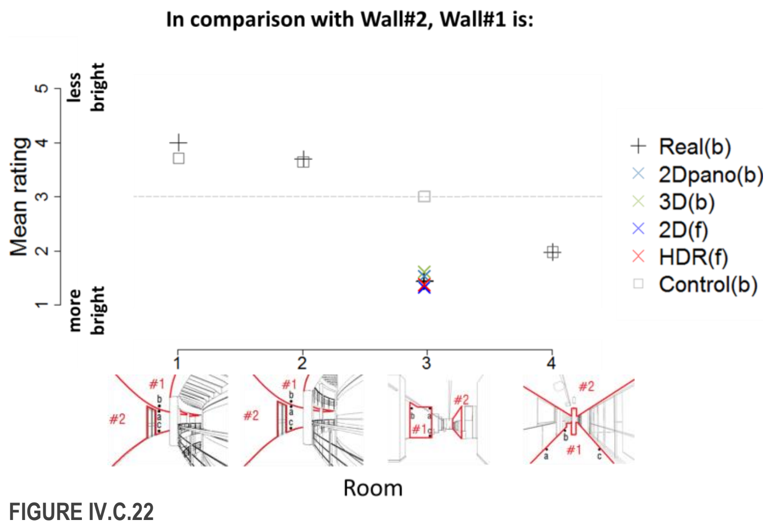


FIGURE IV.C.22
Comparison of two walls for brightness – mean ratings

A wider variety of scores is observed with the paired-comparison for uniformity than in the previous paired-comparison. However, again, perceptions experienced with images are similar to those experienced in the real world (see Fig.IV.C.23).

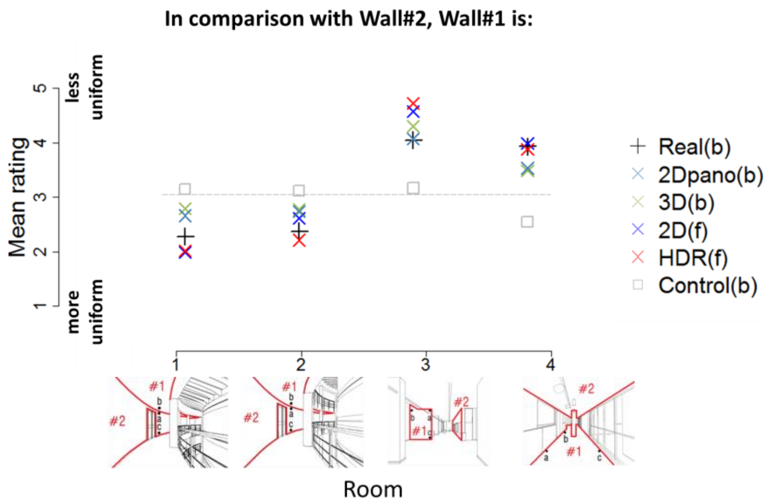


FIGURE IV.C.23
Comparison of two walls for uniformity – mean ratings

At last, Fig.IV.C.24 shows that in the first two rooms, the two walls are perceived as presenting a same roughness while in the real world, Wall#1 was slightly less rough in comparison with Wall#2.

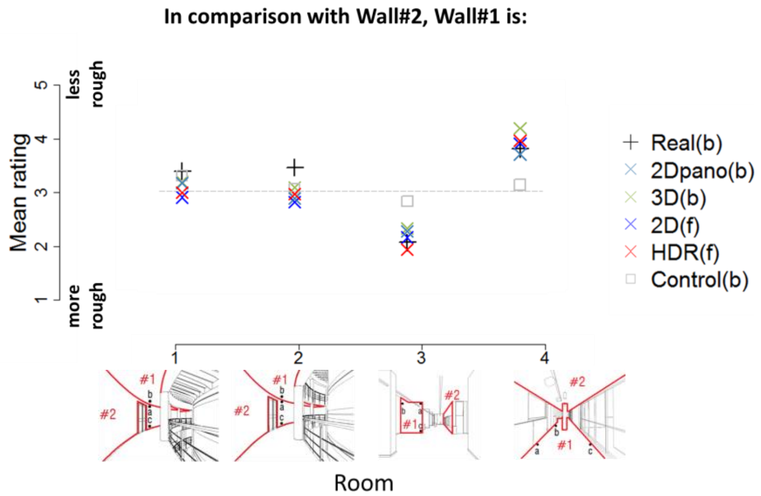


FIGURE IV.C. 24
Comparison of two walls for roughness – mean ratings

Responses in the two other rooms (Rooms #3 and #4) are similar to the responses given in the real world.

IV.C.2.2.2. CLASSIFICATION OF PUNCTUAL ZONES FOR BRIGHTNESS

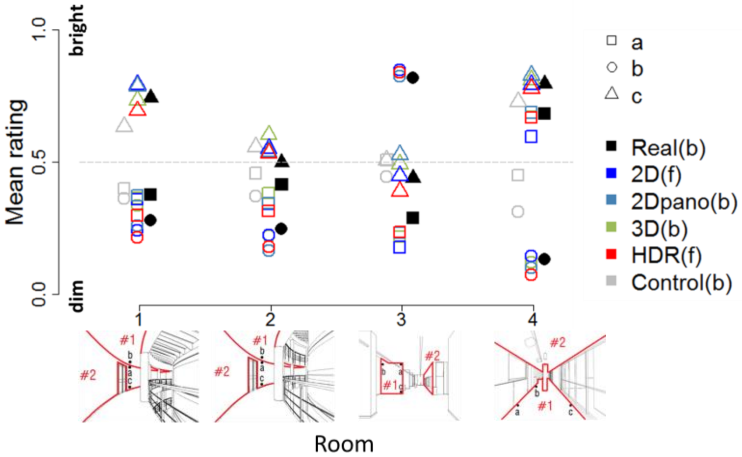


FIGURE IV.C.25
Classification of three points for brightness – mean ratings

Figure IV.C.25 shows that whatever the medium, the points are classified similarly by the participants.

IV.C.2.2.3. DETERMINATION OF ZONES FOR BRIGHTNESS

In Tables IV.C.20 to 23, it appears that similar zones are colored as the brightest and the dimmest parts in the real world and with the pictures.

The consensus is greater with pictures than in the actual rooms, and is particularly high for 2D mode.

TABLE IV.C.20
Room #1 - Brightest and dimmest part maps (the color scale indicates the percentage of participants who identified the areas as the brightest or dimmest parts of the scene)

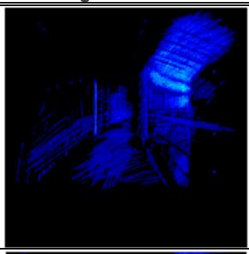
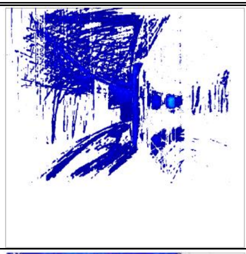
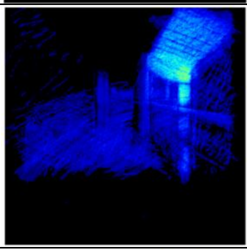
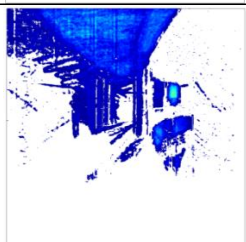
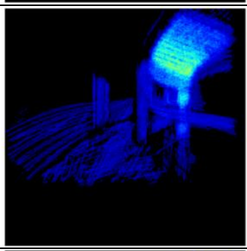
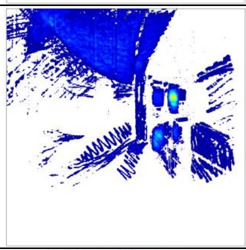
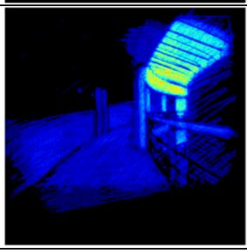
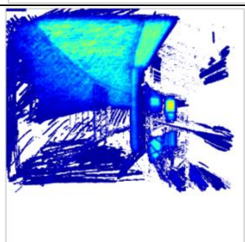
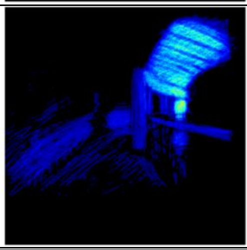
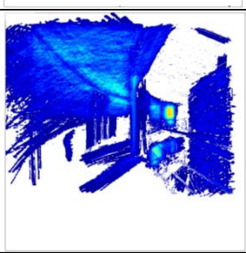
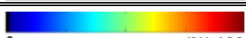
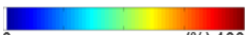
Medium	Brightest zones	Dimmest zones
Real world		
QTVR		
$3D_{belgium}$		
2D		
HDR		
	 0 (%) 100	 0 (%) 100

TABLE IV.C.21
Room #2 - Brightest and dimmest part maps (the color scale indicates the percentage of participants who identified the areas as the brightest or dimmest parts of the scene)

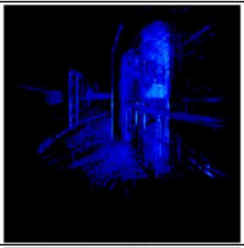
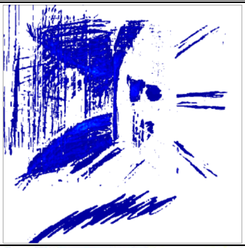
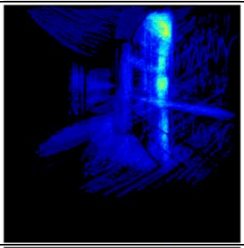
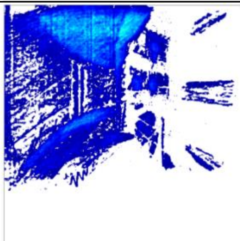
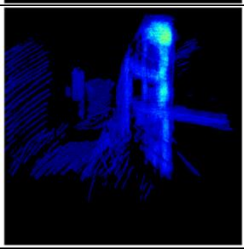
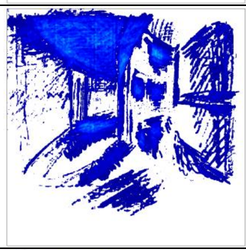
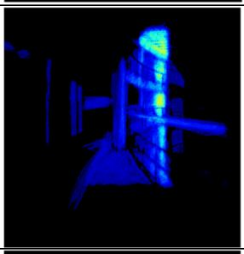
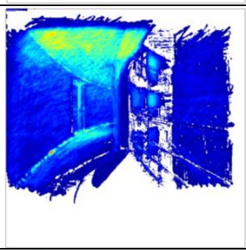
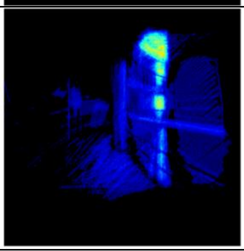
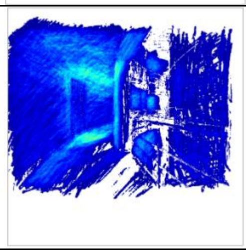
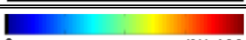
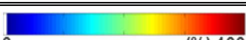
Medium	Brightest zones	Dimmest zones
Real world		
QTVR		
$3D_{belgium}$		
2D		
HDR		
	 0 (%) 100	 0 (%) 100

TABLE IV.C.22

Room #3 - Brightest and dimmest part maps (the color scale indicates the percentage of participants who identified the areas as the brightest or dimmest parts of the scene)

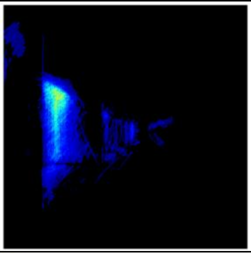
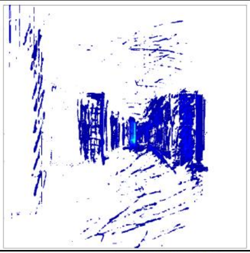
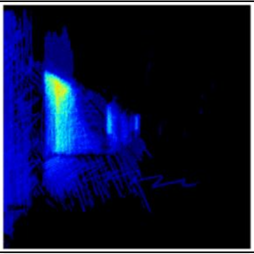
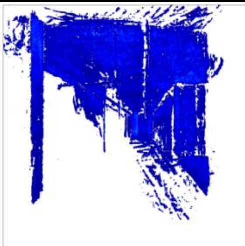
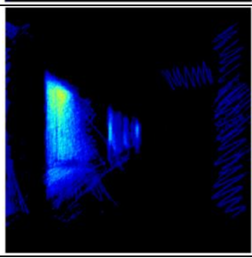
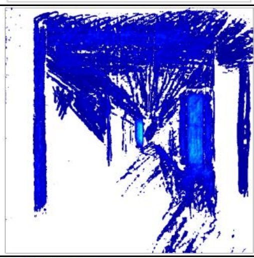
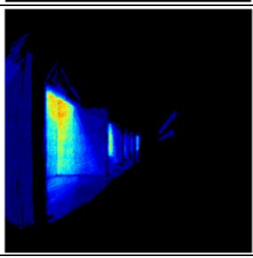
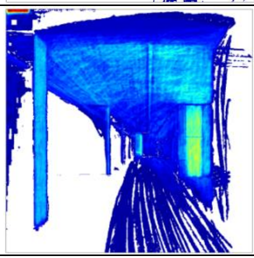
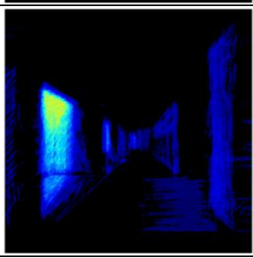
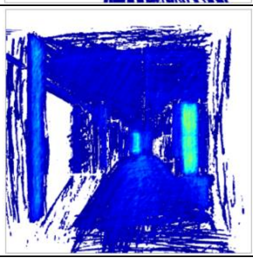
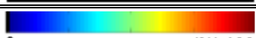
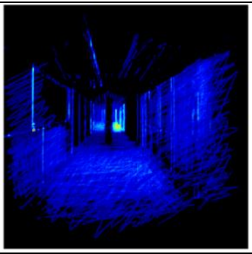
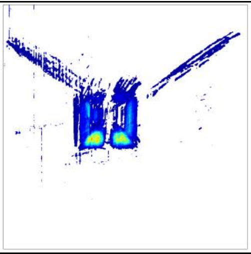
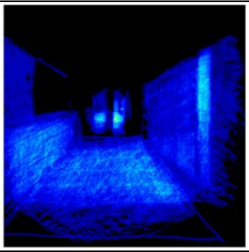
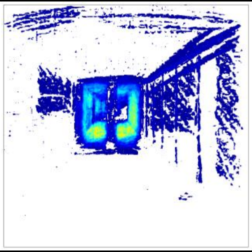
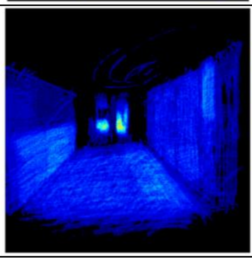
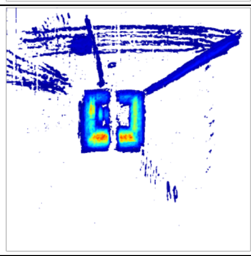
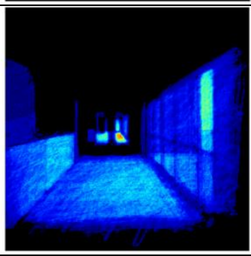
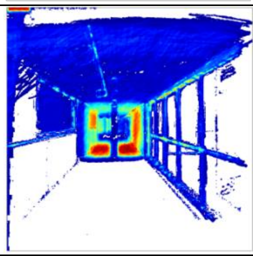
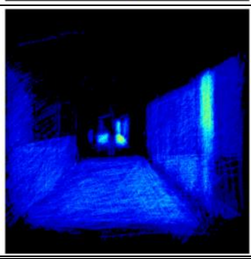
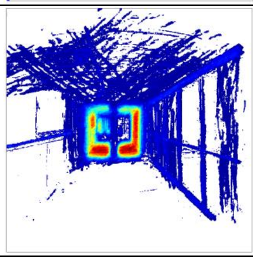
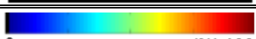
Medium	Brightest zones	Dimmest zones
Real world		
QTVR		
3D$_{belgium}$		
2D		
HDR		
	 0 (%) 100	 0 (%) 100

TABLE IV.C.23
Room #4 - Brightest and dimmest part maps (the color scale indicates the percentage of participants who identified the areas as the brightest or dimmest parts of the scene)

Medium	Brightest zones	Dimmest zones
Real world		
QTVR		
$3D_{belgium}$		
2D		
HDR		
	 0 (%) 100	 0 (%) 100

IV.C.3. Discussion

This chapter seeks to determine whether some presentation modes of pictures better replicate results of the real-world experiment than traditional 2D pictures presented on a conventional display.

If no difference between the Belgian and the French population was observed in the previous chapter (Chapter IV.B), the real-world experiment was taken as the reference for analysis. If differences were detected, the modes tested in Belgium were compared to the real-world experiment (carried out in Belgium), while the 3D and HDR modes tested in France were compared to the 2D mode (tested in France).

Table IV.C.24, which summarizes the two-step analysis performed on the rating scales, highlights the fact that no mode of presentation is particularly distinguished by very high or very low capabilities to replicate the results of the real-world experiment.

TABLE IV.C.24
Summary of the analysis on rating scales

Factor	Ref.	Question	Real world vs.				2D vs.	
			$3D_b$	QTVR	HDR	2D	$3D_f$	HDR
Pleasantness	P0	Pleasantness: low – high	× (red)	× (green)	× (red)	× (red)	-	-
	P1	(light) pleasant – unpleasant	× (green)	✓ (green)	× (red)	× (green)	-	-
Enclosedness	E0	Enclosedness: low – high	× (red)	× (red)	- (red)	- (red)	✓ (green)	✓ (green)
	E1	(corridor) slightly – very spacious	× (red)	× (red)	× (red)	× (red)	-	-
	E2	(corridor) slightly – very narrow	× (red)	× (red)	× (red)	× (red)	-	-
	E3	(corridor) slightly – very deep	× (green)	× (green)	× (orange)	✓ (green)	-	-
Brightness	D11	(corridor) dim – bright	✓ (orange)	✓ (orange)	× (green)	✓ (green)	- (green)	- (green)
	D12	(you) in the dark – light	✓ (orange)	✓ (orange)	× (orange)	✓ (orange)	- (green)	- (green)
Coloration	D21	(corridor) neutral – colorful	✓ (green)	✓ (green)	- (green)	- (green)	✓ (green)	✓ (green)
	D22	(corridor) cold – warm	× (green)	× (green)	- (green)	- (green)	✓ (green)	× (red)
	D23	(light) neutral – colorful	× (green)	× (green)	- (green)	- (green)	✓ (green)	× (green)
Contrast	D31	(corridor) high – low contrast	× (orange)	× (green)	× (green)	× (green)	- (green)	- (green)
Distribution	D41	(distribution) varied – monotonous	× (red)	✓ (green)	× (red)	× (red)	- (green)	- (green)
Directivity	D51	(shadow) sharp – blurry	× (green)	✓ (green)	✓ (green)	✓ (green)	- (green)	- (green)
	D52	(textures) sharp – blurry	× (green)	× (green)	- (green)	- (green)	× (orange)	× (green)
Glare	D61	(corridor) comfortable – glaring	× (red)	✓ (green)	- (green)	- (green)	✓ (green)	✓ (green)
	D62	(you) little – much disturbed < window	× (red)	× (red)	✓ (green)	× (red)	- (green)	- (green)
	D63	(you) little – much disturbed < surface	× (red)	× (red)	× (red)	× (red)	- (green)	- (green)

Grouping of rooms: ✓ reproduced, × not reproduced
Presentation mode effect or interaction:
✓/× (red) interactions, ✓/× (orange) presentation mode effect, ✓/× (green) no presentation mode effect

As illustrated in Fig.IV.C.3, results are considered replicated if no presentation mode-room interaction is detected. If no presentation mode effect is observed (✓/× green), the score can be read in absolute terms. If a presentation mode effect is detected (✓/× orange), the score must be read in relative terms.

IV.C.3.1. VISUAL APPEARANCE OF SPACE

IV.C.3.1.1. PLEASANTNESS

According to our analysis, only the QTVR mode replicates the pleasantness experienced in the real world. Pleasantness of the lighting, on the other hand, is reproduced with three of the four modes of presentation. Only the HDR mode does not replicate the results. Thus, the switch to image appears to cause a loss of information, impacting the perception of pleasantness, but it has a lesser influence on the pleasantness of lighting.

IV.C.3.1.2. ENCLOSEDNESS

Perception of enclosedness is poorly reproduced for all image types. Indeed, interaction effects were detected. They indicate that the effect of the presentation mode on enclosedness varies according to the room. For instance, regardless of the presentation mode of images, Room #1 is perceived as more spacious than in the real world, while Room #4 is perceived as less spacious in images versus the real world. Only the perception of depth is replicated. We also observed that all of the pictures reproduce similar mean profiles. The switch to images thus causes a loss of information, which impacts the perception of enclosedness, but enclosedness is perceived similarly regardless of the image type. Contrary to our hypothesis, 3D pictures do not help replicate spatial perceptions.

IV.C.3.2. VISUAL APPEARANCE OF LIGHTING

IV.C.3.2.1. PERCEIVED BRIGHTNESS

Three of the four presentation modes tested replicate the grouping of rooms observed in the real-world experiment for the perception of brightness. Only the HDR display does not reproduce this grouping of rooms. Nevertheless, we detected an overestimation of the perceived brightness with the image visualizations.

This overestimation can be explained by dark adaptation process and simultaneous contrast. Indeed, in the present study, the visualization of the pictures was organized in a dark room rather than in ambient light conditions similar to those encountered in the actual environments. But we know that, in response to the ambient light level, pupil size changes to adjust the amount of light that reaches the retina while rods and cones modify their sensitivity to adapt to the lighting conditions. And so, when the eyes are kept in a dark environment for a while, they become more sensitive to light and a specific light source is perceived as brighter than in bright conditions. Moreover, due to contrast sensitivity, a region is perceived by the human eye as brighter when its background is dark than when it is bright. The monitor surrounds affect thus also the image appearance and, with a dark surround the image looks brighter.

In general, professional environments use controlled ambient lighting. In the present study, to avoid flickering when visualizing 3D pictures, we organized the visualization of 3D pictures in a dark environment. To not introduce an experimental bias between the various presentation modes of images, we organized all the visualizations in similar ambient light conditions. But, due to the two phenomena cited above (dark adaptation and simultaneous contrast), the visualization of the pictures in this dark environment affected the perceived brightness of the rooms: photographs were perceived as brighter than the real rooms.

To evaluate the impact of displaying the pictures in this dark environment, a complementary study was organized at ENTPE (Cauwerts et al., 2013). Subjects visualized a series of pictures in both dark and lit rooms. This experiment revealed that, as expected, the ambient light conditions in the room influence significantly the perception of brightness, and that the brightness is overestimated when the pictures are visualized in dark conditions.

IV.C.3.2.2. COLORATION

The reproduction of the experiment in France and in Belgium revealed that, while Belgian people perceived the coloration of Room #1 and Room #2 significantly differently, French people rated them as similar. In Chapter IV.B, we hypothesized that the rating scale was not similarly understood due to the imprecision of the term "colorful." In the present chapter, we observed that the difference between the Belgian and French people was reproduced with other types of images. We maintain our hypothesis of a difference in understanding of the scale.

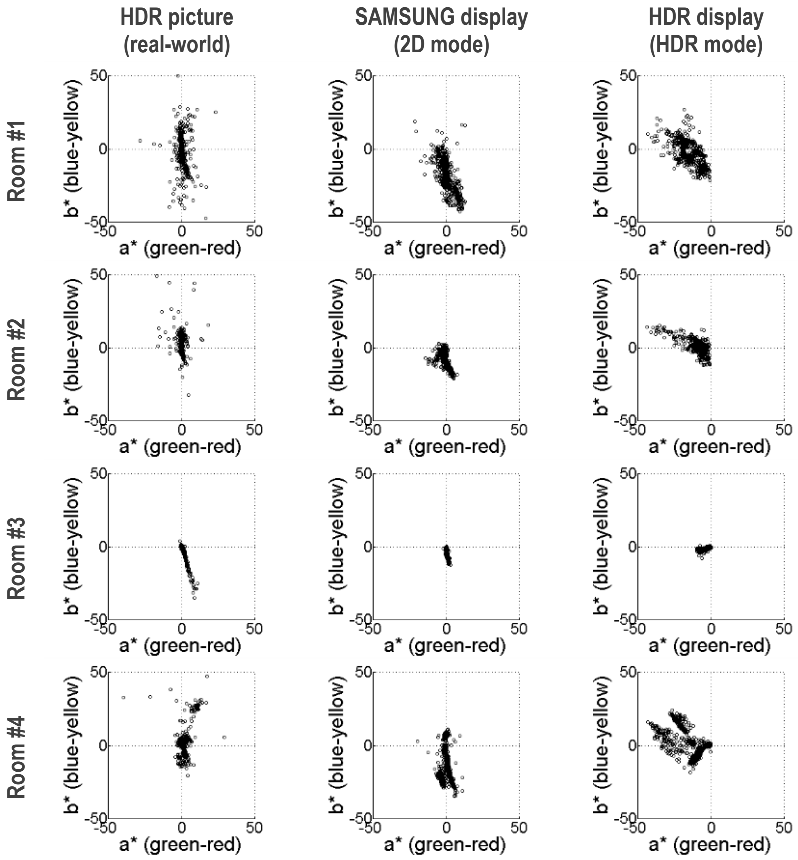
As some differences were detected between the two populations, the $3D_{belgium}$ and QTVR modes were compared to the real-world experiment, and the $3D_{france}$ and HDR modes were compared to the 2D mode carried out in France. Our analysis revealed that the LDR display replicates the perception of coloration experienced in the real world, while the HDR display introduces some distortion. Indeed, three scenes were perceived as warmer when displayed on this device rather than on the LDR display.

To better understand this color shift, HDR pictures of the LDR and HDR devices displaying pictures of Tour #1 were taken. CIE a* b* diagrams were built and compared to those of the real-world experiment presented in Chapter III.B (see Table IV.C.26). The comparison of the CIE a* b* diagrams shows that the Samsung monitor better reproduces the coloration of the actual scenes. Indeed, a shift toward yellow-green is induced by the HDR display in comparison with the Samsung device.

TABLE IV.C.25
Comparison of the CCT of the various modes of presentation

Mode of presentation of the scenes		Correlated color temperature (CCT)
Real world		7000-12000K
SAMSUNG display		8760K
HDR display	Hitachi (with filter)	5990K
	Hitachi (without filter)	6184K
	Christie	6263K

TABLE IV.C.26
CIE a* b* diagrams (TOUR #1)



Additional measurements of each device displaying a white blank screen were taken with a spectrophotometer, and the correlated color temperature (CCT) of each device was determined (see Table IV.C.25).

These measurements reveal that the Samsung display is colder than the HDR device. They also show that the CCT of the two projectors is not identical, and that the glass placed in front of the Hitachi projector reduces the CCT of the projector from 6184K to 5990K. The glass thus accentuates the difference between the Hitachi and the Christie projectors and is partly responsible for observed artifacts.

IV.C.3.2.3. CONTRAST

The statistical analysis revealed no significant difference between the real-world experiment and the images, except the 3D mode, for which the contrast is perceived as lower than in the actual environment.

IV.C.3.2.4. Distribution of light

According to the statistical analysis, the perception of the light distribution experienced in the first actual room is not replicated using images, except with QTVR pictures. That could be explained by the fact that this type of image gives more information to the observer than the other types of images.

Paired-comparisons of walls for brightness and uniformity as well as the classification of points for brightness showed that the participants give similar responses in the real world as when they visualize the pictures of the scenes.

The brightest and dimmest part maps highlighted the fact that, even if the results are similar between the real world and the images, the consensus between the participants is higher when the participants visualize pictures than when they rate the actual environments. This observation suggests that the loss of information content between the real world and the pictures impacts on the responses of the participants. In actual environments, the five senses are on alert while with pictures, participants focus on the visual information. Moreover, pictures cover a substantially reduced field of view in comparison to the one available in the actual environment. That could explain the higher consensus observed with images.

Last, we also observed that the consensus was the highest, when the participants are asked to rate traditional 2D pictures displayed on a conventional display (2D mode).

IV.C.3.2.5. Directivity of light

Shadows are similarly perceived with the images than in the real world. Mean profiles of QTVR and 2D modes are very similar to the real-world experiment for the perception of textures. According to the experiments organized in France, 3D visualization accentuates the sharpness of the textures in comparison with 2D visualization.

