Daylighting and sunlighting in street canyons

A quantitative research on the visual perception and in-situ daylight measurements of four urban canyons in Copenhagen

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Master thesis in Energy-efficient and Environmental Buildings Design
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Lund University

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Keywords: daylighting, sunlighting, urban canyon, visual perception, visual comfort
Thesis: EEBD - 18 / 05

Abstract

"Light creates ambience and the feel of a place, as well as the expression of a structure."
Le Corbusier

With the current urban pressure and large waves of immigration, cities are facing an increase in population and therefore urban densification. This increase in building quantities affects daylight reaching the public space. City densification is easily readable in large metropolitan areas, while its effect is less noticeable in the Nordic countries. However, in such a context where natural light is scarce throughout the year and skies are consistently cloudy, daylight is of great importance. This thesis is based in Copenhagen and is a thorough analysis of the daylight and sunlight parameters that define the visual comfort in the outdoor environment. Four urban canyons, each with different geometry, orientation, materiality and use, were selected as case studies. The research is composed of two parts. The first part consisted of in-situ measurements and calculations, in particular: luminance; illuminance; HDR photographs; false-color diagrams; material reflectance; Daylight Factor and Vertical Daylight Factor. The second one, based on questionnaires, was a thorough investigation of daylight level, daylight adaptation, daylight quality, daylight distribution, visual comfort, sunlight, glare and a qualitative investigation of the feeling of space. The main research question aims at developing a relationship between parameters that defines the optimal urban canyon in terms of visual comfort. The sky condition was found to be a driving force along with other subjective reasons given by people, such as their personal background, urban density or geographical locations of their origins. However, the general conclusion emphasized the importance of the material and its key role on the visual perception of daylight. The material itself has several properties that define its visual performance, such as color contrast, reflection and specularity. The correct combination of these properties can create a different impression even if the geometry remains the same. These conclusions show the complexity of the topic and how subjective assessments are intertwined with daylight metrics. This research opens the door to future research on the subject of outdoor daylight and sunlight perception, for architects and designers alike.

Acknowledgements

I thank Professor Marie-Claude Dubois, my main supervisor, for her expert advice and guidance, inspiring talks, long hours of discussion and great encouragement throughout this interesting and new research topic. I highly appreciate the patience she showed to me and the time devoted to this thesis.

I also thank my local supervisor, Professor Emanuele Naboni for hosting me in KADK, providing me with the necessary technical equipment to complete this research and introducing me to a different academic approach.

I am particularly grateful for the support given by Professor Thorbjörn Laike, my examiner, for his professionalism and his precise comments, which helped to improve this thesis.

Without the support of Erasmus + Traineeship Program which funded my study in Copenhagen, this project would have been impossible.

A very special thank you goes to my parents for their enormous support, their immense love and their great investment, so that this dream came true.

Finally, I would like to thank my friends and colleagues who inspired me with their enthusiasm every day and diligently helped me with site measurements under cold, snowy and rainy conditions: Angel A. Perez Morata, Dario Torrisi, Vincenzo A. Rossi, and Nicola Mancino.

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Acronyms

Canyon “O”	Østergade Canyon
Canyon “M”	Magstræde
Canyon “K”	Krøyers Plads
Canyon “A”	Århusgadekvarter
DF	daylight factor
E_H	horizontal illuminance
E_V	vertical illuminance
E_G	global illuminance
FC	falsecolor
VDF	vertical daylight factor

Terminology[1]

Adaptation	A process by which the state of the visual system is modified by previous and present exposure to stimuli that may have various luminance values, spectral distributions, and angular subtenses.
Chrominance contrast	Fully perceived colors, which occurs under photopic vision.
Contrast	**A**ssessment of the difference in appearance of two or more parts of a field seen simultaneously or successively (hence: brightness contrast, lightness contrast, color contrast, simultaneous contrast, successive contrast, etc.).
Daylighting	Lighting for which daylight is the light source.
Disability glare	Glare that impairs the vision of objects without necessarily causing discomfort.
Discomfort glare	Glare that causes discomfort without necessarily impairing the vision of objects.
Daylight factor	A ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded
Falsecolor	Creation of a false color RADIANCE picture.
Genius-loci[2]	Prevailing character or atmosphere of a place.
Glare	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 by extreme contrasts.
Global illuminance	Exterior illuminance measured on an unobstructed horizontal plane.
Horizontal illuminance	Illuminance on a horizontal plane.
Illuminance	The quotient of the luminous flux $\mathrm{d}\Phi_\mathrm{v}$ incident on an element of the surface containing the point, by the area $\mathrm{d}A$ of that element
Linear atria	A linear shape atrium, or a passage-way, with two out of four sides opened for pedestrians to cross.
Luminance	Quantity defined by the formula: $$L_\mathrm{v} = \frac{\mathrm{d}\Phi_\mathrm{v}}{\mathrm{d}A\cos\theta\,\mathrm{d}\Omega}$$ Where: $\mathrm{d}\Phi_\mathrm{v}$ is the luminous flux transmitted by an elementary beam passing through the given point and propagating in the solid angle, $\mathrm{d}\Omega$, containing the given direction; $\mathrm{d}A$ is the area of a section of that beam containing the given point; θ is the angle between the normal to that section and the direction of the beam. Unit: $\mathrm{cd}\cdot\mathrm{m}^{-2} = \mathrm{lm}\cdot\mathrm{m}^{-2}\cdot\mathrm{sr}^{-1}$
Luminance contrast	Ratio of the luminance of two active parts of a display surface having the same or different colors.
Overcast sky	Completely overcast sky for which the ratio of its luminance, L_γ, in the direction at an angle, γ, above the horizon to its luminance, L_z, at the zenith is given by the relation:

[1] Terminology referred to the electronic source: (CIE: International Commission on Illumination, 2014), (Mischler, 2004-2018).
[2] Terminology referred to the web-post from (CNN, 2008).

$$L_\gamma = \frac{L_Z(1+2\sin\gamma)}{3}$$

Reflectance	Ratio of the reflected radiant flux or luminous flux to the incident flux in the given conditions.
Reflectance gradient	Changes on reflectance values due to background light intensity.
Specularity	Fraction of incident light that is immediately reflected in mirror like fashion.
Sunlighting	Light from the sun.
Clear sky	Sunny conditions with a primarily direct sunlight component (Reinhart, 2014).
Urban canyon	Canyon shape urban landscape created by tall buildings surrounding streets.
Urban densification	Building homes in a more compact way and closer together.
Visual comfort	Subjective perception of the suitability of lighting taking into account uniform illumination, optimal light levels, glare, contrast, correct colors, and the absence of stroboscopic effect or intermittent light.
Veiling effect	Reflection of incident light that partially or totally obscures the details to be seen on a surface by reducing the contrast.
Vertical illuminance	Illuminance on a vertical plane. Unit: $lx = lm \cdot m^{-2}$.
Visual perception	All the information absorbed by the human eye and interpreted in the brain.

1 Introduction

With current pressures for densifying cities around the world, daylighting and sunlighting of outdoor public spaces is jeopardized. Consequently, daylight reaching indoors is drastically reduced. This effect is obvious in large cities such as Hong Kong, New York, Sao Paulo, etc. In the case of Nordic cities, the effect of densification on daylighting and sunlighting in the street canyons occurs at a smaller scale. However, sufficient daylighting is a more important environmental factor in Nordic cities, since they are characterized by a dominance of overcast skies. Especially winter daylight, which is very scarce due to a high latitude.

Compared to the other Scandinavian countries, Denmark is predominantly flat, and possesses a small territory. It has no uninhabited areas and its land which covers less than ten percent the size of Sweden is highly cultivated and built almost everywhere. However, the highest densified areas of more than 100,000 inhabitants are only a few, one of which is Copenhagen with 583,000 residents inside the city and 1.99 million in the big metropolitan area. The capital hosts 10% of the total Danish population (World-Population-Review, 2018). The urban planning of Copenhagen went through drastic changes from its initial stages of conception to today. The process of urbanization included interventions on the old housing blocks, new developments with higher standards, many demolitions of old settlements, new arteries of paths and roads that would ease the flow of cars inside the old city center, as well as the development of many green pedestrian and bicycle paths that would connect the old and new network of parks spread around the city. During the 80s, the new urban renewal did not show quality of architecture in terms of daylight and space (Hall, 1991). Nowadays new areas are being highly developed, going hand in hand with the population growth. In the last decade, the population of the Scandinavian countries has grown from 25 to 27 million in total (Jamholt, 2018). By 2030, the numbers are expected to reach 30 million. For Denmark 80% of the total Danish population growth will be concentrated in the greater Copenhagen areas, East Jutland and Odense (Jamholt, 2018). This pace of growth requires rapid new developments of housing, facilities and recreation areas.

Due to population growth, Copenhagen nowadays is a massive construction site, hosting new housing and commercial buildings. The urban densification requires a greater focus on the quality of the indoor space or livable space. Architects are unfolding their creativity by introducing new designs from layouts to building materials. This means that the public space is being impacted by the scale of interventions. Due to the climate conditions in this location, as well as the scarcity on natural light, public space is occupied by the inhabitants only during a few months. Therefore, the impact of new dwellings in the public space is stronger than in other contexts, while the necessity for daylight harvesting is high. Moreover, as previous research has shown, there stands a gap between what is done so far on urban design studies, and outdoor daylight perception and comfort. This thesis will target to bridge the gap and investigate thoroughly the topic of daylight and its transformation in the outdoor obstructed spaces.

More specifically, the present thesis will investigate daylighting and sunlighting on four urban street canyons in Copenhagen with a focus on visual perception and visual comfort. The research is structured in two sections. Firstly, it represents an investigation based on in-situ measurement of physical aspects of the canyon and daylight parameters. Secondly, it ponders people's assessment through completing a set of questionnaires about visual comfort and perception of daylight and sunlight. The integration of both sections will help clarify the connection between tangible data and the subjective perception. Therefore, this research will build future ground for investigation in the topic of outdoor daylight and sunlight perception and the dynamics involved in the practice.

2 Overall goals, questions and hypothesis

Urban canyon is a term used to describe the canyon-shaped landscape created by a specific urban context consisting of dwellings that frame a narrow street or path. Cities are networks of such compositions and in these canyons, city life thrives. Additionally, daylighting in urban canyons can define the quality of life and influence how we perceive and create memories of the public transit space. However, the daylight incident on the canyon is closely linked to the architecture, color, and materiality of the canyon. Therefore, the research will investigate: the perceived level of daylight influenced by obstructions and material properties such as color and reflection, the daylight distribution and visual comfort in relation to color contrast and visual stimuli, and finally the quality of public space. These factors helped develop the following research questions:

1. Is there a relation between geometry and façade material that will define the optimal canyon in terms of visual comfort?
2. Is there a relation between daylight metrics and perception as measured by in-situ?
3. What are the factors that define livability of a public space according to the respondents?

Therefore, two hypotheses were inferred based on literature review:

- A wide canyon expected to be perceived as bright and a narrow canyon expected to be perceived as dark can be affected by the property of the façade.
- A canyon with excessive contrasts can cause visual discomfort.

The methodology of work for this thesis was structured in a way to investigate these particular daylighting components and the subjective perceptions of people, thus, to answer the research questions.

3 Limitations

This research is based on field work, but due to time when this study was developed, the weather became a driving force and the biggest limitation to follow-up consistently with all the steps. Moreover, the fact of working with people posed some difficulties. The plan was to have 60 questionnaires per street canyon, with 30 for each sky condition (overcast/sunny). However, due to the availability of people to stop and answer the survey, the quantity of questionnaires was reduced to approximately 26 per sky condition.

4 Background

4.1 Outdoor daylight

The Indoor is the Outdoor

A short description on how daylight was used throughout the history of architecture.

From ancient times to nowadays, the aim of architects was to create spatial play of form and light and to generate a variety of perceptions inside their creation. Throughout history, daylight took different shapes and defined styles of architecture. Four chosen groups will describe daylight transformation: the Mediterranean and Middle-East Civilization, represented in here by Ancient Egypt; Classical Antiquity, represented by Ancient Rome, Early Christianity, and Byzantine; Medieval Europe, represented by the Gothic, Renaissance, and Baroque; Neoclassicism, chosen style Beaux-Arts and Art Nouveau; and finally, Modernism.

Ancient Egyptians 3000 BC – 272 AD, would track the sun-path throughout the year and emphasize important astrological events such as summer or winter solstice. A good representation is the Karnak Temple, where sun rays cut the main entrance perpendicularly from the sanctuary of AmunRa'a (*Figure 1*) at the center to the temple to the gates of Hatshepsut's temple (Egypt-Today, 2018). Ancient Romans 600 BC – 323 AD, would use light to show the way towards their gods, and there is no better representation than the Pantheon. Called otherwise the Temple of all Gods, the light falling from the 8.9 m wide opening of the dome, would be a metaphor describing the relationship between heaven and earth (*Figure 2*). Later, during the Early Christianity 100 AD – 500 AD, Byzantine 527 – 1520, Gothic 1140 – 1520, Renaissance 1425 – 1660 and Baroque 1600 – 1800, daylighting was mainly used to create spaces of worship and mystery. It played a fundamental role in the architecture design of churches. Openings from the ceiling used to bring mystique light from the outside to the worship area and the altar. These openings went through changes from one period to the other, peaking during the Gothic with tall pointy windows covering immense surfaces. Two examples of two different eras are the Mont Saint Michele Abbey (*Figure 3*) for the Gothic; and St. Peter's Cathedral (*Figure 4*) for the Renaissance.

Neoclassicism marks the return of architectural details of Classical Antiquity. However, with the upcoming industrial revolution, immense steel structures got integrated with the neoclassical style. Massive steel dome-shaped roofs were enclosing big halls. Covered in glass, these structures were harvesting daylight and bringing natural light to space underneath. One very known project designed during the period of Beaux-Arts in Paris (1800 – 1900), is the prior railway station which was lately transformed into the wellknown Musée d'Orsay (*Figure 5*).

During the mid 20th century, light was one of the parameters that defined Modern architecture (1900 – mid 20th century). Four out of ten main characteristics of Modernism are related to light (A2Modern, 2011). The first one is the interaction between indoor and outdoor, addressed using large window openings. The second one is a wall-free floor plan that increases transparency and accessibility. The third one is the need for higher indoor daylight. And the last one is the use of direct sun and shadow to improve human comfort. The baseline guiding this approach is inhabitant's wellbeing and a closer relation to nature. These characteristics can be easily seen in the wellknown project of Ludwig Mies van der Rohe, El Pabellón de Barcelona (*Figure 6*). For other modernist architects, daylighting took different meanings. To Louis Kahn, light was beyond being just a source, it had induced the metaphor, poesy, and spiritualism (Russ, 2014). While in the Nordic countries where light was a scarce source, architects such as Alvar Aalto pushed this topic further. Hereby, light was not only a source, but it cohabited with material and color. Light became the language of the Nordic architecture and the main driving force that shaped their future spatial, material, industrial and production design.

Figure 1 Karnak temple on winter solstice. Electronic source from www.sis.gov.eg.

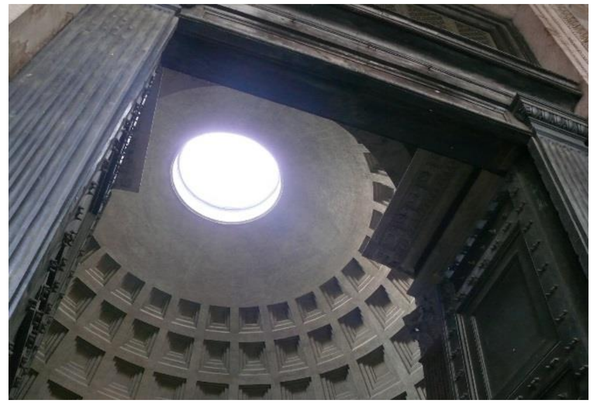


Figure 2 The light falling from the Pantheon oculus. Photo by Olesja Lami.

Figure 3 Interior of Mont Saint Michele Abbey, France. Photo by Olesja Lami.

Figure 4 St. Peter's Cathedral, Vatican City. Daylight falling inside the dome. Photo by Olesja Lami.

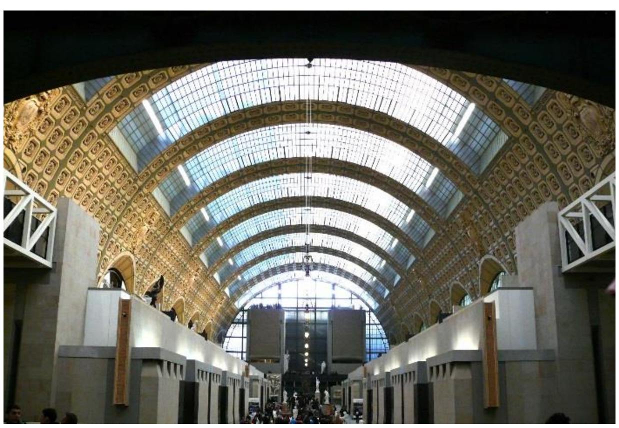


Figure 5 Muse d'Orsay, Paris. Photo by Olesja Lami.

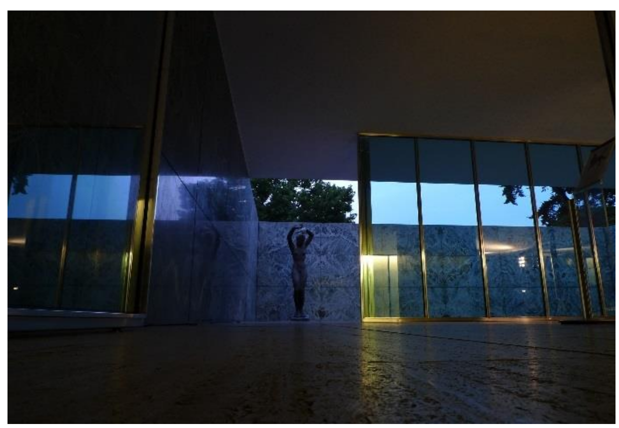


Figure 6 El Pabellón de Barcelona by Ludwig Mies van der Rohe, Barcelona. Photo by Olesja Lami.

Daylighting: beyond being just a play of light
Today daylight in architecture is one step ahead, becoming a component of indoor comfort, both visual and thermal and low energy use in buildings. Generally, daylight studies are focused on indoor light conditions, since people spend 85-90 % of their time in the indoors (Jenkins, Phillips, Mulberg, & Hui, 1992). However exterior daylight conditions i.e. daylight incident on building facades has a direct impact on indoor daylight quality and quantity. The research in the field of outdoor daylighting is quite new and many researchers have focused on different topics such as: obstructions/ geometry of the context and its effect on the quality of light reaching building facades and ground; methodologies on simulating or calculating daylighting parameters; and definitions of new relations between light parameters and materials. However, little has been done on the visual perception of outdoor daylighting and how it is affected by the façade design or material use.

As underlined by Tregenza & Wilson (2011), daylighting and its 24h cycle is affecting the circadian rhythm, which is a natural "clock" in the body of humans, mammals and other organisms. If disrupted in this natural "clock" the whole-body system can change, and people might perceive symptoms such as extreme tiredness or sleep disorders (Tregenza & Wilson, 2011). One stimulus that triggers these changes is the exposure to light. Inside the human eye, besides the photoreceptors responsible for the vision, are the ones responsible for hormonal changes. It is observed that the effect of light is directly related to the illuminance levels, for values as low as 100 lx. For humans' periods of darkness are as important as periods of light.

Additional research has been carried out on the psychological and physiological effects of light and color. According to Abbas (2006), some colors and intensities of light have greater impact than others Even though the research focused into electrical lighting, one of the conclusions was that natural, white light induced the most relaxing condition for 60-73% of the participants in the experiment. The experiment consisted of monitoring changes in emotions, heart rate (HR) and skin conditions (SC) of participants, after being exposed to different light conditions. However, the researcher states that the changes in physiological measures (HR and SC) are subject dependent, thus making it difficult to withdraw a conclusion on the effect of color and light for all the participants.

