# Sensitive apertures

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## Abstract

Light, vision and perception are fundamental aspects of our conception of space and our experience of architecture. The perception of light is affected by the composition and surface of materials, by the geometry of space and by the physiology of the sense of sight. This is a study of 'light itself as a material,' carried out as a Material Technologies Master's Thesis. The research is focused on light at dawn and dusk, when twice a day photoreceptive cells in our eyes, cones and rods, reach a crossover point of equal efficiency. This perceptual phenomenon within the 'mesopic vision range' marks a unique moment of visual awareness and the threshold for a search for the 'right' kind of light. It begs the question: Right kind of light for 'what'? What if through the free and ordered play of light we are able to fine tune the coordinates that affect our inner sense, seeking points of passage in a hypothetical matter-space and time-spirit continuum? What follows is a series of logical propositions, perceptual observations, physical experiments and 'hardware-software' simulations that examine the hypotheses and generate possible heuristic evidence.
*Keywords: light, material, geometry, spatial and temporal perception, reflection, refraction.*

## 1 Introduction

Rather than dimming daylight after using large expanses of translucent materials such as plastic or glass, this study is focused on using opaque materials pierced with small, solar oriented, refractive apertures to admit and redirect a limited amount of light onto the interior surfaces of space. When the direction of the sun and the geometry of the light containers align, light will fill the spaces uniformly. At all other times, the enclosure will admit light in a dynamic way that will reveal the changing light and the passage of time.

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Structurally, this is proposed as a cellular network of ceramic light containers shaped to receive light from the apertures. Together, these cells will form a field of roof or wall enclosures within an otherwise dark space. As vision in the mesopic range primarily affects our ability to distinguish detailed shapes and color, the scale of the light containers and the presence of refracted color will be fine-tuned to highlight this change in our perceptual capacity.

## 2 Solar origin

It appears that most life forms have evolved in response to the radiative power emitted by the sun. Therefore, it is not surprising that the evolution of our sense of sight is genetically linked to the sun's spectral properties. An overlay of the spectral distribution of power from the sun and our range of vision demonstrates that the evolutionary target of human visual sensitivity to light matches the range of most abundant wavelengths of the sun.

Radiative absorption by molecules in our atmosphere significantly impacts energy received at sea level. Note the drastic valleys of irradiance caused by absorption, especially in the longer wavelengths. Radiation within the visible range, however, remains relatively smooth. Within the range of visible wavelengths (380nm - 780nm) our vision has varying sensitivity. Generally speaking, sensation peaks in the middle of this range (around 555nm) and is very week toward the ultraviolet and infrared boundaries—Figure 1.

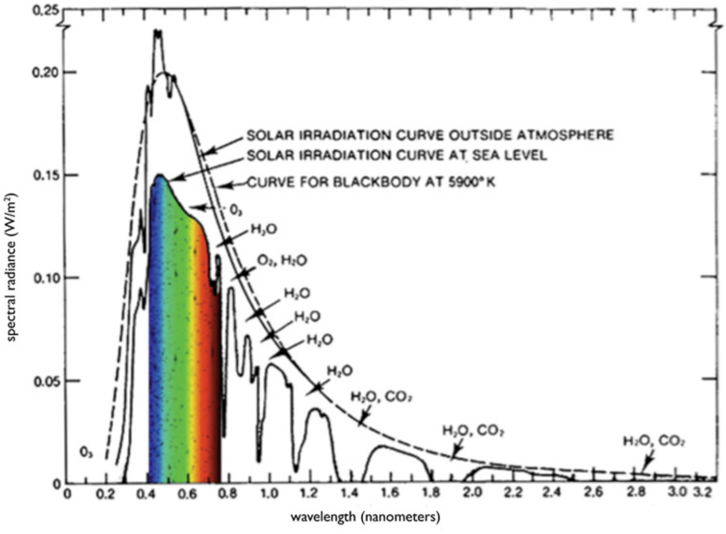


Figure 1: Solar irradiation [1].

### 2.1 Spectral sensitivity

A more subtle fact is that this spectral sensitivity curve changes relative to the amount of light present in our visual field. Our vision goes through three major wavelength sensitivity changes. These are called the photopic, scotopic, and mesopic visual ranges—Figure 2.