IV.C.3.2.6. Glare

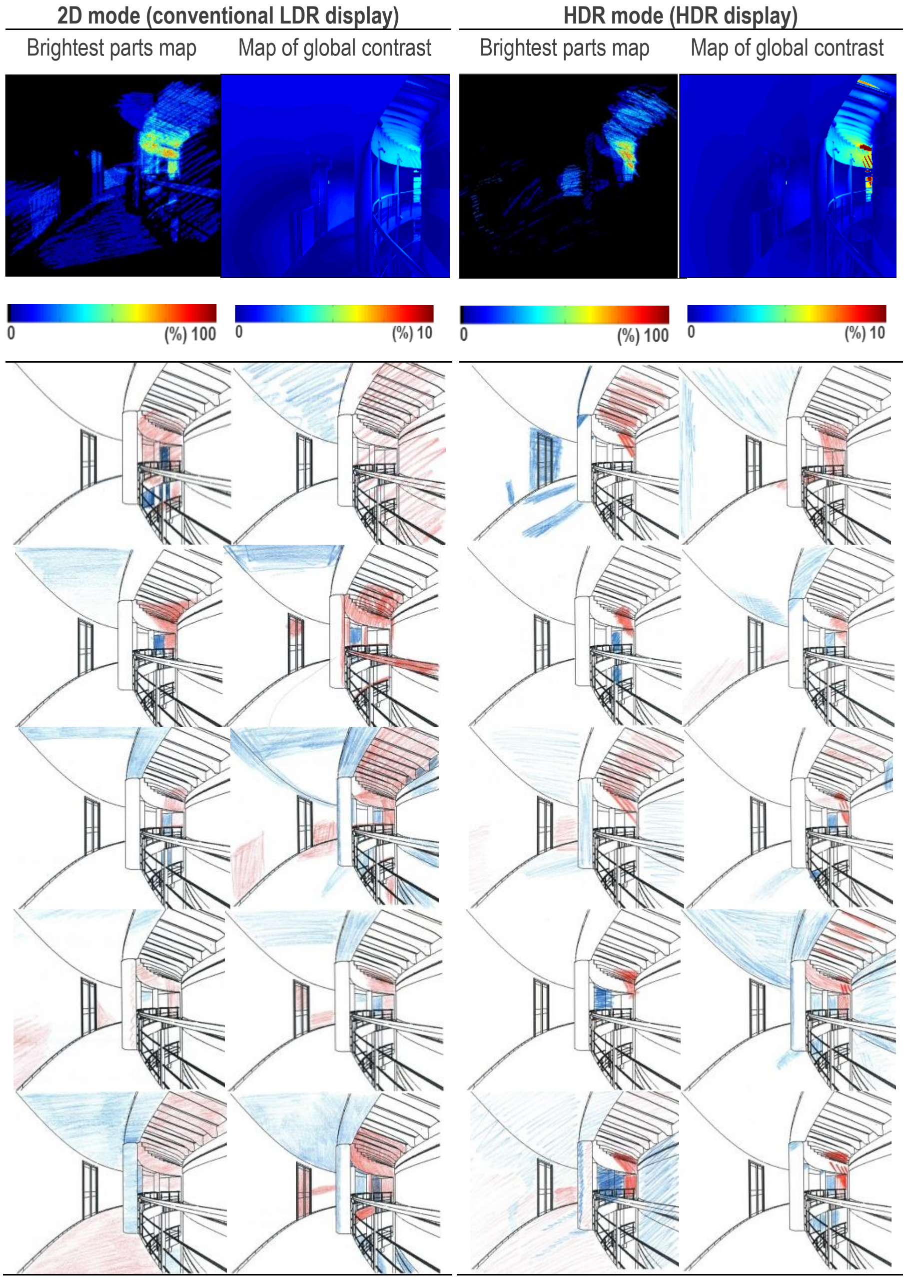
According to the objective analysis presented in Chapter III.B, there was no risk that the subject was disturbed by glare in the visited rooms. The absence of glare during the real-world experiment did not allow to clearly state about the ability of the tested presentation modes to replicate this dimension. However, the rating scales related to glare were kept to determine whether the visualization of pictures on a monitor increases the risk of glare.

We observed that a wall in Room #3 appeared a bit more glaring in images (regardless of presentation mode) than in the real world. We also observed that glare from windows was better replicated with the HDR display than with the other types of pictures.

Moreover, the analysis of the sketches made by the participants visualizing Room #1 in Tour #1 revealed that the subjects of the HDR mode have the ability to detect sun spots contrary to the subjects of the 2D mode (see Table IV.C.27). In this table, brightest part maps are compared to maps of global contrast, created using

HDR pictures taken of the 2D and HDR displays. These maps highlight the fact that the HDR display device presents a higher contrast than the 2D display.

TABLE IV.C.27
Comparison of the sketches made by the participants of the 2D and HDR modes when visualizing Room #1 in Tour #1 (a scene presenting a sun spot)



IV.C.3.3. COMPARISON WITH THE LITERATURE

The previous section pointed out the potential of images for studying the appearance of lighting but also some divergences between the real world and the images for spatial appearance. The present section aims at confronting our results with two main validation works presented in Chapter I.B: the work of Hendrick et al. (1977) who investigated slides, and a more recent study on the potential of HDR displays by Newsham et al. (2010).

As explained in Chapter I.B, in the 1970s, Hendrick et al. studied the potential of slides for assessing the influence of artificial light on human impressions. Using slides, they reproduced a study carried out in mock-ups by Flynn et al. (1973). They first took several photographs of the six lighting arrangements, in the mock-up. Then, they chose those that best reproduced the scenes. They investigated two of the three techniques used by Flynn et al. for assessing the six artificial lighting arrangements, multidimensional scaling and rating scales (7-point scales). According to the authors, multidimensional scaling did not replicate the results of the mock-up experiment. On the other hand, using rating scales, a similar factor structure was observed as well as similar mean ratings between the actual scenes and the images (the following dimensions were studied: evaluative, perceptual clarity, spaciousness, perceived horizontality, spatial complexity, and formality). Despite some slight divergences between the mock-up and the slides, Hendrick et al. concluded that slides are promising if rating scales are used to collect perceptions. The authors did not precisely state which dimensions were particularly well replicated and which were not.

Newsham et al. (2010) tested the hypothesis that the visual appearance of HDR images is judged as more realistic than LDR images. The perception of brightness, uniformity, pleasantness, and glare of six rooms mixing artificial light and daylight were studied. On average, the six rooms studied by Newsham et al. were brightest than the four rooms studied in the present study (see Table IV.C.28).

TABLE IV.C.28
Mean luminances of rooms in Newsham et al. (2010) and in the present study

	Newsham et al. (2010)	The present study
Mean luminance of all the rooms	140 cd/m²	65 cd/m²
Mean luminance of the darkest room	39 cd/m²	37 cd/m²
Mean luminance of the brightest room	458 cd/m²	113 cd/m²

Spatial perceptions were not investigated. Contrary to our study, and to that of Hendrick et al. (1977), the same subjects assessed the scenes in each presentation mode, on continuous scales. Pictures were taken several weeks before the experiment, leading to inevitable differences in lighting conditions between the real-world experiment and the picture

From this study, Newsham et al. concluded that, for the rooms without large areas of high luminance (four of the six studied rooms), there is no benefit to HDR display for reproducing the visual appearance of actual lit scenes. But, the results obtained on the basis of the HDR images were not worse than those obtained with conventional LDR images.

In these two studies (whose important methodological choices are summarized in Table IV.C.29), the authors observed that divergences between the actual scenes and the images vary according to the scenes.

TABLE IV.C.29
Comparison of some methodological choices between the present study and the studies carried out by Hendrick et al. (1977) and Newsham et al. (2010)

	The present study	Hendrick et al. (1977)	Newsham et al. (2010)
Studied modes of presentation	2D pictures on LDR display 2D pictures on HDR display 3D pictures on LDR display Panoramas on LDR display	Slides	2D pictures on LDR display 2D pictures on HDR display
Reference	Real world	Mock-up	Real world
Lighting	Daylight	Artificial light	Daylight and artificial light
Subject	A different group of people by mode	A different group of people by mode	Same people for the three modes
Scales	6-point rating scales	7-point rating scales	Continuous scales
Stimuli	4 corridors	6 lighting arrangements of a conference room	6 rooms of an office building

Hendrick et al. made no assumptions about which type of room replicates which lighting dimensions, while Newsham et al. determined that rooms presenting large areas of high luminance are judged as more realistic in the HDR mode than in the LDR mode. Similar to Hendrick et al., Newsham et al. do not precisely state which dimensions are particularly well replicated and which are not, regardless of the scene. Based on Hendrick et al.'s data, we observed that, among the spacious/cramped, pleasant/unpleasant, and bright/dim scales, only the pleasant/unpleasant scale reproduced a similar order of classification of the rooms between the mock-up and the slides, and that the slides were, on average, judged as more pleasant.

In the lighting design process, one of the objectives of the designer is often to compare several scenes and to choose one according to fixed criteria. In these two studies, the authors graphically present the mean ratings of the differential scales by presentation mode and for each scene separately. We think that it is also interesting to analyze each rating scale separately for analyzing how the scenes are classified, with each mode of presentation.

IV.C.4. CONCLUSIONS

The objective of the present chapter was to determine to what extent 2D pictures, QTVR panoramas, 3D displays and HDR displays replicate the perceptions of the appearance of lighting and space experienced in actual daylit environments. More particularly, we aimed at determining whether QTVR panoramas, 3D displays and HDR displays better replicate perceptions experienced in the actual environment than tone-mapped 2D pictures displayed on a conventional low dynamic range (LDR) monitor.

The absence of glare during the real-world experiment did not allow to clearly state about the ability of the presentation modes to replicate this dimension. Nevertheless, the experiment highlighted the potential of HDR display for assessing scenes presenting sun spots.

As presented in this chapter and summarized in Table IV.C.30, few sharp differences between the tested presentation modes of images were observed. And no mode of presentation was particularly distinguished by very high or very low capabilities to replicate the results of the real-world experiment. Given the high investment in time and money required for making 3D pictures, QTVR panoramas and HDR projections, we thought that the use of these modes of presentation should present a real benefit in comparison with 2D images displayed on a conventional monitor.

TABLE IV.C.30
Summary of the abilities of each mode of presentation for replicating perceptions of space and lighting experienced in the actual environments

	2D mode	QTVR mode	3D mode	HDR mode*
Appearance of space				
Pleasantness	×	✓✓	×	×
Enclosedness	×	×	×	×
Appearance of lighting				
Brightness	✓	✓	✓	✓
Coloration	✓✓	✓✓	✓✓	×
Contrast	✓✓	✓✓	✓	✓✓
Distribution	×	✓✓	×	×
Directivity	✓✓	✓✓	✓✓	✓✓
Glare **	-	-	-	-

✓✓ No significant difference was observed with the real-world experiment
✓ Score must be read in relative terms
× Significant differences were observed with the real-world experiment
* the tested HDR display was under development at ENTPE
** the absence of glare during the real-world experiment did not allow to clearly state about the ability of the presentation modes to replicate this dimension

Concerning the appearance of space, our results suggest that the switch from the actual environment to images causes a loss of information impacting on the appearance of pleasantness and enclosedness (see Table IV.30). Only QTVR panoramas visualization did not present significant differences with the real-world experiment for pleasantness dimension. This suggests that expand the field covered by the picture reduces the loss of information with the real world. This mode should thus be preferred for investigating pleasantness. On the other hand, perception of enclosedness is poorly reproduced regardless the presentation modes. However, we observed that enclosedness was perceived similarly regardless the image. The switch from actual environments to a 2D representation (images) seems thus impacting the spatial perceptions. And, contrary to our hypothesis, 3D pictures do not make it possible to replicate the perception of enclosedness experienced in the real world despite the fact that participants reported an impression of immersion in the scene with this technology. Last, according to our results, enclosedness cannot be studied using images.

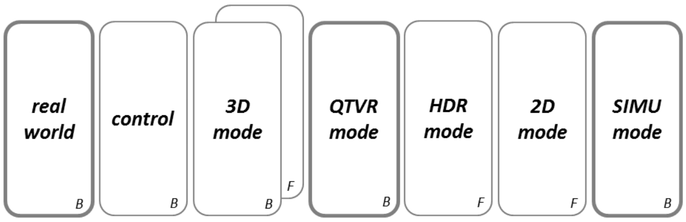
About the appearance of lighting, our results suggest that when assessing daylit ambulatory corridors which do not present large areas of high luminances, 2D tone-mapped pictures displayed on a conventional LDR monitor can be used as surrogate for the real world for studying the following dimensions characterizing the appearance of lighting: coloration, contrast and directivity (see Table IV.C.30). Perceived brightness can also be studied but the results should be read in relative terms. Indeed, this work showed that the order of classification of the rooms for brightness was replicated regardless of image type but that brightness was overestimated. This overestimation can be explained by dark adaptation process and simultaneous contrast and is due to the fact that the visualizations were organized in a dark room (to avoid flickering when visualizing 3D pictures) rather than in ambient light conditions similar to those encountered in the actual environments. To better replicate the perception of brightness experienced in the actual environments, further studies could play with the three following parameters: the ambient light conditions, the luminance of monitor surrounds and the parameters of the tone-mapping operator.

Contrary to 2D mode, QTVR mode allows studying the distribution of light. This mode is the only mode which replicates this dimension. Consequently it is also the only mode which allows studying five dimensions influencing the appearance of lighting.

Contrary to our expectations, we observed no benefit of 3D mode in comparison to 2D mode to study the interplay of light and materials. On the opposite, we found that considerable post-processing is needed for 3D images of high quality and we observed that flickering was experienced by the participants in spite of the precautions taken to avoid this phenomenon.

Last, in comparison to 2D mode, the tested HDR display presents no benefit for studying the appearance of lighting. On the other hand, it distorts coloration dimension. As the tested HDR display was under development, it is not possible to extrapolate the findings to all HDR displays.

PART V
ON THE USE OF VIRTUAL RENDERINGS FOR ASSESSING VISUAL PERCEPTIONS



This last part of the thesis first describes the creation of Radiance renderings used for collecting perceptions in the last step of the experiment (SIMU mode). A comparison between the real-world experiment, the QTVR mode and the SIMU mode is then presented. The objective is to determine whether the switch to the image (QTVR mode) or its virtualization (SIMU mode) distorts perceptions experienced in the real world.

CHAPTER V.A
CREATION OF RADIANCE RENDERINGS AND ASSESSMENT OF IBL

This chapter is devoted to the modeling of our four actual lit environments in the Radiance lighting simulation system (Larson and Shakespeare, 1998).

As explained by Ferwerda (2003), three kinds of realism exist in computer graphics: physical realism, photo-realism and functional realism. Physical realism produces the same visual stimulation as the real-world scene (how the material behaves) while photo-realism produces the same visual response (how the material looks). Functional realism provides the same visual information with a certain level of abstraction like e.g. plans, drawings, sketches or schemas.

Radiance system and its physically-based backward ray-tracing algorithm make it possible to reach a high level of physical realism. And, even if physical realism is computationally expensive and probably not necessary to reproduce visual perceptions, it presents a high interest in the field of lighting quality research. Indeed, it produces reliable physically-based data (illuminances and luminances) as well as images of high quality. It is thus suitable to relate lighting perceptions to physical indicators.

This chapter describes the creation of the virtual renderings used in the last step of our experiment (SIMU mode). Sky conditions encountered during the real-world experiment are used as the light source in the simulations. Two ways to describe these sky conditions in the Radiance systems are investigated and discussed: classical physically-based rendering (PBR) and image-based lighting (IBL). Physically-based renderings used in our experiment are finally presented.

V.A.1. DESCRIBING A SCENE IN RADIANCE

As illustrated in Fig.V.A.1, describing a scene in Radiance requires several steps: the description of the geometry, the description of the materials and the description of the light source(s).

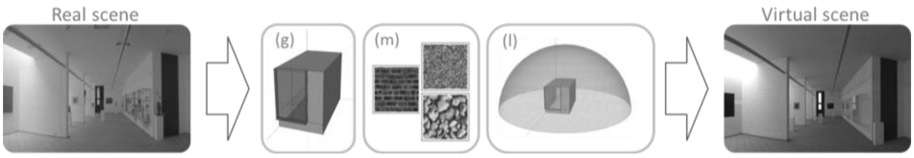


FIGURE V.A.1
Reproducing a real scene in Radiance requires describing the existing geometry (g), the materials (m) and the lighting conditions (l).

Four actual rooms were modeled in the frame of this work. The existing geometry and materials were first determined. Then, measurements done simultaneously to the visit of the actual rooms by the participants allowed the reproduction of the lighting conditions experienced by the participants of the real-world group.

V.A.1.1. GEOMETRY DESCRIPTION

Based on building plans coupled with in situ measurements, the four studied rooms were modeled in Ecotect software. Geometry was then exported from Ecotect to Radiance.

V.A.1.2. MATERIAL DESCRIPTION

Modeling materials in Radiance required some in situ colorimetric measurements. Some hypotheses were made regarding the specularity properties and roughness features of the materials. Colorimetric measurements were carried out using a Konica Minolta Chroma Meters CR-400. Table V.A.1 presents some of the in situ XYZ measured values and the corresponding RGB values describing the material in the Radiance language. The conversion matrix used to convert from XYZ to RGB is those specified by Reinhard et al. (2006):

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2405 & -1.5371 & -0.4985 \\ -0.9693 & 1.8760 & 0.0416 \\ 0.0556 & -0.2040 & 1.0572 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

EQUATION V.A.1
Conversion from XYZ to RGB values

Tile joints were too small to be measured using the colorimeter. So, colorimetric characteristics of a colored paper of similar hue were determined (e.g. the hue of the tile joint in Room #3 was similar to a Canson Mi-Teintes Dark Grey Drawing Paper).

TABLE V.A.1
Material reflectance and RGB values introduced in Radiance

Room		Material	Reflectance	X	Y	Z	R	G	B
Room#1		Ground (blue carpet)	11%	11.1	11.48	16.09	0.10	0.11	0.15
		White wall	52%	49.35	51.98	48.66	0.56	0.52	0.44
		Door (wood)	15%	16.49	15.29	9.32	0.25	0.13	0.08
		Ground (white tiles)	31%	30.3	31.34	27.35	0.36	0.31	0.24
Room#3		Ground (beige tiles)	28%	27.9	27.97	20.66	0.37	0.26	0.18
		Tile joint	13%	11.84	12.53	14.78	0.12	0.13	0.14
		Wall	86%	81.87	85.98	92.18	0.87	0.86	0.84
		Door	6%	6.03	6.22	6.8	0.07	0.06	0.06
Room#4		Ground (grey carpet)	14%	13.73	13.98	12.49	0.17	0.13	0.11
		Window frame (metal)	20%	17.59	19.59	14.24	0.20	0.20	0.12
		White wall	60%	57.62	60.39	57.37	0.65	0.60	0.52
		Wood	40%	41.66	39.94	18.87	0.64	0.35	0.14

As shown in Table V.A.1, the reflectance of the materials in the real scenes varies between 6% (black wood door) and 86% (white painted walls). To increase the realism of the virtual scenes, some details were also modeled (paintings, radiators, lighting fixtures, building signage…).

V.A.1.3. LIGHT SOURCE DESCRIPTION

There are currently two ways to describe the real sky conditions in the Radiance system.

Based on exterior illuminance measurements, the sky description can be generated using the *gendaylit* program. This program produces a Radiance description of the daylit sources at the given month, day and time, using the Perez All-weather model (Perez et al., 1993). In the following sections, renderings realized using these programs will be named physically-based renderings (PBR).

Rather than using the sky models generated using the *gendaylit* program, a HDR picture of the sky vault can be used as the light source (Inanici, 2010, Debevec, 2002). This technique is, in the following sections, named image-based lighting (IBL).

The present section explains first the two techniques. The potential of using HDR sky images as the light source in daylighting simulations is then evaluated in comparing luminances measured in the real world with simulations computed with PBR and IBL techniques.

V.A.1.3.1. *PHYSICALLY-BASED RENDERINGS*

For reproducing real sky conditions in our virtual environment, sky illuminances were measured throughout the real-world experiment presented in Chapter III.A. Illuminance measurements were taken with a Hagner EC1-X Digital Luxmeter.

Horizontal global and diffuse sky illuminances were measured while the *gendaylit* program requires direct normal and diffuse horizontal illuminance. On the basis of the measured illuminances and the altitude of the sun, direct normal illuminance was calculated (see Equation V.A.2). The solar geometry algorithm given by Szokolay (1996) were used to determine the altitude of the sun for the given date, time and location.

$$E_{dir_{normal}} = \frac{\left(E_{glob_{horiz}} - E_{dif_{horiz}}\right)}{\sin(\theta_{sun})}$$

EQUATION V.A.2
Determination of the direct normal illuminance. Edir_normal is the direct normal illuminance, Eglob_horiz is the global horizontal illuminance, E_dif_horiz is the diffuse horizontal illuminance and θ_sun is the altitude of the sun.

Table V.A.2 summarizes diffuse horizontal and direct normal illuminances introduced in the *gendaylit* program to generate the description of the sky as follow:

```
gendaylit month day hour -a latitude -o longitude -m meridian
-L direct_normal_illuminance diffuse_horizontal_illuminance |
xform -rz angle > sky_description.rad
```

CODE V.A.1
Command line for generating the sky description. *xform* program is used to match the North of the sky description with the North of the geometry file.

The absence of direct illuminance during Tour #3 reveals overcast sky conditions (see Table V.A.2).

TABLE V.A.2
Measured diffuse horizontal illuminance and calculated direct normal illuminance (lux) are introduced in the *gendaylit* program for generating the sky distribution

		Measured			Calculated	
Tour	**Room**	**Local standard time (hour)**	**Global horizontal illuminance (lux)**	**Diffuse horizontal illuminance (lux)**	**Sun Altitude (degree)**	**Direct Normal illuminance (lux)**
Tour#1	**Room#1**	11.00	23000	20800	29.4	4478
	Room#2	11.17	50000	16600	30.3	66296
	Room#3	11.42	39100	21350	31.4	34101
	Room#4	11.83	71700	36900	32.9	64114
Tour#2	**Room#1**	12.42	40500	38200	34.2	4094
	Room#2	12.58	55650	40150	34.4	27457
	Room#3	12.83	35050	30350	34.5	8298
	Room#4	13.08	45550	28850	34.4	29527
Tour#3	**Room#1**	13.67	29250	29250	33.6	0
	Room#2	13.83	24300	24300	33.2	0
	Room#3	14.00	15300	15300	32.7	0
	Room#4	14.33	20150	20150	31.4	0

As illustrated in Table V.A.3 and 4 with Room #4, maps of luminances created with this method (PBR) are very similar to maps of luminances captured in the real world, regardless of the kind of sky (partly cloudy or overcast).

TABLE V.A.3
Room #4 under a partly cloudy sky (Tour #1)

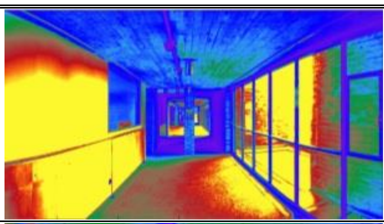
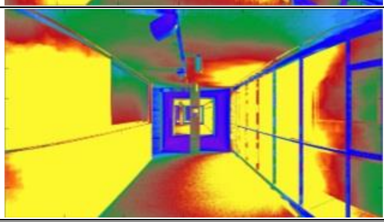
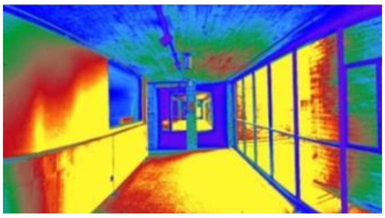
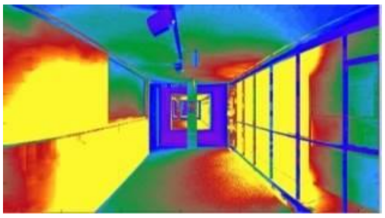
	Luminance (cd/m²)	**Tone-mapped picture (using pcond program and default parameters)**
Real world		
PBR rendering		
	0 **50 cd/m²**	

TABLE V.A.4
Room #4 under an overcast sky (Tour #3)

	Luminance (cd/m²)	Tone-mapped picture (using pcond program and default parameters)
Real world		
PBR rendering		
	0 … 50 cd/m²	

V.A.1.3.2. *IMAGE-BASED LIGHTING RENDERING*

Rather than using the sky models generated with the *gendaylit* program on the basis of sky illuminance measurements, IBL technique suggest using maps of sky luminances as the light source. But while the description of the sky was quite simple with the PBR technique, it is a complex process with IBL technique, as illustrated in Fig.V.A.2.

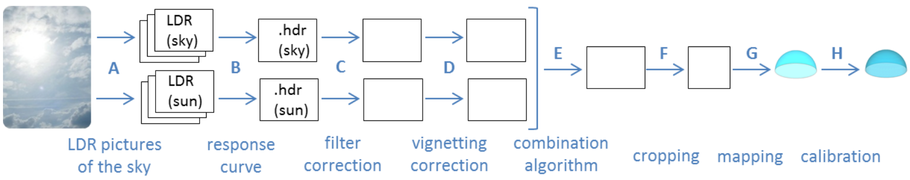


FIGURE V.A.2
Successive steps for the creation of the light probe image

The following sections describe each step of the process.

- *STEP A: LDR PICTURES OF THE SKY*

To create sky luminance maps, pictures of the sky were taken throughout the real-world experiment following the HDR imaging technique. A tripod and a double axis bubble level were used to ensure the horizontality of the camera. To capture the entire vault, a Sigma f/2.8 4.5mm fisheye lens was mounted on a Canon 40D camera. This device (camera + fisheye) creates circular pictures catching a 180° hemisphere (see Fig.V.A.3c)[1].

FIGURE V.A.3
Location of the neutral density filter and resulting circular picture

Similarly to what was done by Stumpfel et al. (2004) to avoid the saturation of the camera's sensor due to the high luminance of the sun, a neutral density filter (Kodak ND 3.00) was placed between the fisheye lens and the camera (see Fig.V.A.3a and b).

TABLE V.A.5
Camera settings

Parameters	Mode
White balance	Daylight
Sensitivity	ISO100
Metering mode	Spot
Image size	1936 pixels * 1288 pixels
Number of f-stops	1 2/3
Number of shots	9
Focusing setting	Infinity

A first series of pictures was realized with a large aperture (f/4) to capture the luminances of the cloud layer. A second series with a smaller aperture (f/16) was then taken to capture the luminances of the sun. Pictures were made using the camera settings specified in Table V.A.5.

- *STEP B: HDR IMAGES*

The two series of LDR pictures were then merged into two HDR pictures using the *hdrgen* program and the response curve of the camera previously determined.

- *STEP C: CORRECTION OF THE NEUTRAL DENSITY FILTER*

The reduction of luminances induced by the neutral density filter was then corrected. The correction was determined in comparing the RGB values of a McBeth Color Chart photographed with and without the filter. As shown in Fig.V.A.4, despite the neutrality of the filter, a shift for the blue channel was observed as in Inanici's work (2010).

[1] Note that some fisheye lenses can be made circular or full frame according to the camera on which they are mounted.

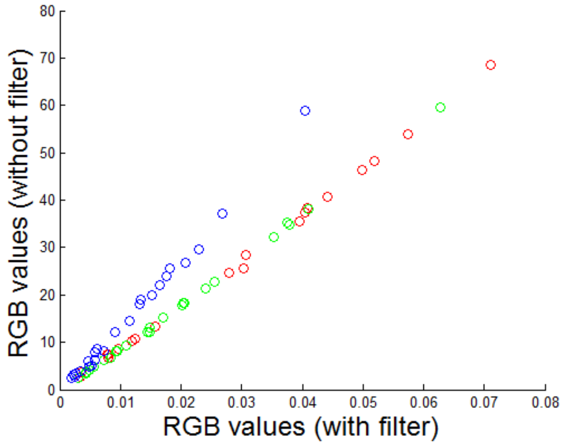


FIGURE V.A.4
Relation between the RGB values of a McBeth Color Chart photographed with and without the filter

Based on these data, a polynomial interpolation of degree 2 was determined for each channel separately and the correction was applied to the HDR pictures as in Code V.A.2.

```
pcomb -f colortransform.cal -o input_image_with_filter.pic >
output_image_without_filter.pic
```

CODE V.A.2
Command line for correcting the use of the neutral density filter (the colortransform.cal file is described in CODE V.A.3)

```
ro=(1776.226*ri(1)^2+837.951*ri(1)+0.160);
go=(1110.402*gi(1)^2+887.244*gi(1)-0.427);
bo=(4342.956*bi(1)^2+1277.025*bi(1)-0.364);
```

CODE V.A.3
colortransform.cal

- *STEP D: VIGNETTING CORRECTION*

The vignetting effect was then corrected. Vignetting effect is the brightness decrease observed from the center of the picture to its periphery when large apertures are used. When using HDR techniques and fisheye lenses for luminance measurements, it is necessary to correct for the vignetting effect in order to obtain reliable data. Indeed, vignetting is accentuated with wide-angle lenses (such as fisheye lenses). The vignetting effect encountered with the Sigma f/2.8 4.5mm lens is not negligible since it can reach, with the largest aperture, a 70% loss of luminance at the periphery of the picture as we presented in (Cauwerts et al., 2012). For a f/4 and a f/16 apertures, the vignetting effect reaches respectively a 51% and a 4% loss of luminance at the periphery of the image, as shown in Fig.V.A.5.