4.2 Daylight inside the Urban Canyon

The effect of the canyon can be defined by different parameters such as location; sunlight hours; canyon geometry; orientation and reflectance of materials. The location is important to get to know the position of the sun during different seasons. It goes hand in hand with the weather conditions of the same location and the sky conditions. In Copenhagen, the sun has a range of eleven degrees in winter to 58° in summer (Egan & Olgyay, 2002). However, for a location like Copenhagen, the sky condition is approximately 60-70% of the year overcast. Overcast sky means that the sky produces diffuse light. In a total overcast condition, the zenith is three times brighter than the horizon. In this case, the light affecting the outdoor visual comfort is different compared to the direct sunlight case. Different light conditions can cause different perceived environments and three basic sources of light are: daylight, sunlight and reflected light (Egan & Olgyay, 2002):

"Daylight – diffuse light through clouds or partially cloudy sky
Sunlight – direct-beam sunlight through clear or partially cloudy skies
Reflected light – light reflected from natural and man-made surface"

The canyon geometry is one of the most effective parameters on influencing daylight. Many studies have been performed about the context and urban obstructions. According to Reinhart (2014) the canyon geometry is interpreted by the definition of several geometrical factors and mathematical relations. It is calculated that the daylit area of a space is reduced by 20% for every 15° changes in sky angles. For sky angles smaller than 15°, in other words a fully obstructed view, the daylit areas disappears entirely (Reinhart, 2014). In a base case study of a canyon where buildings have the same height, a reduction in daylit areas is observed. Moreover, in a relationship where a short building faces a high-rise, the tall building will increase the light quantity falling on the northern façade of the short building (Reinhart, 2014).

Other than geometry, daylit areas are strongly influenced by the window to wall ratio (WWR) of the façades. Researches have defined a rule of thumb called "Daylight Feasibility Test", that consists on the integration of sky angle (θ) and WWR, see *Equation 1*.***Error! Reference source not found.***

$$\theta \times WWR > 2000 \qquad (1)$$

Thus, Reinhard raises the question: "Can all spaces bordering the canyon be daylit?". They discovered that the canyon's façade with the highest WWR gets fully daylit, while the façade with a lower WWR has the first two floors underlit. To withdraw this conclusion Reinhard studied a canyon with different WWR on each side (Reinhart, 2014).

In highly dense urban contexts, the relations between geometry and light quality is more complex. A research about the urban form, density, and solar potential, indicated that a random layout of building plots with a combination of building scales, is best to reach a better light quality on the ground level. This conclusion was reached after simulating eighteen parametric combinations between built form and densities (Cheng, et al., 2006).

Orientation is another important criterion, that goes hand in hand with urban form and building scale. The building or the canyon's orientation plays a vital role in terms of the quantity of light that falls on the ground. Canyons composed of buildings oriented north-south, get diffused light reflected from the facades during morning and afternoon, and direct sunlight during midday. Due to the low sun angle, most of the light that falls on this canyon type is dependent on the sky opening and the view from the street (Egan & Olgyay, 2002). In a second case, the east-west orientation of a canyon, receives more direct sunlight during morning and afternoon hours inside the canyon. During midday sunlight hits only one side of the canyon, giving a stronger amount of light reflected inside the canyon (Egan & Olgyay, 2002).

For an overcast condition, the canyon geometry needs largest opening towards the sky (Egan & Olgyay, 2002). The influence that these openings have on the indoors is better depicted in a study achieved in Israel for an office building. Parametric simulations showed that the availability of daylight inside the office room was proportional to the sky solid angle (the sky patch visible from the window) (Capeluto, 2003). A heavily obstructed environment has a heavy impact on illuminance values. A paper focused on this topic has applied VDF (vertical daylight factor) as a measurement principle to validate the delivery of daylight in buildings. The simulations showed that the VDF values were accurate and compatible for two different simulation methods, thus making that a reliable source for evaluation (Li, Cheung, & Lam, 2009). A more thorough study was carried out about the effect of different street canyon geometries on the VDF and DF (daylight factor). This study revealed that reflectance is an important factor that affects strongly the amount of daylight, especially in a heavy obstructed canyon (Carlos, 2016).

More thorough research has focused on the materials' reflectance and their effect on daylight. A study by Rosso, et al., (2015) focused on the visual perception of natural cool materials used for pavements and roofs. The research consists of questionnaires and investigations on the thermal and visual comfort of respondents during a summer day. It showed that pedestrians preferred grassland instead of asphalt, while gravel evaluation varied according to weather conditions (Rosso, et al., 2015).

4.3. Visual comfort

What is visual comfort?
The human eye is the most important when referring to the sensory organs and 60% of the nerve fibers come directly from the eye to the brain. Approximately 500 000 000 nerve cells are located in the cerebral cortex, and each of them is dedicated to the vision center (Valberg, 1998). Visual comfort is affected by the intensity of light, the reflecting light, the shape of the objects, their material properties and color. In her research Matusiak, (1998) states that:

“Visual comfort is used to describe the lack of visual discomfort.”

On the other hand, perception has always been the estimate of the design quality. However, perception can be deeply affected by different sky conditions which will be directly related to the visual comfort and how the eye adapts or perceives the surrounding. This change in conditions will be the source of different types of light from direct to completely diffuse, that will be interpreted by the eye into different color appearances or clarities of patterns. Many notions are related to the mechanisms that trigger how the eye reacts to stimuli, such as: the perception of brightness and darkness; adaptation; simultaneous contrast; border contrast effect; successive contrast; illusory contours/forms and color perception (Matusiak, 1998). See *Table 1*.

Table 1 Notions related to the eye and its reaction to stimuli.

Notions	**Notions definition**
Perception of brightness and darkness	Dependent on the exposure towards light that the retina has been throughout the past and the intensity of light falling on the eye.
Adaptation	The time that takes for the eye to adapt on a dark or bright context. It takes ¾ hour to adapt to darkness and only a few seconds to adapt to brightness.
Simultaneous contrast	The contrast created by the surrounding and the object. A brighter surrounding makes the object look darker or the other way around.
Border contrast effect	The borders are strengthened by the brain by enhancing their contrast.
Successive contrast	The color perception is influenced by the previous color seen in the past.
Illusory contours / forms	Contours that are not complete, but the brain reads them as a whole.
Color perception	It is composed of: the detection of light and the discrimination of colors; and the color appearance. The first one is about adjustment of the eye to the light and the range of colors it perceives. The second one is about the light

	intensity falling on the material, the wavelength of the light reflected by the material and the ability of the eye to distinguish many simultaneously.

According to Rockcastle & Andersen (2012), visual comfort is guided by luminance values, as the closest measure to how the eye perceives light. In their further book publication, Rockcastle & Andersen (2013) introduce two new metrics that refer to contrast and luminance. They quantify the dynamic part of daylight and introduce "annual spatial contrast" and "annual luminance variability". These two metrics analyze a set of photographs and show a dynamic change of contrast and luminosity throughout the year (Rockcastle & Andersen, 2013). This approach helps to analyze a daylit space as a dynamic context that is affected by light and shadow, and it paves the way to future holistic research on architecture and light.

Moreover, memory plays an important role when an information is collected by the eye and interpreted by the brain. The new information absorbed by the senses is compared to previous memories of similar situations, therefore the quality of this information coming in should be of a high standard. Here comes into play the visual perception, which is influenced by light conditions and the context.

4.3.1 Visual perception

The field of visual perception is complicated and involves different aspects that go beyond the biological functioning of the human eye. A good description of the human perception is given by Lam (1992):

"Human perception is an active, information-seeking process which involves many mechanisms in the eye and brain, some conscious and other unconscious."

Tregenza & Wilson (2011) investigated the topic of visual perception in their book about daylighting where they raise the question:

"How much daylight do people expect? What is "normal" for them?

They state that there is no general criterion for a certain quantity of daylight expected to be perceived. The thing that is accepted and appreciated by the user, or the passerby, depends on the function or use of the space. His judgment of perceived light is as well affected by his cultural background. Tregenza & Wilson (2011) add that individuals with similar backgrounds withdraw similar conclusions or experience similar emotions. This extends further into questioning the type of emotions that individuals develop in relation to a place. In the book the authors define the creation of place as follows:

"A "place" is somewhere with meaning, somewhere that arouses associations, that trigger memories of earlier occasions, that can simulate emotions."

The "place" is well investigated and studied by scholars and one very well-known concept associated with that is the "genius loci". Norberg-Schultz (1991), is describing this concept as:

"A place is a space which has a distinct character. Since ancient times the genius loci, or "the spirit of place", has been recognized as the concrete reality man has to face and come to terms with in his daily life. Architecture means to visualize the genius loci, and the task of the architecture is to create meaningful places, whereby he helps man to dwell."

Tregenza and Wilson (2011), show an experiment achieved with a group of international students on the description of a dark room with small windows. The students coming from warm climates experienced it as a comfortable fresh room, while the ones coming from cold climates described it as dark and gloomy. This means that individuals were influenced by how they were used to perceive the context. A remarkable point underlined by the author is that in a familiar situation, people do not notice the surrounding.

Moreover, in a second research based on questionnaires, Tregenza & Wilson (2011), state that inhabitants of a heavily obstructed residential area in Hong Kong are satisfied with a low level of daylight. Compared to them, another group of inhabitants of social housing in Western Europe, had higher expectations of daylight levels. Tregenza and Wilson (2011) concluded that meeting daylighting standards does not necessarily define a good visual perception or an ideal livable space.

4.4 Direct sunlight, glare and veiling effect

Glare is a phenomenon that is associated with the visual discomfort. As was mentioned so far, many components will define a good visual perception, and consequently visual comfort. However, light levels beyond accepted ones will be interpreted by the eye automatically as signs of discomfort. The visual perception will be corrupted by visual noise, which is caused by a bright light source or in this case direct sunlight.

Glare can be of two different forms one is disability glare and the other discomfort glare. The first one, disability glare, is the most problematic one, and is caused by high luminance on a low luminance background near the sight line (Bjorset, 1992). This effect of high discomfort will cause what is known as the veiling effect. The second one, discomfort glare is caused when inside the visual field are many objects with a high difference in luminance values (Matusiak, 1998).

Further studies done on daylighting and the visual comfort, by the Color and Light Research Group at University College of Arts, Crafts and Design in Stockholm, concluded that a high level of illuminance or the presence of glare, will affect people's visual perception, by making them want more light (Anter, 2013).

4.5 Canyon case study

4.5.1 Linear atria: University Center at Dragvoll, Trondheim

The linear atria can be called the most similar case study to the urban canyon. A linear atrium is a canyon-shaped street or blocks of building covered by a glazed roof. The case study is Matusiak's research on linear atria at high latitudes (Matusiak, 1998). Matusiak states that her findings can be applied to various studies and scenarios. Her thorough research is focused inside the linear atrium at the Dragvoll University Center in Trondheim, see *Figure 7*.

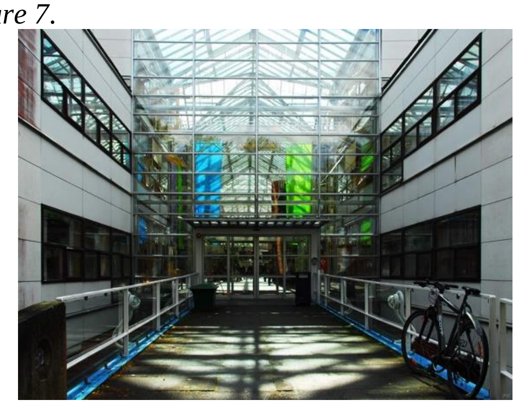


Figure 7 Inside the linear atrium at NTNU - Campus Dragvoll, Trondheim. Electronic source: (Tjelflaat).

The geometry of the atrium and its glazed cover plays a fundamental role when referring to the quantity of light that penetrates space; reflected light; visual comfort and visual perception. Matusiak defines some interesting methods that describe the perception inside the atria, namely: the luminance gradient, color, and pattern. They have the following subdivisions: luminance gradient has reflectance gradient, specularity, and roughness; color has chrominance contrast, and; pattern has luminance contrast and chrominance contrast. Some results from her paper are represented in *Table 2*.

Table 2 A resume of the conclusions on lighting/ daylighting of form. Retrieved from (1998)

Luminance gradient:	Reflectance gradient: The visibility of the canyon depends on the canyon size and the background luminance. Specularity: It is not perceivable if the light that falls into the canyon is diffuse. Roughness: the details of the texture of the façades are unreadable under a diffuse light condition.
Color	Chrominance contrast: the luminance values should be from 10 cd/m^2 to 10^6 cd/m^2 to fully perceive colors, or in other words, a photopic vision (Admesy, 2018). However, very high levels of luminance can drastically change the perception of color.
Pattern	Luminance contrast: A high illuminance level is required to detect differences in a small pattern. Chrominance contrast: The same applies as to the color, but with the difference that the distance between the observer and the object plays a greater role.

4.6 Conclusion of the literature review

As the literature review reads, daylight will always be a source that defines the quality of a space and highlights the architecture’s strongest characteristics. In this thesis, the outdoor daylight and its perception in the urban canyon are given a thorough focus. This choice is to bring some attention on the quality of public space and how much the architecture we design affects the amount and quality of light penetrating the dense urban pattern. Therefore, the research examines the visual perception and visual comfort by referring to several geometrical configurations of the canyon. Façade material, façade color and color contrast are some key elements that structure the research development. As mentioned before, the visual perception is influenced by several factors such as adaptation time, daylight intensity, daylit or shaded areas, etc. On the other hand, visual comfort is related to the luminance gradient, material color, luminance contrast, glare etc. Therefore, the correlation between these parameters and more will be studied in order to develop answers to the optimal urban canyon.

5 Methods

This research concerns the impact of the street canyon geometry and the material properties of the façade on daylighting and sunlighting, as perceived by people walking. The study includes four different urban street canyons located in the city of Copenhagen, Denmark (55 ° N, 12° E). The selected canyons differ in their orientation, geometry, and façade/ground material. The research is a quantitative study with two different approaches, one based on photometric measurements and in-situ observations and the other based on a survey. The strict steps for lighting and daylighting described in Dubois, Gentile & Amorim (2016) are used as a baseline for this research. The measurements were carried out at three points in each canyon, covering a length of 60 m and including different geometries of the canyon and façade materials.

5.1. Copenhagen and its street canyons

Copenhagen is a vibrant capital city and its urban pattern is constantly changing and developing. The case studies were selected according to following conditions: location in town; orientation; shape; functional use and densification level. Two of the canyons are newly developed and the other two are typically representative of the Copenhagen housing and commercial street canyon. *Figure 8* shows the urban pattern of Copenhagen and the location of each selected canyon.

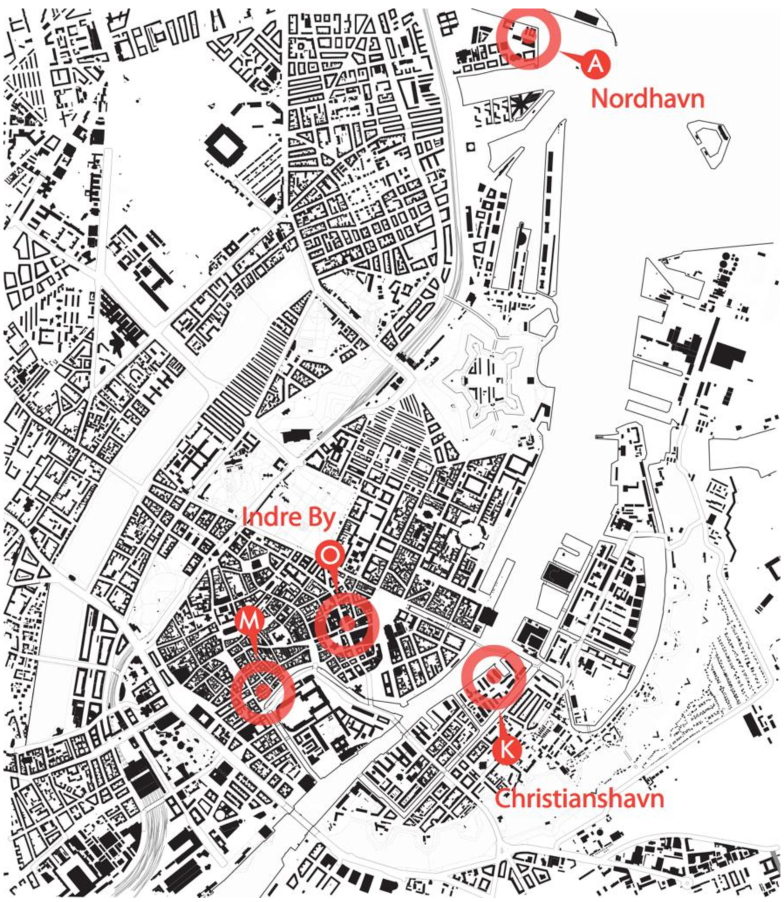


Figure 8 Diagram of Copenhagen's urban pattern

As shown in *Figure 8,* Copenhagen is characterized by a complex network of canals and parks in which streets and bridges are integrated. The city center has a regular urban pattern that revolves circularly around the old medieval town of Indre By. However, the full map of Copenhagen resembles to the shape of the hand. This form, which is more of a radial growth, shows how new and old developments have followed the line of a canal or street. The pattern depends on the location and the main function of the area. The most typical urban block identifies with a white/ red brick or painted façade in the inner courtyard and has about five to six floors. New developments introduce new typological forms and different relationships with space. The typical stone-covered pedestrian street is found in the old center and ranges from 7 to 10 m wide. Another case is the street that is integrated with the water canal, both covering a width of about 15 to 25 m. If the road is accessible by car, the width varies between 10 and 40 m. All of these observations influenced the choice of case studies. Two of the canyons are long and the other two are of 60 m in length. Therefore, the length of the study of each canyon is 60 m.

Two canyons are located in Indre By, respectively canyon "O" Østergade and "M" Magstræde, canyon "K" Krøyers Plads in Christianshavn and canyon "A" Århusgadekvarter in Nordhavn. *Figure 9* shows photographs of the selected ones.

Figure 9 Street canyon photographs. From left top: "O" Østergade - Indre By, "K" Krøyers Plads - Christianshavn, "A" Hamborg Plads, Århusgadekvarter - Nordhavn, "M" Magstræde - Indre By.

Canyon O is a typical commercial street canyon that follows a South-West – North-East axis. This canyon is chosen as a typical illustration of the Copenhagen street canyon and is one of the busiest streets for locals and tourists. It is centrally located and a commercial street connecting Kongens Nytorv to Amagertorv. Its geometry is 10 m wide, surrounded by buildings five to six stories high and up to 18 m high. *Figure 10* and *Figure 12* show the plans and sections of the canyon. The canyon shape dominates the southwest side, while the northeast side opens to the square. The façades are characterized by white bricks or white paint with light gray or brown colors. Ground floors and first floors are mainly business-related services and the predominant façade material is glass.

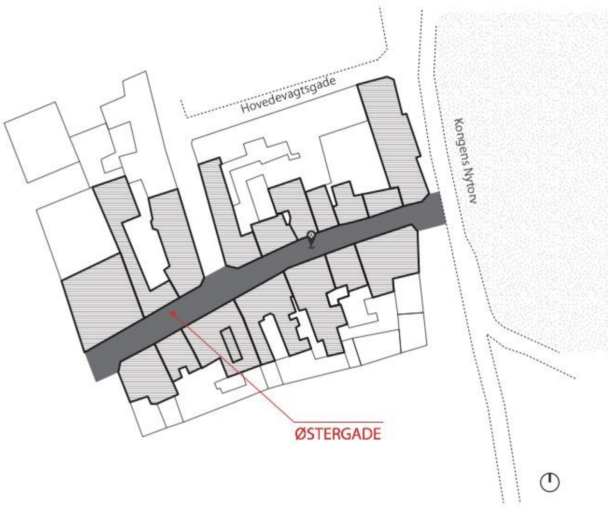


Figure 10 Canyon "O", geometry and orientation.

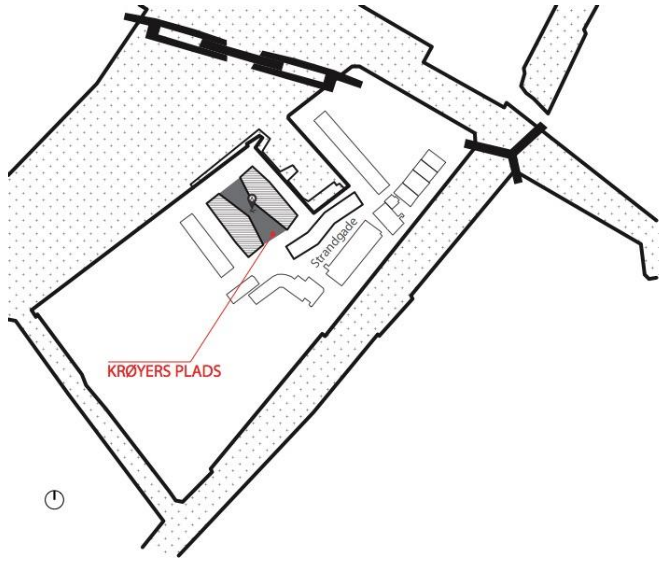


Figure 11 Canyon "K", geometry and orientation.