Most of our daily visual experience occurs within the photopic range (> 3 cd/m2). This is our light-adapted vision. At these levels, cone cells are the most active. Strong signals from the three types of cone receptors allow us to maximize our sensing ability for color and detail. The great majority of cone cells are packed in the fovea of the eye—Figure 3—, which corresponds to the center of our vision.

Vision in the scotopic (< .001 cd/m2) range requires dark adaptation. At these light levels, rod cells are the dominant receptors and cone response is nearly non-existent. Because there is only one type of rod cell, scotopic vision is color-blind. What rods lack in color detection, however, is made up for by an increased ability to sense peripheral vision, detect movement, and detect subtle changes in shape and contrast. An example of this phenomenon occurs during stargazing when an object in the sky is invisible to the center of vision but is revealed when we avert our eyes slightly to allow more rod cells to pick up a response.

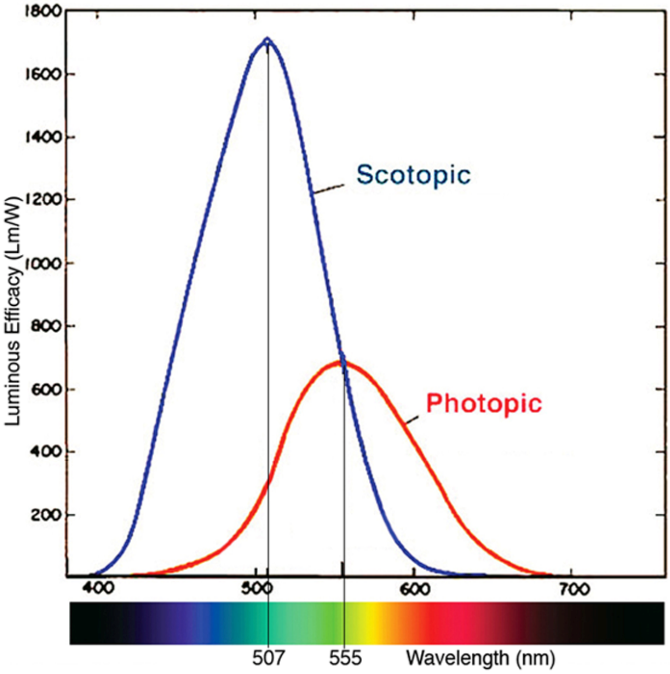


Figure 2: Luminous efficacy functions [2].

Finally, mesopic vision range (.001cd/m2 - 3 cd/m2) occurs in between light and dark. Within this range, rod and cone response is shared. As of yet, there is no standard luminous efficacy function for mesopic vision. It appears that vision in this range undergoes rapid changes that are the result of a complex set of factors including illumination level, spectral content of the image, and adaptation time. Owing to a lack of scientific knowledge relating to the mesopic range, it might be best described experientially as a combination of photopic and scotopic vision. Color and detail are simultaneously detectable with peripheral vision, motion detection, and light sensitivity.

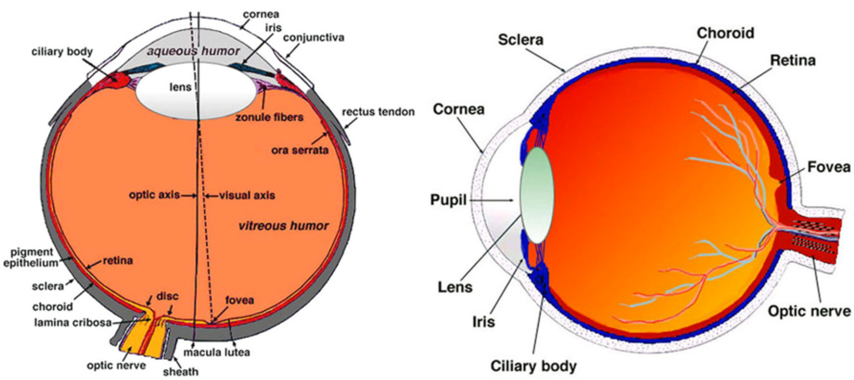


Figure 3: Sagittal horizontal and vertical sections of the adult human eye [2].