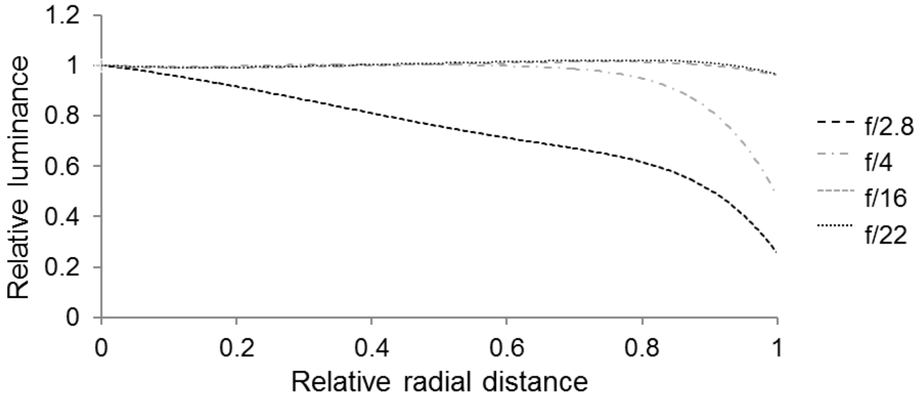


FIGURE V.A.5
Approximated vignetting curves for four apertures of the Sigma f/2.8 4.5mm lens mounted on a Canon 40D camera

A correction of the vignetting effect was applied to the two pictures of the sky (sun and cloud layer) as in Code V.A.4.

```
pcomb –f vignettingfilter.cal –o input_with_vignetting.pic >
output_ vignetting_corrected.pic
```

CODE V.A.4
Command line for correcting the vignetting effect (the vignettingfilter.cal file is described in Code V.A.5)

```
xr=(x-HDR_picture_size_x/2);
yr=(y- HDR_picture_size_y/2);
sq(xr)=xr*xr;
sq(yr)=yr*yr;
r=(sqrt(sq(xr)+sq(yr)))/HDR_circular_image_radius;
ro=(ri(1)*(1/((a*r^6+b*r^5+c*r^4+d*r^3+e*r^2+f*r+1))));
go=(gi(1)*(1/((a*r^6+b*r^5+c*r^4+d*r^3+e*r^2+f*r+1))));
bo=(bi(1)*(1/((a*r^6+b*r^5+c*r^4+d*r^3+e*r^2+f*r+1))));
```

CODE V.A.5
vignettingfilter.cal (a, b, c, d, e and f are the coefficients of the polynomial vignetting function and vary according to the aperture of the camera as presented in Table V.A.6)

TABLE V.A.6
Coefficients of the polynomial vignetting functions for f/4 and f/16

	a	b	c	d	e	f
f/4	-15.288	37.876	-36.327	16.449	-3.418	0.2295
f/16	-13.755	37.011	-36.973	16.613	-2.9019	-0.0651

- *STEP E: COMBINING THE TWO HDR PICTURES IN A SINGLE ONE*

The next step consisted in combining the unvignetted picture of the sun with the one of the cloud layer to obtain a single picture containing the luminances of the whole sky (sun and cloud layer). Luminances higher than 2 000 000 cd/m² were extracted from the picture of the sun (smaller aperture pictures) while luminances inferior to 40 000 cd/m² were extracted from the HDR picture of the cloud layer (larger aperture picture). Luminances included in the range of 40 000 cd/m² to 2 000 000 cd/m² were linearly combined (see Code V.A.6).

```
pcomb -e 'Low:223;High:11173' -e 'vlong(v)=v*if(v-High,0,
if(Low-v,1,1-(v-Low)/(High-Low)))' -e 'vshort(v)=v*if(v-
High,1,if(Low-v,0,(v-Low)/(High-Low)))' -e
'ro=vlong(ri(1))+vshort(ri(2))' -e
'go=vlong(gi(1))+vshort(gi(2))' -e
'bo=vlong(bi(1))+vshort(bi(2))' sky.pic sun.pic > combined.pic
```

CODE V.A.6
Combination of the two HDR pictures in a single one

- *STEP F: CROPPING*

Finally, the combined picture was cropped using *pcompos* program (see Code V.A.7) in order to have a squared picture whose size equals the diameter of the circular fisheye (see Fig.V.A.6).

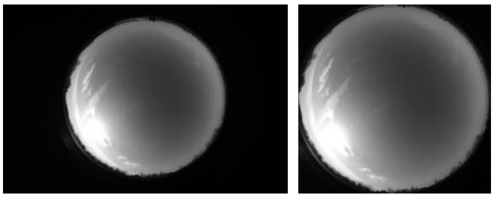


FIGURE V.A.6
Uncropped and cropped picture

```
ra_xyze -r -o combined.pic | pcompos -x new_size -y new_size
-crop_x -crop_y > combined-crop.pic
```

CODE V.A.7
Cropping of the picture

- *STEP G: MAPPING THE LIGHT PROBE IMAGE ONTO THE SKY VAULT*

The sky picture can now be introduced in the Radiance scene in specifying the mathematical formula for mapping it onto the sky vault (see Fig.V.A.7).

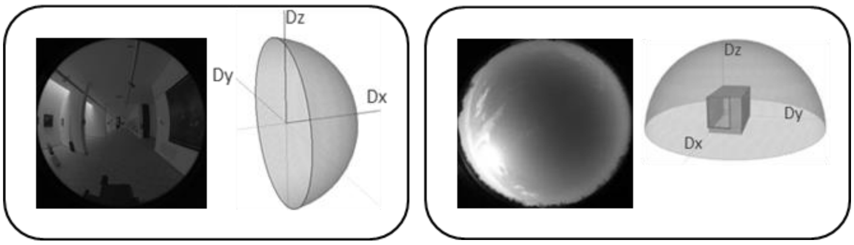
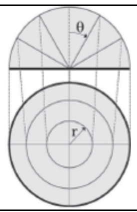
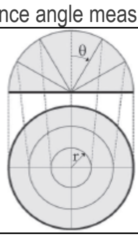
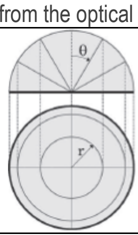
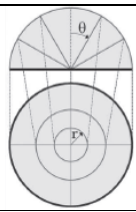


FIGURE V.A.7
Mapping the light probe image onto an hemispherical vault (a) vertical picture (ex: picture in a room); (b) horizontal picture (ex : picture of the sky)

The method described by Debevec (2002) was followed. However, as the projection type of our fisheye lens (equisolid projection type, see Table V.A.7) is different from the one of Debevec (equidistant projection type), the mapping formula was modified (see Code V.A.9).

TABLE V.A.7
Fisheye projection types and correspondence with Radiance fisheye views

Projection type	**Equidistant (also called equiangular)**	**Equisolid (also called equal-area)**	**Orthographic (also called hemispherical)**	**Stereographic (also called planispheric)**
Radiance fisheye view (*rpict*)	-vta	/	-vth	-vts
Projection formula	$r = f*\theta$	$r = 2*f*\sin(\theta/2)$	$r = f*\sin(\theta)$	$r = 2*f*\tan(\theta/2)$
	where r is the distance from the optical axis, f is the focal length, and θ is the entrance angle measured from the optical axis.			
Scheme				
Lens	Sigma 8mm f/3.5 Nikon FC-E8 or E9 Nikkor 8mm f/2.8	Sigma 4.5mm F2.8	Nikkor 10mm F5.6 OP	Samsyang 8mm

The luminance distribution of the sky was described as in Code V.A.8. For convenience during the measurements in situ, the camera was not positioned to have the y-axis coinciding with the North but the angle of rotation was determined later on the basis of the picture. The correct orientation of the sky was introduced in Radiance with the *–rz* option (see Code V.A.8).

```
void colorpict hdr_probe_image
9 red green blue image_combined_crop.pic solmap.cal u v -rz 17
0
0

hdr_probe_image glow light_probe
0
0
4 1 1 1 0

light_probe source ibl_environment
0
0
4 0 0 1 180
```

CODE V.A.8
Description of the luminance distribution of the sky (the solmap.cal file is described in Code V.A.9)

```
d = sqrt(Dx*Dx + Dy*Dy);
r = if(d, 0.707106781*(sin(acos(Dz)/2))/d,0);
u = 1 - (0.5 + Dx *r);
v = 0.5 + Dy *r;
```

CODE V.A.9
solmap.cal convert from directions in the world (Dx, Dy, Dz) into coordinates on the picture (u,v)

- *STEP H: CALIBRATING THE HDR PICTURE OF THE SKY*

The HDR picture was finally calibrated as follow:

$$CF = \frac{measured\_E_{glob_{horiz}}}{IBL\_E_{glob_{horiz}}}$$

EQUATION V.A.3
Determination of the calibration factor (measured_Eglob_horiz is the global horizontal illuminance measured under the actual sky, IBL_Eglob_horiz is the global horizontal illuminance calculated using the non-calibrated HDR image of the sky as a light source)

Table V.A.8 summarizes the calculated calibration factors (CF #1) which are very low for partly cloudy skies and close to 1 under overcast sky.

TABLE V.A.8
Calibration factor for sky picture

TOUR	LOCAL	E_dif_horiz (measured)	E_glob (measured)	CF #1	CF #2
Tour #1 (partly cloudy)	Room #1	20800	23000	0.02	1.14
	Room #2	16600	50000	0.04	1.00
	Room #3	21350	39100	0.04	0.99
	Room #4	36900	71700	0.04	0.90
Tour #2 (partly cloudy)	Room #1	38200	40500	0.03	0.83
	Room #2	40150	55650	0.14	0.92
	Room #3	30350	35050	0.75	0.86
	Room #4	28850	45550	0.08	0.98
Tour #3 (overcast)	Room #1	29250	29250	1.11	1.08
	Room #2	24300	24300	1.07	1.04
	Room #3	15300	15300	1.77	1.11
	Room #4	20150	20150	1.11	1.09

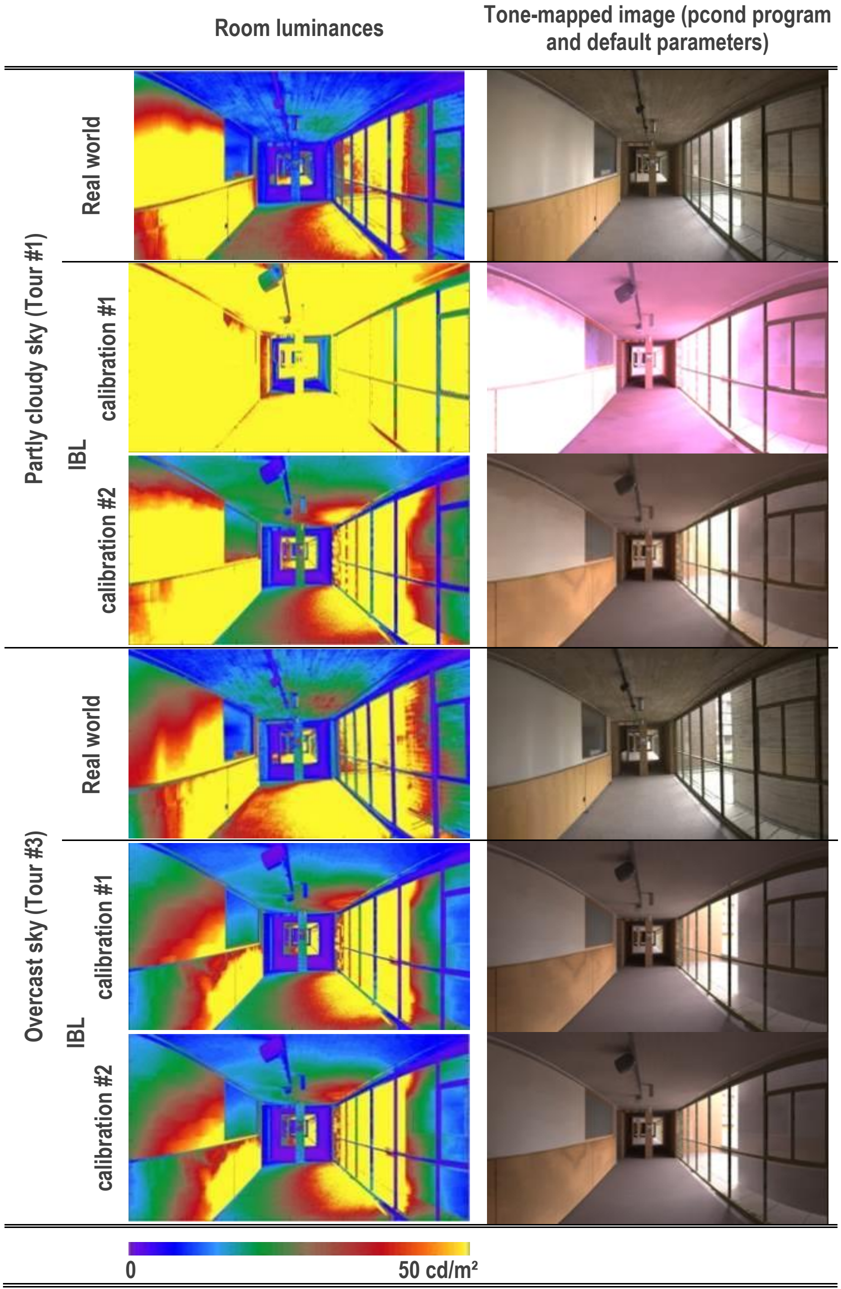
Note: E_dif_horiz: diffuse horizontal illuminance, E_glob: global horizontal illuminance
CF: calibration factor

HDR pictures were first calibrated using these factors with the *pcomb* program as in Code V.A.10. But we observed that the resulting IBL scenes were overexposed for partly cloudy skies and that the rendering was reddish (see Table V.A.9).

```
pcomb -o non_calibrated_picture.pic -s calibration_value -o
non_calibrated_picture.pic > calibrated_picture.pic
```

CODE V.A.10
Calibration of the HDR sky picture

TABLE V.A.9
Room #4 - calibration #1



We hypothesized that chromatic aberrations and other lens artifacts are responsible for the red color shift which appears in IBL simulations under the partly cloudy sky (see Table V.A.9). Indeed chromatic aberrations results in abnormal coloration of some pixels of the picture and are accentuated with wide-angle lenses.

Besides, in the IBL approach, as explained by Inanici (2011), in contrast to the PBR approach, the light sources are not defined explicitly but the luminances of the HDR image are used as a light source. And, the stochastic algorithm used in Radiance can lead to large errors if no ray reaches the sun of the HDR picture.

As a consequence of these problems, another method of calibration was envisaged. Luminances higher than 200 000 cd/m² were first extracted from the HDR sky picture (chromatic aberrations observed around the sun were so removed). The sky picture was then calibrated based on the measured diffuse horizontal illuminance. As presented in Table V.A.8, the calibration factors (CF #2) are now close to 1 regardless of the sky conditions (partly cloudy and overcast skies). A direct sun was then generated using the *gendaylit* program and added to the scene.

Figure V.A.8 compares two types of sky (an overcast sky and a partly cloudy) calibrated with the first and the second calibration method (CF #1 or CF #2).

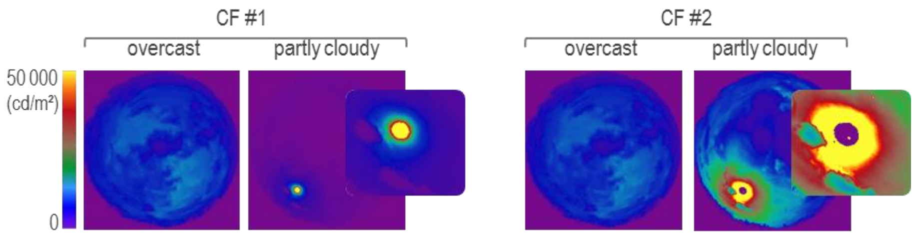


FIGURE V.A.8
Influence of the calibration factor on the luminances of the sky maps

Table V.A.9 presents the renderings created when CF #2 is used for calibrating the sky picture for IBL. As shown in this table, for partly cloudy sky, the rendering performed with this method is closer to the reality than the one generated with the first calibration factor (see Table V.A.9). The difference between the two methods under overcast sky is not pronounced.

V.A.2. PBR VS. IBL RENDERINGS

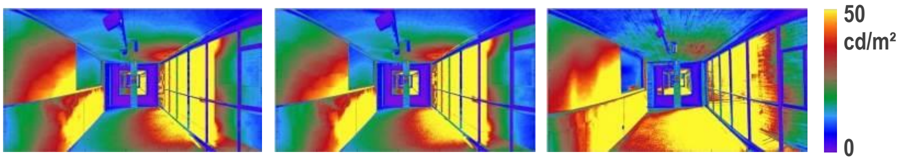
To evaluate the interest of IBL renderings, a numerical comparison was done between luminance values extracted:

- from the HDR pictures captured in the real-world scenes ;
- from the physically based renderings realized using the sky description generated with the *gendaylit* program ;
- from the IBL renderings realized using HDR picture of the sky as the light source.

First, luminance maps were visually compared. As illustrated in Table V.A.10, for Room #4 in Tour #3, luminances resulting from PBR and IBL are globally similar and reproduce the luminance distribution of the actual environment.

TABLE V.A.10
Maps of luminances (a) created using PBR technique (b) created using IBL technique (c) captured in the real world (Tour #3 / Room #4)

PBR	IBL	Real world

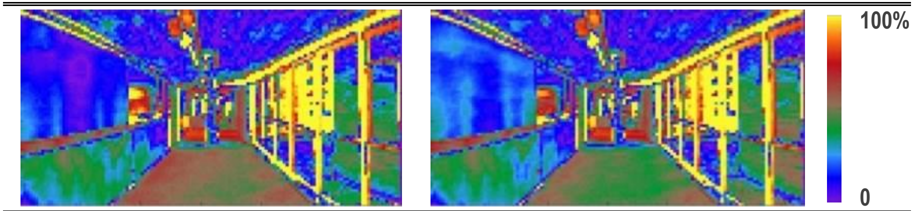


Mean relative error between PBR and the real world, and between IBL and the real world were then calculated. As HDR photographic pictures taken in the real world are not perfectly aligned with virtual images, a pixel to pixel comparison was avoided. To reduce the errors due to the geometrical misalignment while keeping a quick visual identification of regions with large relative errors, we worked with 10-pixel to 10-pixel comparisons.

As shown in Table V.A.11, the resulting maps make it possible to visually identify regions with large relative errors (e.g. luminances of the window) or geometrical misalignments (e.g. the window frame). In this example, a large part of the error is due to a geometrical misalignment between the photograph and the rendering.

TABLE V.A.11
Relative error between each technique of renderings (PBR or IBL) and the real world HDR picture

PBR vs. Real world	IBL vs. Real world



Last, in order to obtain numerical values easy to compare, a surface to surface comparison was done as well as a comparison between the several regions of the visual field (namely, ergorama and panorama). Relative errors calculated for Room #4 in Tour #3 are presented in Fig.V.A.9.

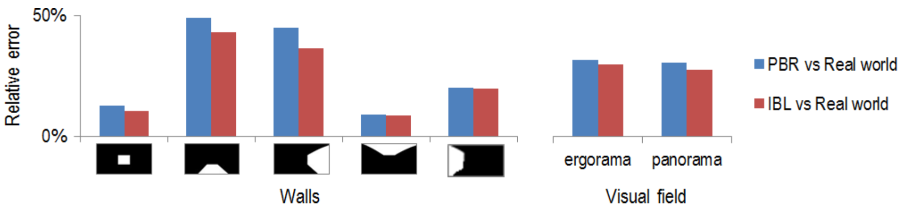
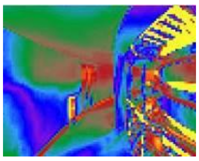
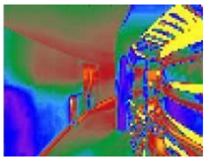
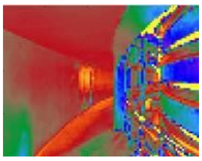
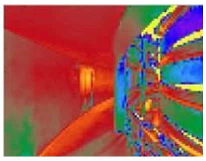
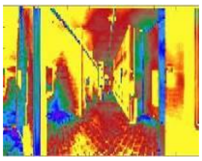
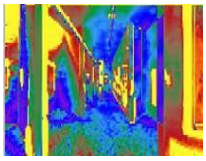
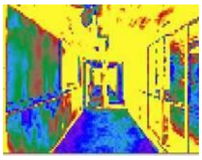
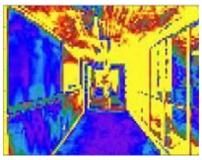


FIGURE V.A.9
Relative error between PBR and real-world luminances (blue) and between IBL and real world luminances (red), calculated wall by wall, in the ergorama, and in the panorama

In this example, the IBL rendering minimizes the error with the real world in comparison with the PBR scene. But it is not always the case as shown in Tables V.A.12 and 13.

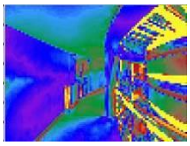
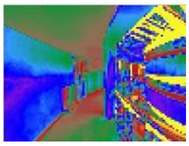
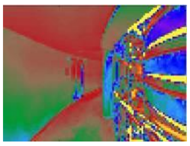
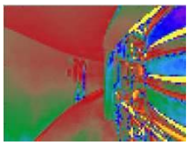
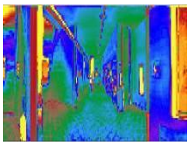
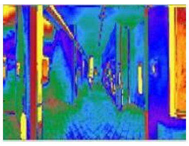
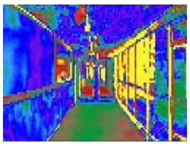
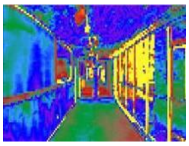
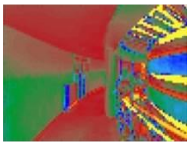
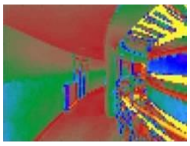
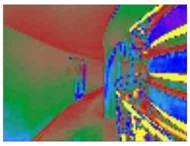
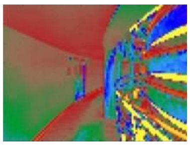
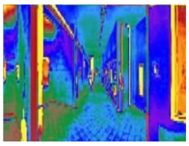
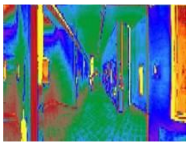
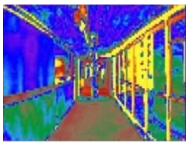
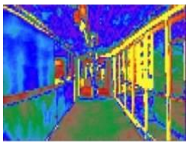
TABLE V.A.12
Tour #1 (partly cloudy sky) – Comparison between PBR, IBL and real world (relative error - %)

		10-pixel to 10-pixel comparison		Walls		Visual field	
		PBR vs. real world	IBL vs. real world	PBR vs. real world	IBL vs. real world	PBR vs. real world	IBL vs. real world
Tour #1 (partly cloudy)	Room #1			*29%*	33%	*49%*	52%
	Room #2			*44%*	47%	*64%*	68%
	Room #3			117%	*74%*	105%	*58%*
	Room #4			126%	*100%*	117%	*93%*
		0 (%) 100	0 (%) 100				

As shown in Table V.A.12, in Tour #1, two rooms (Rooms #1 and #2) present a relative error with the real world inferior with PBR than with IBL. The two other rooms present larger errors regardless of the kind of simulation, but IBL minimizes this error. Globally, Tour #1 presents errors higher than Tour #2 (see Table V.A.13). The errors under overcast sky are similar to Tour #2 (see Table V.A.13).

As shown in these tables, the relative error with the real world is sometimes minimized with PBR and sometimes with IBL. The difference between the two kinds of renderings is moreover not large regardless of the room and the kind of sky.

TABLE V.A.13
Tour #2 (partly cloudy sky) and Tour #3 (overcast sky) – Comparison between PBR, IBL and real world (relative error - %)

		10-pixel to 10-pixel comparison		Walls		Visual field	
		PBR vs. real world	IBL vs. real world	PBR vs. real world	IBL vs. real world	PBR vs. real world	IBL vs. real world
Tour #2 (partly cloudy)	Room #1			**19%**	**28%**	**32%**	**45%**
	Room #2			**41%**	**45%**	**45%**	**48%**
	Room #3			**17%**	**14%**	**23%**	**19%**
	Room #4			**44%**	**40%**	**41%**	**39%**
Tour #3 (overcast)	Room #1			**48%**	***42%***	**51%**	***50%***
	Room #2			***40%***	**42%**	***39%***	**40%**
	Room #3			***14%***	**39%**	***18%***	**42%**
	Room #4			**27%**	***24%***	**31%**	***29%***
		0 (%) 100	0 (%) 100				

V.A.3. DISCUSSION

As presented in this chapter, the procedure for realizing IBL renderings is quite cumbersome in comparison with classical PBR which gives good results and is about 20% faster (in running time).

Given the lack of validation of our IBL procedure, the problems encountered with the capture of sunny skies, and the good results obtained with PBR, we decided to pursue the experiment with this second method (PBR).

To not introduce in the comparison of the three media (real world, photographs and renderings) a bias linked to the cultural background of the participants, the three media should be tested on a same population. As the real-world experiment was carried out in Belgium and the 2D mode tested in France, we decided to replicate the QTVR experiment carried out in Belgium using Radiance renderings. So, we realized QTVR Radiance renderings rather than classical 2D renderings. To obtain high quality renderings, Radiance options specified in Table V.A.14 were used. Renderings options were set according to the scene dimension in order to obtain accurate renderings minimizing artifacts.

TABLE V.A.14
Radiance options and resulting running time

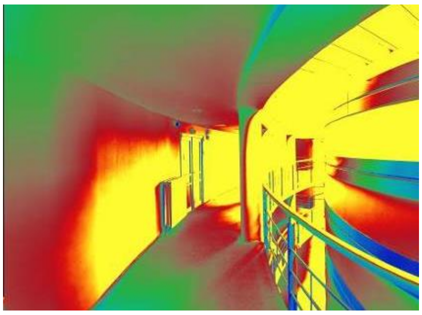
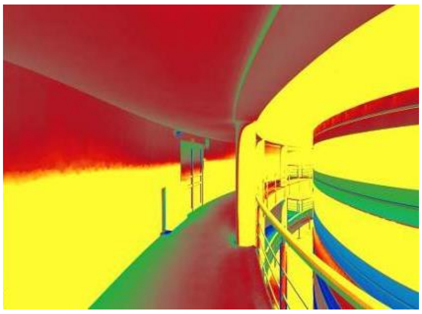
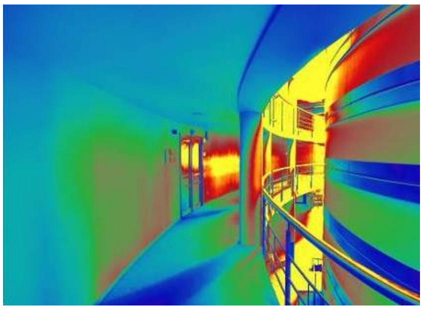
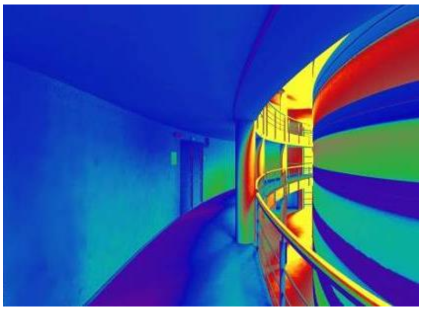
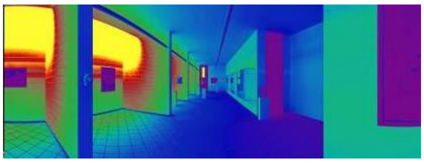
		Room #1	Room #2	Room #3	Room #4
rpict options	-ab	7	7	7	7
	-aa	0.04	0.04	0.08	0.04
	-ar	512	512	512	512
	-ad	4096	4096	4096	2048
	-as	1024	1024	1024	1024
	-av	0 0 0	0 0 0	0 0 0	0 0 0
Resolution (pixels)		4000*2917	5000*3646	7000*2827	7000*3938
Running time		4 days 18 hours	4 days 18 hours	3 days	2 days 22 hours

Tables V.A.15, 17 and 19 compare the luminances of the HDR pictures taken in each room during the real-world experiment, and the luminances of the Radiance renderings[2]. As these images were intended to be displayed on a LDR display (the Samsung SyncMaster 2233rz as for the QTVR mode), the renderings were tone-mapped using the operator and the same settings than those used for the photographs (see Chapter IV.A). Table V.A.16, 18 and 20 compare the luminances of each tone-mapped panoramic photograph (QTVR mode) with luminances of the corresponding tone-mapped rendering (SIMU mode).