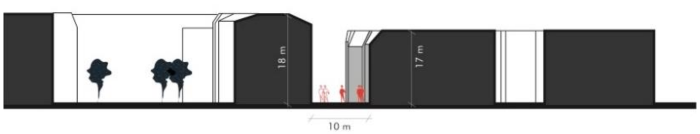


Figure 12 Canyon "O", section.

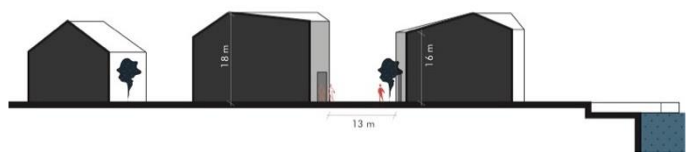


Figure 13 Canyon "K", section.

Canyon K is a newly built housing area. This canyon is chosen for its contemporary architecture style, its particular geometry and the green areas and water canals surrounding it. The canyon is oriented along the north-west – south-east axis and consists of two building blocks of five floors. The north-west side faces the canal while the south-east opens to the square, the street, and surrounding blocks. The space between the buildings is a public area with trees and urban furniture for leisure time. The canyon is between 10 and 25 m in width and 15 m in height. The façade is entirely covered with dark red bricks and black-metal frames. This canyon has a particular geometrical detail, two pedestrian paths that cut through the buildings and frame two different views, one towards another public space and the other towards the canal. *Figure 11* and *Figure 13* show the plan and section of this canyon and its surroundings.

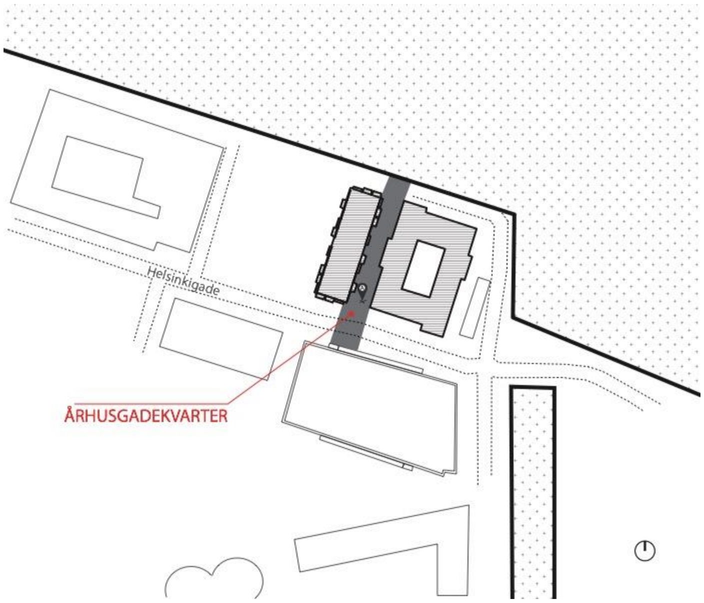


Figure 14 Canyon "A", geometry and orientation.

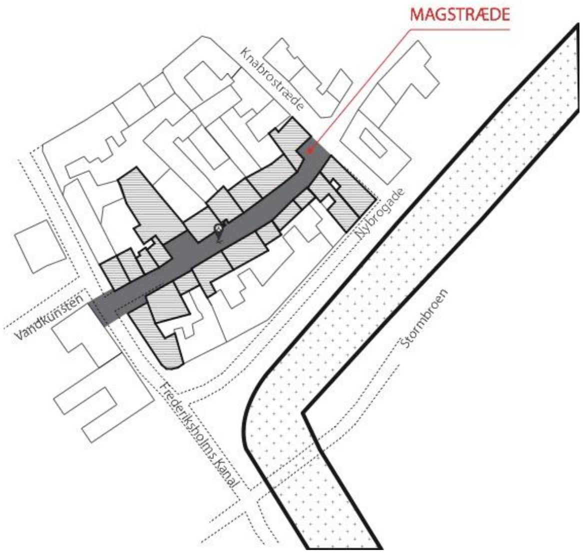


Figure 15 Canyon "M", geometry and orientation.

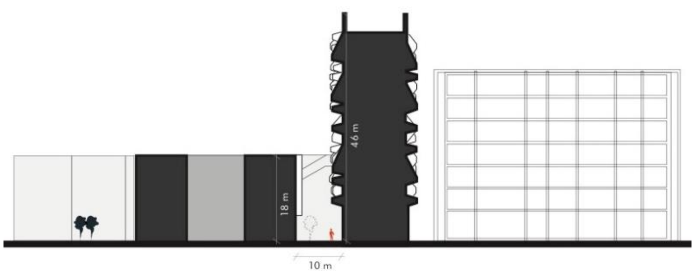


Figure 16 Canyon "A", section.

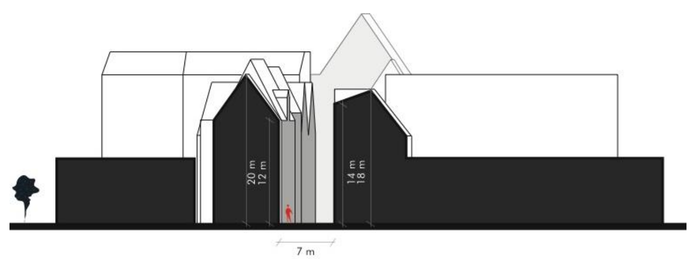


Figure 17 Canyon "M", section

Canyon A is located in the city's northern outskirts and is an ex-industrial site that has become a housing and office complex. This canyon is chosen because of its particular geometry, orientation and façade material. See *Figure 14* and *Figure 16.* The canyon length is the same as canyon K, about 60 m. The canyon is 10 m wide along the north-south axis. The north side of the canyon faces the canal and the south side has an obstruction that blocks the view. The west side is bordered by a 46 m tall tower with a metal-gray finish, while the east side is bordered by a 15 m high housing block with a dark-brown brick façade. There are some small urban furniture and decorative trees in the pedestrian space between the buildings.

The fourth, canyon M, named Magstræde, is one of Copenhagen's oldest streets. This makes it one of the most visited streets for tourists, because its buildings survived the great fire of 1728. The old urban pattern is reflected in its geometry and architecture. It is 7 m wide and features a stone covered floor and colorful plaster finishes on its façade. Magstræde's orientation is along the north-east – south-west axis and both sides of the canyon have an elevation of 14 to 20 m, see *Figure 15* and *Figure 17*.

5.2 Objective Assessment

The objective assessment includes in-situ measurements and observations. A monitoring protocol was followed each day and it outlines the time to start and finish measurements, sky conditions (either overcast or sunny sky), the definition of the same grid of points for each canyon, the specific points for different measurements or observations in the grid, the procedures for working with equipments, and directions of observations.

The measurements are used to supplement the subjective evaluations and to determine whether relationships between subjective assessments and the objectively measurable photometric values can be established.

5.2.1 Measurements and observations

The objective assessment includes both measurements and observations. The list bellow mentions all the data collected in situ and their specific locations.

- Photometric assessment covering light distribution measurements:
  - Task position HDR photography (from one point "Point A" in the center of the canyon);
  - Vertical illuminance (on each point of the grid in the vertical plane at eye level);
  - Horizontal illuminance (on each point of the grid);
  - Global illuminance (unobstructed location, "Point B");
  - Luminance values from materials (on each side of the façade).
- Observation covering light perception, people's movement and physical characteristics of the canyon:
  - The possibility of glare (in situ observations and survey);
  - Photographs of the view and materials (center point / each material).

5.2.1.1 Grid definition

The first step is to define a base grid with measurement points. This process is carried out on every canyon before starting the measurements, after the daily protocol. As seen in *Figure 18*, the grid covered an area of 60 meters and was located at a height of 1,65 m. This is an approximated value that corresponds to the height of the human eye and was chosen as a standard point of observation. The grid in itself is composed of nine points, with three points located in the center of the canyon, and six others on the sides. The points have a distance of 30 m from each other and cover dark and bright areas. Horizontal illuminance, E_H, was measured in point (1, 2, and 3), and vertical illuminance, E_V, was measured in point (1', 1", 2', 2", 3', 3").

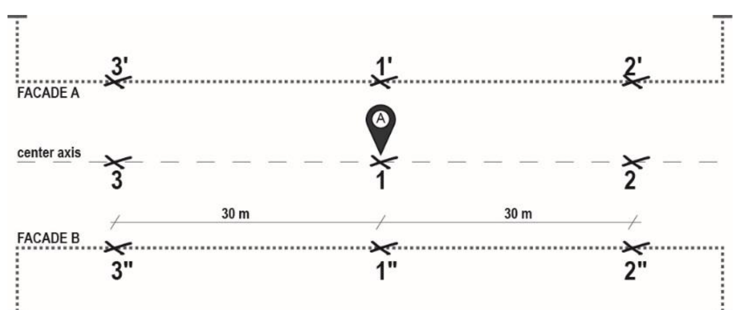


Figure 18 Grid diagram.

5.2.1.2 Measuring tools

A set of tools is used to undertake all the needed measurements:

- Digital Camera (CANON EOS REBEL XT DS126071 with 17-85mm Lens) – taking HDR photographs.
- Illuminance meter model (EXTECH, Easy View) – measuring illuminance.
- Luminance meter model (HAGNER – Universal Photometer S4) and a diffuse plate model (B Hagner AB Solna Sweden) with reflection factor 94.1% - measuring luminance.

5.2.1.3 Illuminance measurements and calculation of DF and VDF

The measured illuminance values are E_H, E_V, and E_G, – global illuminance. Illuminance values are measured both for overcast and sunny conditions, besides the global illuminance which is measured only under an overcast condition. This final value was measured at an unobstructed location varying for each case from big squares to empty plots. The collected data are used to calculate the Daylight Factor (DF) using *Equation 2*, and the Vertical Daylight Factor (VDF) using *Equation 3.*

$$DF = \frac{Horizontal\ Illuminance_{\ point\ X}}{Global\ Illuminance} \tag{2}$$

$$VDF = \frac{Vertical\ Illuminance_{point\ X}}{Global\ Illuminance} \tag{3}$$

5.2.1.4 Luminance measurements and material reflectivity

The luminance values of each façade and the luminance from the “diffuse plate” was measured with an illuminance meter. The data collected helped on mapping the whole reflectivity of the materials. The reflectance is calculated using *Equation 4.* The plate reflectance is known, and it is 94,1%.

$$Surface\ Reflectance = \frac{Reflectance\ of\ the\ plate \times Luminance\ from\ surface}{Luminance\ from\ the\ plate} \tag{4}$$

5.2.1.5 The visual frame: observation point. HDR photographs and False-color diagrams.

One important element to define was the visual frame for in situ observations. For that a point was chosen in the center of the canyon, shown on the diagrams as “Point A” or in the grid as “Point 1”. The visual frame implies to a certain height and a certain angle of observation. The height as mentioned on the grid definition section was 1,65m, while the angular opening of the camera view is 67 degree horizontally and 47,6 degrees vertically for a 17mm lens, calculated online (Atkins, 2017).

The camera placed on a tripod was used to take a set of photos facing two sides of the canyon. The range was a set of ten photos with an exposure from dark to bright. See *Table 3* for more detailed information on the camera settings, referenced from the monitoring protocol (Dubois, Gentile, & Amorim, 2016). The program Photosphere-Alpha was used for the creation of HDR photos. Through the use of this program false-color diagrams are produce showing the light distribution inside the canyon on a luminance scale and representing it in different color tones.

Table 3 Camera parameters for HDR photographs.

Parameters	**Recommended selection**
White balance	Daylight or other appropriate to the case
Sensitivity	100 ISO
Aperture size, fixed	f/8
Difference in exposure values between photos taken	1 EV[2]

5.3 Subjective Assessment

The first part of the research consisted of questionnaires covering the topic of daylight comfort in the outdoors. The questions retrieved information of perceived daylight levels, the experience of space, daylight distribution, direct sunlight, preferences, and comfort. The total number of subjects was a key factor for the overall study. According to previous studies, the margin of error and the confidence level should be established before deciding the total number of questionnaires (SurveyMonkey, 2018). Considering the test subjects and the topic of the study the margin of error was considered 5% and the confidence level 95%. As a starting number it was considered a total of 240 questionnaires. This number came from 30 planned questionnaires per each of the two sky conditions and from four street canyons. With these data it was calculated that 148 questionnaires were the relevant number to withdraw conclusions (SurveyMonkey, 2018). Therefore, for this research were completed 192 questionnaires, a few more than the minimum required.

5.3.1 Questionnaires

Developing a Questionnaire

To design a successful questionnaire some important steps should be followed. The process involves the following steps: language and explanation; the structure of questions and answers; order of questions and finally, testing the questionnaire beforehand (Bryman & Teevan, 2005).

Language and explanation: The language used to develop the questionnaires should be easy to understand and follow. If a printed questionnaire is used, it should include an introduction explaining the purpose and how to answer each question.

Questions and answers: Questions should be short, developed through a neutral point of view, easy to answer, have one possible answer (which makes the results easy to analyze) and be relevant to the research topic. Answers should have no double meaning or inversions, should have one choice and leave no room for interpretation. Preferably answers should be ranked on a scale from “good” to “bad” with choices in-between.

The order of questions: It is important to have a logical continuation of questions, and group them according to the interest. Usually, easiest answers are at the beginning, to make the survey understandable and easy to follow. The attention of the respondent should be triggered consistently for the success of the test.

Testing of questionnaires: The questionnaire will have problems and unclear parts unless the questions are tested beforehand on a small group of people.

This research was composed of six groups of close-ended questions to keep an easy and understandable survey. The language used is basic and only one technical term is mentioned and explained in one of the sections. The questions were all straightforward, the answers had no double meaning and covered a simple range of choices e.g. “less” to “much” or “dark” to “light”. All groups of questions had an independent title to make it easy to follow. The structure of these groups went from simple to more complex. The work achieved by Levin (2017) was used as a reference for the development of each question. Her research consisted of questionnaires that were tested for daylight on residential building in Malmö.

Moreover, the questions were tested with a group of thirty people under an overcast condition. This test showed some problems in understanding and structure. Therefore, questions and answers of the final questionnaire were simplified.

The Survey

The survey was an interview between the researcher and respondents. The interviewer stopped the pedestrians crossing the canyon and asked them to complete the close-ended questionnaire. Ideally, the survey was completed on the same day as the on-site measurements. However, this part of the research has been extended over several days due to the availability of the pedestrians to stop and answer. Therefore, a strict procedure was followed for each interviewing day:

- Questionnaires were taken during a defined range of hours, from 11:00 to 15:00 hours;
- Questionnaires were completed for two sky conditions, one overcast and one sunny sky;
- The sky condition was the same as the previous day when completing the set of 30 questionnaires per street;
- Questionnaires were taken in the middle of the canyon.

This questionnaire was developed to examine the intertwined relation of many factors that influence light perception. Questions have been simplified to make the survey clear. The group of questions covered several aspects during the walk of the pedestrian before reaching the canyon, their familiarity with the street and the range of perception. The survey, which consisted of six parts, took five to ten minutes to complete.

The frequency of crossing, familiarity to the street and the adaptation of the pedestrian with outdoor daylight were investigated in the first and second part of the survey. These two parts gave statistical data. The question concerning the origin of the respondents enhanced the research and the relationship between daylight expectations and perception. See *Table 4.*

Table 4 Questionnaire Part 1 and 2

Part 1: Personal information and familiarity with the street canyon

1a. Are you a local or tourist?

Tourist	Local

1b. Do you live nearby this street?

No	Yes

1c. Do you usually cross this street?

Rarely/ First time	Usually	Always

1d. What is your age?

19	19-29	30-39	40-49	50-59	60-69	70

1e. What is your gender?

M	F	Other

Part 2: Daylight Adaptation
2a. Where were you before reaching the canyon?

Indoor	Outdoor

2b. How long have you been walking outside?

Less than 5 min	Approximately 10 min	More than 10 min

The third part of the survey investigated the visual perception of light. The questions covered both the amount of daylight perceived by the pedestrians and their preference of comfort.

Table 5 Questionnaire Part 3

Part 3: Daylight Perception
3a. How would you describe daylight in this street canyon?

Very Dark	Dark	Neither dark nor bright	Bright	Very Bright		I don't know

3b. How would you wish to change daylight in this street canyon?

Less daylight	No change	More daylight		Does not matter		I don't know

The fourth part of the survey studied daylight distribution. This group of questions was a little complicated to answer without any support, therefore the researcher had to explain further. The purpose of daylight distribution questions was to explore material and color perception. Questions 4b and 4c concerned the visual comfort and discomfort of respondents, see *Table 6*.

Table 6 Questionnaire Part 4

Part 4: Daylight Distribution
4a. How would you describe the spreading of daylight (how light spreads) in this street canyon?

Very even	Normal	Very uneven		I don't know

4b. Does this street canyon have many dark areas (dark corners or tunnels) that make the space uncomfortable?

No	Yes, a few	Yes, many		I don't know

4c. Does this street canyon have many brighter areas (with higher contrast) that make the space uncomfortable?

No	Yes, a few	Yes, many		I don't know

The fifth part of the survey examined the canyon in sunny conditions. The questions investigated direct sunlight, glare and veiling effect. These questions yielded different results while asked during the period of 11:00-15:00. In order to correct inconsistency, the time span for this part of the survey was reduced to one hour.

Table 7 Questionnaire Part 5

Part 5: Sunlight Distribution

5a. Do you experience direct/ reflected sunlight in this street canyon?

Not at all	Moderately	Normally	Much	Very much		I don't know

5b. Do you experience outdoor glare (or veiling effect) in this street canyon?

Not at all	A little	Much	Very much		I don't know

The final part of the survey concerned more personal and perceptive public space issues. It examined the perception of the physical environment, the densification and the sense of place in both sky conditions.

Table 8 Questionnaire Part 6

Part 6: The Canyon Environment

6a. How would you describe the street canon density?

Not dense at all	Moderately dense	Normally dense	Dense	Very dense	I don't know

6b. Would you choose to stop and enjoy the public space inside this street canyon:

No	Perhaps	Yes	I don't know

6c. How would you describe the sky condition now?

Sky fully covered with clouds	1 2 3 4 5 6 7	Completely sunny sky

6 Results

6.1 Objective Assessment

This section of the research was based entirely on in-situ measurements and observations. Each site visit started and finished as planned in the daily protocol. Measurements were carried out at 12:00 noon, and observations were collected between 11:00 and 15:00, covering a wide range of sunlight hours and movement within the canyon. Observations were made for both overcast and sunny conditions and excluded cases of partially sunny, partly cloudy, hazy or other unstable conditions.

The observation point was located at the center of the grid for each canyon and is called “Point A”. The diagrams below represent each canyon and provide this information:

- Point “A” – observation point / HDR task position.
- A’ and A” field of view – show the direction of the camera when taking photos.
- Red lines/ arrows – the movement within the canyon.
- The number of people – the most crowded areas.
- Urban obstructions – trees and canyon geometry.
- Noticed glare – red dots; and sun patches – blue dots.
- Point “B” – measuring point for global illuminance.
- Photographs of each canyon’s façade material and its reflectance.

Some definitions were developed by the researcher to describe the canyon geometry and its color: “dense – white”; “wide – dark”; “high obstructed – specular”; and “high obstructed – colorful”.

O – Østergade

Canyon O is located in a commercial area. It has a dominating white façade on top of the buildings and glazed façade on the ground floors. This canyon is therefore called “dense – white”.

This canyon was highly accessible under sunny conditions and crowds of people would stop along the way. In an overcast condition, the number of pedestrians is reduced by ¾ of the sunny condition. The canyon itself did not have any other obstacles such as urban furniture or vegetation. Under sunny conditions, the façade causes glare. This phenomenon happened at the top of the canyon due to direct sunlight. That part was made of either glass or white paint. Both discomfort and disability glare, that causes the veiling effect, were observed. See *Figure 19*. All the data observed are shown in *Figure 20*.