## 2.2 Pupil aperture

Adaptive pupil size helps the eye to accommodate the broad range of light levels spanning photopic and scotopic vision. Beyond the basic principle of letting more or less light into the eye, the size of the pupil—Figure 3—also determines the region of the retina that receives light and helps to explain the perceptual changes of dark versus bright environments. In bright light, the pupil contracts and limits incoming light to distribution in the center of vision containing most of the cone cells. In diminished light, muscles in the iris relax, resulting in an enlarged pupil that admits light to a much larger portion of the retina, thus allowing rod cells increased opportunity for response.

## 2.3 Light and awareness

The study of light, particularly since the invention of the electric variety, has had a strong connection with productive activity—for good cause, since we need light to do most things. We need light to bathe, cook, read, work, play, etc. A lot of effort has been put into finding the most appropriate light levels to facilitate productive efficiency. Organizations like the IESNA (Illuminating Engineering Society of North America) have published recommended light values for tasks ranging from writing, to assembly-line production, to casual reading in bed.

This study is not focused on the production-based tradition of light investigation. After initial unbiased examination of spaces with very low light levels, it was evident that this work was not aimed at probing the use of light for conventional tasks like reading, working or recreation. Instead, what emerged was a desire to study the kind of light that is most conducive to the act of thinking—or meditation.

While it is possible to think in the dark, or with closed eyes, it is plausible to make an argument that our mind is stimulated and merged in a continuum with our senses, and that an environment that is fine-tuned to sharpening sensorial perception may also be one that opens our mind to more creative thinking.

## 3 Light measurement and perception

A large part of this study investigates the relationship between ambient light level and perceptual awareness. To test this relationship, a method was needed for recording objectively light along a smooth gradient from bright to dark. The transitioning sky during twilight emerged as the ideal environment for doing this. The sky offers a uniform field of light that eliminates potentially distracting detail.

Light level recording is a complicated task. Until recently, without significant financial investment on sensitive luminance meters, it has been difficult to find an affordable and accurate device that is adjustable to the unique sensitivities of human vision. Recently, however, it has become possible and affordable to measure light data with greater accuracy using an average digital camera. In fact, any picture taken with a calibrated digital camera can be interpreted by a software program to measure accurate luminance values (visual power per unit area, measured in candelas/m2) for each pixel of the image. The advantage of this method is that the record of light is closely matched with the field of interest to the observer.

In this study, the field was an observed area of the sky. Using the imaging software, a reliable average luminance value was calculated over a selected area of the image. This value was then associated with the perceptual observations taken at the same time during twilight.

### 3.1 Recording software

Photosphere (software written by Greg Ward, Anywhere Software) was used to measure luminance values [3]. The first step of the process involved calibrating the user camera to the software. A series of 9-bracketed photographs were taken of an interior scene with a large range of light values. These photographs were then merged in Photosphere to create a single high dynamic range (HDR) image that was stored as the calibration data.

Figure 4 shows a typical example of an HDR image displayed in Photosphere as a false color luminance map. This particular image is from the overhead sky at 7:35 on May 9th (west is up). Even though the brightness of the sky was

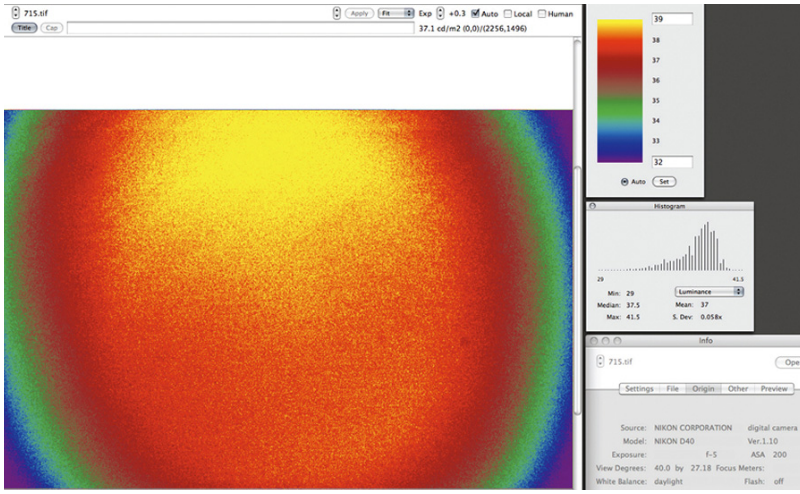


Figure 4: Photosphere false color luminance of zenithal sky at twilight.