[2] Computational resources for final renderings have been provided by the supercomputing facilities of the Université catholique de Louvain (CISM/UCL) and the Consortium des Equipements de Calcul Intensif en Fédération Wallonie Bruxelles (CECI) funded by the Fond de la Recherche Scientifique de Belgique (FRS-FNRS).

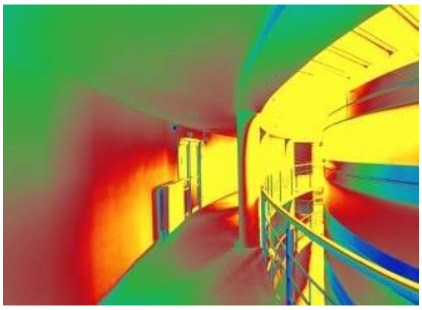
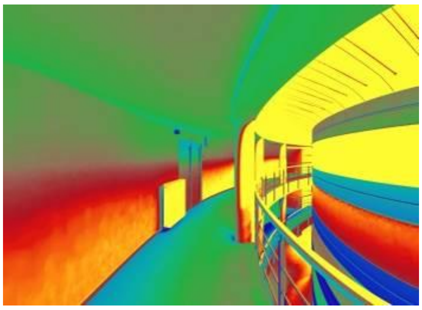
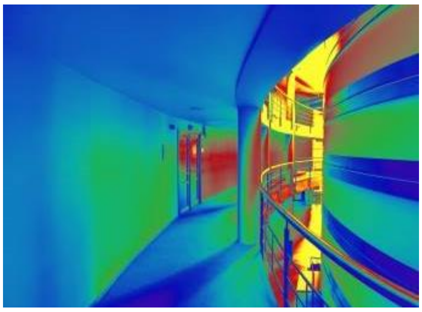
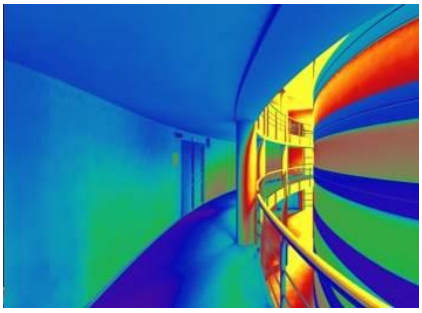
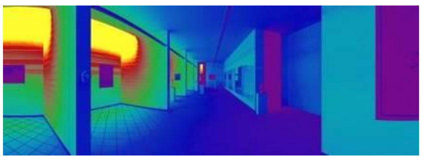
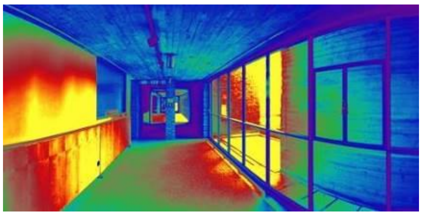
As shown in Table V.A.15, luminances of Room #1 are slightly overestimated by the rendering while luminances in Room #2 are slightly underestimated. Room #3 and Room #4 are rather well reproduced.

TABLE V.A.15
Tour #1 – Luminances of the HDR file

	QTVR mode	SIMU mode
Room #1		
Room #2		
Room #3		
Room #4		
	0 50 cd/m²	0 50 cd/m²

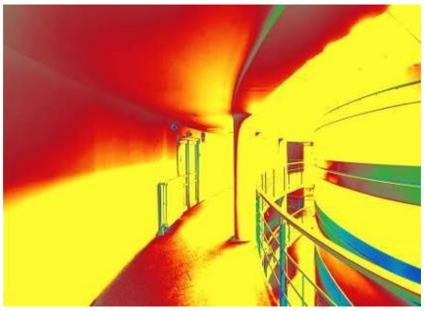
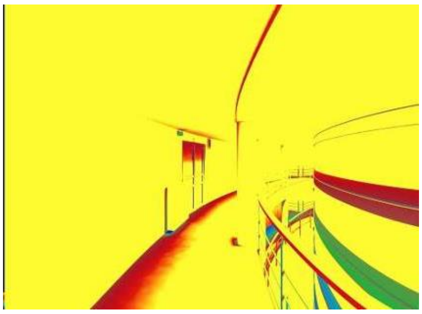
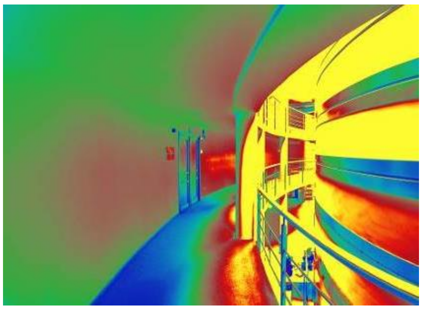
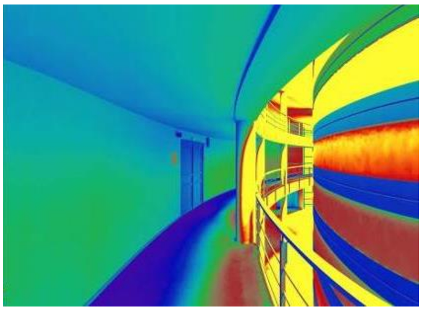
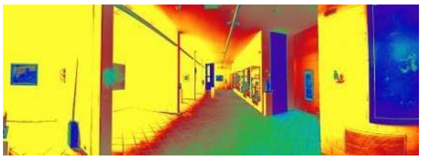
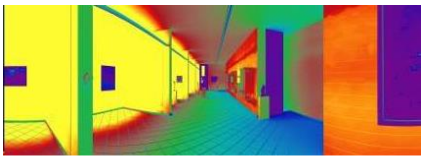
After tone-mapping (see Table V.A.16), luminances of the images are similar between the two modes (QTVR and SIMU modes).

TABLE V.A.16
Tour #1 – Luminances of the tone-mapped file

	QTVR mode	SIMU mode
Room #1		
Room #2		
Room #3		
Room #4		
	0 … 50 cd/m²	0 … 50 cd/m²

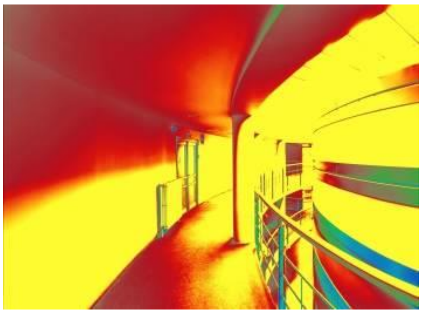
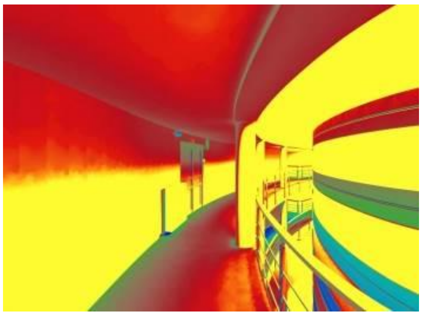
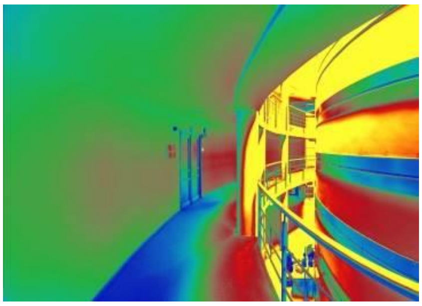
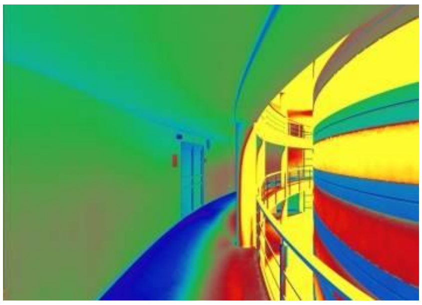
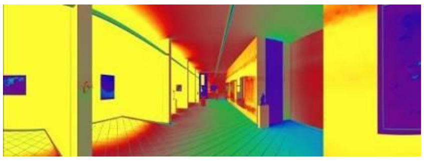
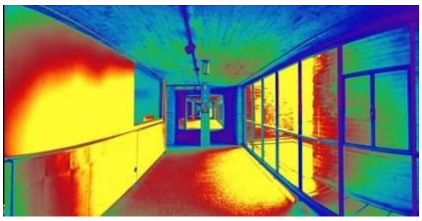
Again, luminances of Room #1 are slightly overestimated by the rendering while luminances in Room #2 are slightly underestimated (see Table V.A.17).

TABLE V.A.17
Tour #2 – Luminances of the HDR file

	QTVR mode	SIMU mode
Room #1		
Room #2		
Room #3		
Room #4		
	0 50 cd/m²	0 50 cd/m²

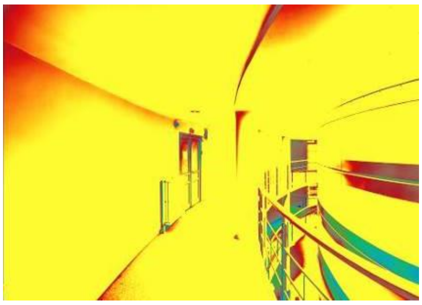
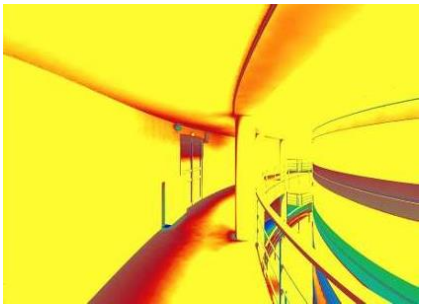
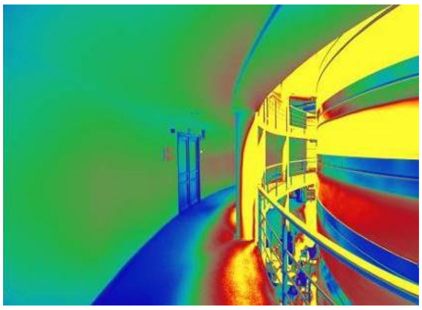
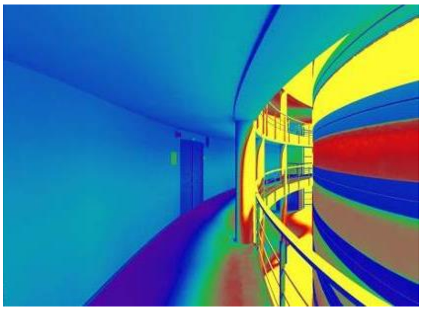
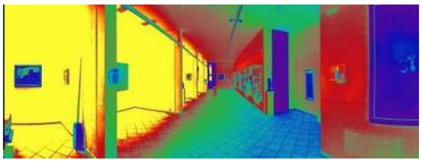
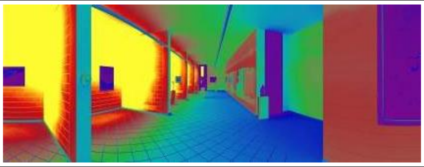
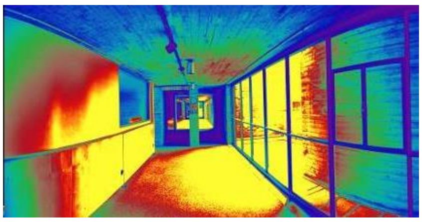
After tone-mapping, luminances of the two types of images are similar as shown in Table V.A.18.

TABLE V.A.18
Tour #2 – Luminances of the tone-mapped file

	QTVR mode	SIMU mode
Room #1		
Room #2		
Room #3		
Room #4		
	0 – 50 cd/m²	0 – 50 cd/m²

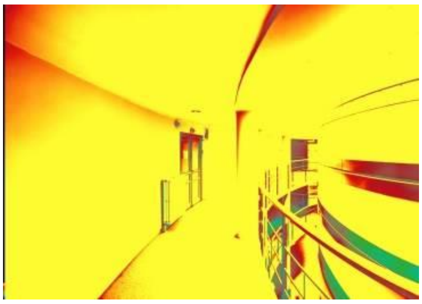
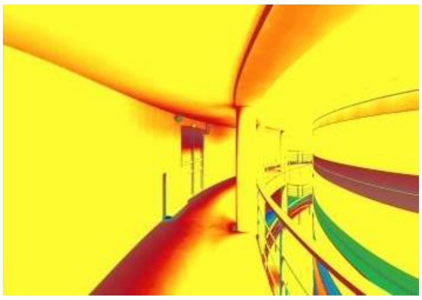
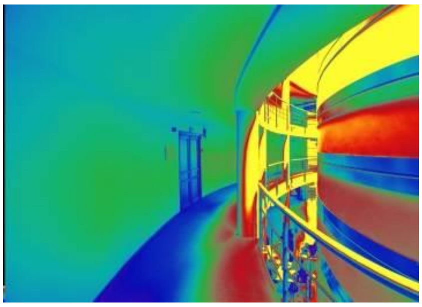
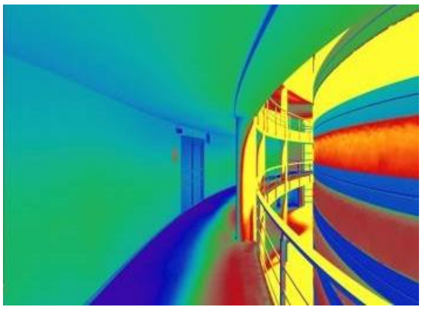
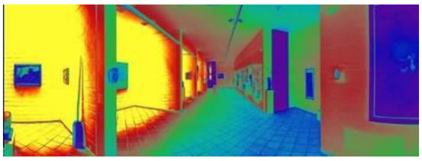
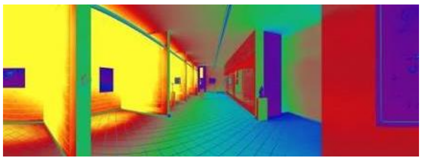
For Tour #3, luminances of Room #2 are slightly underestimated in the rendering (SIMU mode) in comparison with the real world (QTVR mode) as shown in Table V.A.19.

TABLE V.A.19
Tour #3 – Luminances of the HDR file

	QTVR mode	SIMU mode
Room #1		
Room #2		
Room #3		
Room #4		
	0 … 50 cd/m²	0 … 50 cd/m²

Again, after tone-mapping, luminances of the pictures are similar (see Table V.A.20).

TABLE V.A.20
Tour #3 – Luminances of the tone-mapped file

	QTVR mode	SIMU mode
Room #1		
Room #2		
Room #3		
Room #4		
	0 … 50 cd/m²	0 … 50 cd/m²

Finally, Tables V.A.21 to 23 compare the pictures displayed to the participants of the QTVR mode and the renderings displayed to the participants of the SIMU mode.

TABLE V.A.21
Tour #1 – Final tone-mapped images

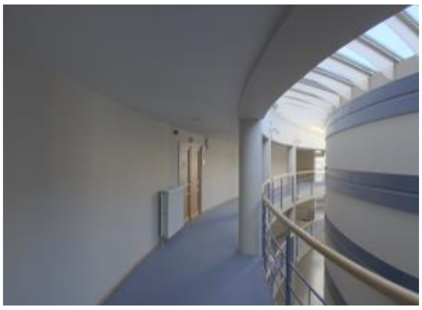
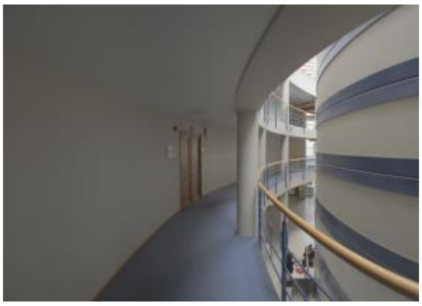
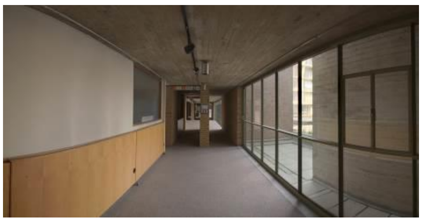
	QTVR mode (photographic picture)	SIMU mode (Radiance rendering)
Room #1		
Room #2		
Room #3		
Room #4		

Table V.A.21 highlights a distortion of the coloration of Room #3 between the QTVR and the SIMU modes: the photograph is a little bluer than the Radiance rendering.

In fact, we described in Radiance a sky which is not colored. To obtain this bluish atmosphere in Room #3 and to have a blue sky through the window in Room #1, we could introduce a slight blue coloration of the sky when describing the glow material for sky in slightly increasing the B-value while reducing R and G, and in keeping $0.265*R + 0.670*G + 0.065*B = 1$, to not affect the luminosity of the sky.

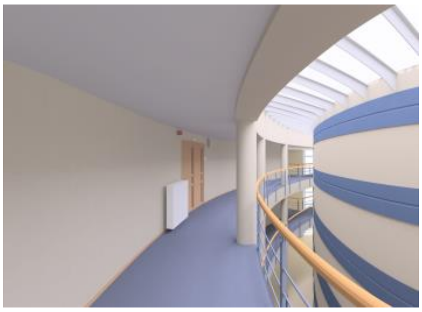
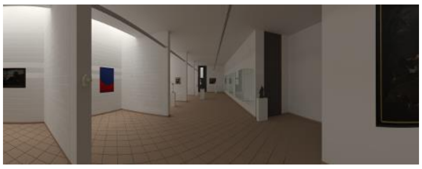
In Tables V.A.22 and 23, the coloration of the sky is no longer a problem as the blue sky is now turning into partly cloudy and overcast.

TABLE V.A.22
Tour #2 – Final tone-mapped images

	QTVR mode (photographic picture)	SIMU mode (Radiance rendering)
Room #1		
Room #2		
Room #3		
Room #4		

No large difference is observed between the two types of images either in Tour #2 (see Table V.A.22) or in Tour #3 (see Table V.A.23).

TABLE V.A.23
Tour #3 – Final tone-mapped images

	QTVR mode (photographic picture)	SIMU mode (Radiance rendering)
Room #1		
Room #2		
Room #3		
Room #4		

V.A.4. Conclusion

This chapter has provided some evidence of the similarity between panoramic photographs and panoramic renderings in terms of luminance distribution.

The comparison between the actual complex environments and physically-based renderings (PBR) has shown that the luminance distribution was rather well reproduced with this method and that it was not necessary to have recourse to image-based lighting renderings (IBL). As pointed out by Inanici (2010), IBL presents nevertheless an interest for less complex rooms (rooms with a single aperture) in which a HDR vertical fisheye picture taken outside the window can help to better take into account the vegetation and the surroundings than PBR does.

This comparison with the real world has also shown that our procedure for capturing luminances of sunny skies was not enough validated but promising.

At last, difficulties for comparing virtual renderings and photographs were encountered due to geometrical misalignment of the two types of images. This comparison pointed out a lack of appropriate method in the literature.

CHAPTER V.B
VALIDITY OF THE USE OF VIRTUAL RENDERINGS FOR ASSESSING VISUAL PERCEPTIONS

This chapter presents the comparison between the SIMU mode (visualization of QTVR Radiance renderings), the QTVR mode (visualization of QTVR photographs) and the real-world experiment (see Fig. V.B.1).

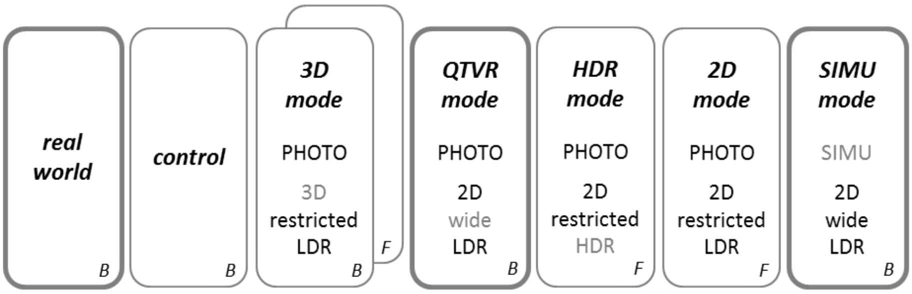


FIGURE V.B.1
Real world, QTVR and SIMU modes are compared to determine whether the appearance of lighting and space is replicated using Radiance renderings

The objective of this comparison is to determine whether the virtualization of the pictures (the switch from photographs to virtual renderings) introduces differences of perceptions or whether differences with the real world are rather due to the switch to images.

V.B.1. MATERIAL AND METHOD

The QTVR experiment organized in Belgium with photographs was reproduced using Radiance renderings. The same protocol than the one implemented for the QTVR experiment was carried out. Images were displayed on the same Samsung SyncMaster 2233rz monitor, in a black room. Thirty-nine participants presenting similar characteristics than those enrolled for the other media were recruited by e-mails (see Table V.B.1). They were paid 10 euros.

TABLE V.B.1
Characteristics of the recruited sample of participants

Medium	Real world	QTVR	SIMU
Location	Belgium	Belgium	Belgium
Number of participants (women, men)	43 (26,17)	39 (23,16)	39 (23,16)
Native language	French	French	French
Educational background	Students at UCL	Students at UCL	Students at UCL
Age (mean +/- standard deviation)	21.8 +/- 1.7	21.5 +/- 1.3	21.6 +/-1.4

V.B.2. RESULTS

V.B.2.1. RATING SCALES

A similar approach than the one adopted in Chapter IV.C for the comparison of the various presentation modes of images and the real world was implemented.

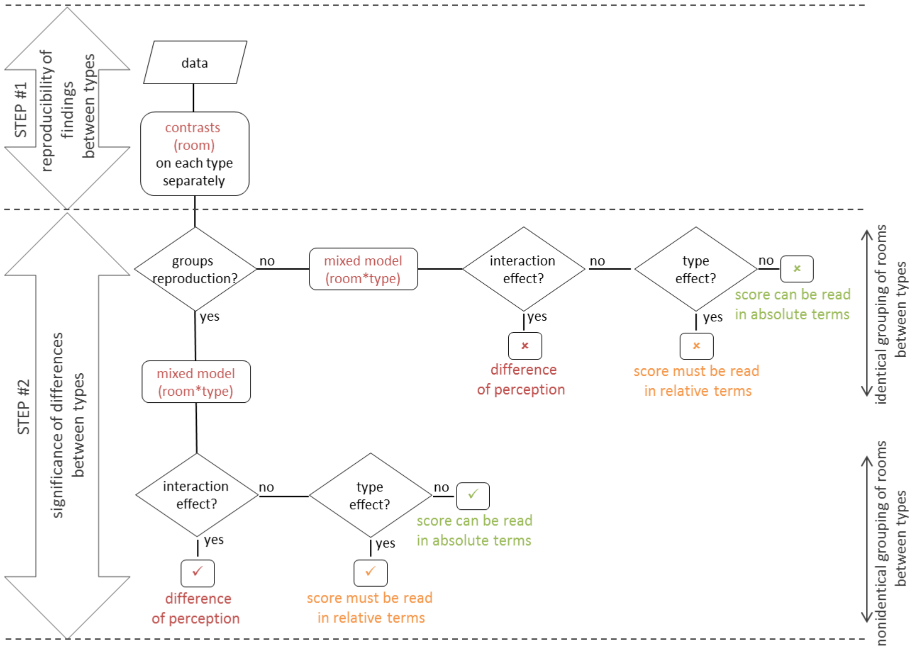


FIGURE V.B.2
Illustration of the approach adopted to determine whether the perceptions experienced when visualizing Radiance renderings are similar to those experienced in the real world

For each image type, the rating scales replicating the groupings of rooms observed in the real world were first determined. A mixed model analysis was then performed on the three media (real world, QTVR mode and SIMU mode). Analysis of contrasts was realized in taking first the real-world experiment as the reference level and then, the SIMU mode. Our aim was to determine whether visual perceptions experienced in the real world were reproduced with each type of images (photographs or renderings). But we also sought to determine whether differences between photographs and renderings were significant.

Statistical analyses were performed using R software. Descriptive results are presented in Appendix III.

V.B.2.1.1. *VISUAL APPEARANCE OF SPACE*

Figure V.B.3 compares ratings for pleasantness and enclosedness given by each group of participants: the real-world group, the QTVR group (visualization of QTVR photographs) and the SIMU group (visualization of QTVR renderings).

As shown in this figure, the groupings of rooms are not identical between the media.

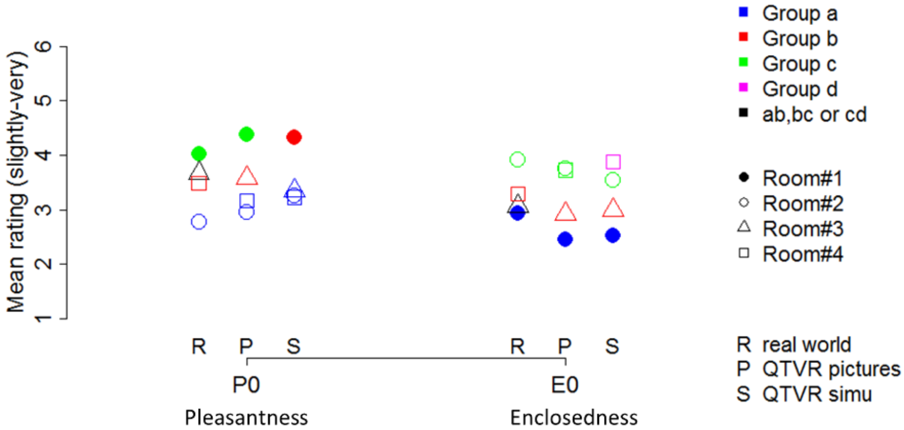


FIGURE V.B.3
Visual appearance of the space – Reproducibility of findings

Table V.B.2 presents the results of the contrasts analysis. For the perception of pleasantness (P0), there is, in one room (Room #2), a significant difference between the real world and the SIMU mode while no difference was detected between the real world and the QTVR mode. Moreover the analysis reveals also that the difference between QTVR and SIMU is not significant.

Concerning the perception of enclosedness, in two rooms (Rooms #1 and #4), significant differences between the two types of images and the real world were detected. No significant difference is observed between QTVR and SIMU modes.

TABLE V.B.2
Visual appearance of the space – Results of the contrasts analysis (MCMCmean and p-value)

Factor	AIC without interaction	AIC with interaction	Room	QTVR vs. real world	SIMU vs. real world	QTVR vs. SIMU
Pleasantness P0	1282.4	1277.6	#1	0.34, 0.09	0.28, 0.17	0.06, 0.76
			#2	0.18, 0.35	0.48, 0.02*	-0.29, 0.17
			#3	-0.09, 0.65	-0.31, 0.11	0.23, 0.26
			#4	-0.32, 0.11	-0.27, 0.18	-0.05, 0.82
Enclosedness E0	1291.3	1279.0	#1	-0.46, 0.02*	-0.40, 0.05*	-0.07, 0.73
			#2	-0.16, 0.44	-0.37, 0.07	0.21, 0.32
			#3	-0.14, 0.49	-0.06, 0.78	-0.08, 0.70
			#4	0.43, 0.03*	0.59, 0.00***	-0.16, 0.44

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Figure V.B.4 illustrates the mean ratings for the additional questions linked to the pleasantness and enclosedness dimensions. Mean profiles are similar between the three media. However grouping of rooms are not identical.

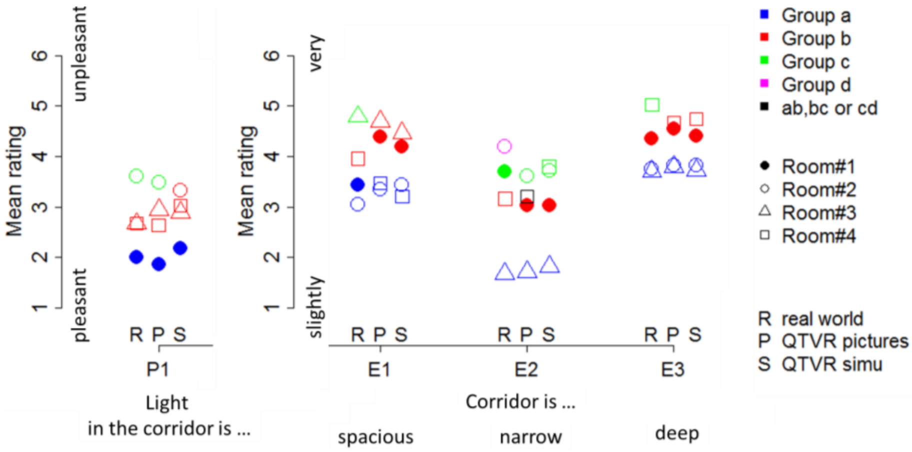


FIGURE V.B.4
Visual appearance of the space (additional questions) – Reproducibility of findings

Table V.B.3 presents the results of the contrasts analysis. Significant differences of perceptions are detected between the image and the real world for two scales: the perception of spaciousness (E1) and narrowness (E2). No difference is observed between the QTVR and SIMU modes.