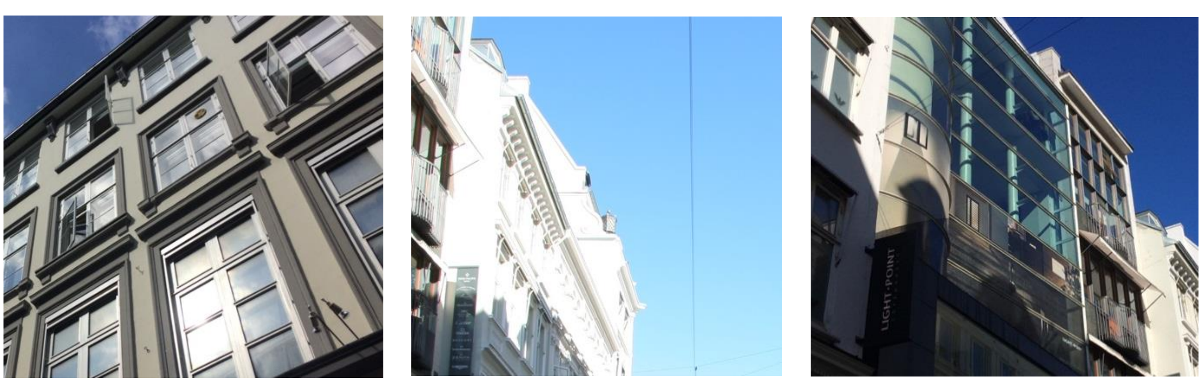


Figure 19 Images of glare - canyon O: left – glazing of the windows, center – the white façade, right – entirely glazed façade.

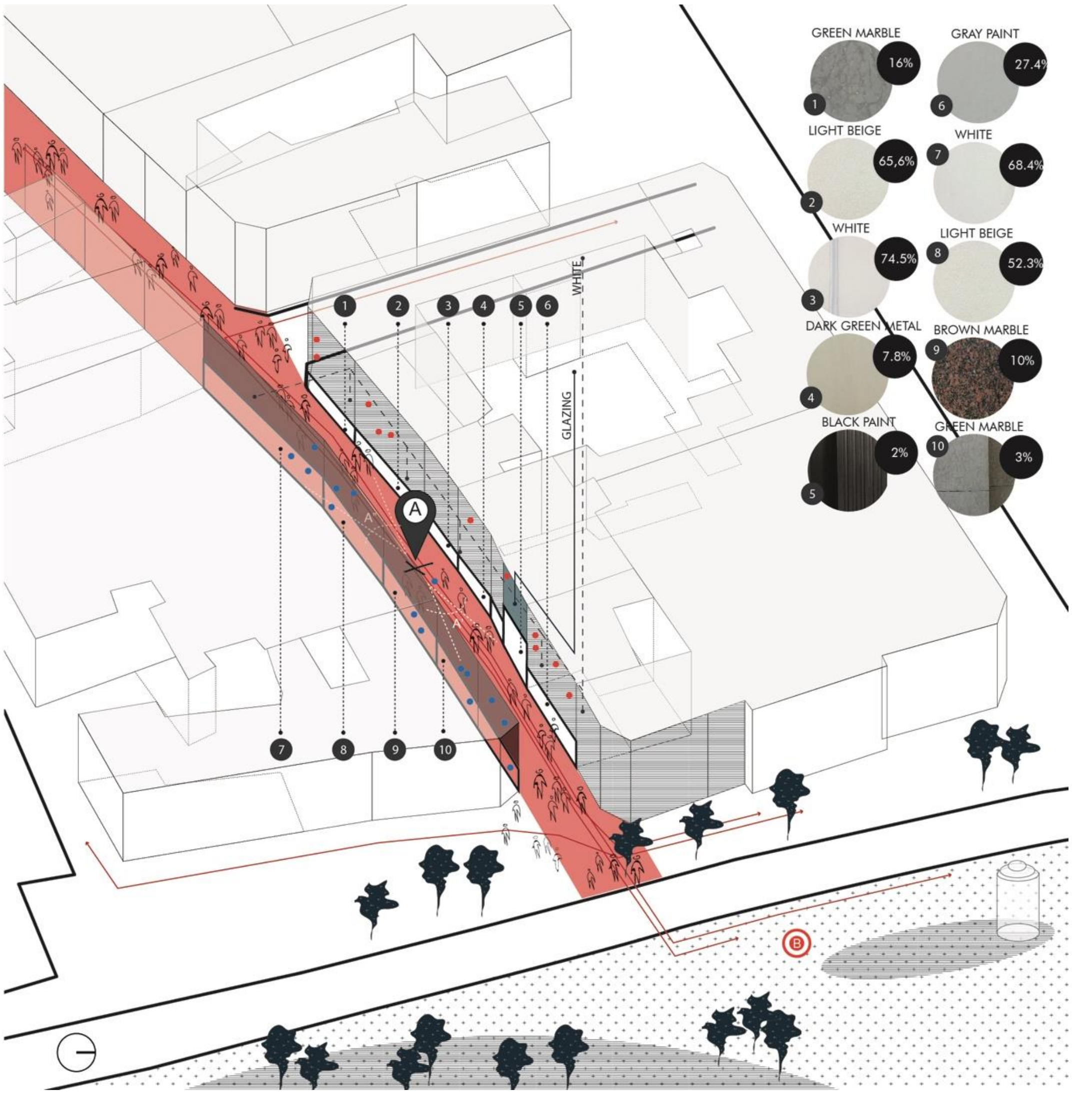


Figure 20 Canyon "O" measurements and additional information.

K – Krøyers Plads

Figure 22 shows canyon K, which the researcher referred to as a "wide – dark" canyon. This is one of Copenhagen's latest housing projects. Its geometry is wider than the other chosen canyons and the urban location gives the group of buildings a special characteristic. The façade is covered by dark brown brick material with a 12% reflection, while the balconies and entrances are framed by a 3% reflective black metal frame.

This canyon is regarded as a stop for people under sunny conditions. The most accessible paths are around the buildings. However, a small number of pedestrians walk through the canyon. A highly used path crosses the eastern building and leads to the canal. The favorite places to stop for people are along the canals and the small square in the southern part of the site, which also has small café. Under an overcast condition, pedestrians walk along the sides and avoid crossing the canyon. The canyon has other obstructions such as urban furniture and vegetation. In general, the canyon does not cause glare under sunny conditions, apart from some very specific occasions depending on the sun path. Glare is only caused by a small glazed façade. Some cases of glare are shown in *Figure 21*.

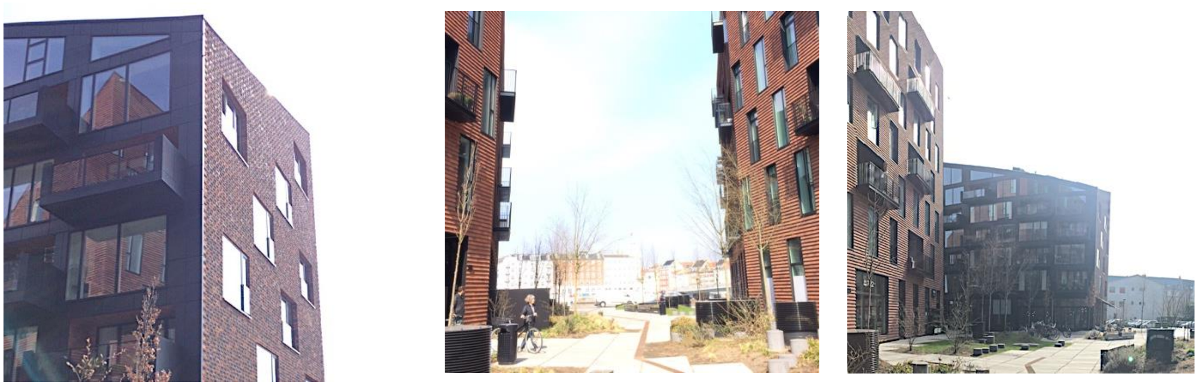


Figure 21 Images of glare – canyon K: left – obstructions, center – ground; right – glazing on the façade.

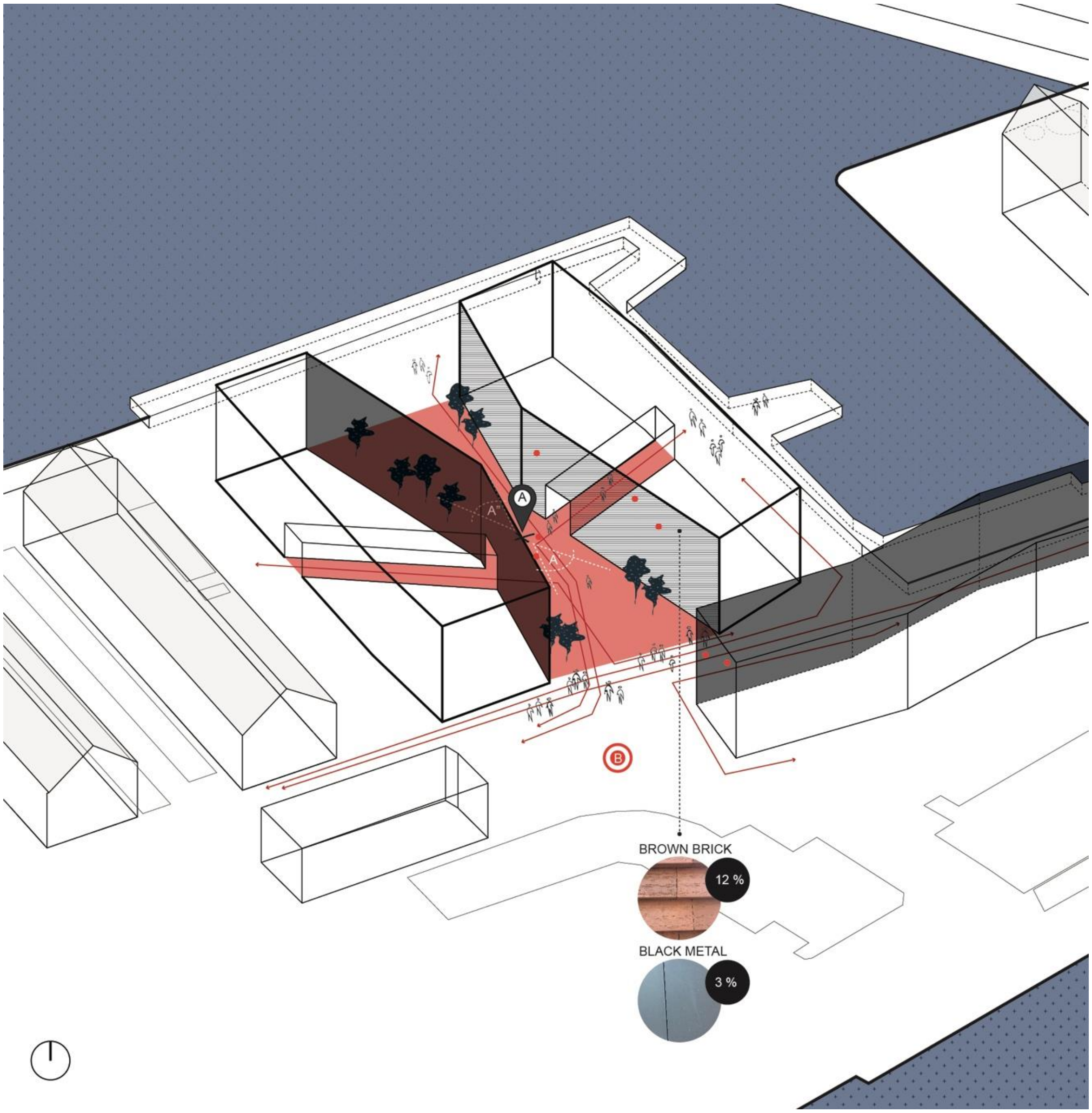


Figure 22 Canyon "K" measurements and additional information.

A – Århusgadekvarter

Figure 24 shows the "high obstructed – specular" canyon A. The canyon is located in a newly developed area characterized by innovative design and high buildings. This canyon has a gray metal façade with a reflection of 32.4% on one side and a dark brown brick façade with a reflection of 9.8% on the other.

This street is the access area to the residential building and has no additional public space function. It is rarely used as a street crossing to the canal, because the neighborhood is new and only a few people are around. The case study does not present any additional obstructions besides two small trees. We observed that under sunny conditions glare is caused by the metal façade or by the glazed windows of the front building. *Figure 23* shows some specific glare cases.

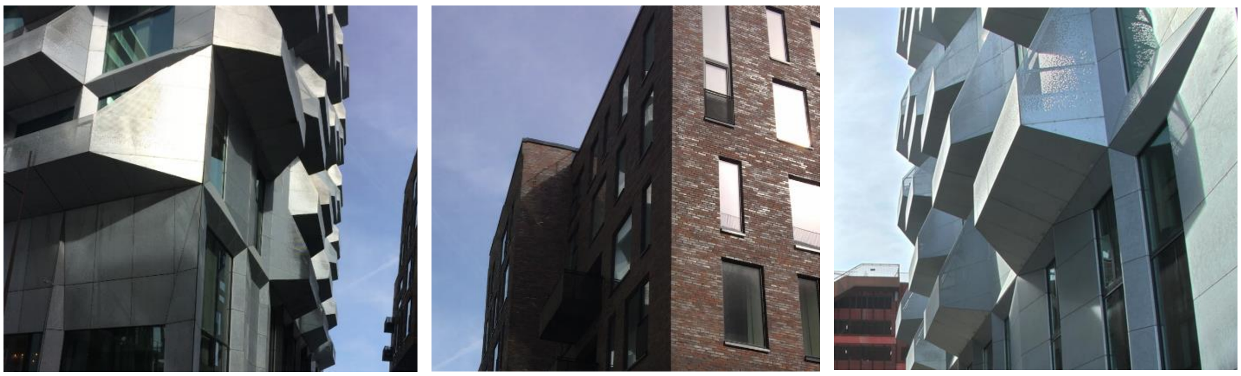


Figure 23 Images of glare – canyon A: left – metallic façade, center – glazed window; right – transparent metal grid.

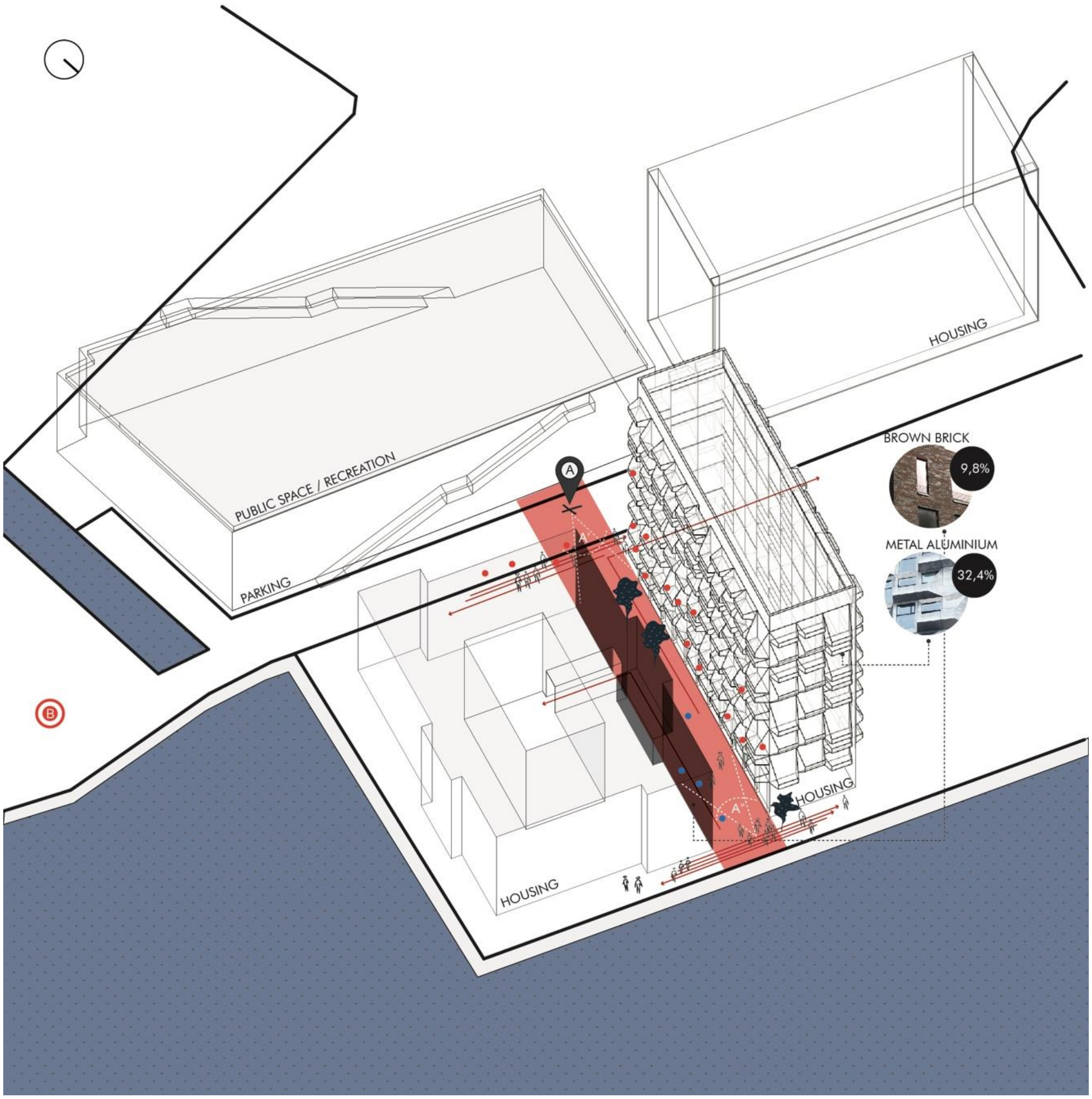


Figure 24 Canyon "A" measurements and additional information.

MG – Magstræde

Figure 26 shows the "high obstructed – colorful" canyon M. It is located in the center of town and is one of Copenhagen's oldest streets. Its façade consists of a mix of colored materials, bricks, plaster, and details. The material reflectance ranges from 11.4% for gray paint to 72% for light beige paint.

Under sunny conditions, this canyon was visited by many tourist groups. The road is overcrowded in certain occasions and accessibility is then disrupted. This canyon has some rare occurences of glare or sun-patches caused by the windows. *Figure 25* shows some cases of glare. In an overcast condition the number of foot-travelers drops dramatically, but the street was still appreciated for crossing. The canyon had no other obstructions.

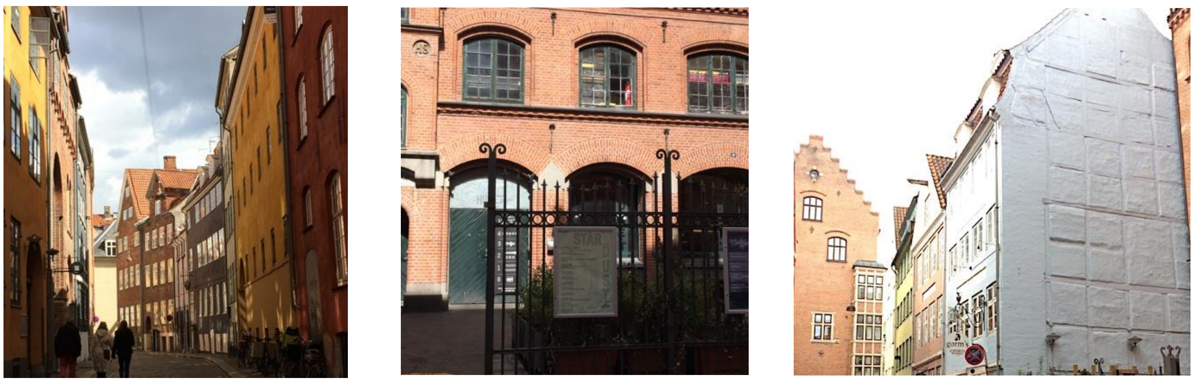


Figure 25 Images of glare – canyon M: left – glazed windows, center – reflective details or materials variation; right – the light color of the façade.