relatively consistent to the naked eye across the image, the luminance map clearly shows more brightness, as it should, toward the western-setting sun. Because the range of luminance values is so narrow (32-39 cd/m2), the luminance value recorded for this time is an average of the entire image.

Proceeding this way, average luminance values corresponding to observed areas of sky were recorded for each image. Another way to visualize luminance values across an entire twilight session can be done by setting a custom range for the false color map based on the brightest values from the early photo and darkest values from the latest photo.

### 3.2 Perceptual observations

The twilight observation sessions provided a good deal of insight into how light levels affect perception. After the first few evenings a series of indicators emerged which became useful to record and track within and between evenings.

"To what is it due, this sense of infinite calm emanating from these [twilight] light phenomena? Compare them with the rainbow, arousing feelings of cheerfulness and joy [4]."

#### 3.2.1 Floaters

One of the first, readily perceived phenomena was the visual presence of 'floaters'. These are microscopic fibers within the vitreous humor (the clear gel that fills the space between the lens and the retina) that have clumped together. These clumps of debris float around within the vitreous cavity, and they can cast tiny shadows on the retina. The degree of distraction these floaters cause varies widely among subjects but what was interesting to note was that they disappeared when there was no longer sufficient light to cast their shadows—and how at that moment seeing became more pleasurable.

#### 3.2.2 Stars

A subtler phenomenon was the occurrence of a field of 'shooting stars'. These random-appearing, uniformly distributed flashes were most visible during the early part of twilight. However, slowly as the sky darkened, they became less and less visible until a certain time when they would vanish completely. Again, this phenomenon is highly variable from person to person. If extreme, they can be the sign of some type of eye disease—but normally the explanation is that the vitreous is tugging on the retina, causing the flashes and shooting stars. The fact that this phenomena disappeared beyond a particular light level suggests the over abundance of light contributes to the friction between the vitreous and retina. Because it was also observed that the most comfortable light level was consistently experienced within minutes of the absence of visual stars, there is reason to think that visual comfort is directly related to the light level that causes the least physiological tension within the eye.

#### 3.2.3 Periphery

Peripheral vision is another factor relevant to the degree of perceptual awareness and comfort level. As the sky gradually darkened, it was possible to experience the increasing awareness of visual periphery. In bright light, most of our visual attention is given to the center of vision where cones provide the dominant response. This limits our visual awareness because we do not get much feedback about a broader spatial environment. Of course, the opposite is true in darkness when peripheral vision is good but we struggle to see color and detail. During the twilight studies, it was observed that there is a middle ground where both rod and cone vision is enabled without sacrificing too much of one or the other. This condition was found to heighten the state of perceptual awareness.

#### 3.2.4 Sound

Though most attention during the observation sessions was given to visual perception, the emergence of a heightened acoustic sense was also noticed. Offering a reason for this goes beyond the intent of this study, but the experience was straightforward; it was sensed that during twilight a general white noise gradually receded, creating an acoustic calm in which the range of hearing increased, allowing wildlife, or human chatter, or distant cars to stand out and be heard much more clearly.

### 3.3 Analysis

Once the perceptual values could be matched with numerical luminance data, it was possible to graph the outcome and look for trends. Across all observations, the ideal comfort luminance level ranged between 3.92 and 8.00 cd/m$^2$. This consistency within a much larger range of observed light levels was not expected. It suggests that an ideal luminance level for perceptual awareness may exist and opened a window for future investigations.