TABLE V.B.3
Visual appearance of the space (additional questions) – Results of the contrasts analysis (MCMCmean and p-value)

Factor		AIC without interaction	AIC with interaction	Room	QTVR vs. real world	SIMU vs. real world	QTVR vs. SIMU
Pleasantness	P1	1518.5	1524.5	-	-0.00, 0.99	0.13, 0.37	-0.13, 0.37
Enclosedness	E1	1433.5	1405.8	#1	0.95, 0.00***	0.74, 0.00***	0.22, 0.34
				#2	0.29, 0.22	0.38, 0.11	-0.09, 0.74
				#3	-0.10, 0.68	-0.34, 0.15	0.24, 0.32
				#4	-0.48, 0.04*	-0.75, 0.00***	0.27, 0.25
	E2	1466.3	1454.2	#1	-0.67, 0.01**	-0.67, 0.01**	-0.00, 0.96
				#2	-0.58, 0.02*	-0.47, 0.06	-0.12, 0.66
				#3	0.04, 0.89	0.15, 0.55	0.11, 0.66
				#4	0.05, 0.85	0.63, 0.01**	-0.58, 0.02
	E3	1504.0	1512.1	-	0.01, 0.97	-0.02, 0.91	0.02, 0.91

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05.

Differences of perception for enclosedness are observed between the images and the real world while no difference is detected between the QTVR

and SIMU modes. The loss of information content caused by the switch to image impacts thus on the perception of enclosedness. However, the passage from the photographs into virtual renderings does not influence the perceptions of this dimension. Concerning the pleasantness, it appears in one room (Room #2) that the difference of perception between the image and the real world is accentuated with the renderings (in comparison with the photographs). However, the difference between the two types of image is still non-significant.

V.B.2.1.2. *VISUAL APPEARANCE OF LIGHTING*

Mean ratings for the scales related to the appearance of the lighting and collected in the real world, with the QTVR mode and with the SIMU mode are compared in Fig.V.B.5.

Four scales (D11, D21, D51 and D52) reproduce the same groupings in the three media.

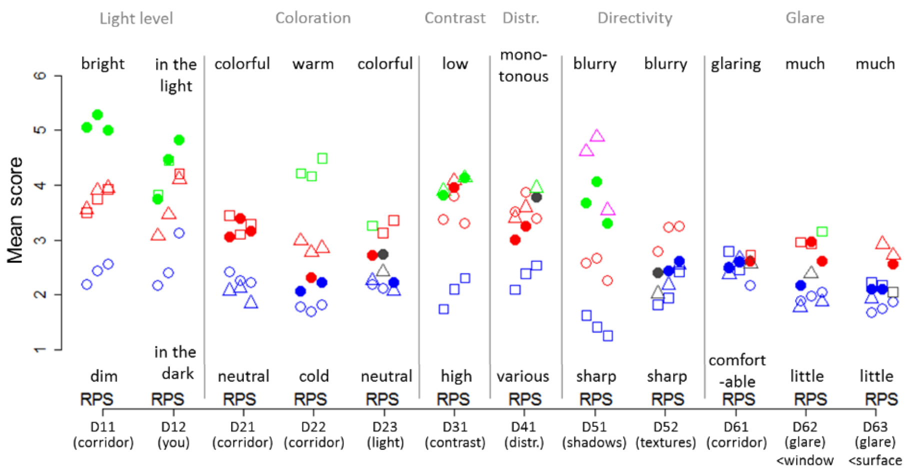


FIGURE V.B.5
Visual appearance of the lighting – Reproducibility of findings. Comparison between real world (R), QTVR (P) and SIMU (S) modes.

Results of the contrasts analysis performed on the data set are presented in Table V.B.4. SIMU mode presents more significant differences with the real world than the QTVR mode. Indeed, significant differences of distribution (D41) and directivity (D51, D52) are detected between the SIMU mode and the real world while they were not observed for the QTVR mode. But, only one of the two scales (D51) presents a significant difference between the QTVR and SIMU modes. Significant differences between the images and the real world are detected for brightness (D11, D12) and glare (D63). Difference between QTVR and SIMU modes is significant for D12.

Similarly to what was observed for the QTVR mode, brightness is significantly overestimated in the SIMU mode in comparison with the real-world experiment.

Moreover, the subjects felt significantly more in the light when visualizing Radiance renderings (SIMU mode) than photographs (QTVR mode) (see D12 in Table V.B.4).

The distribution of light in the rooms was perceived as more monotonous with the Radiance renderings than in the real world (see D41 in Table V.B.4). No difference was detected between the QTVR mode and the real world for this scale or between the QTVR mode and the SIMU mode.

Shadows in the Radiance renderings are perceived as sharper than in real-world and SIMU modes (D51). No significant difference was observed between QTVR mode and real-world experiment. Textures are perceived as blurrier with the QTVR mode than in the real world (D52). But there is no significant difference either between QTVR and real world or between QTVR and SIMU modes.

At last, similarly to what was observed in the QTVR mode, a surface in Room #3 is perceived, in the SIMU mode, a bit more glaring than in the real world.

TABLE V.B.4
Visual appearance of the lighting – Results of the contrast analysis (MCMCmean and pvalue)

Factor		AIC without interaction	AIC with interaction	Room	QTVR vs. real world	SIMU vs. real world	QTVR vs. SIMU
Brightness	D11	1397.7	1405.9	-	0.27, 0.02**	0.28, 0.01**	-0.02, 0.87
	D12	1575.3	1576.3	-	0.49, 0.01**	0.87, 0.00***	-0.38, 0.04*
Coloration	D21	1557.6	1564.8	-	-0.03, 0.85	-0.12, 0.46	0.09, 0.59
	D22	1491.7	1500.6	-	-0.03, 0.78	0.09, 0.50	-0.12, 0.36
	D23	1497.7	1501.8	-	-0.00, 0.99	-0.14, 0.42	0.13, 0.44
Contrast	D31	1576.6	1582.9	-	0.28, 0.10	0.26, 0.13	0.02, 0.91
Distribution	D41	1730.8	1736.0	-	0.28, 0.08	0.41, 0.01**	-0.13, 0.41
Directivity	D51	1503.8	1499.8	#1	0.37, 0.14	-0.37, 0.14	0.75, 0.00***
				#2	0.08, 0.74	-0.33, 0.18	0.41, 0.11
				#3	0.27, 0.29	-1.07, 0.00***	1.34, 0.00***
				#4	-0.22, 0.38	-0.38, 0.13	0.16, 0.55
	D52	1558.2	1567.2	-	0.19, 0.24	0.44, 0.01**	-0.25, 0.15
Glare	D61	1381.4	1382.8	-	0.04, 0.79	-0.03, 0.86	0.07, 0.67
	D62	1585.6	1587.7	-	0.37, 0.06	0.23, 0.22	0.15, 0.41
	D63	1544.5	1538.7	#1	0.01, 0.98	0.48, 0.07	-0.47, 0.09
				#2	0.07, 0.79	0.21, 0.42	-0.13, 0.63
				#3	0.99, 0.00***	0.79, 0.00***	0.20, 0.46
				#4	-0.06, 0.84	-0.17, 0.53	0.12, 0.66

Significance: *** = p ≤ 0.001; ** = p ≤ 0.01; * = p ≤ 0.05

The virtualization of the picture (the switch from photograph to virtual rendering) introduces some differences with the real world which were not significant with the photograph. When the scenes are visualized with renderings rather than with photographs, the distribution of light is perceived as more monotonous than in the real world, the shadows are sharper and the textures are blurrier.

V.B.2.2. NON-CONVENTIONAL QUESTIONS

V.B.2.2.1. *PAIRED COMPARISON OF WALLS (#1, #2)*

Figure V.B.6 to 8 compare the mean ratings of the participants of each group when asked to compare, on a five-point rating scale, two walls for brightness, uniformity, and roughness.

No difference is observed for the comparison of brightness in Room #3 (see Fig.V.B.6).

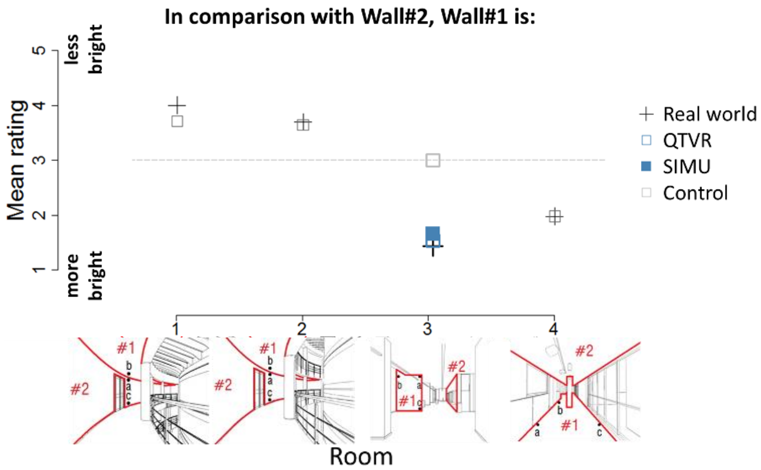


FIGURE V.B.6
Comparison of two walls for brightness– mean ratings

As illustrated in Fig.V.B.7, Room #3 is perceived differently on the basis of the picture and the rendering.

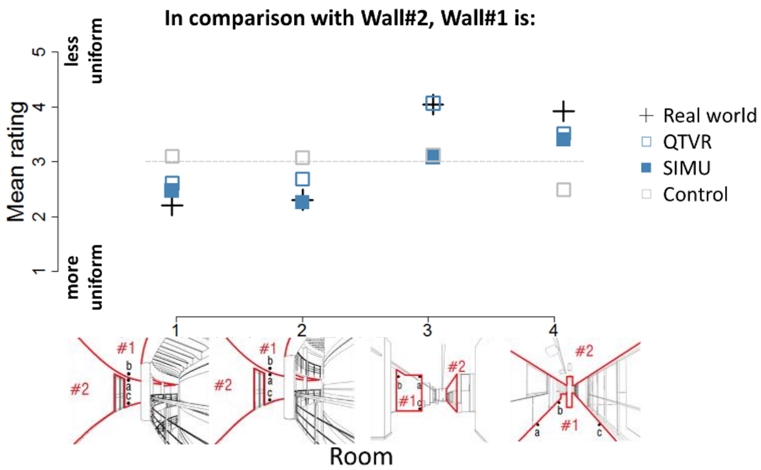


FIGURE V.B.7
Comparison of two walls for uniformity – mean ratings

With the rendering (SIMU mode), the two walls are perceived as presenting a similar uniformity while in the real world and with the QTVR mode, the subjects perceived Wall #1 as less uniform than Wall #2.

Figure V.B.8 illustrates the fact that, in the four rooms and on the basis of Radiance renderings, the roughness of Wall #1 is perceived as similar to the roughness of Wall #2. In the real world and with QTVR mode, a more pronounced difference between each pair of walls was observed.

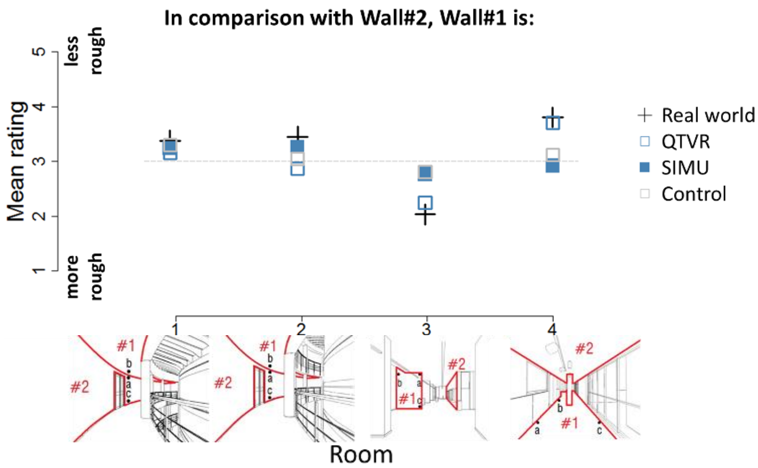


FIGURE V.B.8
Comparison of two walls for roughness – mean ratings

Figure V.B.9 zooms in on a portion of Wall #1 and of Wall #2 in Room #3.

FIGURE V.B.9
Comparison of two walls roughness (Room #3)

As shown in this figure, the brick pattern of Wall #1 is perceptible with SIMU mode. However, the wall is smoother with the SIMU mode than with the QTVR mode. Regardless of the medium, Wall #2 is less rough than Wall #1 and it seems that the pattern of Wall #2 is not perceptible.

Figure V.B.10 zooms in on a portion of Wall #1 and of the Wall #2 in Room #4. Again, a loss of roughness is visible between the QTVR mode and the SIMU mode.

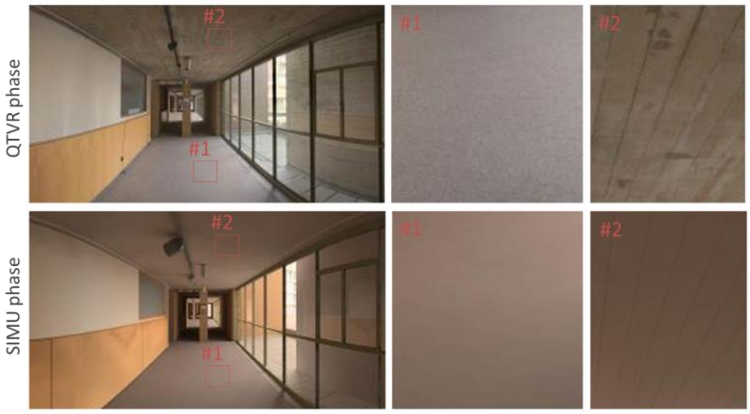


FIGURE V.B.10
Comparison of the roughness of two walls in Room #4

These results are in accordance with mean scores collected with the rating scales: Radiance renderings leads to blurrier textures and a loss of roughness.

V.B.2.2.2. *CLASSIFICATION OF PUNCTUAL ZONES FOR BRIGHTNESS*

As illustrated in Fig.V.B.11, regardless of the medium, the participants classified the three points similarly. However, in Room #3, a slight difference is observed for the point b, with the SIMU mode. This difference reveals that the wall is perceived as more uniform with the SIMU mode than with the other media. That is in accordance with results presented in Fig.V.B.8.

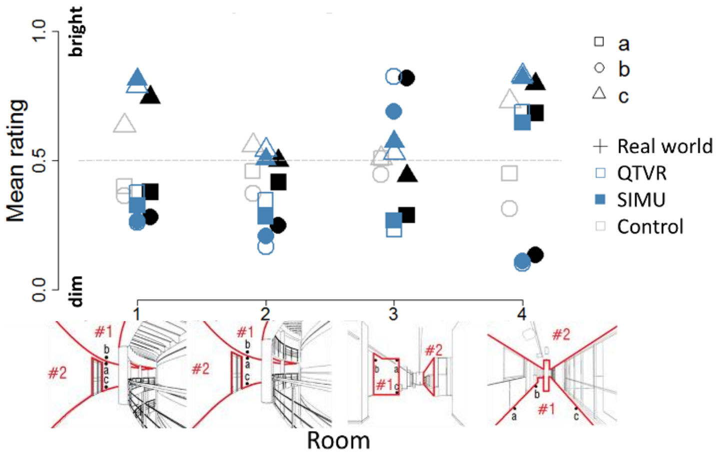


FIGURE V.B.11
Classification of three points for brightness

V.B.2.2.3. *Determination of zones for brightness*

Tables V.B.5 and 6 illustrate the fact that the participants of QTVR and SIMU modes judge the same parts of the scene as being the brightest or the dimmest.

TABLE V.B.5
Brightest part maps (the color scale indicates the percentage of participants who identified the areas as the brightest part of the scene)

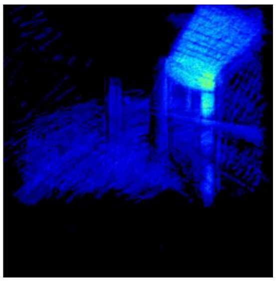
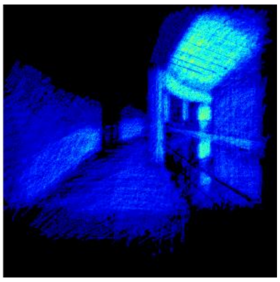
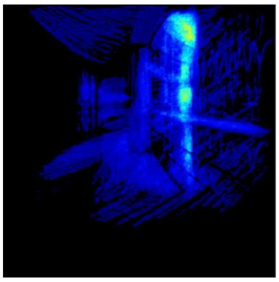
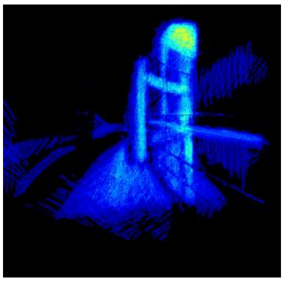
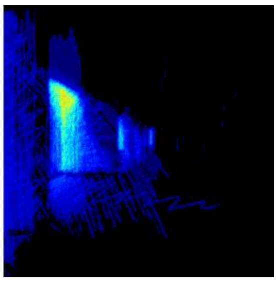
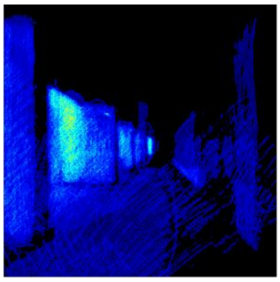
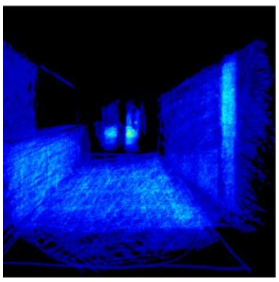
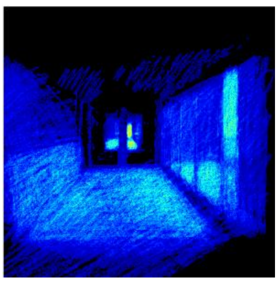
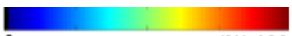
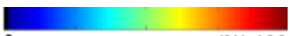
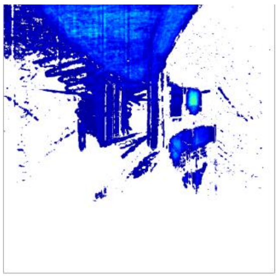
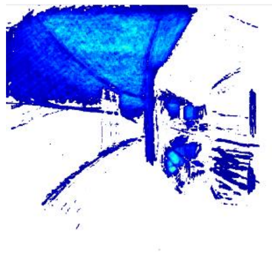
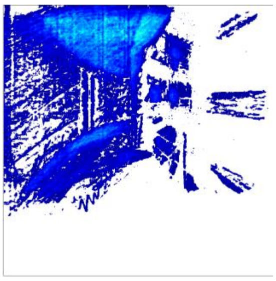
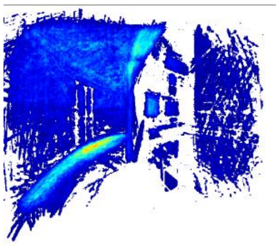
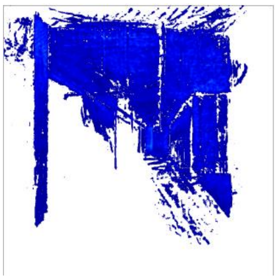
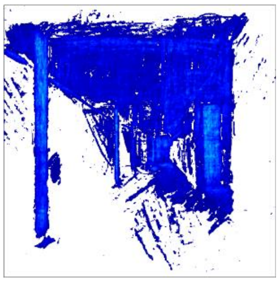
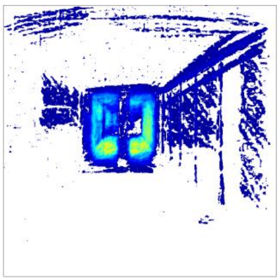
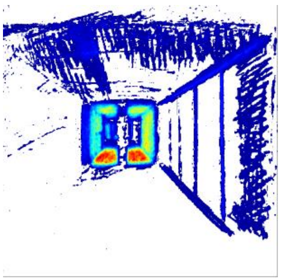
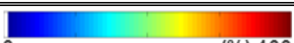
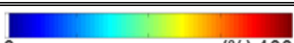
	QTVR mode	SIMU mode
Room #1		
Room #2		
Room #3		
Room #4		
	 0 (%) 100	 0 (%) 100

TABLE V.B.6
Dimmest part maps (the color scale indicates the percentage of participants who identified the areas as the dimmest part of the scene)

	QTVR mode	SIMU mode
Room #1		
Room #2		
Room #3		
Room #4		
	 0 (%) 100	 0 (%) 100

V.B.3. DISCUSSION

The main aim of this comparison was to determine whether Radiance renderings can be used to study the perception of the appearance of lighting and space. Our approach consisted in comparing three modes of presentation of the scenes: actual environments, photographs, and Radiance renderings. Our more specific objective was to determine whether differences of perception with the real world were due to the switch in images or to the virtualization of the scenes.

We first captured the scenes using photographic material (as explained in Chapter IV.A), then we reproduced it in a virtual environment (as explained in Chapter V.A). To avoid introducing a bias linked to the cultural background, we realized the three experiments on a Belgian population: we worked with QTVR panoramic renderings rather than classical 2D renderings as the QTVR mode was tested in Belgium while the 2D mode was tested in France.

The comparison of the three media revealed that information content necessary for assessing the appearance of space is more impacted by the switch to the image (the passage from the real world to the image) than by the virtualization of the picture (the switch from photographic pictures to virtual renderings). As shown in Table V.B.7, there are more significant differences between each image type and the real world than between QTVR and SIMU modes.

TABLE V.B.7
Summary of the comparison of the visualization modes

Factor	Ref.	Question	QTVR vs. real world	SIMU vs. real world	QTVR vs. SIMU
Pleasantness	P0	Pleasantness is: low – high	×	×	×
	P1	(light) pleasant – unpleasant	✓	×	×
Enclosedness	E0	Enclosedness is: low – high	×	×	×
	E1	(corridor) slightly – very spacious	×	×	✓
	E2	(corridor) slightly – very narrow	×	×	✓
	E3	(corridor) slightly – very deep	×	×	✓
Brightness	D11	(corridor) dim – bright	✓	✓	×
	D12	(you) in the dark – light	✓	✓	✓
Coloration	D21	(corridor) neutral – colorful	✓	✓	✓
	D22	(corridor) cold – warm	×	✓	×
	D23	(light) neutral – colorful	×	×	✓
Contrast	D31	(corridor) high – low contrast	×	✓	×
Distribution	D41	(corridor) lit unevenly – uniformly	✓	×	×
Directivity	D51	(shadow) sharp – blurry	✓	✓	×
	D52	(textures) sharp – blurry	✓	✓	✓
Glare	D61	(corridor) comfortable – glaring	✓	×	×
	D62	(you) little – much disturbed < window	×	×	×
	D63	(you) little – much disturbed < surface	×	×	×

Grouping of rooms: ✓ reproduced, × not reproduced
Image type effect or interaction: ✓/× no type effect, ✓/× image type effect, ✓/ × interactions

As observed in Part IV.C, while the appearance of lighting is rather well reproduced using images, the appearance of space and more particularly the spatial perceptions is perceived differently on the basis of the images than in the actual environments (see the enclosedness dimension in Table V.B.7). This first observation is in accordance with the study by Mahdavi et al. (2002) who compared five actual artificially lit environments to Lightscape renderings. Two groups of 50 participants were invited to evaluate either the actual scenes or the images on 7-grade scales dealing with the following dimensions: evaluative, perceptual clarity, spaciousness, light distribution, spatial complexity, formality and thermal, acoustic and haptic associations. According to the regression analysis the authors performed on each scale separately, the small/large and unpleasant/pleasant scales, related to the appearance of space, present a lower correlation between the two modes of presentation than the following scales, related to the appearance of lighting: dim/bright, cool/warm, and non-uniform/uniform. These scales related to the appearance of lighting are thus more reliable than the others related to the appearance of space for predicting, on the basis of renderings, the perceptions experienced in the actual scenes.

In our study, even if the appearance of lighting was, in general, well reproduced, brightness is overestimated in comparison with the real world, regardless of the image type. The difference is accentuated with the renderings.

At last, the comparison of the three media pointed out that the perception of the textures was impacted by the passage from the photographs to the renderings. The participants perceived a poor reproduction of the textures in our Radiance renderings despite the use of the *texfunc* function.

V.B.4. CONCLUSION

The replication of the QTVR experiment using renderings rather than photographs made it possible to strengthen some observations made in Chapter IV.C. Differences observed between the real-world experiment and the QTVR visualization are also observed with the SIMU visualization. The main additional difference observed with the virtual renderings is the misreproduction of the actual textures in our Radiance renderings.

Table V.B.8 summarizes the abilities of QTVR photographs and virtual renderings for replicating perceptions experienced in the actual environment.

The observed similarity between photographs and virtual renderings suggest that the passage from photographs to virtual renderings impacts the perception of pleasantness, distribution and directivity. However, differences between QTVR mode and SIMU mode are not significant for pleasantness and distribution (see Section V.B.3). On the other hand, for directivity, the difference between the two presentation modes is significant. Directivity cannot thus be studied with Radiance virtual renderings.

TABLE V.B.8
Summary of the abilities of QTVR photographs (QTVR mode) and QTVR virtual renderings (SIMU mode) for replicating perceptions of space and lighting experienced in the actual environments

		QTVR mode	SIMU mode
Appearance of space			
	Pleasantness	✓✓	× **
	Enclosedness	×	×
Appearance of lighting			
	Brightness	✓	✓
	Coloration	✓✓	✓✓
	Contrast	✓✓	✓✓
	Distribution	✓✓	✓ **
	Directivity	✓✓	×
	Glare* *	-	-

✓✓ No significant difference was observed with the real-world experiment
✓ Score must be read in relative terms
× Significant differences were observed with the real-world experiment
* the absence of glare during the real-world experiment did not allow to clearly state about the ability of the presentation modes to replicate this dimension
** difference between SIMU mode and QTVR mode is not significant

CONCLUSIONS AND FURTHER WORK

"There are three kinds of lies: lies, damned lies, and statistics." Attributed to Benjamin Disraeli (1804–1881), British politician.

Virtual renderings are increasingly used to support lighting design and research. In daylighting research, especially, this type of images is a way to reduce costs and overcome the uncontrollable variability of light when studying the visual appearance of daylit environments from a psychophysical approach. Over the past 20 years, many advances in imaging and display technologies developed to create more "realistic" images in better approaching some of the characteristics of human vision (binocularity, large range of luminances perceived and wide visual field) has increased enormously the number of ways to present these renderings. Regrettably, to date, there is still little work asserting that such images replicate the visual appearance of actual daylit scenes.

This PhD thesis aimed at investigating the potential of virtual renderings as well as various presentation modes of images for studying visual perceptions of daylit spaces. The two main objectives of the thesis were the following:

- Determining to what extent some presentation modes of images replicate the perceptions of the appearance of lighting and space measured in actual daylit environments. The following images were studied: tone-mapped 2D pictures on LDR display, tone-mapped 3D pictures on LDR display, tone-mapped QTVR panoramas on LDR display, and 2D pictures on HDR display.
- Determining whether virtual rendering is an image type that can be used as a surrogate for the real world to study the perceptions of the appearance of lighting and space. These virtual renderings were created using Radiance software, a physically-based rendering system which is currently the most accurate software for daylighting simulations.

To reach these objectives, the first step of the work consisted of collecting visual perceptions in actual daylit environments, using a questionnaire dealing with the appearance of lighting and space. To respond to our first objective, we then replicated the real-world experiment using various types of photographs. Finally, to respond to the second objective of the study, we replicated the experiment using virtual renderings.

As described in Part III of the present thesis, we first collected perceptions in actual daylit rooms using a questionnaire developed for the purpose of the study.

This questionnaire, adapted from Küller (1991) and Bülow-Hübe (1995), mixed rating scales, multiple choice questions (MCQ) and questions based on blank sketches. The non-conventional questions based on blank sketches aimed at investigating the perception of lighting in a more precise way than the rating scales or the MCQ. Indeed, using rating scales or MCQ, the spatial dimension is lost and the subject is invited to respond globally, at the risk of being reductive. Our results suggest that relating these subjective sketches with objective maps of luminances could be a way to better understand the interaction between the light and the space and to set thresholds determining the presence of dark areas, zones presenting high local contrast, and so one.

To check possible instrument bias as suggested by Danford and Willems (1975), a control group was introduced in the experimental design. Divergent validity between the real-world group and the control group was demonstrated in Chapter III.B. This divergence suggests that the real-world stimuli influenced participants' ratings. But, we also observed that participants of the control group were able to guess where daylight was coming from, when looking at blank sketches.