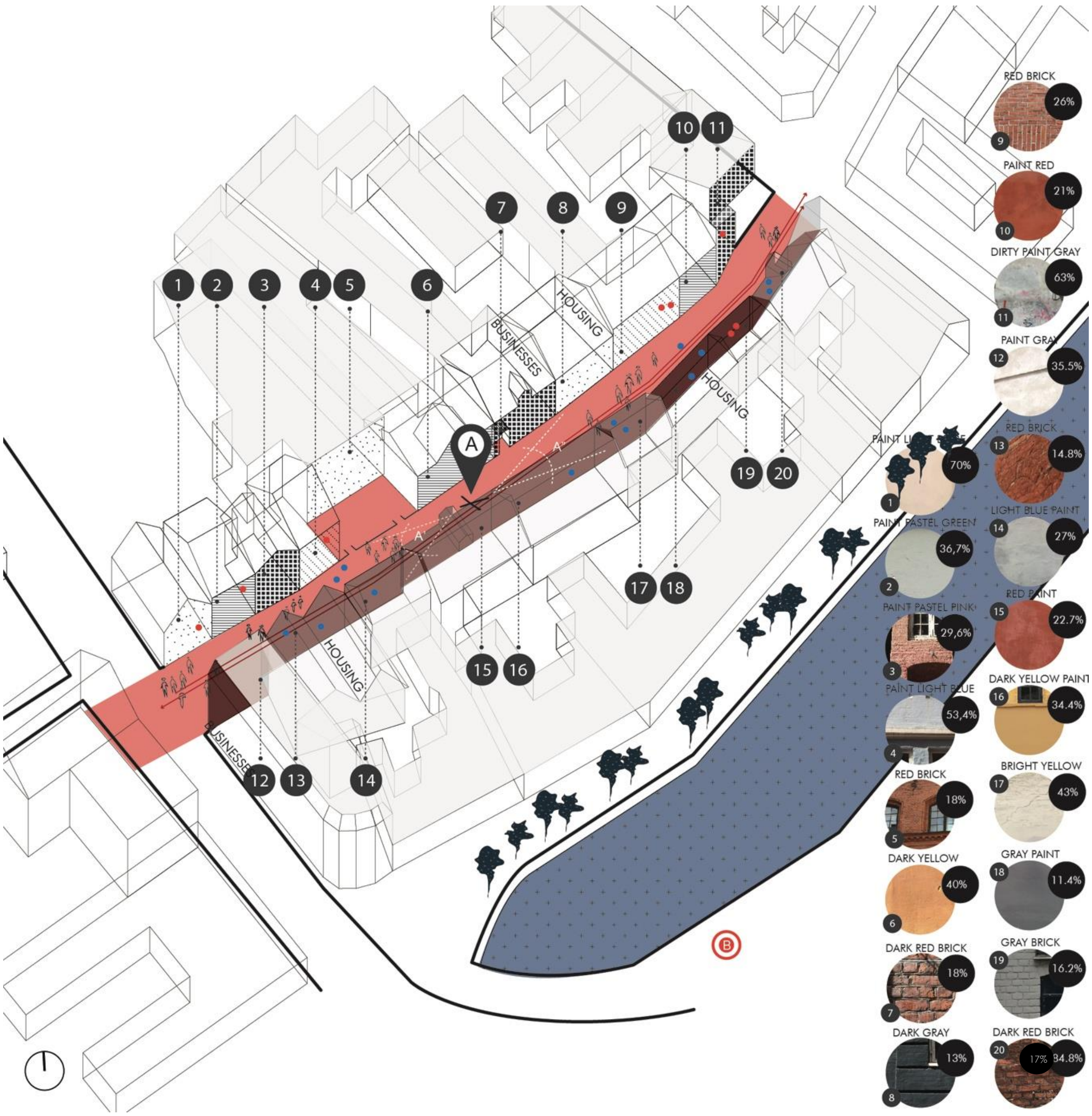


Figure 26 Canyon "M" measurements and additional information.

6.1.1 Illuminance and luminance measurements under sunny condition

The in-situ measurements were the basis for the development of light distribution analysis. The values obtained were illuminance (E) and luminance (L) in two zones, A^{I} and A^{II}. HDR photos are taken at point 1, covering both zones. *(NOTE one exception: the HDRs are taken from the sides only for canyon A).* The HDRs are used to produce false color luminance diagrams. The weather for this measurement set was sunny. See diagrams in *Figure 27*.

How to read the diagrams?
All numbers in red show the grid of points on a height 1.65 m.
All numbers in blue spread over the façade are measured in Photosphere-Alfa.
Blue pin A – camera location.
Low contrast numbers – unmeasured data.
High red contrast numbers – measured values of illuminance.
Blue numbers – measured luminance values.

The camera took a set of ten pictures with ten different exposures ranging from 10 (bright) to 4000 (dark). A luminance value was measured only at one point of the façade. The set of photos is assembled in the Photosphere-Alpha program and a false color diagram has been produced. The measured value is used to calibrate the false color diagram. The same value is entered manually in the pixel box corresponding with the measured point. Different luminance values were extracted for several points through the use of the program. The choice of points covered both bright and dark spots. *Table 9* contains the data acquired.

Interpreting Table 9

The contrast between canyon A and canyon O is higher than canyon K and canyon M. A white plaster material under direct sunlight can yield values of up to 15 600 cd/m^2 while the same material can fall to 716 cd/m^2 in the shadow. Canyon A has a higher luminance range between 42 600 cd/m^2 and 221 cd/m^2. This is because it has a high specular material. Canyon M, made up of many colorful façades, has a range from 12 400 cd/m^2 under direct sunlight to 232 cd/m^2 under the shadow. While the dark façade of canyon K has luminance values from 4010 cd/m^2 under the sun to 291 cd/m^2 under the shadow.

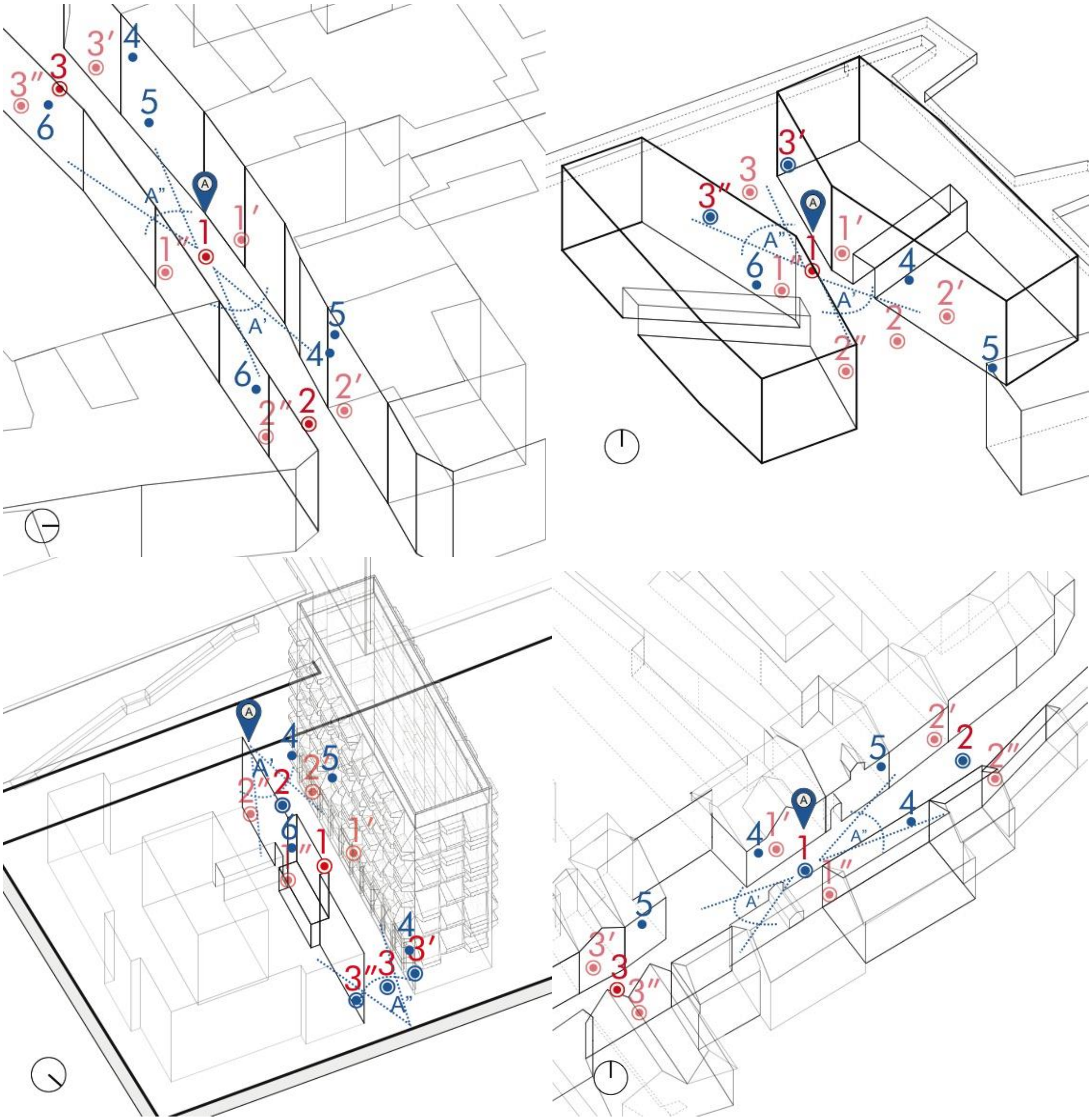


Figure 27 Diagrams with points of measurement of illuminance and luminance values and HDR photographs

Table 9 Illuminance and luminance values on different points of the canyons.

CANYONS[3]/ POINTS[4]			P 1	P 2	P3	P 3’	P 3”	P 4	P 5	P 6
O – Østergade	A^I	E_H (lux)	7255	6780	- !	- !	- !	- ^	- ^	- ^
		L_V (cd/m^2)	- !	- ^	- !	- !	- !	931	12500*	1520
	A^{II}	E_H (lux)	7255	- !	7634	- #	- #	- ^	- ^	- ^
		L_V (cd/m^2)	- #	- !	- #	- #	- #	15600*	716	3090
K – Krøyers Plads	A^I	E_H (lux)	77570	11490	- !	- !	- !	- ^	- ^	- ^
		L_V (cd/m^2)	- #	- #	- !	- !	- !	3480*	792*	**132**
	A^{II}	E_H (lux)	77570	- !	**81790**	- !	- !	- !	- !	- !
		E_V (lux)	- !	- !	- !	6578*	**6344**	- ^	- !	- !
		L_V (cd/m^2)	- #	- !	- #	**4010***	**291**	789	- !	- !
A - Århusgad ekvarter	A^I	E_H (lux)	**809**	833	1484	- ^	- ^	- !	- !	- !
		L_V (cd/m^2)	- #	1050	- ^	- ^	- ^	**42600***	4560	**221**
	A^{II}	E_H (lux)	**809**	833	1484	- #	- #	- ^	- !	- !
		L_V (cd/m^2)	- #	- ^	952	504	149	9390*	- !	- !
M – Magstræde	A^I	E_H (lux)	9294	- 9915	- #	- #	- #	- !	- !	- !
		L_V (cd/m^2)	391	- !	- #	- #	- #	4990*	**14700***	389
	A^{II}	E_H (lux)	9294	- 6234	- !	- !	- !	- ^	- ^	- !
		L_V (cd/m^2)	- #	524	- !	- !	- !	942	2400*	- !

NOTE: some of the values in Table 9 are missing for different reasons. The symbols explain each reason. Please read carefully.
! – does not exist in that field of view / or does not exist as a value
^ – cannot be measured because the point is too far to reach
 # – it is not measured because is not needed or too far away to have an impact

The consecutive set of photos, *Figure 28, Figure 29, Figure 30, Figure 31* shows the collection of HDRs and the falsecolor diagrams produced by Photosphere-Alpha in sunny condition. The luminance values produced by the program are included in the FC diagrams.

[3] *All the values that have the symbol (*) show that the sun is falling directly on the material. All the rest of the data is collected under the shadow.*

Figure 28 Canyon "O". Top – A^{I}, bottom – A^{II}. Left side – HDR photos, right side – false color diagrams and points of measurements.

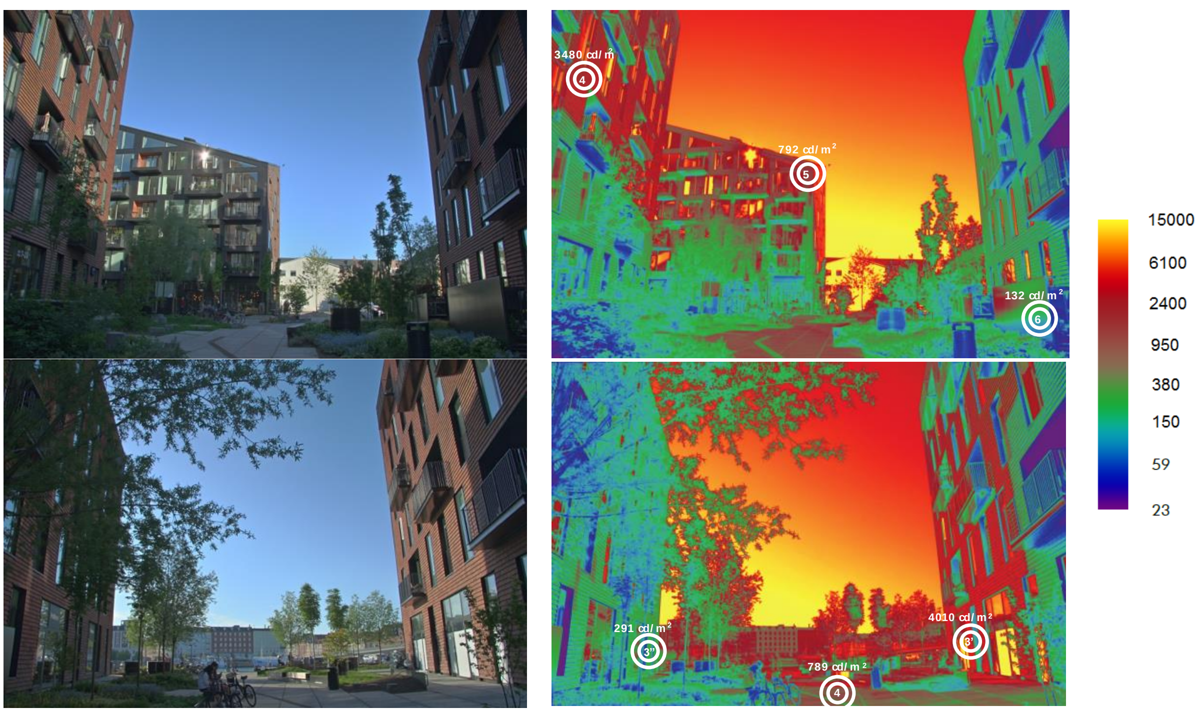


Figure 29 Canyon "K". Top – A^{I}, bottom – A^{II}. Left side – HDR photos, right side – false color diagrams and points of measurements.

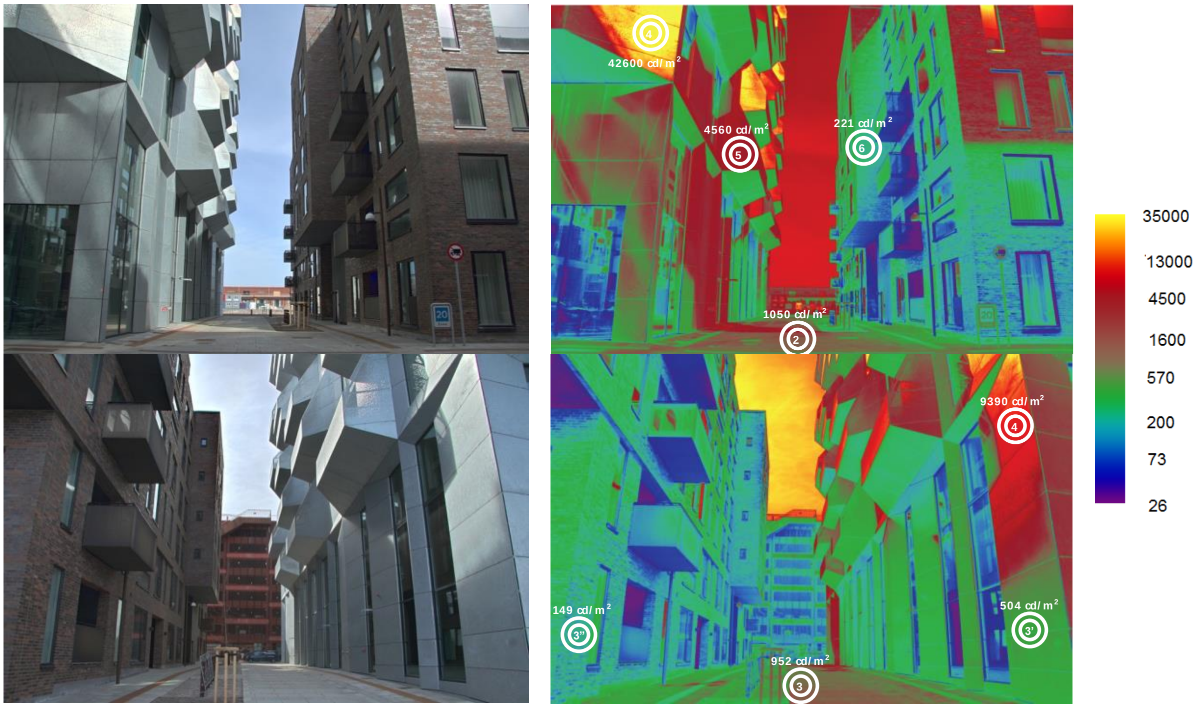


Figure 30 Canyon "A". Top – A^I, bottom – A^{II}. Left side – HDR photos, right side – false color diagrams and points of measurements.

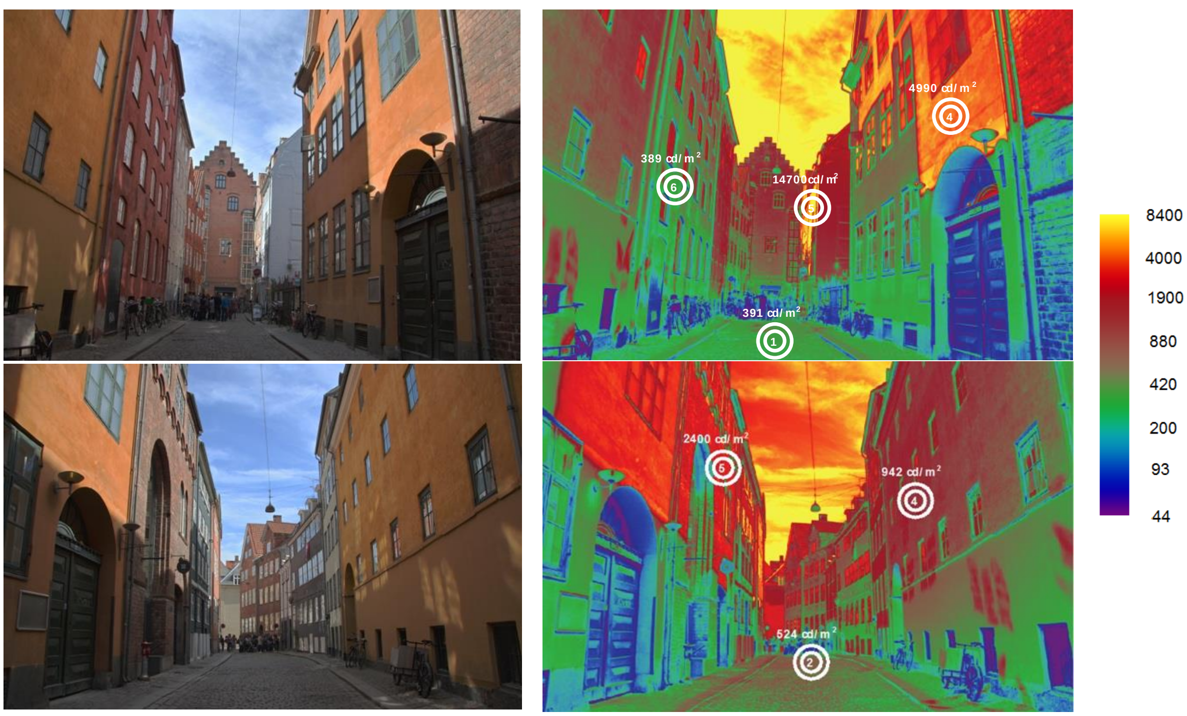
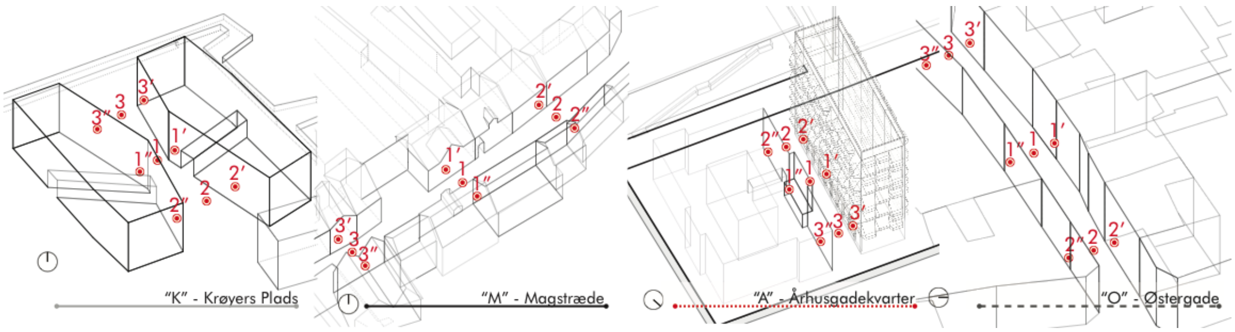


Figure 31 Canyon "M". Top – A^I, bottom – A^{II}. Left side – HDR photos, right side – false color diagrams and points of measurements.