# 4 Light containers

To set up a space conducive to perceptual awareness and thinking, the final stage of this study was to create an architectural enclosure system that could function as an analogue of the desired luminance level of the twilight sky. The first major constraint of this system was that the light levels needed to be drastically reduced from outside to inside. To accomplish this using predominantly opaque material, a field of apertures was proposed to evenly distribute small quantities of light.

Secondly, the light that was allowed to enter through the enclosure needed to be as uniform as possible. This requirement sparked the notion to use refraction at the aperture and spatial depth within the enclosure in order to spread the light on the inside surface of the enclosure. Using packing geometry from previous cube corner experiments to create a uniform field, it made sense to place the aperture at the apex of a tetrahedral geometry—the light 'container'.

## 4.1 Refraction studies

A series of diagrams and graphs looked into the range of possible refraction angles using materials such as acrylic and glass. These clearly indicated that the more refractive materials are able to more effectively bend the light. These diagrams were then used to create the specific geometry of a typical light container needed to contain the refracted light.

Lead crystal glass, with an index of refraction (n) of 1.60 was chosen for the final form. To ensure that the surface of the light container captured the refracted light, the form was made slightly steeper—Figure 5.

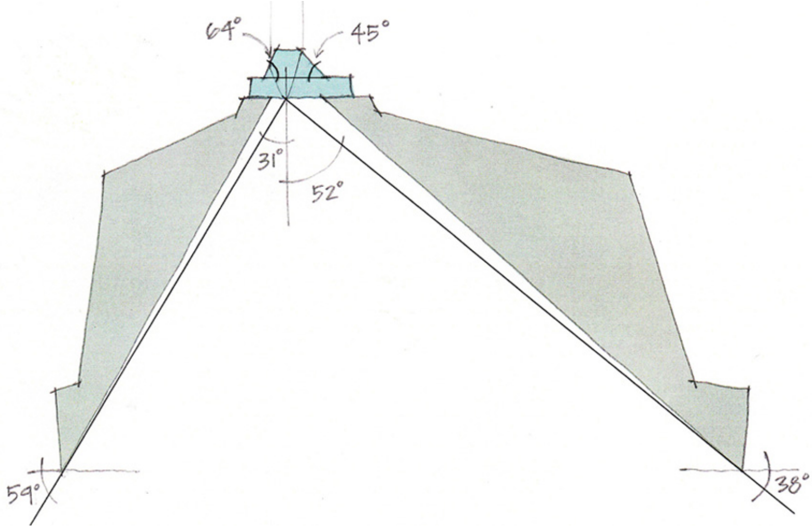


Figure 5: Typical container refraction analysis.

### 4.2 Aperture fabrication: glass

A strict requirement of the apertures was that they had to be optically clear—the surface of the glass had to be smooth and specular. Any light scattering at the surface would have hindered the refractive performance of the glass.

After talking with glass fabricators, it became clear that graphite might be a perfect mold material for casting glass. Even though graphite is an ideal material for casting glass into, it is prone to oxidation when exposed at temperatures above 480°C. This required glass to be melted in a crucible first, then poured into the graphite mold and subsequently placed in a separate oven for annealing—fortunately, graphite's oxidation threshold was also the annealing temperature of the lead crystal glass used for the casting.

After annealing, the glass apertures required grinding to remove the upper half. This was followed by wheel polishing using water-lubricated abrasive pads decreasing in grit size from 240 to 400 to 800 to 1200. A final polish was made using a 9-micrometer polycrystalline diamond lubricant.

### 4.3 Light container fabrication

Slip-cast ceramic was chosen as the material for the light containers for its white firing color, structural integrity, and ability to provide insulation as a hollow form. Mold making became a critical process for producing the slip cast containers. Corian countertop material was tested for its machining ability and was eventually chosen as the ideal material for casting molds because it did not require any sealing treatment beyond spray mold release.

The surface finish of the light containers greatly affected the quality of light. To reinforce the intention of an evenly scattered interior light, a matte white glaze was chosen to minimize any specular behavior. After an initial bisque fire, the light containers were glazed using a spray applicator.