As participants' responses to the various types of questions were coherent and in accordance with the objective analysis of the rooms' luminous conditions, the work was pursued in comparing perceptions experienced in the real-world with those experienced by other people visualizing virtual renderings and photographs of the same rooms.

The second step of the experiment, presented in Part IV, consisted in replicating the real-world experiment using photographs.

As explained in Chapter IV.A, the visualization on the high dynamic range (HDR) device required some changes to the system to avoid artifacts and to display accurately luminances experienced in the real world. The visualization on the conventional low dynamic range (LDR) display raised the issue of the use and the choice of a tone-mapping operator (TMO), but also of the determination of its settings to ensure that real-world luminances were faithfully displayed by the device. The results presented in Cauwerts et al. (2013) suggest that the brightness perceived in the real-world rooms is better replicated when the TMO parameter affecting the luminosity of the picture is determined to minimize the relative error between the luminances of the HDR picture and those of the tone-mapped picture, rather than when the default settings are used.

For material reasons, some presentation modes of images were tested in France and others in Belgium (our Belgian lab has no HDR display). It was the opportunity to compare two populations very similar in many regards and sharing a same language: the francophone Belgians and the French people. In addition to highlighting divergences in the perception of glare and enclosedness, the comparison of the two populations, presented in Chapter IV.B, pointed out some imprecisions in the questionnaire resulting in significant differences between the two populations.

Indeed, Belgian and French people appear not to understand in an identical way the term "colorful"[1]. This observation was replicated with all the presentation modes.

The last step of our study, presented in Part V, was the evaluation of the potential of Radiance renderings for replicating the results of the real-world experiment.

This step was the opportunity to develop our image-based lighting (IBL) procedure and to compare this technique with classical physically-based rendering (PBR) (Chapter V.A). Luminance maps produced with Radiance were compared to those captured in the real world using HDR imaging techniques. This comparison showed a good reproduction of the light distribution and the brightness using simulations based on the actual sky conditions whatever the technique (PBR or IBL). Given the similarity of the classical physically-based renderings (PBR) with the real world and due to the lack of validation of our IBL procedure, we pursued the experiment with PBR.

We chose in the present study, to cast a wide net in working with four presentation modes of images (2D, 3D, QTVR and HDR) and two types of images (photographs and virtual renderings). Moreover, we investigated both several dimensions characterizing the appearance of lighting (brightness, coloration, contrast, distribution, directivity, and glare) and several dimensions characterizing the appearance of space (pleasantness and enclosedness).

Our results suggest that the appearance of lighting experienced in the actual daylit environments is reasonably replicated using images, regardless of the presentation mode (2D, 3D, QTVR or HDR) and regardless of the image type (photograph or virtual rendering). On the other hand, the appearance of space is poorly reproduced using images.

More precisely, according to the present study, the four tested presentation modes of images (2D, QTVR, 3D and HDR) allow studying the following dimensions related to the appearance of lighting: perceived brightness, contrast and directivity. Nevertheless, the ambient lighting conditions in the visualization room influenced the perceived brightness and contrast. Coloration dimension was replicated with 2D, QTVR and 3D modes but distorted with the HDR system. And, perceived distribution of light and pleasantness were only replicated with QTVR mode. Consequently, this mode (QTVR mode) is the only mode which allows studying five dimensions influencing the appearance of lighting. Last, contrary to our expectations, we observed no benefit of 3D images in comparison to 2D pictures to study the enclosedness dimension or the interplay of light and materials. On the contrary, we found that considerable post-processing is needed for 3D images of high quality and we observed that flickering was experienced by the participants in spite of the precautions taken to avoid this phenomenon. 3D mode is thus not recommended for studying the appearance of lighting and space.

[1] "coloré" in French

The comparison between the real-world results and the results collected using Radiance virtual renderings strengthen some observations made with photographs. Indeed, the differences observed between the real-world and the photographs were replicated when photographs were replaced by virtual renderings. The main difference due to the virtualization of the image (the passage from the photograph to the virtual rendering) is the misreproduction of the textures in our renderings. These results suggest that Radiance virtual renderings produce similar responses than photographs except for directivity.

As a consequence of these results, and by economy of means, we recommend using 2D tone-mapped images displayed on conventional LDR monitors for studying perceived brightness, coloration, contrast and directivity. While the first three dimensions could be studied using virtual renderings or photographs, directivity should be studied using photographs due to the poor reproduction of textures observed in virtual renderings. Distribution of light and pleasantness dimension should be studied exclusively using QTVR images. Last, according to our results, the enclosedness perceived in actual environments is not replicated using images. This dimension should be studied in actual environments. Table 1 summarizes these recommendations.

TABLE 1
Recommended image medium for the various dimensions characterizing the appearance of lighting and space

	Recommended image medium	Other validated presentation modes	Other validated image type
Perception of the space			
Pleasantness	QTVR virtual renderings *	-	photographs*
Enclosedness	-	-	-
Perception of the lighting			
Brightness	2D virtual renderings *	3D,QTVR,HDR	photographs*
Coloration	2D virtual renderings *	3D,QTVR	photographs*
Contrast	2D virtual renderings *	3D,QTVR,HDR	photographs*
Distribution	QTVR virtual renderings *	-	photographs*
Directivity	2D photographs *	3D,QTVR,HDR	-
Glare**	-	-	-

* to avoid over-exposed or under-exposed areas, a tone-mapping operator should be applied to the images presented on the LDR monitor
** the absence of glare during the real-world experiment did not allow to clearly state about the ability of the presentation modes to replicate this dimension

Note that the studied HDR display was under development and that our results related to this mode cannot be generalized to all the HDR displays. Moreover, the absence of glare in the actual environments the day of the experiment did not allow to clearly state about the ability of the tested presentation modes to replicate this dimension. Nevertheless, when the pictures were displayed using the HDR system, we observed that participants detected sun spots that they did not detect with the LDR monitor.

Although the research was carefully prepared and has reached its aims, there are some unavoidable limitations.

First, this research focused on ambulatory corridors which are spaces where the occupants are moving and only going through. This activity is, for instance, far away different from office activities. Indeed, in an office, the occupant has, most of the time, a fixed position, realizes a series of specific tasks and is more easily disturbed by glare than in a corridor. As a consequence, our results can be generalized to other ambulatory spaces but not to any type of spaces.

Second, in the present study, actual room luminances vary between about 0 and about 7800 cd/m² (median: 43 cd/m², first quartile: 31 cd/m², third quartile: 59 cd/m²). Our results can only be generalized to rooms presenting a similar range of luminances. Moreover, only four rooms were studied. A larger number of rooms could make possible the identification of some interactions not detected in the present study. To not exceed 45 minutes survey and to avoid fatigue effect, the length of the questionnaire should decrease if the number of rooms increases.

Third, the research was conducted on university students (aged between 18 and 25 years). Students in architecture were excluded from the recruitment because differences in perceptions and preferences exist between the architects and the non-architects as observed by Devlin and Nasar in a study cited in Walsh et al.' work (2000). As explained in Chapter II.B, students are often recruited for psychological research, mainly for their accessibility and availability. However their use is controversial and it often questions the generalization of the results to a non-student population. But in lighting quality research, a previous work presented some proofs that subjective lighting assessment does not differ significantly between students and housewives aged between 22 and 36 years (Lau, 1972). That is why we think that our results can be generalized to people aged between 20 and 40 years (lens elasticity is typically progressively modified after this age). However, to confirm this, the experiment needs to be replicated on non-student populations.

Last, the main shortcoming of the work is probably the variation of luminous conditions observed during the visit of the actual daylit rooms. In taking pictures the day of the real-world experiment, we aimed at reducing the difference, encountered in Newsham et al.'s study (2010), between the luminous conditions experienced by the participants visiting the real spaces and the conditions in the environments when pictures were taken. Regrettably, despite the precautions taken (in each room, we tried to minimize the duration of the visit by the participants), the analysis of the rooms' luminous conditions revealed some important changes in the lighting conditions during the real-world experiment. We decided to pursue the study in using the three series of pictures made in each room during the visit of the real-world group of participants. These uncontrollable daylight variations introduced a bias between the real-world experiment and its replication in images. To minimize this bias, future works could place a fixed camera in each room to take a series of pictures for each subject assessing the room.

Despite these limitations, our results suggest that images, and more particularly QTVR virtual renderings, are a promising tool for studying the appearance of lighting and space. Further studies are desirable to confirm our results and to generalize it to other rooms (in terms of activities and lighting conditions) and to other populations. These further investigations could use full QTVR panoramas rather than partial ones (as it is the case in the present study due to technical limitations). Moreover, rather than studying purely perceptual response, the emotional response (see Chapter I.B) could be investigated.

Last, the following research issues should be address preliminary to pursuing the investigation of images.

- Collecting vocabulary and developing a universal questionnaire

In the present work, a questionnaire was first developed on the basis of the literature around two dimensions characterizing the space (pleasantness and enclosedness) and six dimensions characterizing lighting in interiors (brightness, coloration, contrast, directivity, distribution, and glare).

We made the decision to investigate in a very descriptive way the appearance of the lighting. However, as pointed out in Appendix I presenting an analysis of the adjectives used by the subjects to describe the lit environment, people also use adjectives related to emotions to describe the lighting in the corridors. This observation is in accordance with the work by Vogels (2008). Rather than only using descriptive words, as we did, or only using emotional words, as Vogels did, we think that developing a universal questionnaire mixing descriptive and emotional words could enrich the assessment of the perceptions in the field of lighting appearance. Moreover, lighting research would benefit from developing a universal questionnaire similar to what Küller did, in the Seventies, for assessing visual appearance of built environments. Indeed, such a questionnaire would facilitate the comparison of various studies carried out on similar issues.

The vocabulary words could be collected in a method similar to Vogels' method, asking people to imagine various types of rooms and describe them with their own words. This collection should be gathered from people accustomed to manipulating light (such as architects, film directors, designers, and so on) and people a priori less sensitive to the use of light. Indeed, in our experiment, to test the comprehensibility of the questions, we conducted a pilot test with students of architecture. While the questions related to the perception of textures were not problematic for them, about one-third of the non-architect participants interviewed found them difficult and appeared to be unfamiliar with the interplay of light and materials.

- Determining the parameters of the tone-mapping operator according to the ambient lighting conditions of visualization

Whatever the type of image and due to the fact that the visualization was organized in a black room, participants who visualized pictures tented to overestimate the perception of the brightness in comparison to real-world participants. However, they reproduced the order of classification of the rooms. As discussed in our complementary study (Cauwerts et al., 2013) and due to adaptation phenomena, the lighting conditions in the room of visualization significantly influences the perception of brightness but also the perception of contrast and glare. Moreover, the tone-mapping operator (TMO) also influences the perception of brightness. For a better match between the real-world and the images, it is necessary to determine the TMO parameters according to the conditions of visualization (light level and background luminance). Note that, according to Villa and Labayrade's study (2012) who aimed at validating online lighting quality surveys, a sample of 100 participants makes it possible to remove the bias linked to the lighting ambiance and allows online surveys without controlling lighting conditions.

- Facilitating the modeling of textures in Radiance

In the present work, we chose to work with Radiance, a validated physically-based rendering system. Rather than favoring software mimicking the visual response (how the material looks) we aimed at mimicking the visual information (how the material behaves). However, we found that the modeling of textures such as bricks or carpets is quite difficult in Radiance. The results of the SIMU mode pointed out that even if the pattern is rather well reproduced in the virtual scenes, the non-reproduction of the textures in our renderings leads to the impossibility of studying the interplay of light and materials. Nevertheless, the interaction between the light and the materials, including the interplay of light and shadow, has always been of great interest for architects. Studying lit environments using images in which textures are poorly reproduced is unthinkable. It is therefore essential to develop tools, methods, or documentation to simplify the modeling of textures in Radiance.

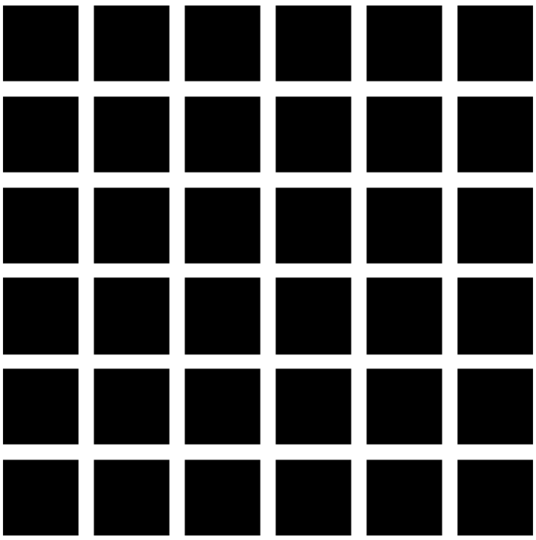
- Pursuing the validation of image-based lighting

The aim of the comparison between the actual scenes, the classical physically-based renderings (PBR) and the image-based lighting (IBL) was to determine whether the actual daylit scene is more faithfully reproduced with IBL than PBR. Our comparison showed that it was not necessary, in our case, to have recourse to IBL, because PBR satisfactorily reproduces the lit environment. But, as explained in an earlier study (Inanici, 2010), one of the main interests of IBL is to simulate a difficult environment to model (vegetation, neighboring buildings, and so on) using vertical HDR fisheye pictures taken outside the window. In such cases, IBL could thus be more interesting than PBR. This points out the need to fine-tune our method for capturing sunny skies.

- Developing metric for comparing photographs and virtual renderings

Last, the comparison between maps of real-world luminances and renderings highlighted the difficulty in comparing photographs and renderings due to geometrical misalignments. In the continuity of the work of (Rushmeier et al., 1995), exploring techniques for comparing real and synthetic images, a metric could be developed for easily and accurately comparing two images not perfectly aligned.

To conclude, the present study allowed determining, among four presentation modes of images (2D, 3D, QTVR and HDR) and two types of images (photographs and virtual renderings), the media to use for studying each dimension characterizing the appearance of lighting and space. Specific directions for future validation works have been pointed out, as well as research issues to address preliminary.



Hermann grid illusion illustrates that our perceptions depends both on the response of our visual system to a stimulus and on the interpretation of our brain.

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APPENDIX I
OPEN QUESTION

Unless performing physiological tests, measuring perceptions entails the use of language and assumes that everybody understands the words similarly. But it is not always the case, even if a definition is given.

The questionnaire used in the present work was built on the basis of the litterature as explained in Chapter III.A. To check the comprehensibility of the vocabulary, a pilot test was conducted on students in architecture.

The present appendix discusses the responses of the participants when they are asked to describe daylight in the rooms. Results show that a work on the collection of vocabulary words for describing the appearance of lighting should be pursued. Moreover, lighting research would benefit from developing a universal questionnaire for assessing the appearance of lit scenes.

1 | MATERIAL AND METHOD

In three phases of the experiment (see Fig.A.I.1), the participants were invited before responding to the form to describe the scene using their own words. The question was: “Succintly and using your own words, describe how you perceive daylight in the room”[1]. The objective of this question was to check the coherence between these responses and the rating scales but also and mainly, to enrich our database vocabulary.

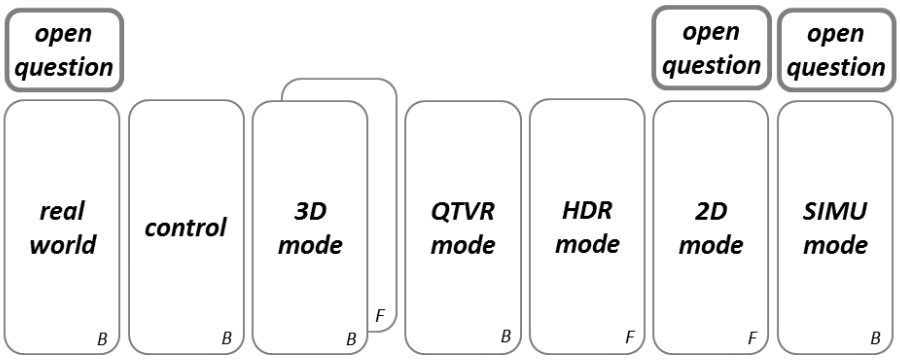


FIGURE A.I.1
Three groups of participants were invited to respond to an additional question (open question)

[1] Original question in French was: “De manière succincte et avec vos propres mots, décrivez comment vous percevez l’éclairage naturel dans l’espace.”

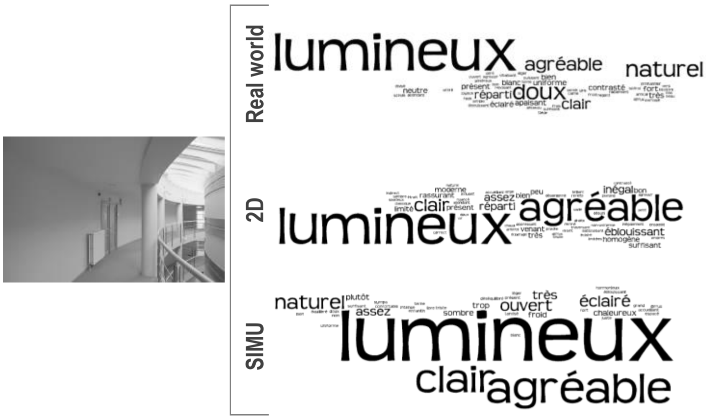
The forty-three participants of the real world phase responded to this open question as well as the forty French participants of the 2D phase and the thirty-nine participants of the SIMU phase. Participants of the 2D and SIMU phases were also invited to indicate the questions they found difficult to answer.

2 | RESULTS

2.1. WORD CLOUDS

Tables A.I.1 to 4 present the words used by the participants of the different groups to describe daylight in the actual rooms. In each word cloud, only the words used by at least two people of the group are presented. The size of the words varies according to the frequency with which they have been used.

TABLE A.I.1
Room #1 - Word clouds by group of participants (Real world group, 2D group, SIMU group)



Whatever the phase, there is a consensus to say that the first room is luminous. Indeed, fifteen participants of the real world cited the word "lumineux" to describe the room. Forteen participants of the 2D phase used this same word and 18 people of the SIMU phase.

According to the participants and whatever the phase, the second room is perceived as dark. The consensus is greater in the real world phase (60% of the participants cited the word "sombre") than in the image phases (36% of the participants cited the word in the 2D phase and 49%, in the SIMU phase). Participants also mentionned the word "triste".

As illustrated by the word clouds, the consensus on the words is weaker in Room#3 whatever the phase: many different words are mentionned by the participants. It appears nevertheless that Room#3 is described as "sombre" by 19% of the respondents of the real world group and 23% of the participants of the SIMU group. Ten pourcents of the participants of the 2D phase mentionned the word "faible".

TABLE A.I.2
Room #2 - Word clouds by group of participants (Real world group, 2D group, SIMU group)

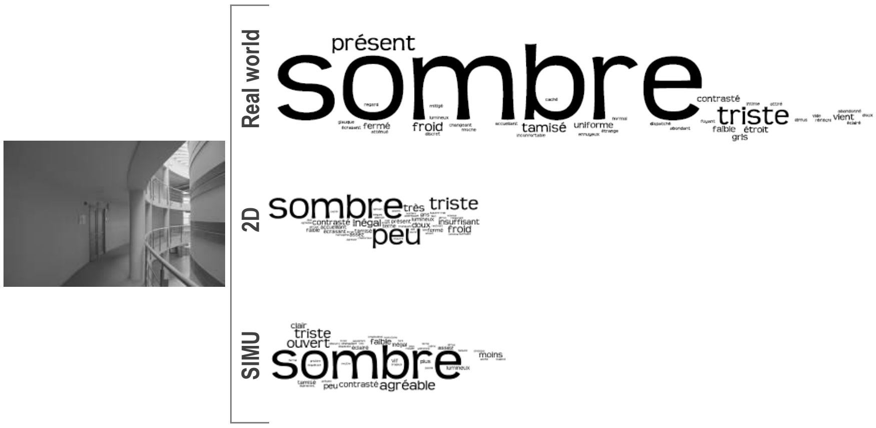


TABLE A.I.3
Room #3 - Word clouds by group of participants (Real world group, 2D group, SIMU group)

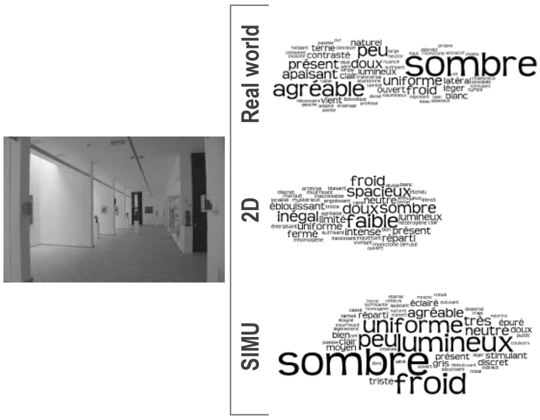
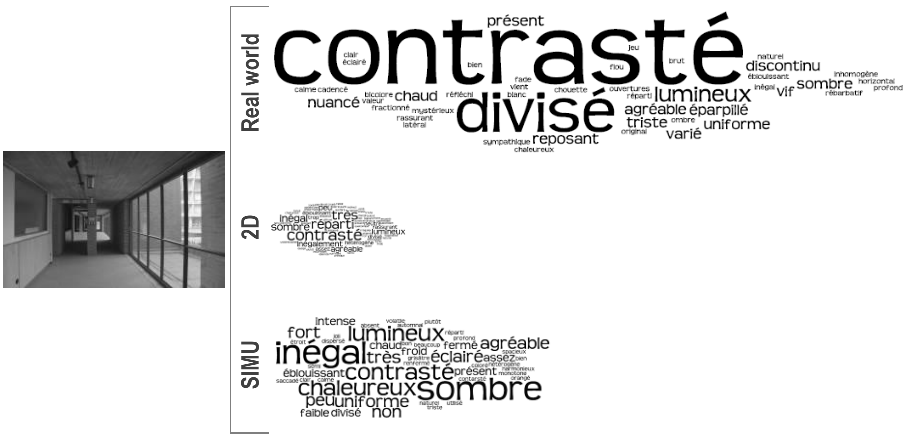


TABLE A.I.4
Room #4 - Word clouds by group of participants (Real world group, 2D group, SIMU group)



In Room#4, many participants (30% of the respondents) of the real world group describe the room as "contrasté". The French participants of the 2D phase also agree on the word "contrasté", however the consensus is weaker that in the real world group: only 13% of the participants of this phase uses the word. At last, the participants of the SIMU phase describe this room as "sombre" (18%) and "inégal" (18%).

Whatever the room and the phase, these results are in accordance with the rating scales.

2.2. LISTING OF WORDS

On the basis of the open question, the following vocabulary words were collected: *(*in alphabetical order) *abandonné, abondant, absent, accueillant, aéré, agréable, agressif, apaisant, austère, beau, bicolore, bien, blanc, bon, caché, calme, chaleureux, chaud, clair, classique, cloisonné, coloré, contrasté, délimité, déséquilibré, diffus, diffusé, discontinu, discret, dispersé, divisé, doux, éblouissant, éclairé, écrasant, ennuyeux, ensoleillé, éparpillé, épuré, espacé, étroit, fade, faible, fermé, foncé, fort, frais, froid, gris, grisâtre, harmonieux, hétérogène, homogène, indirect, inégal, inhomogène, inquiétant, insuffisant, intense, laid, large, latéral, léger, libre, limité, lumineux, moche, moderne, monotone, morne, moyen, mystérieux, naturel, neutre, nuancé, ombre, oppressant, ouvert, paisible, pastel, petit, présent, profond, puissant, rassurant, réfléchi, regard attiré, réparti, reposant, simple, sobre, sombre, spacieux, stimulant, suffisant, sympathique, tamisé, terne, triste, uniforme, varié, venant de, vient, vif.*

Note that the participants often used the following words to weight their perceptions: (in order of occurence) *peu, très, assez, non, pas, mal, inégalement, ni trop, plutôt, un peu, bien, moins, plus, assez bien, fort, légèrement, pas très, presque, ni, pas assez, quasi, sans, semi, trop.*

2.3. DIFFICULTY OF THE QUESTIONS

Among the words of the questionnaire related to the appearance of the space, three vocabulary words have been problematic for the participants: *délicat*, *idyllique*, *bien.* In the lighting questionnaire, two questions were problematic for about one third of the participants: the two questions related to the interaction between the light and the materials.

TABLE A.I.5
Pourcentage of participants considering the following questions difficult to answer

Factor		Question		2D phase	SIMU phase
Space	Pleasantness	P0-8	Le couloir est délicat	73%	54%
		P0-6	Le couloir est bien	33%	36%
		P0-5	Le couloir est idyllique	40%	33%
Lighting	Directivity	D51	Les textures sont floues/nettes	28%	33%
		C3	Le mur #1 est plus rugueux – moins rugueux que le mur #2	35%	41%

3 | DISCUSSION

Among the vocabulary words used by the participants to describe daylight, some words present in the questionnaire are not reused, which could indicate a lack of understanding of the question: *confortable, délicat, flou, haut, idyllique, inexistant, nette, obscur, unifie, rugueux.*

Moreover, among the vocabulary words used by the participants, three categories of words similar to those highlighted in the works of Vogels (2008) and Fernandez (2012) are formed. The asterisk (*) indicates the words used by the three groups, but not present in the original questionnaire.

- descriptive words : *blanc*, chaud, clair*, contrasté, délimité, diffuse*, discret*, doux*, éblouissant, éclairé, étroit, faible*, fermé, froid, gris*, inégal, naturel*, neutre, nuancé*, ombré, ouvert, present*, réparti, sombre, spacieux, tamisé*, terne*, uniforme, vif*.*
- words for emotions : *accueillant*, agréable, agressif*, chaleureux*, écrasant*, rassurant, sobre*, triste*.*
- words for judgement : *bien, bon*, suffisant**

4 | CONCLUSIONS

In the present PhD work, we chose to build our questionnaire on the basis of the litterature and focusing on descriptive words. As a result of this work, we realized that mixing descriptive and emotional words could enrich the measurement of the perceptions.

We also think that the creation of a universal questionnaire such as Küller did for assessing visual appearance of build environements would facilitate the comparison between the studies in a same field. However, in order that the questionnaire meets the objectives of various researchers a great job of collection of vocabulary words and translation must be done. Also, a long version of the questionnaire and a simplified version could also be proposed, to let the possibility to the researcher to complete the survey with additional and more specific questions.

APPENDIX II
QUESTIONNAIRE IN FRENCH

The present appendix presents the original questions in French asked to the participants for each scene.