6.1.2 Grid based illuminance measurements under overcast conditions

The illuminance on a grid of points was measured for overcast conditions. The horizontal illuminance was measured for points 1, 2 and 3, while the vertical illuminance was measured for the rest. Global illuminance was measured in an unobstructed location. These data are used to calculate the DF and VDF. The canyon is treated as an "indoor" space in theory. The graphs in *Figure 32* and *Figure 33* show data collection for both DF and VDF. The DF values on the DF scale are 40 points higher than the VDF values. Canyon K has a DF of ten points higher than canyon O on the DF scale.



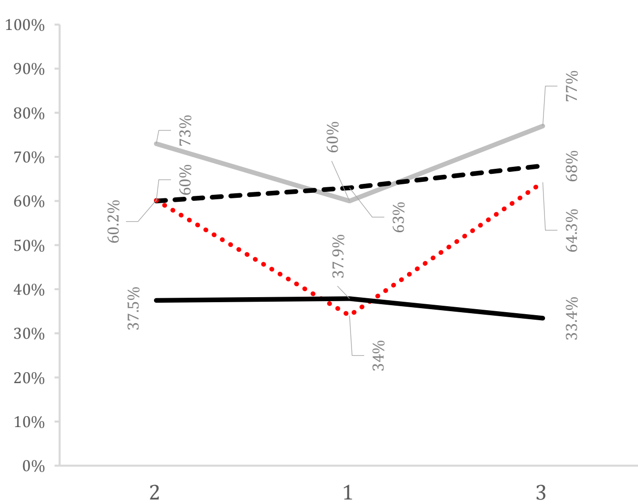


Figure 32 DF for all the canyons

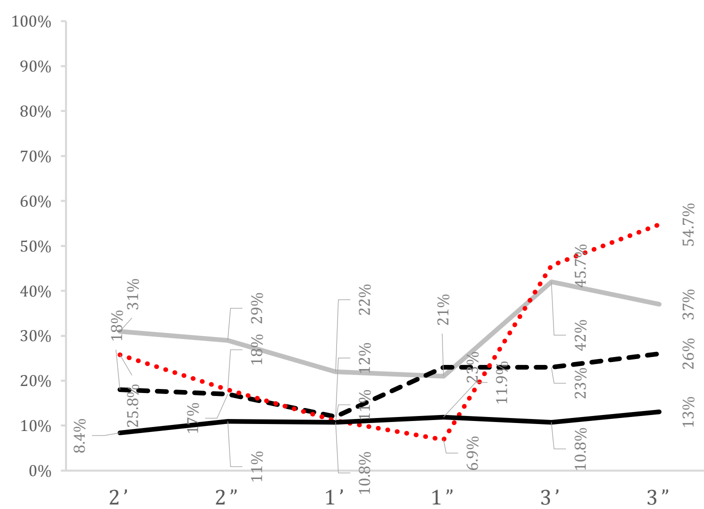


Figure 33 VDF for all the canyons

6.2 Subjective assessment

6.2.1 Part 1 & 2 – statistical data on the quantity of surveys, familiarity with the street canyons and visual adaptation

For each street canyon, 60 questionnaires were planned, 30 for overcast and 30 for sunny sky condition. Of the 240 intentional surveys, a total of 192 were completed due to weather conditions, lack of time and unavailability of the pedestrians. *Table 10* shows all the statistical data concerning the number and gender respondents in each canyon.

Table 10 Number of answered questionnaires per street canyon.

Questionnaires / Canyons	O - Østergade	K – Krøyers Plads	M - Magstræde	A - Århusgadekvarter
Sunny condition	28	22	21	26
Overcast Condition	25	27	21	22
Total Number of respondents	**53**	**49**	**42**	**48**
Male / Female	25 / 28	19 / 29	17 / 25	22 / 26

Of the 192 responders, 147 were tourists and the rest were residents. Tourists came from Mediterranean countries with a small percentage of Nordic countries, whereas the local population was few. Only the locals were familiar with the canyons, while the majority of tourists visited the canyon for the first time. See *Figure 34* for more.

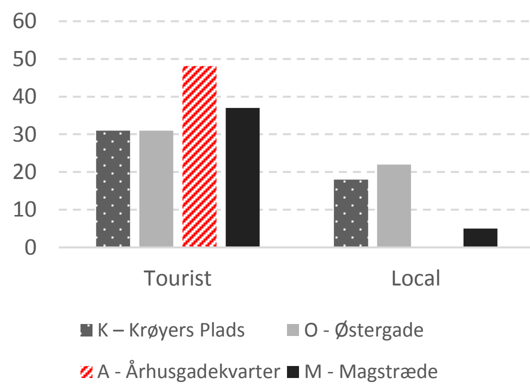


Figure 34 Quantity of tourists and locals per each urban canyon.

The majority of the respondents were outside for about 30 minutes to an hour. *Figure 35* shows the exact number of people. The major age group was between 19 and 29, see *Figure 36.*

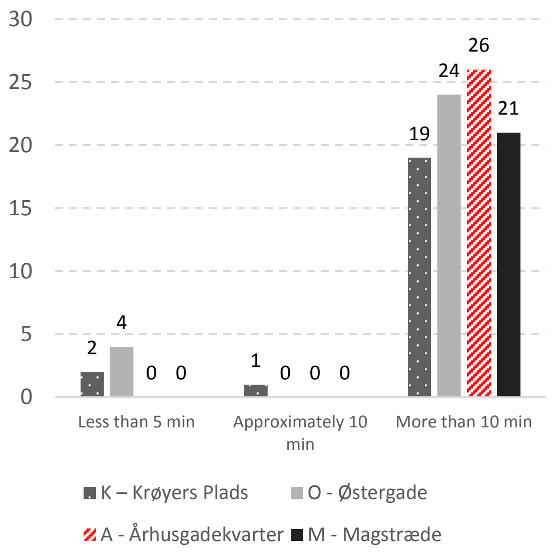


Figure 35 Respondents' quantity and the time they spent outdoors before reaching the canyon.

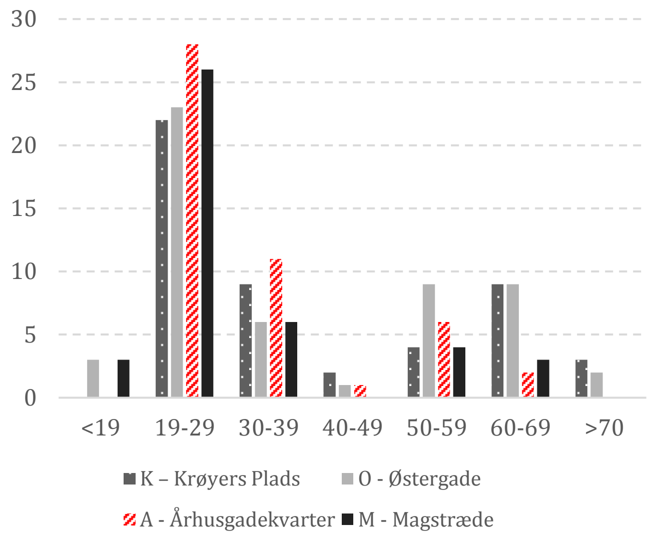


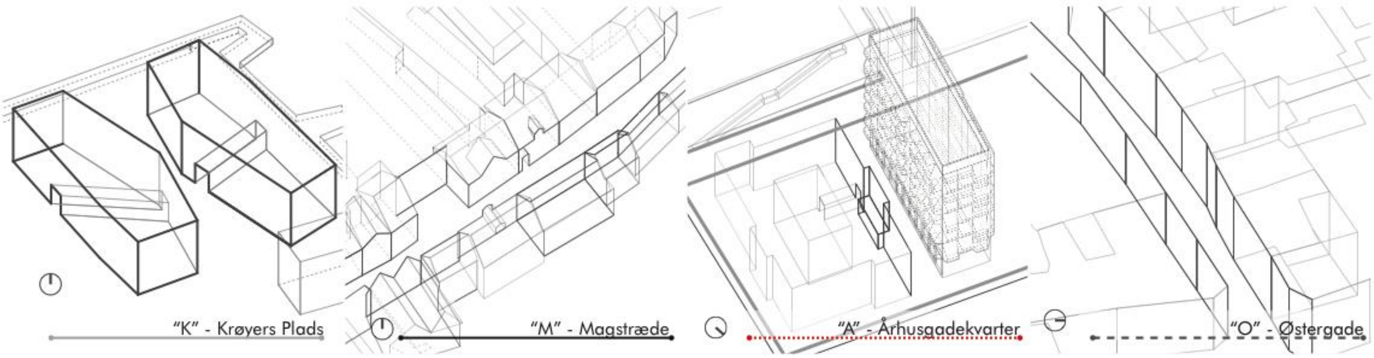
Figure 36 The age group of respondents.

6.2.2 Mixed results

This section presents the results in two graphs for each individual question, one for an overcast and one for a sunny condition. All four canyons are represented together in the same graph. Please find detailed graphs in **Appendix A**.

6.2.2.1 Part 3 - daylight level

3a. How would you describe daylight in this street canyon?



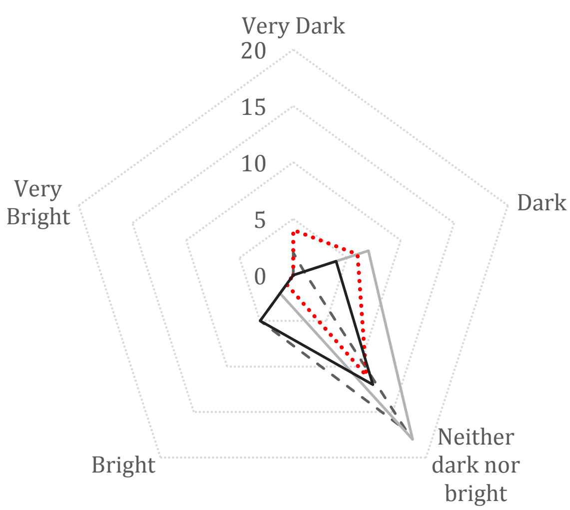


Figure 37 Question 3a – overcast condition

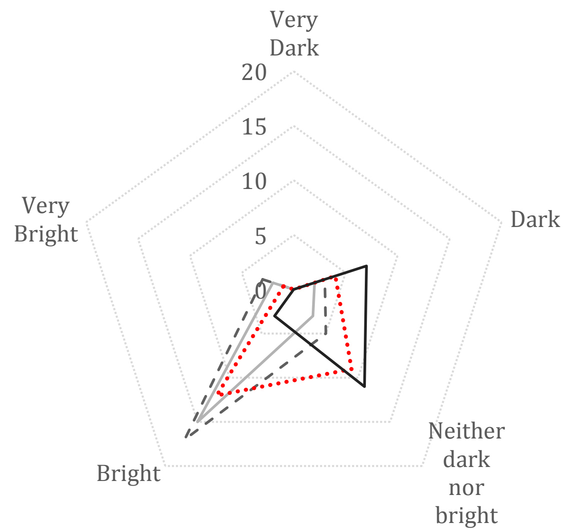
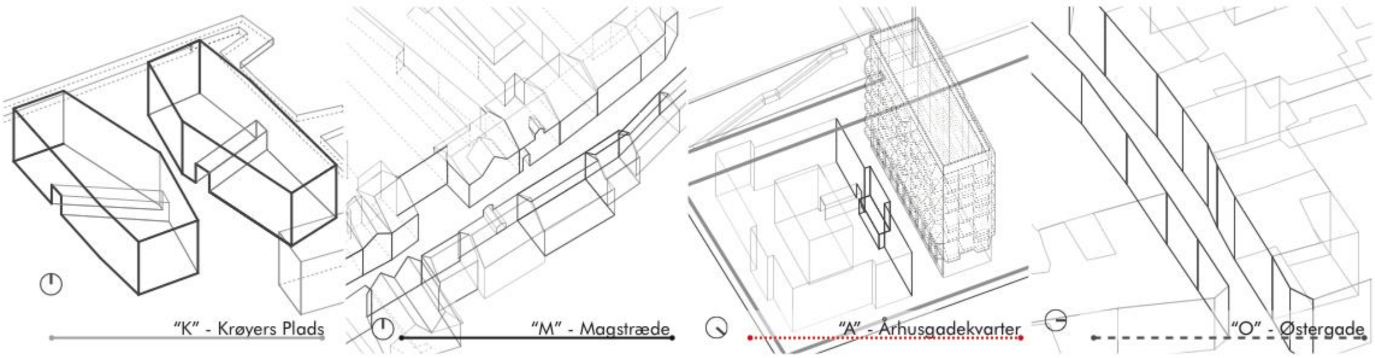


Figure 38 Question 3a – sunny condition

Overcast: "neither dark nor bright" was the dominating answer for this chart, see *Figure 37*. Canyons K and O top the chart. They have 18 and 17 answers respectively, making 68% of the respondents. O matches M with five respondents in the range of "bright", accounting for 20% of their total. It is noted that the "dark" range dominates K and A with 7 answers (26%) and 6 answers (27%) respectively, while canyon A dominates the "very dark" range with 4 answers (18%).

Sunny sky: In *Figure 38* canyon K and O dominate the chart as “bright” canyons with 15 answers (68%) and 17 answers (61%). Canyon A is perceived “bright” by 12 (46%) respondents and as “neither dark nor bright” by 9 respondents (35%). Canyon M is seen as “neither dark nor bright” by 11 respondents (52%) and as “dark” by 7 respondents (33%).

3b. How would you wish to change daylight in this street canyon?



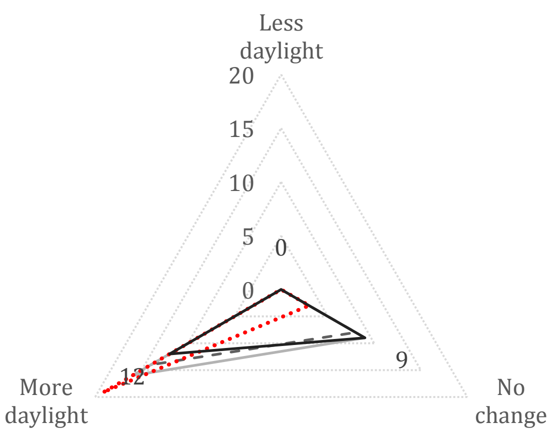


Figure 39 Question 3b – overcast condition

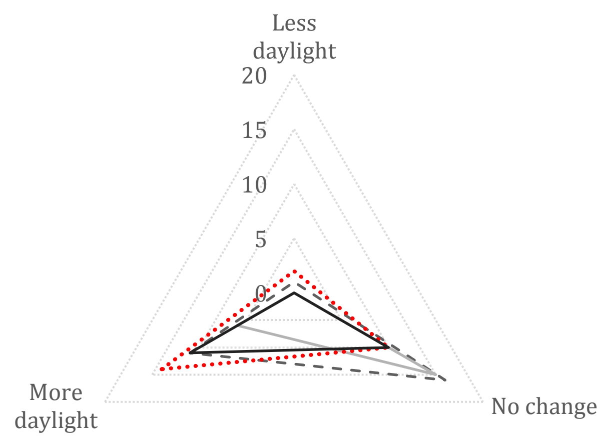


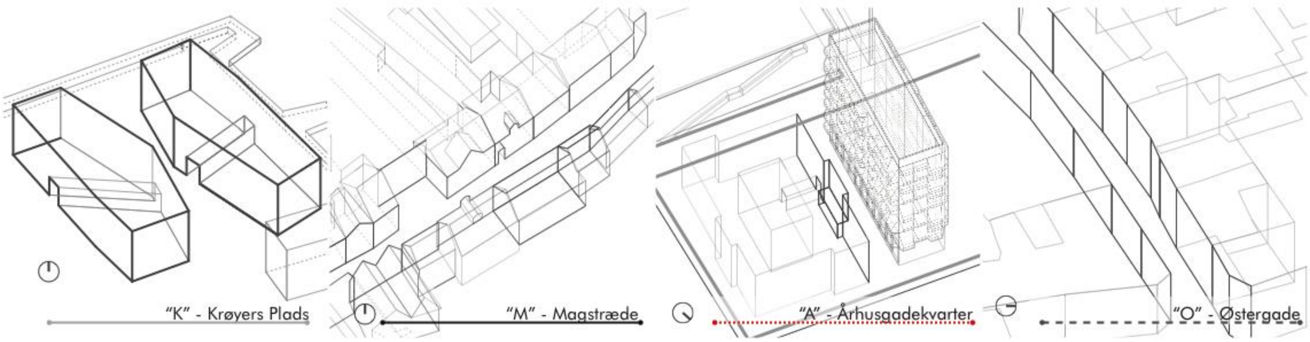
Figure 40 *Question 3b – sunny condition*

Overcast: The chart, as shown in *Figure 39*, is dominated by the “need for more daylight”. The answers for canyons O, K, A, and M are respectively: 14 (58%), 16 (59%), 19 (86%) and 12 (57%). Canyon A dominates the chart with the highest number of respondents requiring additional daylight. A small amount replies, “there is no need for change”. That group is: nine respondents making (43%) for M, nine respondents for K and eight for O making (33%) of the total per each canyon.

Sunny sky: the answers changed under this condition, see *Figure 40*. Canyon A has a proportionate distribution of answers, same as canyon M. The dominant answer was a "need for more daylight", with 14 respondents (54%) for canyon A and 11 respondents (52%) for canyon M. Another similar pattern appears with canyon O and K. Respondents answered mainly "they need no change". For this answer, canyon O and canyon K dominated the chart with 16 respondents (58%) and 15 respondents (71%) respectively.

6.2.3 Part 4 - daylight distribution

4a. How would you describe the distribution of daylight in this street canyon?