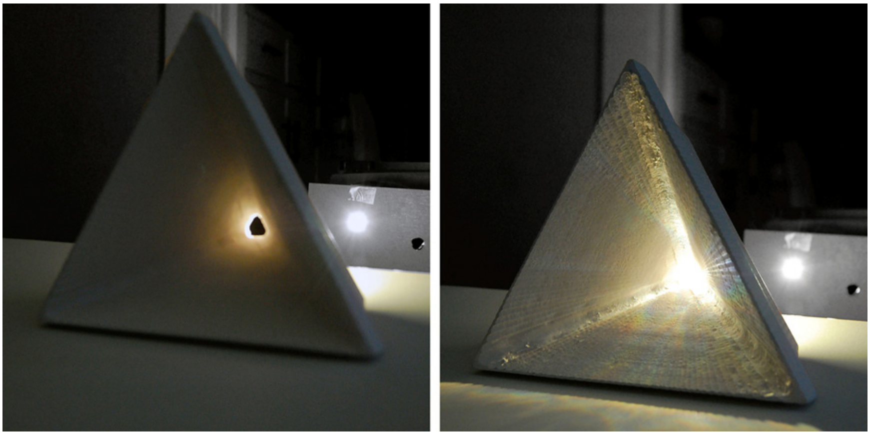

Figure 6: Light test, without aperture (left) and with aperture (right).

### 4.4 Assembly

Individual light containers were bonded into larger cell assemblies using fiberglass and epoxy resin. The space between cells on the outside of the enclosure provided opportunity for reinforcement, weather sealant, and additional insulation. Prior to the assembly of a large number of cells, a brief light study looked at the refractive performance of one container. The performative difference between aperture and no aperture provided some assurance that the cells would function as designed—Figure 6.

## 5 Experiencing light

Refractive colors were very visible in most of the cells and showed how the light was redirected. Irregularities in the geometry of the light path caused light to spill past the boundary of individual cells, as seen projected onto the walls of the drum in Figure 7. Finally, an HDR image of the enclosure was made to demonstrate the proposed method for analyzing the resultant luminance values. Despite the arbitrary luminous intensity of the projected light source, Figure 8 shows significant presence of light levels falling near the target luminance values at the upper boundary of the mesopic vision range.

The initial hypothesis of this research posed a provocative phenomenal question that has not yet been sufficiently addressed: that is how light affects our inner sense, our mental disposition. The empirical and epistemological method of that research is still elusive and is proposed as a topic for future studies.

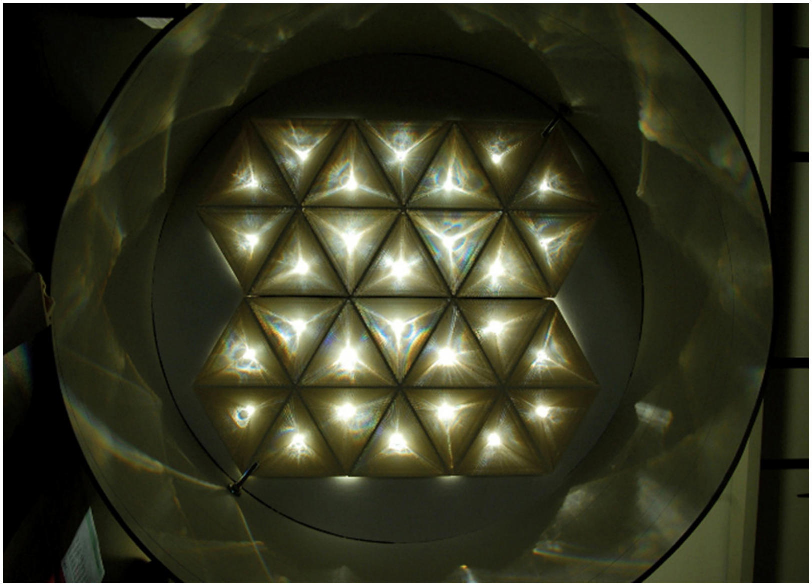

Figure 7: Light container assembly.