Page 1

Le couloir, en tant que lieu de passage, vous paraît visuellement :

AGRÉABLE (P0.7)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

ÉTROIT (E2)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

STIMULANT (P0.2)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

FERMÉ (E0.1)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

RASSURANT (P0.3)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

LARGE (coherence check)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

ENNUYEUX (P0.4)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

SPACIEUX (E0.4/E1)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

DÉLIMITÉ (E0.3)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

DÉLICAT (P0.8)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

OUVERT (E0.2)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

PROFOND (E3)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

BIEN (P0.6)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

IDYLLIQUE (P0.5)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

LAID (P0.1)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

HAUT (E4)
Peu ☐ ☐ ☐ ☐ ☐ ☐ Très

Page 2

Ce couloir, en tant que lieu de passage, vous semble :

(D11) GLOBALEMENT SOMBRE ☐ ☐ ☐ ☐ ☐ ☐ GLOBALEMENT LUMINEUX

(D61) CONFORTABLE ☐ ☐ ☐ ☐ ☐ ☐ ÉBLOUISSANT

(D21) NEUTRE ☐ ☐ ☐ ☐ ☐ ☐ COLORÉ

(check) ÉCLAIRÉ INÉGALEMENT ☐ ☐ ☐ ☐ ☐ ☐ ÉCLAIRÉ UNIFORMÉMENT

(D22) VISUELLEMENT FROID ☐ ☐ ☐ ☐ ☐ ☐ VISUELLEMENT CHAUD

(D31) TRÈS CONTRASTÉ ☐ ☐ ☐ ☐ ☐ ☐ PEU CONTRASTÉ

La lumière, dans le couloir, est :

(D23) NEUTRE ☐ ☐ ☐ ☐ ☐ ☐ COLORÉE

(D41) distribuée de manière VARIÉE ☐ ☐ ☐ ☐ ☐ ☐ MONOTONE

(P1) AGRÉABLE ☐ ☐ ☐ ☐ ☐ ☐ DÉSAGRÉABLE

Vous êtes :

(D12) DANS L'OBSCURITÉ ☐ ☐ ☐ ☐ ☐ ☐ DANS LA LUMIÈRE

(D62) PEU ÉBLOUI ☐ ☐ ☐ ☐ ☐ ☐ TRÈS ÉBLOUI par une fenêtre

(D63) PEU ÉBLOUI ☐ ☐ ☐ ☐ ☐ ☐ TRÈS ÉBLOUI par une surface

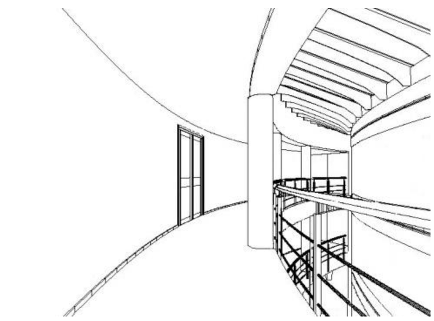
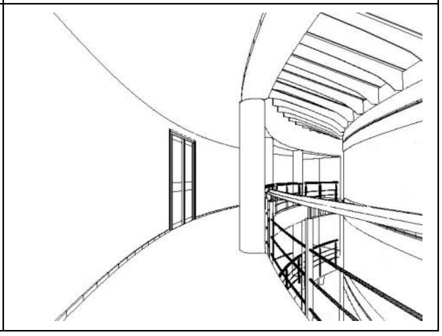
Les ombres dans le couloir vous semblent :

(D51) NETTES ☐ ☐ ☐ ☐ ☐ ☐ INEXISTANTES

La texture des matériaux vous paraît :

(D52) NETTE ☐ ☐ ☐ ☐ ☐ ☐ FLOUE

Sur le schéma, entourez, s'il y en a …

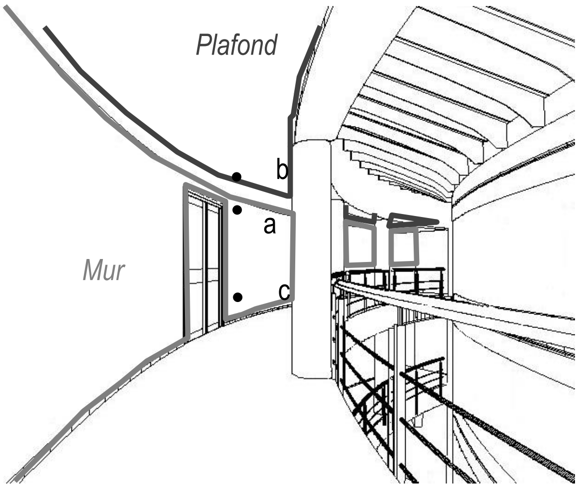
… les zones de votre champ visuel qui attirent particulièrement votre regard	… les parois dont le matériau est mis en valeur par la lumière
	

Vous préféreriez que le couloir, en tant que lieu de passage, soit :

LUMINEUX
(A11) plus ☐ ☐ ☐ ☐ ☐ moins

COLORÉ
(A21) plus ☐ ☐ ☐ ☐ ☐ moins

CONTRASTÉ
(A31) plus ☐ ☐ ☐ ☐ ☐ moins



Comparez le plafond et le mur

Le plafond est … …que le mur

LUMINEUX

plus ☐☐☐☐☐ moins

UNIFORMÉMENT ECLAIRÉ

plus ☐☐☐☐☐ moins

RUGUEUX

plus ☐☐☐☐☐ moins

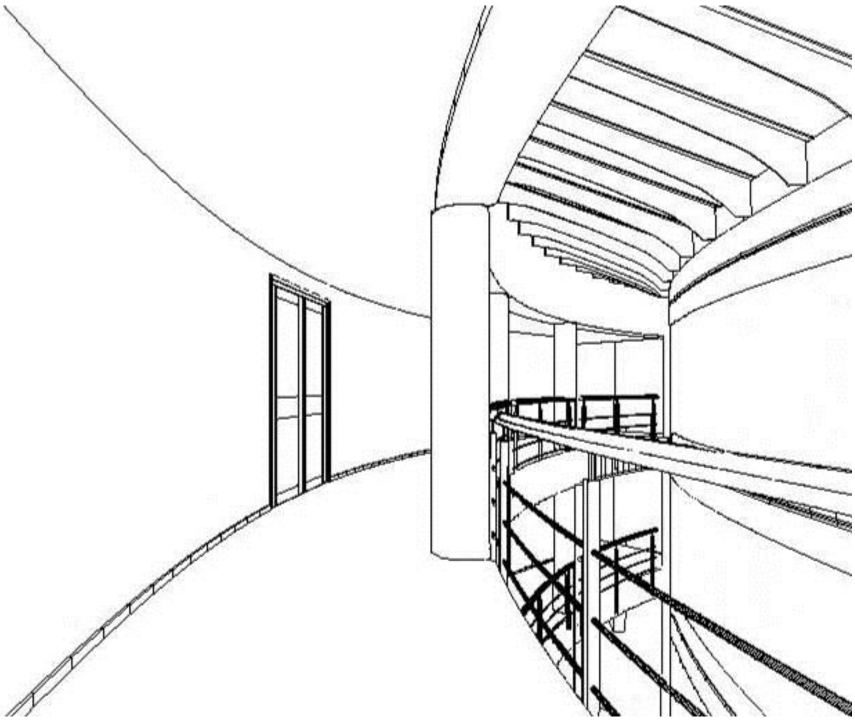
Comparer la luminosité des points a, b, c

SOMBRE ________________________ LUMINEUX

Sur ce schéma, coloriez les zones DE VOTRE CHAMP VISUEL :

[en rouge] Les plus lumineuses

[en bleu] Les plus sombres



Parmi les espaces évalués (1, 2, 3, 4), et sans regarder vos precedentes réponses, quel est celui que vous avez trouvé :

- **le plus agréable ?** ....
- **le moins agréable ?** ....

- **le plus enclos ?** ....
- **le moins enclos ?** ....

- **le plus lumineux ?** ....
- **le moins lumineux ?** ....

- **le plus coloré ?** ....
- **le moins coloré ?** ....

- **le plus contrasté ?** ....
- **le moins contrasté ?** ....

- **le plus spacieux ?** ....
- **le moins spacieux ?** ....

APPENDIX III
DESCRIPTIVE RESULTS

1 | RATING SCALES

1.1. APPEARANCE OF THE SPACE

1.1.1. PLEASANTNESS

Question	Phase	Mean rating (standard deviation)				Range of score
		Room #1	Room #2	Room #3	Room #4	
P0 Pleasantness	REAL	4.0 (0.93)	2.7 (0.86)	3.6 (0.93)	3.4 (1.12)	1.3
	CONTROL	3.9 (0.66)	3.8 (0.80)	3.6 (0.95)	3.6 (0.94)	0.3
	3Db	4.4 (0.62)	3.4 (0.80)	3.4 (1.13)	3.1 (0.76)	1.3
	3Df	3.9 (0.70)	3.2 (0.84)	3.6 (0.91)	3.0 (0.83)	0.9
	QTVR	4.3 (0.78)	2.9 (0.77)	3.5 (1.05)	3.1 (0.98)	1.4
	HDR	3.9 (0.65)	3.2 (0.84)	3.4 (0.94)	2.6 (1.02)	1.3
	2D	4.2 (0.68)	2.7 (0.76)	3.4 (1.10)	3.0 (1.06)	1.5
	SIMU	4.3 (0.60)	3.2 (0.74)	3.3 (0.93)	3.2 (0.97)	1.1
P1 Pleasantness of light	REAL	2.0 (1.07)	3.6 (1.07)	2.7 (1.06)	2.7 (1.48)	1.6
	CONTROL	2.3 (0.95)	2.8 (1.18)	2.9 (1.11)	2.7 (1.38)	0.6
	3Db	1.8 (0.78)	3.3 (1.21)	2.8 (1.29)	2.9 (1.33)	1.5
	3Df	2.1 (1.23)	3.0 (1.17)	2.6 (0.99)	3.4 (1.41)	1.3
	QTVR	1.9 (0.86)	3.5 (1.23)	2.9 (1.28)	2.6 (1.27)	1.6
	HDR	2.2 (0.87)	3.1 (1.06)	2.8 (1.17)	3.8 (1.48)	1.6
	2D	2.2 (0.66)	3.7 (1.12)	3.0 (1.42)	3.2 (1.31)	1.5
	SIMU	2.2 (0.94)	3.3 (1.08)	2.9 (1.33)	3.0 (1.06)	1.1

1.1.2. ENCLOSEDNESS

Question	Phase	Mean rating (standard deviation)				Range of score
		Room #1	Room #2	Room #3	Room #4	
E0 Enclosedness	REAL	2.9 (0.91)	3.9 (0.99)	3.0 (0.92)	3.2 (0.86)	1.0
	CONTROL	2.9 (0.97)	3.3 (0.90)	3.4 (1.10)	3.6 (1.11)	0.7
	3Db	2.6 (0.87)	3.5 (0.83)	3.0 (1.03)	3.7 (0.85)	1.1
	3Df	2.8 (0.82)	3.8 (0.98)	3.1 (0.98)	4.1 (0.87)	1.3
	QTVR	2.4 (0.81)	3.7 (1.05)	2.9 (1.18)	3.7 (0.91)	1.3
	HDR	2.9 (0.87)	3.9 (0.78)	3.1 (0.95)	4.1 (0.96)	1.2
	2D	2.8 (0.80)	4.1 (0.73)	2.9 (1.01)	4.1 (0.96)	1.3
	SIMU	2.5 (0.66)	3.5 (0.95)	3.0 (0.92)	3.8 (0.84)	1.3
E1 spacious	REAL	3.4 (1.04)	3.0 (1.17)	4.8 (0.97)	4.0 (0.97)	1.8
	CONTROL	4.0 (1.28)	3.5 (1.29)	4.3 (1.24)	3.4 (1.40)	0.9
	3Db	4.1 (1.1)	3.6 (1.06)	4.6 (0.78)	3.5 (1.08)	1.1
	3Df	4.2 (1.01)	3.3 (1.01)	4.5 (1.17)	2.9 (0.80)	1.6
	QTVR	4.4 (1.07)	3.3 (1.17)	4.7 (1.13)	3.5 (1.25)	1.4
	HDR	4.0 (1.21)	3.4 (1.06)	4.6 (0.96)	2.8 (1.13)	1.8
	2D	4.0 (1.38)	2.7 (1.06)	4.7 (0.88)	2.9 (1.11)	2.0
	SIMU	4.2 (0.93)	3.4 (1.02)	4.5 (0.97)	3.2 (1.08)	1.3

Question	Phase	Mean rating (standard deviation)				Range of score
		Room #1	Room #2	Room #3	Room #4	
E2 narrow	REAL	3.7 (1.23)	4.2 (1.14)	1.7 (0.68)	3.2 (1.29)	2.5
	CONTROL	3.4 (1.36)	3.6 (1.29)	2.8 (1.28)	3.8 (1.27)	1.0
	3Db	2.8 (1.14)	3.6 (1.18)	1.9 (0.98)	3.7 (1.31)	1.8
	3Df	3.2 (1.33)	3.8 (0.97)	1.7 (0.75)	3.6 (1.57)	2.1
	QTVR	3.0 (1.20)	3.6 (1.15)	1.7 (0.73)	3.2 (1.23)	1.9
	HDR	2.8 (0.85)	3.6 (1.09)	1.9 (0.75)	3.3 (1.49)	1.7
	2D	3.0 (1.30)	3.9 (0.98)	1.7 (0.82)	3.7 (1.34)	2.2
	SIMU	3.0 (1.26)	3.7 (1.32)	1.8 (0.79)	3.8 (1.20)	2.0
E3 deep	REAL	4.3 (1.31)	3.7 (1.27)	3.7 (1.44)	5.0 (0.80)	1.3
	CONTROL	4.4 (1.03)	4.0 (1.33)	4.4 (1.42)	4.5 (1.35)	0.5
	3Db	4.6 (0.75)	3.9 (1.14)	3.8 (1.17)	4.8 (1.11)	1.0
	3Df	4.2 (1.25)	3.3 (1.21)	3.8 (1.23)	4.9 (1.10)	1.6
	QTVR	4.6 (1.06)	3.8 (1.12)	3.8 (1.34)	4.7 (1.24)	0.9
	HDR	3.7 (1.33)	3.6 (1.21)	3.5 (1.28)	4.5 (1.22)	1.0
	2D	4.3 (1.08)	3.7 (1.20)	3.9 (1.16)	4.9 (1.19)	1.2
	SIMU	4.4 (0.99)	3.8 (1.17)	3.7 (1.07)	4.7 (1.02)	1.0
E4 tall	REAL	3.2 (1.50)	2.2 (1.01)	4.4 (1.09)	2.1 (0.86)	2.3
	CONTROL	4.0 (1.24)	3.7 (1.47)	3.3 (1.27)	2.8 (1.5)	1.2
	3Db	4.0 (1.41)	3.2 (1.03)	3.7 (0.98)	2.1 (0.88)	1.9
	3Df	3.6 (1.41)	2.7 (1.13)	3.8 (1.55)	2.1 (0.97)	1.7
	QTVR	4.4 (1.06)	3.2 (1.12)	3.7 (1.37)	2.1 (0.88)	2.3
	HDR	4.0 (1.04)	3.5 (1.02)	4.2 (1.02)	2.2 (0.8)	2.0
	2D	3.5 (1.32)	2.9 (1.24)	4.0 (1.22)	2.2 (0.97)	1.8
	SIMU	4.4 (1.22)	3.3 (1.21)	3.6 (1.21)	2.1 (0.94)	2.3

1.2. APPEARANCE OF THE LIGHTING

1.2.1. LIGHT LEVEL

Question	Phase	Mean rating (standard deviation)				Range of score
		Room #1	Room #2	Room #3	Room #4	
D11	REAL	5.0 (0.80)	2.2 (0.78)	3.5 (1.16)	3.5 (1.05)	2.8
	CONTROL	4.7 (1.02)	4.3 (1.2)	3.7 (1.42)	4 (1.48)	1.0
	3Db	5.7 (0.48)	3.1 (1.15)	3.7 (1.45)	3.5 (1.04)	2.6
	3Df	5.3 (0.79)	2.7 (0.92)	3.9 (1.48)	3.3 (1.23)	2.6
	QTVR	5.3 (0.85)	2.4 (0.85)	3.9 (1.38)	3.7 (0.89)	2.9
	HDR	4.9 (0.81)	2.8 (0.98)	3.7 (1.18)	2.9 (0.98)	2.1
	2D	5.0 (1.00)	2.2 (0.82)	3.6 (1.43)	3.5 (1.15)	2.8
	SIMU	5.0 (0.84)	2.5 (0.85)	3.9 (1.49)	3.9 (0.97)	2.5
D12	REAL	3.7 (1.32)	2.1 (0.91)	3.0 (0.90)	3.8 (1.39)	1.7
	CONTROL	4.6 (1.10)	4.1 (1.33)	4.0 (1.14)	4.3 (1.47)	0.6
	3Db	4.5 (1.45)	2.9 (1.01)	3.6 (1.41)	4.6 (1.41)	1.7
	3Df	4.4 (1.37)	2.8 (0.98)	3.4 (1.13)	4.9 (1.07)	2.1
	QTVR	4.4 (1.54)	2.4 (0.81)	3.4 (1.39)	4.4 (1.60)	2.0
	HDR	4.5 (1.10)	3.1 (1.10)	3.5 (1.07)	4.3 (1.43)	1.4
	2D	4.5 (1.38)	2.4 (0.81)	3.4 (1.05)	4.6 (1.03)	2.2
	SIMU	4.8 (0.89)	3.1 (1.17)	4.1 (1.33)	4.2 (1.48)	1.7

Question	Phase	Mean rating (standard deviation) Room #1	Room #2	Room #3	Room #4	Range of score
A11	REAL	2.5(0.59)	1.5(0.51)	2.1(0.75)	2.4(0.73)	1.0
	CONTROL	2.1(1.09)	2.4(1.02)	2.3(0.94)	2.2(0.99)	0.3
	3Db	2.7(0.57)	1.7(0.75)	2.3(0.87)	2.3(0.74)	1.0
	3Df	2.7(0.69)	1.7(0.72)	2.3(0.82)	2.2(0.8)	1.0
	QTVR	2.6(0.75)	1.5(0.51)	2.1(0.7)	2.3(0.8)	1.1
	HDR	2.6(0.68)	1.9(0.74)	2.3(0.7)	1.9(0.79)	0.7
	2D	2.7(0.6)	1.7(0.66)	2.2(0.72)	2.4(0.84)	1.0
	SIMU	2.5(0.68)	1.8(0.66)	2.2(0.78)	2.6(0.72)	0.8

1.2.2. COLORATION

Question	Phase	Mean rating (standard deviation) Room #1	Room #2	Room #3	Room #4	Range of score
D21	REAL	3.0 (1.22)	2.4 (1.07)	2.0 (1.05)	3.4 (1.47)	1.4
	CONTROL	2.9 (1.41)	3.0 (1.22)	2.8 (1.27)	3.1 (1.42)	0.3
	3Db	3.2 (1.17)	2.5 (1.10)	2.2 (1.19)	3.6 (1.45)	1.4
	3Df	2.3 (1.08)	2.2 (0.81)	2.4 (1.19)	3.6 (1.29)	1.4
	QTVR	3.4 (1.22)	2.2 (1.09)	2.1 (1.29)	3.1 (1.53)	1.3
	HDR	2.3 (1.04)	2.5 (0.93)	2.4 (1.09)	3.5 (1.37)	1.3
	2D	2.4 (1.05)	2.2 (0.89)	2.4 (1.30)	3.8 (1.58)	1.6
	SIMU	3.1 (1.00)	2.2 (0.89)	1.8 (1.05)	3.3 (1.43)	1.5
D22	REAL	2.0 (1.07)	1.8 (0.82)	3.0 (1.34)	4.2 (1.31)	2.4
	CONTROL	3.0 (1.49)	2.8 (1.17)	3.5 (1.55)	3.7 (1.38)	0.9
	3Db	2.5 (0.96)	2.2 (1.01)	2.9 (1.38)	4.3 (1.07)	2.1
	3Df	2.0 (0.78)	1.9 (0.83)	3.4 (1.17)	4.1 (1.41)	2.2
	QTVR	2.3 (0.92)	1.7 (0.74)	2.7 (1.43)	4.1 (1.28)	2.4
	HDR	2.6 (1.01)	2.7 (1.13)	3.6 (1.21)	4.0 (1.37)	1.4
	2D	2.0 (0.95)	2.0 (1.03)	3.0 (1.31)	4.4 (1.17)	2.4
	SIMU	2.2 (1.00)	1.8 (0.86)	2.8 (1.21)	4.5 (1.23)	2.7
D23	REAL	2.7 (1.26)	2.2 (0.95)	2.2 (0.90)	3.2 (1.36)	1
	CONTROL	2.9 (1.21)	2.6 (1.09)	3.0 (1.20)	3.3 (1.30)	0.7
	3Db	2.9 (1.41)	2.2 (1.03)	2.2 (1.10)	3.3 (1.46)	1.1
	3Df	2.0 (0.99)	1.8 (0.80)	2.4 (1.10)	2.6 (1.26)	0.8
	QTVR	2.7 (1.41)	2.1 (0.91)	2.4 (1.17)	3.1 (1.41)	1
	HDR	2.0 (0.93)	2.3 (1.08)	2.6 (1.19)	2.5 (1.28)	0.6
	2D	2.0 (1.04)	2.1 (1.00)	2.6 (1.11)	2.9 (1.34)	0.9
	SIMU	2.2 (1.08)	2.2 (0.98)	2.1 (0.97)	3.3 (1.24)	1.2
A21	REAL	2.2 (0.85)	2.0 (0.84)	2.1 (0.80)	2.3 (0.77)	0.3
	CONTROL	2.7 (1.24)	2.6 (0.99)	2.5 (1.04)	2.3 (1.15)	0.4
	3Db	2.4 (0.71)	2.3 (0.76)	2.0 (0.78)	2.6 (0.70)	0.6
	3Df	2.1 (0.79)	2.1 (0.65)	2.3 (0.62)	2.4 (0.66)	0.3
	QTVR	2.5 (0.64)	2.1 (0.74)	1.9 (0.69)	2.2 (0.82)	0.6
	HDR	2.0 (0.64)	2.0 (0.69)	2.1 (0.62)	2.4 (0.83)	0.4
	2D	2.0 (0.70)	2.0 (0.60)	2.2 (0.69)	2.7 (0.76)	0.7
	SIMU	2.2 (0.67)	1.9 (0.65)	1.8 (0.66)	2.3 (0.68)	0.5

1.2.3. CONTRAST

Question	Phase	Mean rating (standard deviation)				Range of score
		Room #1	Room #2	Room #3	Room #4	
D31	REAL	3.8 (1.28)	3.3 (1.09)	3.9 (1.34)	1.7 (1.02)	2.2
	CONTROL	4 (1.31)	4 (1.2)	3.8 (1.23)	3.8 (1.44)	0.2
	3Db	4.4 (0.9)	3.9 (1.15)	3.8 (1.28)	1.9 (1.14)	2.5
	3Df	4.5 (0.97)	3.6 (1.36)	3.7 (1.21)	1.7 (0.98)	2.8
	QTVR	3.9 (1.3)	3.8 (1.4)	4.1 (1.28)	2.1 (1.16)	2.0
	HDR	4.4 (1.03)	3.5 (1.17)	3.8 (1.26)	1.6 (1.18)	2.8
	2D	4.2 (1.09)	3.5 (1.22)	3.7 (1.27)	1.6 (0.81)	2.6
	SIMU	4.1 (1.33)	3.3 (1.17)	4.1 (1.23)	2.3 (1.36)	1.8
A31	REAL	2.8 (0.75)	2.9 (0.84)	2.7 (0.85)	3.6 (0.98)	0.9
	CONTROL	3.1 (1.16)	3.1 (1.01)	3.0 (1.01)	2.8 (1.11)	0.3
	3Db	2.8 (0.71)	3.0 (0.83)	2.6 (0.98)	3.7 (0.83)	1.1
	3Df	2.8 (0.93)	2.7 (0.97)	2.8 (0.59)	3.8 (0.81)	1.1
	QTVR	3.1 (0.83)	3.0 (0.84)	2.8 (0.86)	3.6 (0.90)	0.8
	HDR	2.8 (0.75)	3.1 (0.86)	2.9 (0.80)	4.1 (0.90)	1.3
	2D	3.0 (0.82)	3.0 (0.66)	2.9 (0.74)	3.9 (1.00)	1.0
	SIMU	2.9 (0.64)	3.1 (0.8)	2.5 (0.79)	3.7 (0.82)	1.2

1.2.4. DISTRIBUTION

Question	Phase	Mean rating (standard deviation)				Range of score
		Room #1	Room #2	Room #3	Room #4	
D41	REAL	3.0 (1.22)	3.5 (1.45)	3.4 (1.51)	2.1 (1.33)	1.4
	CONTROL	3.8 (1.41)	3.9 (1.27)	3.3 (1.46)	3.4 (1.45)	0.6
	3Db	4.0 (0.95)	3.6 (1.37)	3.4 (1.43)	2.3 (1.44)	1.7
	3Df	3.6 (1.58)	3.5 (1.43)	3.4 (1.44)	2.5 (1.43)	1.1
	QTVR	3.2 (1.51)	3.8 (1.42)	3.6 (1.48)	2.4 (1.55)	1.4
	HDR	3.7 (1.35)	3.0 (1.26)	3.1 (1.55)	1.9 (1.21)	1.8
	2D	3.7 (1.38)	3.8 (1.51)	3.2 (1.68)	2.0 (1.24)	1.8
	SIMU	3.7 (1.23)	3.4 (1.50)	3.9 (1.46)	2.5 (1.47)	1.4

1.2.5. DIRECTIVITY

Question	Phase	Mean rating (standard deviation)				Range of score
		Room #1	Room #2	Room #3	Room #4	
D51	REAL	3.7 (1.31)	2.6 (1.39)	4.6 (1.14)	1.6 (0.95)	3.0
	CONTROL	3.6 (1.48)	3.5 (1.45)	3.4 (1.40)	2.7 (1.49)	0.9
	3Db	3.9 (1.33)	2.7 (0.98)	4.2 (1.24)	1.3 (0.52)	2.9
	3Df	3.8 (1.57)	2.2 (0.89)	4.3 (1.30)	1.5 (0.88)	2.8
	QTVR	4.0 (1.50)	2.6 (1.18)	4.8 (0.99)	1.4 (0.67)	3.4
	HDR	3.9 (1.16)	2.4 (0.99)	4.6 (1.16)	1.5 (0.93)	3.1
	2D	3.6 (1.33)	2.5 (1.05)	4.5 (1.24)	1.3 (0.66)	3.2
	SIMU	3.3 (1.30)	2.2 (0.74)	3.5 (1.47)	1.2 (0.48)	2.3

Question	Phase	Mean rating (standard deviation)				Range of score
		Room #1	Room #2	Room #3	Room #4	
D52	**REAL**	2.4 (1.11)	2.8 (1.15)	2.0 (0.95)	1.8 (0.89)	1.0
	CONTROL	2.2 (1.19)	2.7 (1.44)	2.6 (1.15)	2.6 (1.32)	0.5
	3Db	2.3 (1.24)	2.5 (1.11)	2.3 (1.28)	1.5 (0.82)	1.0
	3Df	1.7 (1.17)	2.4 (1.13)	2.4 (1.08)	1.7 (0.89)	0.7
	QTVR	2.4 (1.55)	3.2 (1.22)	2.2 (1.11)	1.9 (1.26)	1.3
	HDR	2.9 (1.43)	3.0 (1.17)	2.6 (1.21)	1.8 (0.89)	1.2
	2D	2.4 (1.36)	3.1 (1.11)	2.2 (1.26)	2.0 (1.31)	1.1
	SIMU	2.6 (1.43)	3.2 (1.27)	2.5 (1.45)	2.4 (1.20)	0.8

1.2.6. GLARE

Question	Phase	Mean rating (standard deviation)				Range of score
		Room #1	Room #2	Room #3	Room #4	
D61	**REAL**	2.5 (1.20)	2.5 (0.86)	2.3 (0.97)	2.8 (1.02)	0.5
	CONTROL	3.0 (1.19)	3.1 (1.11)	3.1 (1.18)	3.4 (1.36)	0.4
	3Db	3.1 (1.24)	2.5 (0.88)	2.4 (1.00)	2.9 (0.97)	0.7
	3Df	2.8 (1.41)	2.1 (0.87)	2.0 (0.80)	2.4 (0.98)	0.8
	QTVR	2.6 (1.27)	2.6 (0.68)	2.6 (0.84)	2.4 (0.92)	0.2
	HDR	2.7 (1.24)	2.3 (0.82)	2.5 (1.19)	2.8 (1.14)	0.5
	2D	2.8 (1.10)	2.1 (0.93)	2.0 (0.86)	2.8 (1.24)	0.8
	SIMU	2.6 (1.14)	2.2 (0.87)	2.5 (1.25)	2.7 (1.17)	0.5
D62	**REAL**	2.1 (1.04)	1.9 (1.17)	1.7 (1.29)	2.9 (1.32)	1.2
	CONTROL	2.7 (1.36)	2.8 (1.27)	2.4 (1.27)	3.6 (1.52)	1.2
	3Db	2.9 (1.33)	1.7 (0.79)	2.3 (1.30)	2.7 (1.41)	1.2
	3Df	2.9 (1.47)	2.0 (0.99)	1.9 (1.31)	3.1 (1.54)	1.2
	QTVR	2.9 (1.32)	1.9 (1.17)	2.4 (1.50)	2.9 (1.39)	1.0
	HDR	2.5 (1.26)	2.3 (1.04)	2.2 (1.41)	3.3 (1.43)	1.1
	2D	3.3 (1.62)	2.4 (1.46)	2.4 (1.53)	3.1 (1.56)	0.9
	SIMU	2.6 (1.25)	2.0 (0.99)	1.8 (0.96)	3.1 (1.54)	1.3
D63	**REAL**	2.1 (1.08)	1.7 (1.09)	1.9 (1.11)	2.2 (1.08)	0.5
	CONTROL	2.8 (1.38)	2.9 (1.32)	2.3 (0.99)	2.9 (1.42)	0.6
	3Db	2.5 (1.34)	1.9 (1.18)	2.9 (1.33)	2.3 (1.20)	1.0
	3Df	2.6 (1.43)	1.8 (0.90)	2.3 (1.30)	2.1 (1.24)	0.8
	QTVR	2.1 (1.22)	1.7 (0.89)	2.9 (1.54)	2.2 (1.37)	1.2
	HDR	2.6 (1.44)	2.2 (1.32)	3.6 (1.59)	2.2 (1.38)	1.4
	2D	2.8 (1.40)	2.1 (1.19)	3.1 (1.72)	2.7 (1.57)	1.0
	SIMU	2.5 (1.23)	1.8 (1.04)	2.7 (1.40)	2.0 (1.28)	0.9