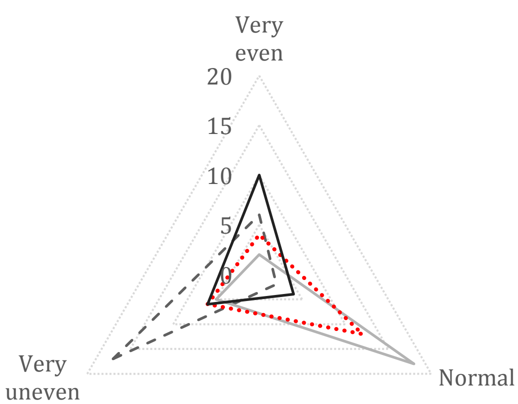


Figure 41 Question 4a – overcast condition

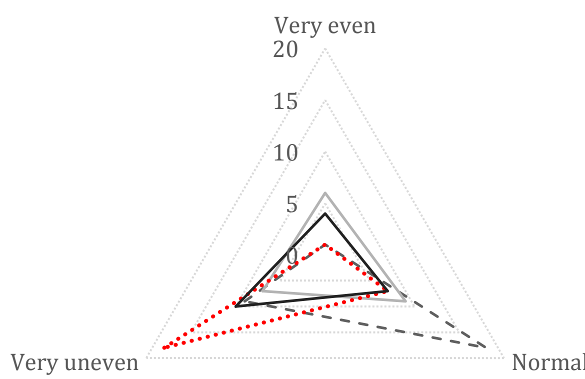
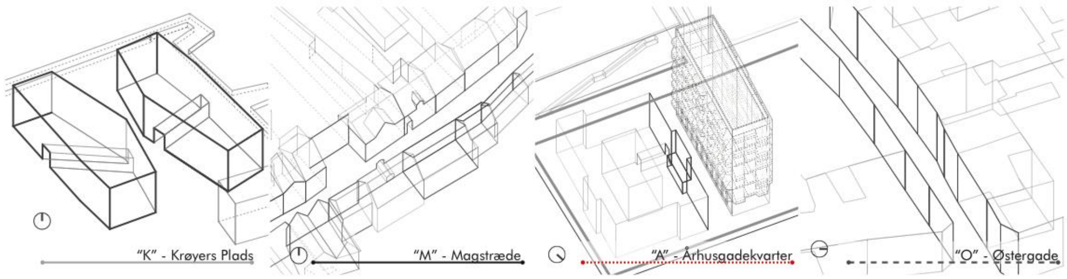


Figure 42 Question 4a – sunny condition

Overcast: Canyon O dominates the graph as a canyon with a very uneven daylight distribution for 17 (68%) respondents under overcast condition. M is dominant as a canyon with a very even daylight distribution for 10 respondents (50%) and an uneven daylight distribution for 6 respondents (30%). For K the perception of light distribution is normal for 18 (72%) respondents. For canyon A, 12 (55%) say that daylight distribution is normal, while 6 (27%) say that it is very uneven and 4 (18%) say that it is very even.

Sunny sky: the perception changes completely for each canyon under direct sunlight. Canyon A dominates for an uneven daylight distribution with 18 respondents (63%) and K for a normal daylight distribution with 9 respondents (41%). For K and M, the answers are: 7 (32%) very uneven, 6 (27%) very even, 9 (41%) normal; and 10 (48%) very uneven, 5 (19%) very even, 7 (33%) normal. The daylight distribution in canyon O is considered normal for 18 (64%) and uneven for 9 (32%) respondents.

4b. Does this street canyon have many dark areas that make the space uncomfortable?
4c. Does this street canyon have many bright areas that make the space uncomfortable?



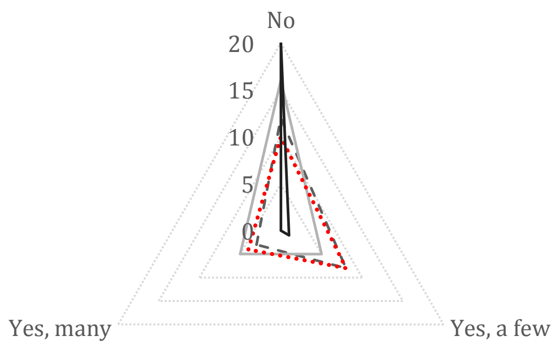


Figure 43 Question 4b - overcast condition

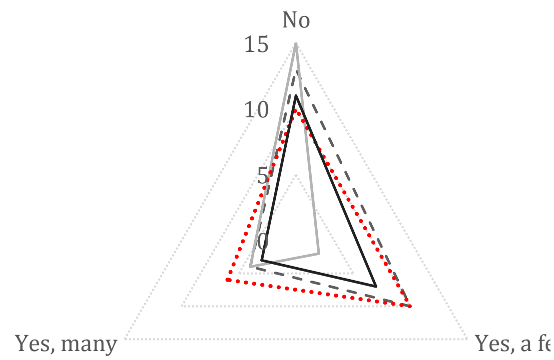


Figure 44 Question 4b – sunny conditions

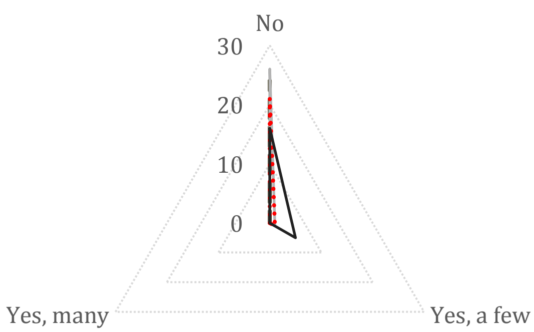


Figure 45 Question 4c – overcast condition

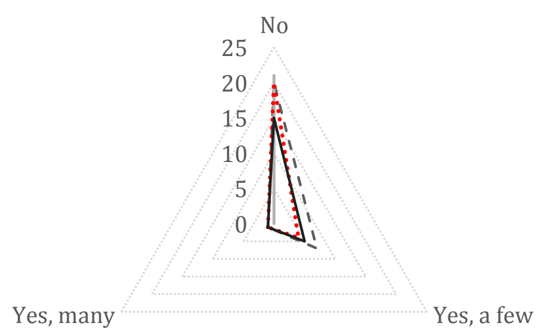


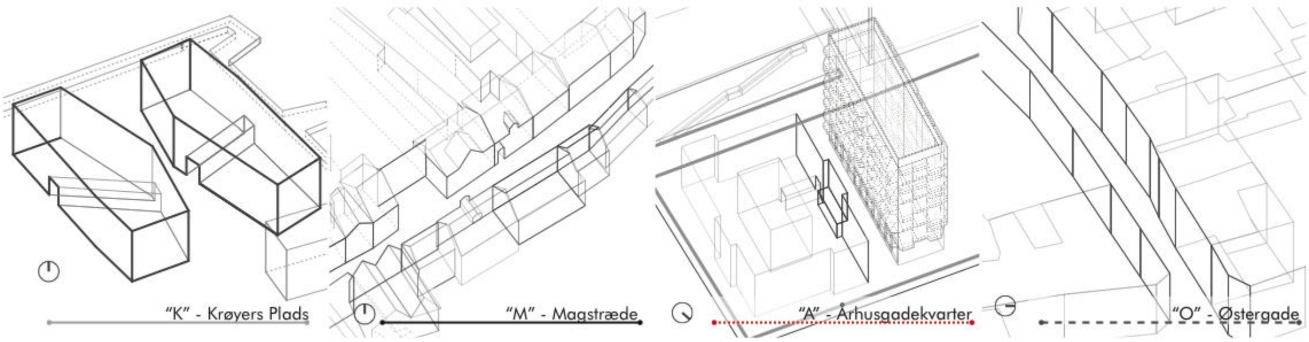
Figure 46 Question 4c – sunny condition

Overcast: ***Error! Reference source not found.*** shows dark areas of discomfort. The dominating answer w as "no dark discomfort". However, the difference between "yes" and "no" was very narrow. Canyon A and O had 12 respondents (54%) and 11 respondents (48%) who felt a dark discomfort, respectively. Canyon K had ten respondents (38%) who felt a bit of discomfort, while canyon M did not have any discomfort. *Figure 45* shows discomfort caused by bright areas. The survey revealed no such discomfort.

Sunny sky: Figure 44 shows discomfort caused by dark areas under a sunny sky condition. In this chart canyon A is dominating with 16 respondents (61%) reporting discomfort. The same applies for canyon O and canyon M with a total of 14 respondents (52%) and 10 respondents (47%). In canyon K, discomfort is almost non-existent. *Figure 46* shows discomfort caused by bright areas. The dominating answer for this chart was "no discomfort". However, a very small percentage of respondents felt discomfort: five (20%) in canyon A; eight (29%) in canyon O; and five (24%) in canyon M. Nobody reported any kind of discomfort from bright areas in canyon K.

6.2.4 Part 5 – direct sunlight

5a. Do you experience direct sunlight in this street canyon?
5b. Do you experience outdoor glare in this street canyon?



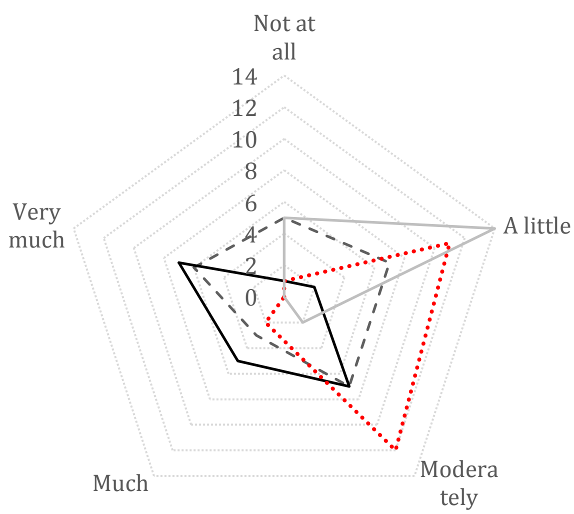


Figure 47 Experiencing direct Sunlight.

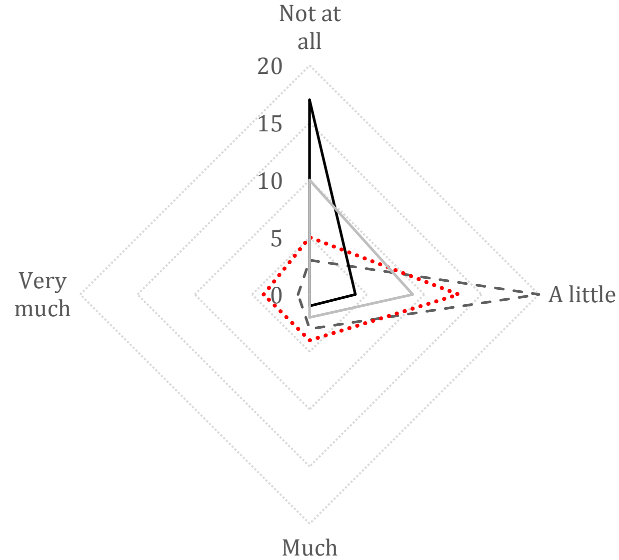


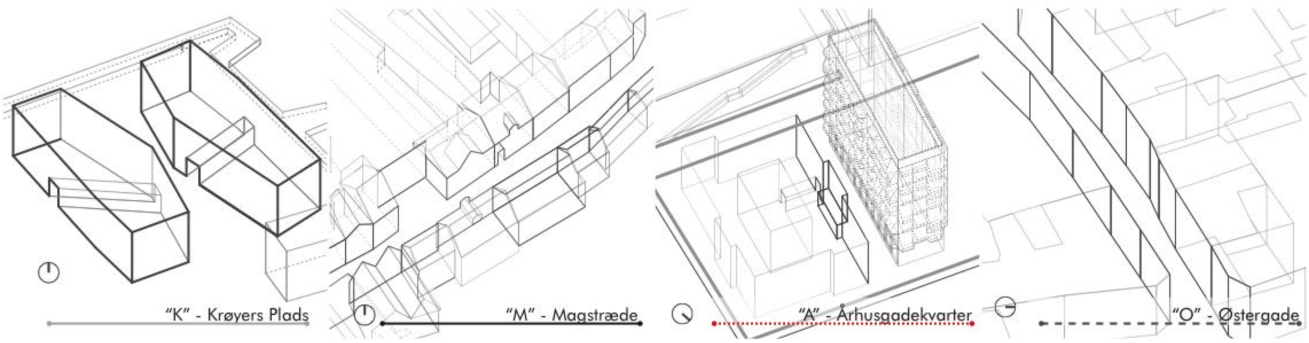
Figure 48 Experiencing glare.

Figure 47 shows the effect of direct sunlight on every canyon. Canyon K receives the highest amount of direct sunlight with 7 respondents (32%) saying "very much and moderately" and 5 respondents (23%) saying "much". Canyon M is one of the darkest with 14 respondents (67%) answering as "a little" and 5 respondents (24%) answering as "not at all". Canyon O varies greatly on how people perceive direct sunlight. The respondents answered to the following 6 (21%) as "very much", 3 (11%) as "much", 7 (25%) as "moderately"/ "a little" and 5 (18%) as "not at all". Canyon A gets "moderate" sunlight according to 12 respondents (46%) and "a little" according to 11 respondents (42%).

Figure 48 shows the perceived glare caused by direct sunlight or reflected sunlight. The graph shows that canyon K lacks the effect of glare. Additionally, canyon M has 10 respondents (48%) answering “not at all glare” and 9 respondents (43%) answering “a little glare”. With 20 respondents (74%) canyon O dominates the chart for having “a little glare”. While canyon A contains 13 respondents (50%) answering “a little glare”.

6.2.5 Part 6 – physical environment

6a. How would you describe the street canyon geometry/ buildings densification?
6b. Would you choose to stop and enjoy the public space inside this street canyon?



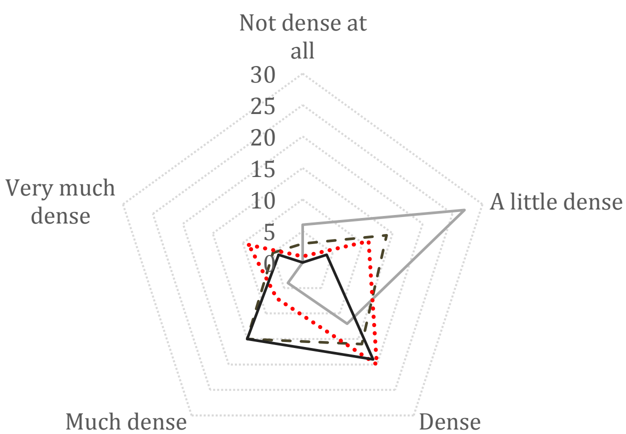


Figure 49 Question 6a – both sky conditions

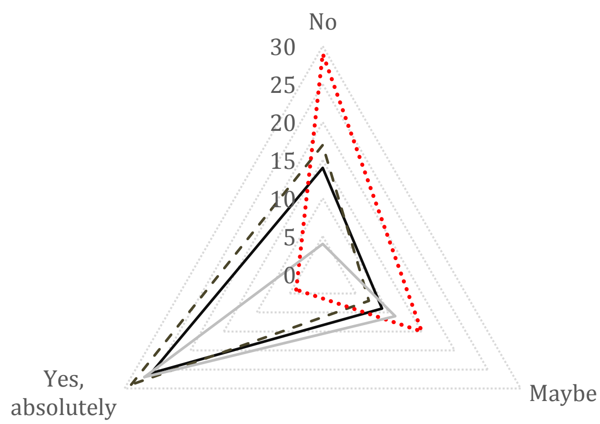


Figure 50 Question 6b – both sky conditions

Figure 49 shows how people perceive the amount of obstructions, or in other words, the density of building. This answer includes both overcast and sunny condition. Canyon M is perceived as “dense” for 19 respondents (45%) and “much dense” for 15 respondents (36%). Canyon A is considered “a little dense” for 11 (23%), “dense” for 20 (42%), “much dense” for 7 (15%) and “very much dense” for 9 (19%) respondents. Canyon O is perceived as “a little dense” for 26%, “dense” for 30%, “much dense” for 7 (28%) and “very much dense” for 9 (19%) respondents. Canyon K is perceived “a little dense” for 27 respondents (55%) and “dense” for 12 respondents (24%).

Figure 50 examines the quality of the space inside the canyon and whether the pedestrians want to stop and enjoy the space. The graph shows that canyons K, O, and M are popular, and most respondents choose to stop and enjoy the public space. However, 17 (38%) respondents in canyon O and 14 (29%) respondents in canyon K would not stop. For canyon A, 29 (60%) respondents do not stop to enjoy the space inside the canyon.

6.3 A grading scale

All the data collected and described on the results are shown in the following group of figures. To compare all the results, it was important to define a weighting system for each answer and scale it. A scale from one to five is used for this case. This distribution is shown in *Table 11*.

Table 11 Grading scale from 1-5 for each question of the questionnaire.

Questions / Grading Scale	1	2	3	4	5
3a. Daylight perception	Very dark	Dark	Neither dark nor bright	Bright	Very Bright
3b. Need for more or less daylight	Less Daylight		No change		More Daylight
4a. Daylight distribution	Very uneven		Normal		Very even
4b. Dark discomfort areas	No		Yes, a few		Yes, many
4c. Bright discomfort areas	No		Yes, a few		Yes, many
5a. Direct Sunlight	Not at all	A little	Moderately	Much	Very much
5b. Glare	Not at all	A little		Much	Very much

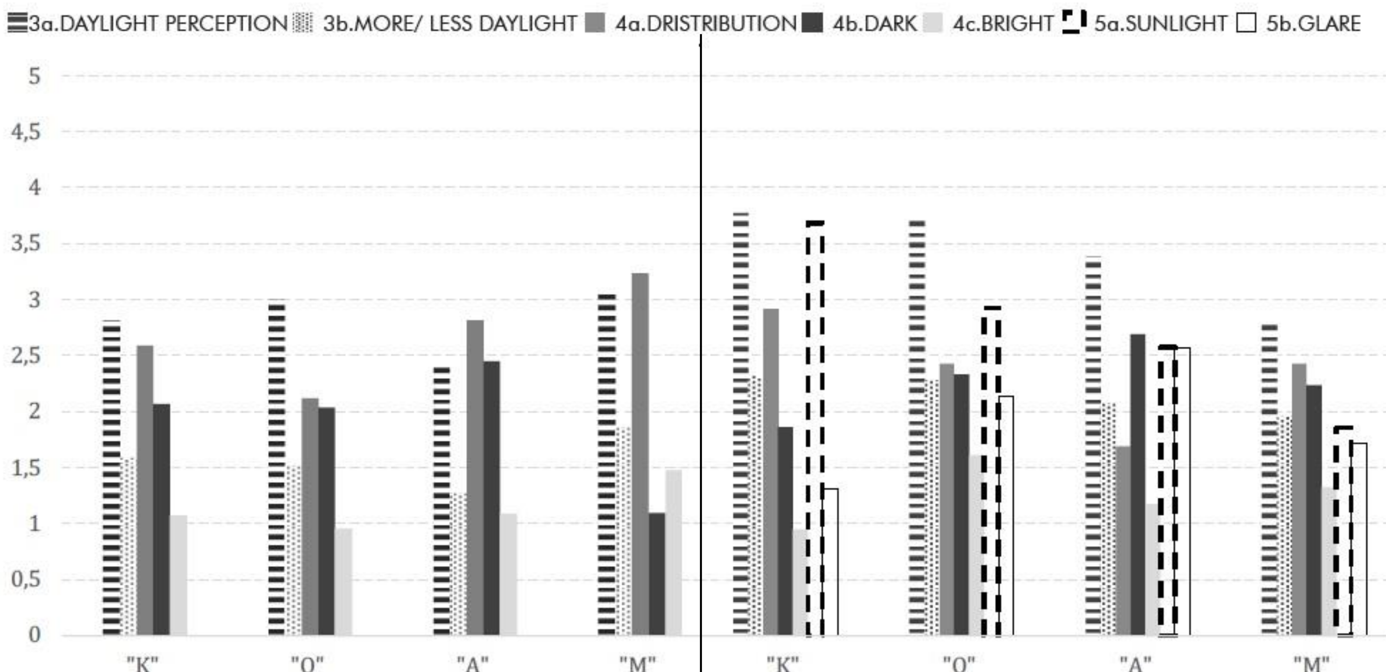


Figure 51 Grading system for four canyons under overcast conditions.

Figure 52 Grading system for four canyons under sunny conditions

Figure 53 and *Figure 54* show the grade given to each question after weighting all results. This grading system allows the canyons' results to be compared. The general trend shows that all the canyons need more daylight for both sky conditions. It is also noted that for every sky condition the effect of each canyon is totally different.

6.4 A diagrammatic explanation of questionnaires and data

The results including questionnaires and the measured data are represented in *Figure 53* and *Figure 54*, for two sky conditions. The thin lines crossing the diagram represent each canyon and its performance on various daylight aspects.