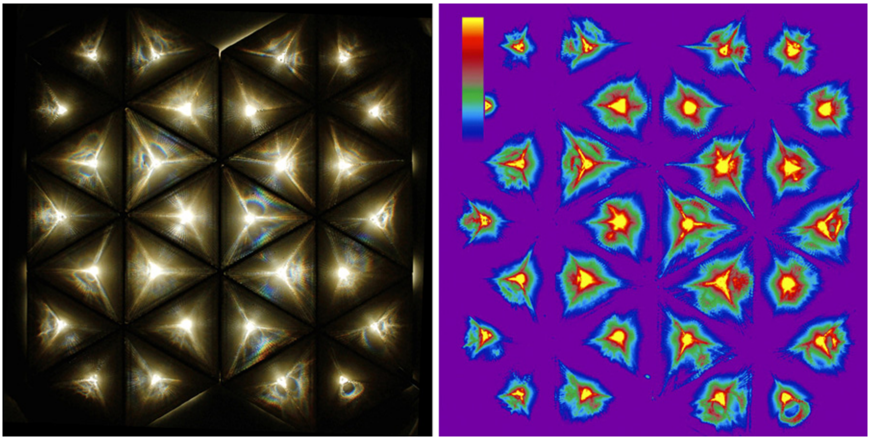

Figure 8: HDR composite photo (right), false color luminance image for values between 10 and 0.2 cd/m$^2$.

## 6 Future studies

There is historical evidence that perceptual awareness of subtle differences of intensity levels and chromatic composition of light at precise moments of the day was a key ingredient in religious celebrations and spiritual activities. It is worth noticing that a significant number of worship spaces have similar light levels to the ones investigated here. And, there is a precedent for the occurrence of spiritual rituals at precise moments of the day, namely the *matins* and the *vespers*, the first and the sixth canonical hours that are celebrated in prayer or song by many cloistered monastic orders, Benedictines, Cistercians, etc.

This intuitive cultural refinement in the selection of the nuances of light and its effect, perhaps subliminal, in our perceptual awareness and self-consciousness may have been dulled, or anaesthetized, by recent choices of a more pragmatic lifestyle. The enabling technology that brought about the advent of artificial lighting has undeniable benefits; but it has also generated as by-products the sacrifice of perceptual acuity and phenomenal loss.

A recovered knowledge and practice of the fine-tuning of light in space can bring extraordinary depth to the exploration of aesthetics in architecture; aesthetics considered not merely as a matter of conventional taste, but as a broader and finer integrative tuning of the sensual manifold, seeking both physiological comfort and mental well being. There are also precedents for the kinds of practice that require a fine-tuning of the body and relaxation of the senses to induce paradoxically a kind of *indifference*, or ‘peace of mind’: the Epicurean *ataraxia*, the Stoic *apatheia*, the extreme Stoic *adiaphora*, the Zen not-thinking, and the more general practices of ‘transcendental meditation’ [5].

Why should we seek this kind of light, this peace of mind? What may we get out of it? A simple answer may be that the benefit of such experience could have profound ethical and aesthetic consequences. It is an approach to the imagination and sensibility delineated in Kant's *Critique of Judgment*, and a reflection of the cognitive function analyzed in the "Transcendental Aesthetic," in the *Critique of Pure Reason*. Kant differentiates three kinds of syntheses that are supposed to be necessary to present objects to knowledge: synthesis of apprehension in intuition, of reproduction in the imagination, of recognition in the concept—or logical form in reason. There are two movements in the initial synthesis: one is to seize or touch, which is the inflow of the sensual manifold; the other is to bring together, to mix, the comprehension of this flow, as instantaneous intuition. The second is a fastening onto, a withholding of this intuition, and this occurs as a diachronic reproduction in the imagination. Finally, it is possible for the intuitive 'object' to be grasped out of the diachronic flow and captured through a final synthesis of recognition, a synthesis that opens the way to knowledge proper.

If there is a sufficient and necessary philosophical framework for this continued research, the proposed empirical modeling and testing will continue to follow a heuristic method, whereby the knowledge acquired will be confirmed through direct sensorial experiences leading to mental perceptions, and further on to phenomenal concepts. In the ensuing rheology, the researchers will become the prime materials of their own experiment: sensating, imagining, reasoning, emerging materials—finding stochastic portals, or inflections, in the hypothetical matter-space and time-spirit continuum.

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