2 | PAIRED COMPARISON OF WALLS

2.1. BRIGHTNESS

Question	Phase	Mean rating (standard deviation) Room #1	Room #2	Room #3	Room #4	Range of score
C1	REAL	4.0 (0.93)	3.7 (0.83)	1.4 (0.55)	2.0 (0.67)	2.6
	CONTROL	3.7 (1.20)	3.6 (1.12)	3.0 (1.50)	2.0 (0.98)	1.7
	3Db	4.2 (0.77)	4.1 (0.61)	1.6 (0.54)	1.7 (0.86)	2.6
	3Df	4.1 (0.76)	3.7 (0.86)	1.7 (0.62)	1.7 (0.76)	2.4
	QTVR	4.4 (0.78)	4.0 (0.90)	1.5 (0.68)	1.6 (0.68)	2.9
	HDR	4.2 (0.72)	3.6 (0.72)	1.4 (0.55)	2.1 (0.63)	2.8
	2D	4.3 (0.86)	3.8 (0.81)	1.4 (0.55)	1.9 (0.63)	2.9
	SIMU	4.4 (0.94)	3.8 (0.80)	1.7 (0.53)	1.5 (0.60)	2.9

2.2. UNIFORMITY

Question	Phase	Mean rating (standard deviation) Room #1	Room #2	Room #3	Room #4	Range of score
C2	REAL	2.2 (1.13)	2.3 (0.92)	4.0 (1.25)	3.9 (1.12)	1.8
	CONTROL	3.1 (0.98)	3.1 (1.09)	3.1 (1.33)	2.5 (1.06)	0.6
	3Db	2.8 (1.30)	2.7 (1.20)	4.3 (0.64)	3.4 (1.05)	1.6
	3Df	2.0 (1.14)	2.2 (0.83)	4.4 (0.63)	3.9 (0.97)	2.4
	QTVR	2.6 (1.29)	2.7 (1.17)	4.0 (1.04)	3.5 (1.19)	1.4
	HDR	2.0 (1.14)	2.2 (0.81)	4.7 (0.71)	3.8 (1.04)	2.7
	2D	2.0 (1.14)	2.5 (0.82)	4.5 (0.60)	4.0 (0.90)	2.5
	SIMU	2.5 (1.30)	2.3 (0.92)	3.1 (1.20)	3.4 (1.02)	1.1

2.3. ROUGHNESS

Question	Phase	Mean rating (standard deviation) Room #1	Room #2	Room #3	Room #4	Range of score
C3	REAL	3.4 (0.87)	3.4 (0.88)	2.0 (0.97)	3.8 (1.08)	1.8
	CONTROL	3.3 (1.15)	3.0 (0.91)	2.8 (0.89)	3.1 (1.33)	0.5
	3Db	3.2 (0.78)	3.1 (0.80)	2.3 (0.92)	4.2 (0.91)	1.9
	3Df	3.4 (0.86)	3.3 (0.78)	2.1 (1.07)	4.0 (1.10)	1.9
	QTVR	3.2 (0.78)	2.9 (0.73)	2.3 (0.94)	3.7 (1.17)	1.4
	HDR	3.0 (0.55)	2.9 (0.47)	1.9 (1.09)	3.9 (1.15)	2
	2D	2.9 (0.94)	2.9 (0.95)	2.1 (1.04)	3.9 (1.21)	1.8
	SIMU	3.2 (0.81)	3.3(0.64)	2.8 (0.81)	2.9 (1.04)	0.5

3 | CLASSIFICATION OF PUNCTUAL ZONES IN TERMS OF BRIGHTNESS

Question	Phase	Mean rating (standard deviation)		
		a	b	c
Room #1	REAL	0.4 (0.15)	0.3 (0.18)	0.7 (0.16)
	CONTROL	0.4 (0.23)	0.4 (0.28)	0.6 (0.27)
	3Db	0.4 (0.14)	0.3 (0.20)	0.7 (0.17)
	3Df	0.4 (0.15)	0.3 (0.18)	0.7 (0.17)
	QTVR	0.4 (0.19)	0.3 (0.15)	0.8 (0.14)
	HDR	0.3 (0.14)	0.2 (0.16)	0.7 (0.21)
	2D	0.4 (0.17)	0.2 (0.14)	0.8 (0.14)
	SIMU	0.3 (0.11)	0.3 (0.16)	0.8 (0.09)
Room #2	REAL	0.4 (0.20)	0.2 (0.14)	0.5 (0.21)
	CONTROL	0.5 (0.22)	0.4 (0.26)	0.6 (0.23)
	3Db	0.4 (0.15)	0.2 (0.14)	0.6 (0.17)
	3Df	0.4 (0.12)	0.2 (0.15)	0.6 (0.19)
	QTVR	0.3 (0.17)	0.2 (0.09)	0.5 (0.18)
	HDR	0.3 (0.17)	0.2 (0.09)	0.5 (0.20)
	2D	0.3 (0.17)	0.2 (0.16)	0.5 (0.18)
	SIMU	0.3 (0.13)	0.2 (0.11)	0.5 (0.19)
Room #3	REAL	0.3 (0.18)	0.8 (0.15)	0.4 (0.13)
	CONTROL	0.5 (0.27)	0.4 (0.27)	0.5 (0.25)
	3Db	0.2 (0.16)	0.8 (0.11)	0.5 (0.13)
	3Df	0.2 (0.15)	0.8 (0.11)	0.5 (0.09)
	QTVR	0.2 (0.15)	0.8 (0.14)	0.5 (0.15)
	HDR	0.2 (0.14)	0.8 (0.21)	0.4 (0.20)
	2D	0.2 (0.11)	0.9 (0.16)	0.4 (0.15)
	SIMU	0.3 (0.17)	0.7 (0.23)	0.6 (0.17)
Room #4	REAL	0.7 (0.17)	0.1 (0.17)	0.8 (0.16)
	CONTROL	0.5 (0.20)	0.3 (0.21)	0.7 (0.21)
	3Db	0.7 (0.14)	0.1 (0.11)	0.8 (0.20)
	3Df	0.6 (0.14)	0.1 (0.08)	0.8 (0.13)
	QTVR	0.7 (0.13)	0.1 (0.06)	0.8 (0.12)
	HDR	0.7 (0.15)	0.1 (0.07)	0.8 (0.16)
	2D	0.6 (0.16)	0.1 (0.16)	0.8 (0.12)
	SIMU	0.6 (0.16)	0.1 (0.16)	0.8 (0.17)

APPENDIX IV
BOXPLOT – REAL-WORLD EXPERIMENT

This appendix presents the boxplot distribution of scores to the rating scales for the real world experiment. Figure A.IV.1 illustrates the boxplot legend.

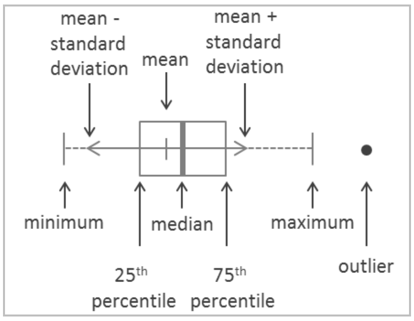
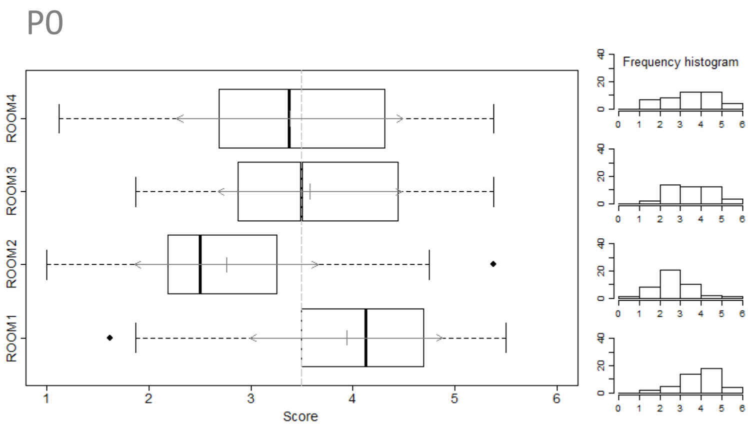


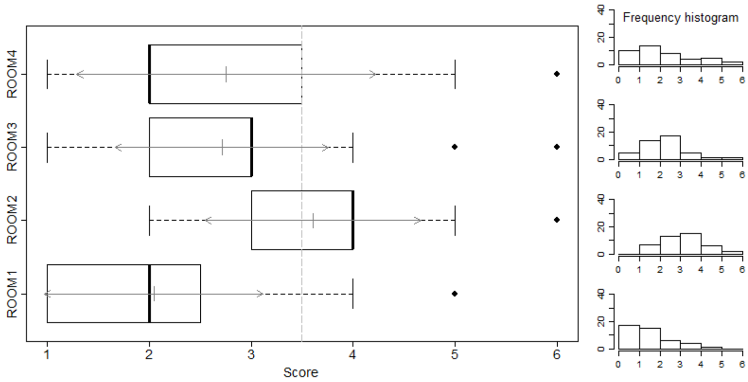
Figure A.IV.1
Boxplot key

3.1. APPEARANCE OF SPACE

3.1.1. PLEASANTNESS

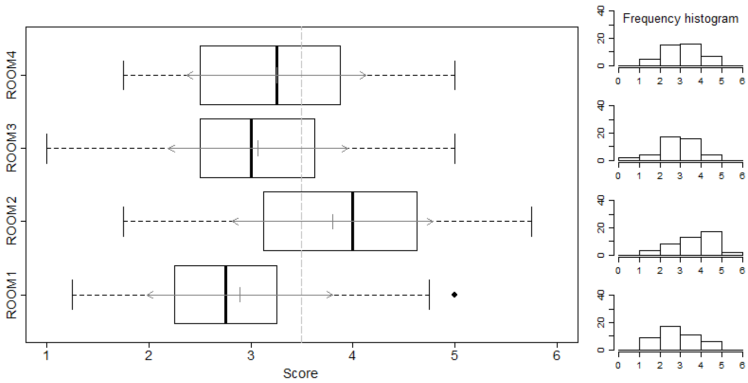


P1

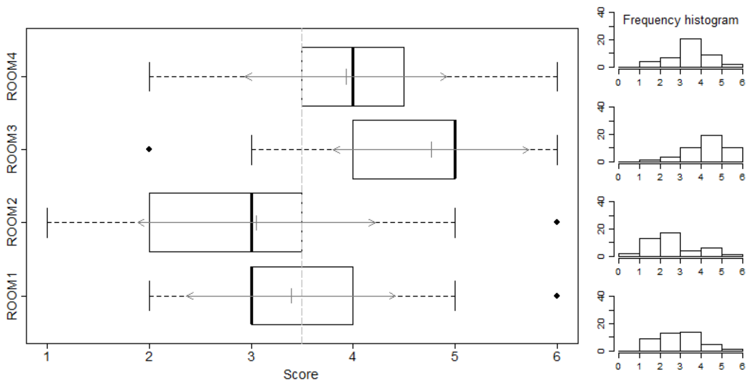


3.1.2. ENCLOSEDNESS

E0



E1



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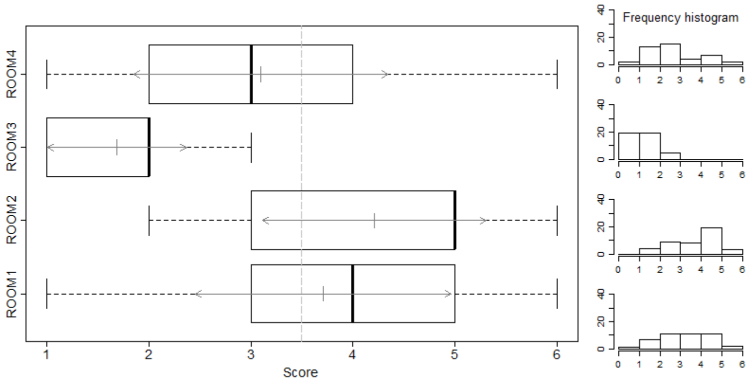
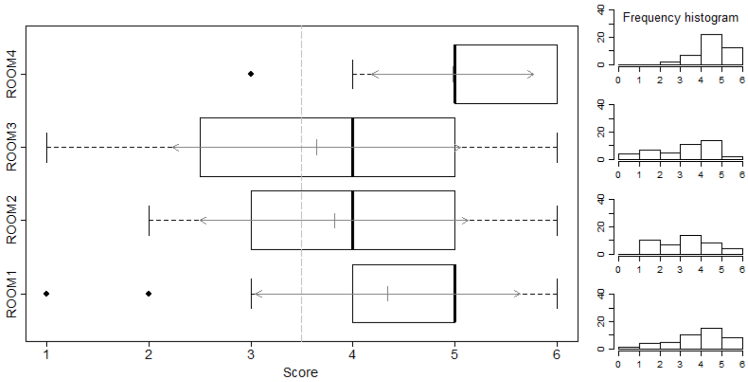
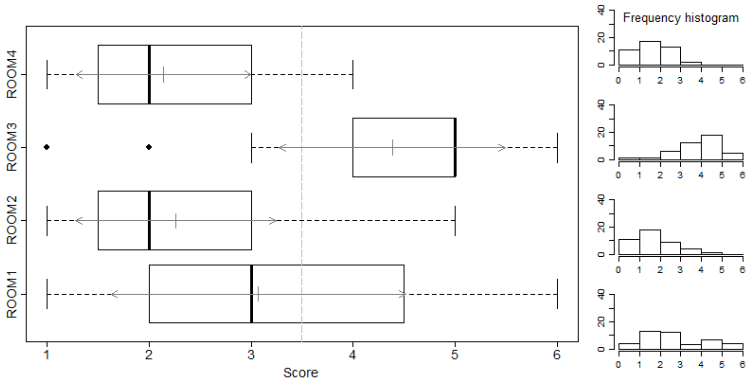

ROOM4
ROOM3
ROOM2
ROOM1
1 2 3 4 5 6
Score
Frequency histogram

E3


ROOM4
ROOM3
ROOM2
ROOM1
1 2 3 4 5 6
Score
Frequency histogram

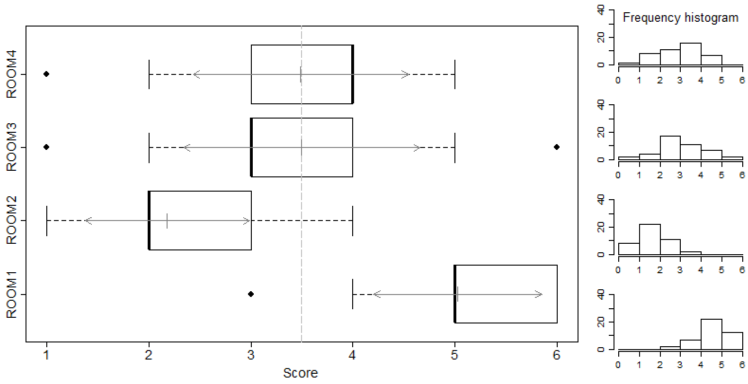
E4


ROOM4
ROOM3
ROOM2
ROOM1
1 2 3 4 5 6
Score
Frequency histogram

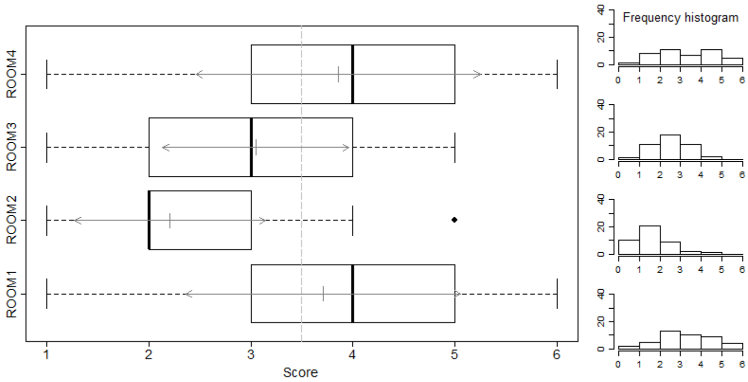
3.2. Appearance of Lighting

3.2.1. Light level

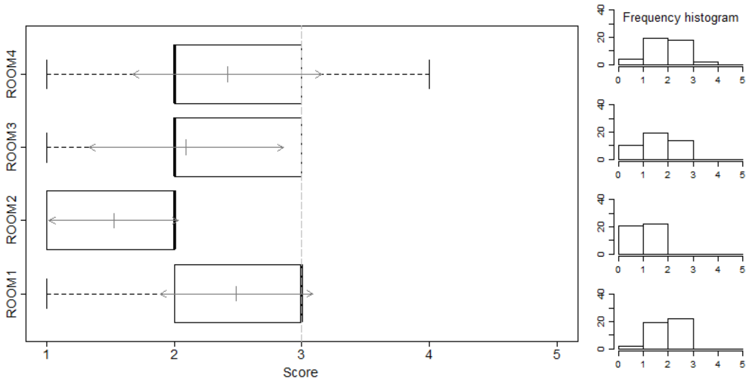
D11



D12

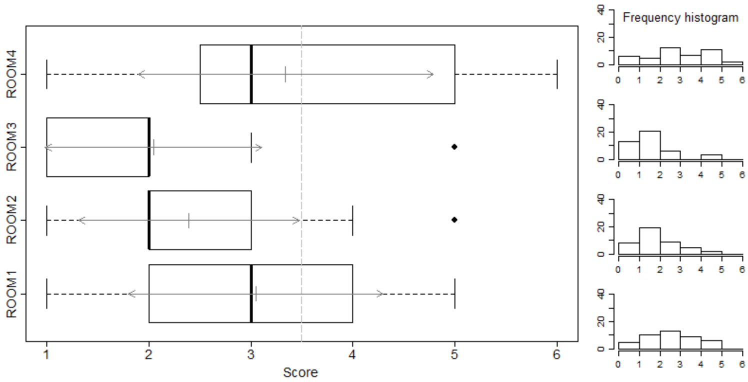


A11

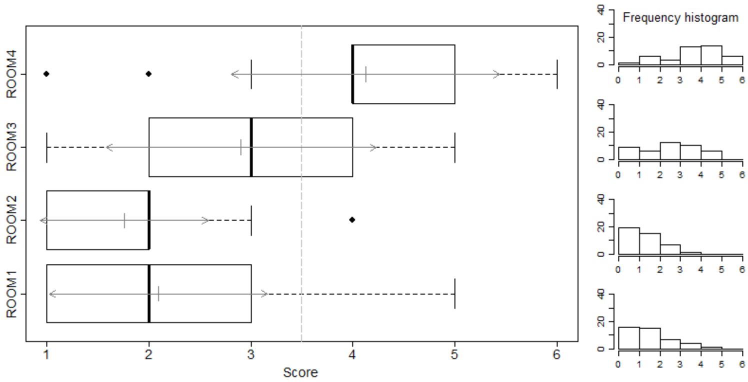


3.2.2. COLORATION

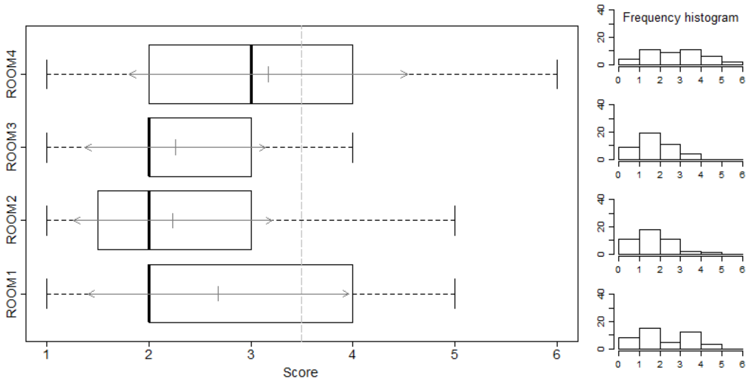
D21



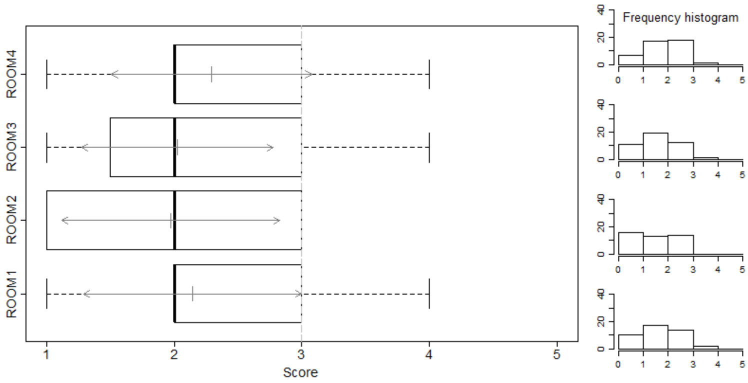
D22



D23

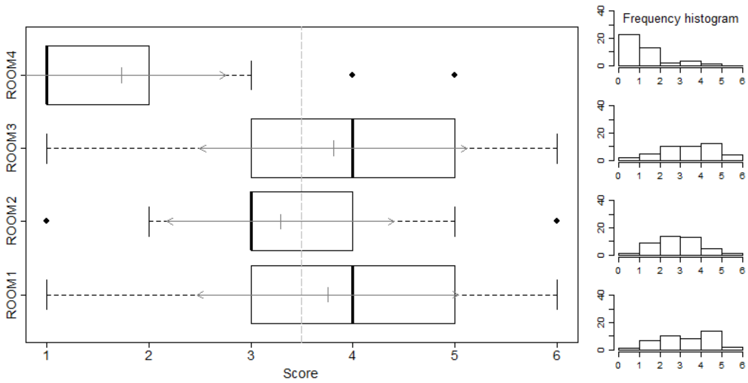


A21

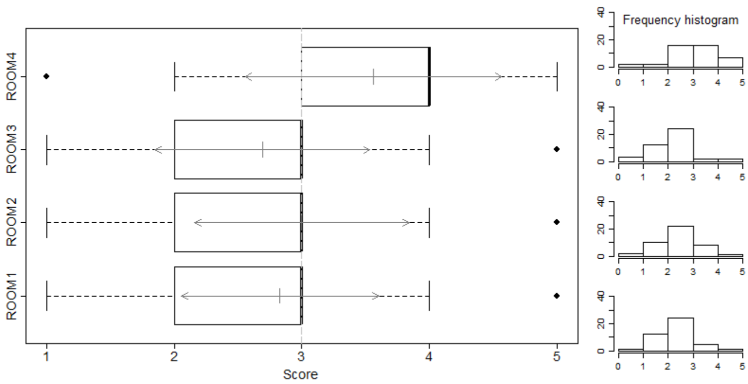


3.2.3. CONTRAST

D31

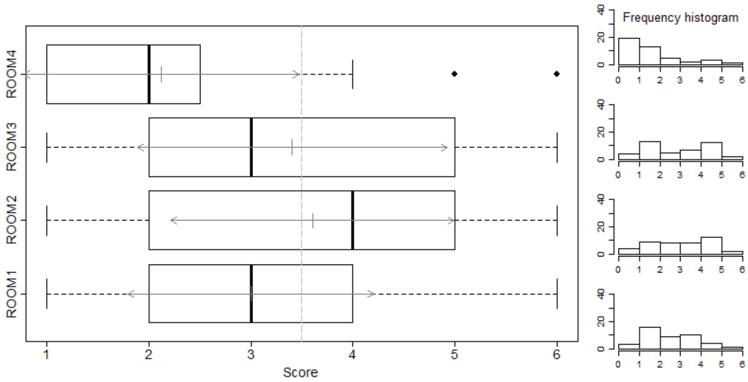


A31



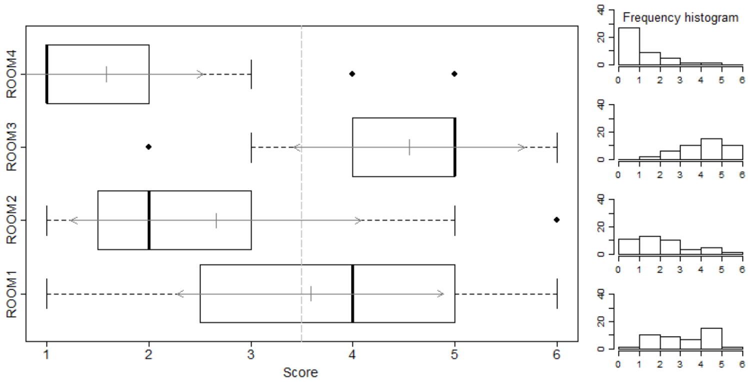
3.2.4. DISTRIBUTION

D41

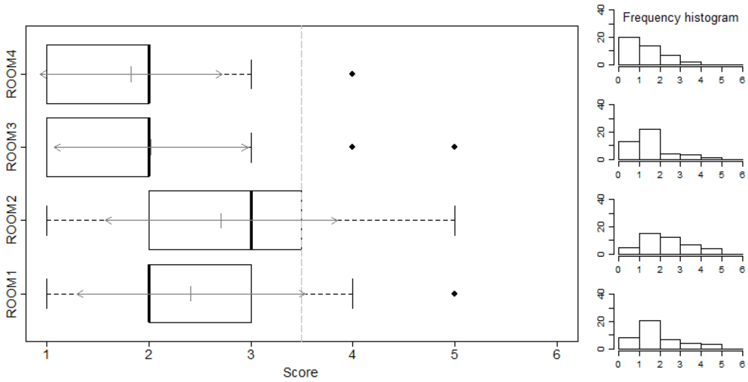


3.2.5. DIRECTIVITY

D51

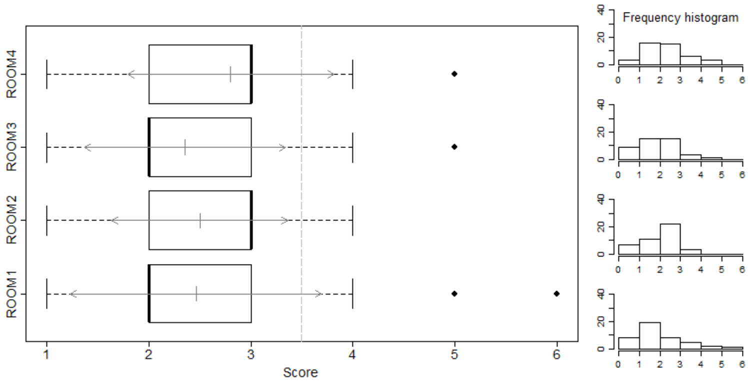


D52

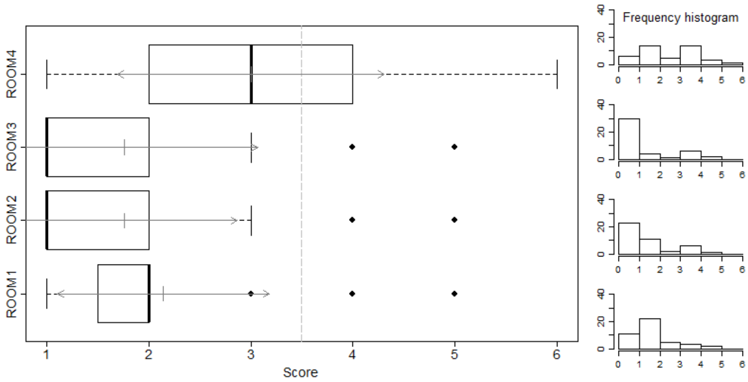


3.2.6. GLARE

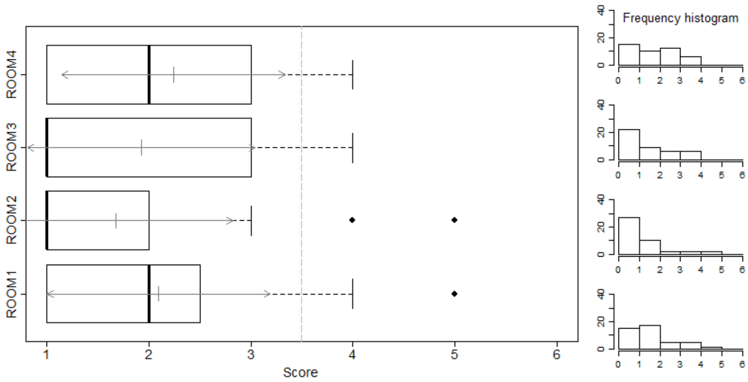
D61



D62



D63



I would like to thank each of the 379 people who took part in the surveys I realized during this PhD work. I would also like to thank the many people who supported me: my supervisors André and Magali for giving me the opportunity to pursue a research in daylighting, my accompanying committee and Raphaël Labayrade for the guidance, my numerous colleagues at UCL and ENTPE for the helping hands, my friends and family for their patience. I also thank Alain Guillet (UCL/SMCS) for statistical advices, Benoit Michel for making me discover 3D stereoscopic imaging, Carole Lemaire (SST/LOCI) for her help in participants' recruitment, and the Musée de Louvain-la-Neuve for having opened its doors for the in situ experiment. I thank for lending equipment: Light and Building Laboratory at BBRI, the Communications and Remote Sensing Laboratory (UCL/TELE) and Prof. Christian Eugène. Last but not least, thanks to all those I forgot to mention and to Velux Belgium who financed my first research at UCL.