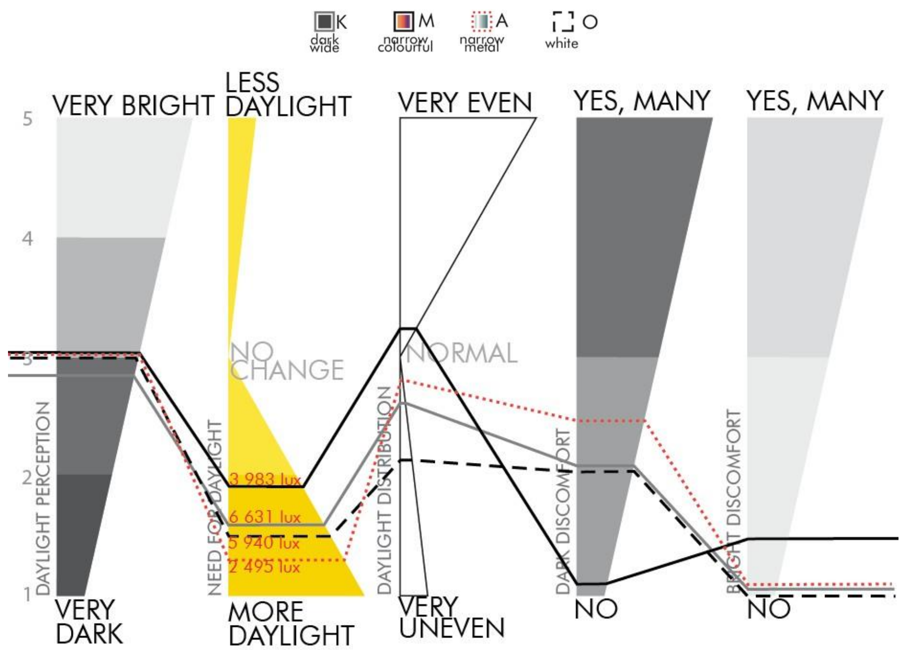


Figure 53 Grading scale showing survey results and measurements under overcast condition.

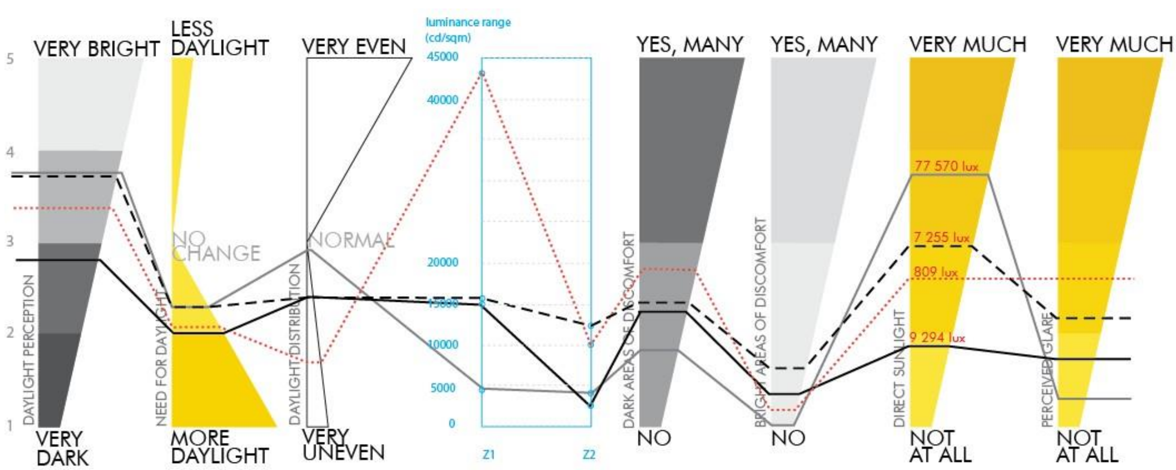


Figure 54 Grading scale showing survey results and measurements under sunny sky conditions.

Overcast condition: Daylight level and illuminance measurements.

- If we compare the illuminance value for canyon K and canyon O, there is a difference of 691 lux. This number is not that high, which means that canyon O performs nearly the same as a wide canyon. The façade material affects the illuminance value.
- If we compare canyon O and canyon M, the illuminance range between the two is 1957 lux. Canyon M has a material that absorbs more daylight and bounces less back. Therefore, it looks darker than canyon O.
- If we compare canyon M and canyon A, the difference is 1488 lux. It means that canyon A blocks more daylight due to the geometry and its highly reflective material that reflects the color of the gray sky.
- Canyon A is a “high obstructed – specular” canyon. It stands in the first place due to the gloomy experience created inside the canyon. The façade material of one side had a high-specularity reflection of 32,4% and created a dark impression inside the canyon. While the other side of the canyon had a brick façade with a reflection of 9,8%, eventually bouncing low amounts of light.
- Canyon M is a “high obstructed – colorful” canyon. The façade, painted in a variety of colors, reflected light differently from 11% to 70%. The colors were perceived dark under overcast condition even though measurements show a wide spectrum of reflectance. However, this observation is affected by the location of the people inside the canyon and the range of colors located closer to their visual field. Inside their visual field, the colors fall in the range of low reflectance from 11% to 35%.
- Canyon K is a “wide – dark” canyon. This canyon had a wide geometry, but its dark red brick façade with a reflectance of 12% and black finishes of 3% created a dark atmosphere.
- Canyon O is a “dense – white” canyon. It needs less daylight compared with the others because of the white reflective material of 74,5%.

Sunny sky condition: Daylight level and illuminance measurements.

- If we refer to the geometry, canyon K which is a wide canyon has the highest illuminance value. For sunny condition, its façade material does not play any significant role.
- If we compare canyon O with A and M, which were perceived same density, in terms of illuminance level show that canyon M, “high obstructed – colorful”, had the highest values. While canyon O stands in the second place and canyon A in the third place. This means that the white reflective façade of 74,5% in canyon O affects the light level, while façade color impacts the most the illuminance measured in the ground.
- Canyon A “high obstructed – specular” complies expectations, showing low illuminance values.
- Canyon M, “high obstructed – colorful”, seemed the darkest canyon and respondents asked for more daylight. The big range of reflectance and the variety in colors affect visual perception and the eye adaptability by requiring more daylight.
- Canyon A, “high obstructed – specular”, stands on the second place as dark and it needs more daylight.
- Canyon O, “dense – white”, stands on the third place with high daylight level. The façade affects the results, even though the density of this canyon is same as canyon A and M.
- Canyon K, “dark – wide”, had the highest daylight level and no change was required.

Overcast condition: Daylight distribution and visual comfort.

- Canyon O was the one with the most uneven distribution of light. This is caused by white color creating simultaneous contrast. According to the literature review, this contrast is caused by a dark background and a bright object or vice versa. This makes the canyon look brighter or darker, and therefore creating the feeling of an uneven distribution of light. Another strong contrast happening is the border contrast. This one is a contrast that makes borders look sharper because of the color differences between the sky and the facades. Regarding dark discomfort, this canyon had same results as canyon K, the wide one. Both canyons, influenced by the dark sky color, do not give excessive contrasts and obvious dark areas.
- Canyon K was having a normal distribution of light and not much dark discomfort. This happens due to the wide geometry and the sky inside the field of view.
- Canyon A was perceived to be the same as canyon K, but it had much darker discomfort than the rest of the canyons. The high reflective metal façade mirrored gray skies down to the street level and created a gloomy surrounding and minor dark discomfort.
- Canyon M had an even distribution of light and no discomfort at all. Color discrimination occurs inside the canyon happens due to the overcast condition. This means that the colors are reflected in a more unified wavelength due to the small amount of light. They will thus look alike with low contrasts and a very equal distribution of light. This canyon, however, can be fully observed by the effect of simultaneous contrast and border contrast. It means that the canyon looks darker compared to the sky, which makes borders look brighter and sharper.

Sunny sky condition: Daylight distribution, visual comfort and luminance measurements.

- Canyon A has a very uneven daylight distribution under sunny conditions, the highest dark discomfort and the highest glare discomfort while receiving only 809 lux on street level. The bright color of the sky and the dark color of the façade caused simultaneous contrast and border contrast. The façade looks darker, and the borders are sharper. The luminance values show a range of 33210 cd/m^2, proving high contrast. This demonstrated that the human eye took longer to adapt when going from a bright to a dark surface.
- Canyon O matched canyon M with a normal distribution of light. This canyon was perceived as having a few dark areas that cause visual discomfort with a score of 2,3. Canyon O has the highest discomfort from bright areas, with perceived glare and a value of 7255 lux falling in the center of the canyon. The contrast range was 3100 cd/m^2. The canyon itself had little contrast, but the amount of reflected light showed the effect of color and material on the visual comfort. Canyon O showed as well simultaneous contrast and border contrast.
- Canyon M has a high range of luminance due to the variety of color of about 9710 cd/m^2. It had not many dark or bright areas of discomfort. On the other hand, people perceived this canyon as not receiving direct sunlight and having non-existent glare.
- Canyon K has a normal distribution of light, and the contrast range was 530 cd/m2. It has no perceived discomfort of dark or bright areas and no glare. However, due to the geometry, it receives direct sunlight and in the center is measured 77570 lux.

Genius Loci: The feeling of place.

Respondents selected as the most pleasant canyon in Copenhagen, one of the oldest streets, canyon M. Although it is a narrow and dense canyon, it represents history. In the second-place stands canyon K and O, while the less enjoyable is canyon A. Finally, the respondents were free to comment about the public space. The following table shows some of the answers related to the feeling of a place, the effect of architecture, material, reflectance, and color.

Table 12 Respondents' comments for each canyon

Canyon M	- It feels brighter towards the end of the canyon. - Even though is a bit dark, it is a nice atmosphere. - It is a beautiful street, I would stop for a while. - We would stop if it was sunny and had coffee shops. - It feels a bit dark due to the façade color. - I would not stop, is too narrow and there is not much to do.
Canyon K	- I think that this is a good solution, a harmonic relation between urban space and architecture. - There is space, green areas, light, benches, small bars, nice view, and a nice urban design with a lot of attention to the details. - It is a well-designed building. I like the view towards the canal and the public space. - As a local, I don’t appreciate the architecture choice. Is too dark. - Colors are too dark.
Canyon O	- I think that this road has a commercial character, I would pass here just to do shopping. I don't think it offers any comfort to sit and enjoy the view. There is no direct sunlight except in a specific time of the day. - To stop and enjoy the public space I prefer green squares, not narrow places like this. - As a Danish, I would not stop in this canyon for pleasure.
Canyon A	- The buildings are relatively close compared to their height. I think I would be comfortable here as long as there is direct sunlight. During winter I don't think I would spend time here, there are tall building all around, and I would like to enjoy some green space or a riverbank. Maybe if there would be street art or sculptures, I would spend more time enjoying them. - I don’t think I would stop if there was no particular event happening inside this canyon.

7 Discussions

The most important goal of this research was to define a relationship between the visual perception of daylight in urban canyons by pedestrians and the measured daylight parameters that define light quality. The canyons gave different results for each sky condition; therefore, several conclusions are developed. In order to answer the research questions that guided this project the discussion part is divided in three subsections: “Geometry and daylight level”, “Daylight distribution and visual comfort”, and a discussion about the “Genius loci” or the feeling of place. This grouping covers both questionnaires and measurements related to each hypothesis and research question.

7.1. Geometry and the daylight level

According to the earlier literature review, the geometry should affect the amount of light within the canyon, while materials should influence the perceived luminosity of a space. The first hypothesis examines the relationship between the two and questions if the visual perception of light can change by manipulating the façade material. To prove this assumption, the results are analyzed according to what the respondents perceived, after classifying canyons from less to high dense. This section discusses question 3A, 3B and 6A, together with the measured illuminance values.

Overcast condition: Daylight level and illuminance measurements
The first observation is that under overcast conditions people’s perception was affected by the adaptation to the outdoor condition. The majority of respondents was walking outdoors for more than ten minutes; therefore, they were visually adapted to the dark sky condition. It was as well observed, that the illuminance measurements comply with the geometry by giving higher values for the widest canyons and vice versa.

The conclusion under overcast conditions is that the façade properties affect the visual perception of a narrow and wide geometry between dark and bright. A wide canyon can be perceived darker if its façade reflectance is low. On the other hand, a narrow canyon can be perceived brighter if the material reflectance is high and the color is vivid. However, a narrow canyon with a high specular material but dark colors can be perceived as dark.

Sunny condition: Daylight level and illuminance measurements
The first observation is that illuminance values partially comply with the geometry under sunny conditions. Moreover, façade properties can affect the dark/bright perception of a narrow canyon and cannot affect the dark/bright perception of a wide canyon. The investigation showed that wide canyons will have high illuminance values without getting affected by the façade color or reflectance. However, in narrow canyons, material reflectance can play an important role in daylight level or need. A colorful narrow canyon is perceived dark, while a narrow specular metal material canyon is perceived bright.

7.2. Daylight distribution and visual comfort

According to earlier literature studies, the light-to-dark contrast is higher for bright materials. A bright material is a material that has a high reflectance and a vivid color. To investigate contrast and comfort a group of questions was developed about daylight distribution. These questions combined with reflectance and luminance measurements, gave a better understanding of the impact of materials, colors, and contrast. Therefore, the second hypothesis was developed. It assumes that a canyon with excessive contrasts will cause visual discomfort. This section discusses questions 4A, 4B, 4C, 5A and 5B, together with the calculated DF and VDF values and measured luminance values.

Overcast condition: Daylight distribution, visual comfort and DF, VDF measurements.
For the overcast condition horizontal illuminance was measured on three points in the center of each canyon and the vertical illuminance on both sides of the canyon making a total of six points. With those data and the global illuminance values, DF and VDF were calculated. To compare all four canyons only the results of the center point were selected. This solution would avoid mistakes caused by the geometry of the sides of each canyon. It was observed that a wide canyon with dark façade color and a narrow canyon with bright façade color have the same DF values. This means that the material reflectance is influencing the illuminance measurements inside the canyon by increasing the daylight level.

The second hypothesis stating that excessive contrasts can cause visual discomfort, under overcast conditions, cannot be proved. It is observed an inconsistency on the results. Canyon O, which had the highest uneven distribution of daylight, therefore excessive contrast, had almost no visual discomfort created by dark or bright areas. On the other hand, on the rest of the canyons with a normal distribution of light, more discomfort and darkness were perceived. Therefore, we could say that for an overcast condition the visual discomfort is not related to excessive contrasts created by light, but mainly on the geometry and color perception.

Sunny sky condition: Daylight distribution, visual comfort and luminance measurements.
For this part of the analysis the luminance value of each canyon was measured at a point of direct sunlight and at a shaded point in the same façade color. This approach helps to understand the contrast range inside the canyons. The values show big differences on the amount of light reflected by the surface of each canyon. The canyons with the high contrast are the ones with high reflective material and white façade color. While, the ones with low contrast are canyons with low reflective colors. Moreover, dark discomfort showed to be related to the color reflectance of a material, where low reflectance was more prone to cause discomfort. On the other hand, under sunny conditions, no canyon showed signs of bright discomfort.

Bright discomfort areas were associated with spotted glare. The results were inconsistent showing the canyons with the highest direct sunlight to have the lowest glare discomfort. This implies that people's perception of glare discomfort is related to the façade material and not the canyon geometry. Therefore, the second hypothesis, which states that excessive contrasts can cause visual discomfort, is true. It is observed that canyon A, with a high reflecting material but a narrow geometry was causing the highest discomfort in terms of visual adaptation, border contrast, and simultaneous contrast. Both color and material reflectance were major causes of discomfort glare.

7.3. Genius Loci

On a level of appreciation, all the canyons were classified from very much to less enjoyable. The majority of respondents answered influenced by the architecture design and inclusiveness of the canyon. For most of them, the relation to the place would play a fundamental role. Tourists would describe the place optimistically, while locals would be influenced by their previous experiences.

Factors such as design, architecture, urban furniture, events and location of the canyon were the most influential to the participants. They would prefer a canyon with colorful façades, with the presence of public furniture and a canal nearby. Moreover, they also linked their choice to the function. They would emphasize that a commercial canyon is not as inviting as a canyon with a nice green public space or recreational function. However, the favorite canyon for respondents was the one with most history, canyon M. This canyon was narrow in its typology and had only a few cafes nearby its ends. However, its architecture was a landmark for the old town and its colors were attractive to the eye.

8 Conclusions

This research project was a thorough investigation of the outdoor visual perception and visual comfort of four different urban canyons in Copenhagen. These canyons were selected with specific orientation, geometry, and materiality. Daylighting and sunlighting metrics were studied using on-site measurements and surveys. The main findings of this paper are as follows:

- In line with the first research question, the conclusion is that there is a link between geometry and façade material for visual comfort, but this relationship is affected by the sky condition.
- If the façade has the right material reflectance, material color, color contrast, and light distribution, we can have an optimum outdoor visual comfort under overcast conditions
- A narrow canyon with high reflectance and bright colors shows visual comfort, for the same sky condition.
- A material with a high contrast but low specularity does not pose any feeling of visual discomfort under overcast conditions.
- If the canyon has a narrow geometry it can provide an optimal outdoor visual comfort only under sunny conditions.
- A wide canyon, under sunny conditions, has no effect on visual comfort because the view of the sky dominates field of vision and people cannot perceive the effect of the façade.
- A narrow canyon, under sunny conditions, with high reflectance, low specularity, bright colors and low color contrast yields visual comfort.
- A narrow canyon, under sunny conditions, with high specularity, and high color contrast causes glare and veiling effect, therefore visual discomfort.
- In line with the second research question, the conclusion is that different daylighting metrics will comply with people's perceptions under different sky conditions. The factors that can cause a mismatch between measured and perceived data are the change of color or material specularity.
- There is a relation between color contrast and visual comfort under sunny conditions. And there is a relation between illuminance values and perceived light quantity under overcast conditions.
- There are several social factors affecting the perception of people such as their origins, the weather they are usually exposed to, the density of hometowns, or personal interests or opinions about case studies.
- People will choose to stop or enjoy the public space only if space had a meaning to them.

9 Future Research

This research concluded that the visual perception of daylight in an urban street canyon is a very broad topic and influenced by many physical or cultural factors. It gave a broader view of people's subjective perception and the relationship to measured daylighting metrics. This will help future designers to further investigate the subject of outdoor daylighting and the impact of façade design on the outdoor visual perception. In order to achieve visual comfort, which is a very relative concept, designers should comply with some degree of discomfort in order to have their best design performance. In Copenhagen, which most of the year is characterized by cloudy conditions, it is essential to have high outdoor daylight levels. Therefore, it implied that a certain visual discomfort can be tolerated in sunny conditions so that the rest of the year has good daylight conditions. The above-mentioned relations and factors contribute to the visual perception of urban space, its comfort and the sense of belonging. As Norberg-Schultz (1991) says:

"The place represents architecture's share in truth. The place is the concrete manifestation of man's dwelling, and his identity depends on his belonging to places".

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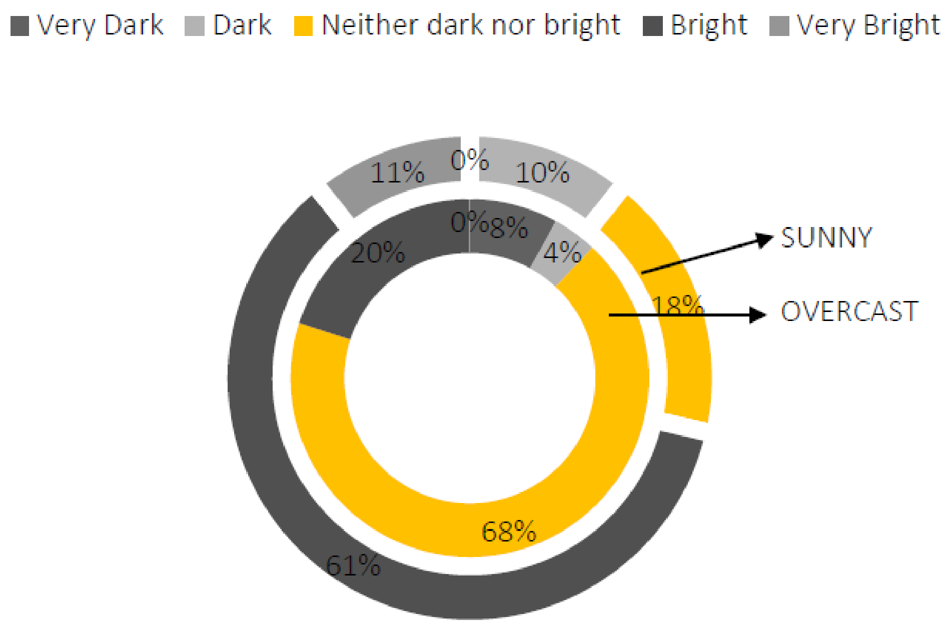
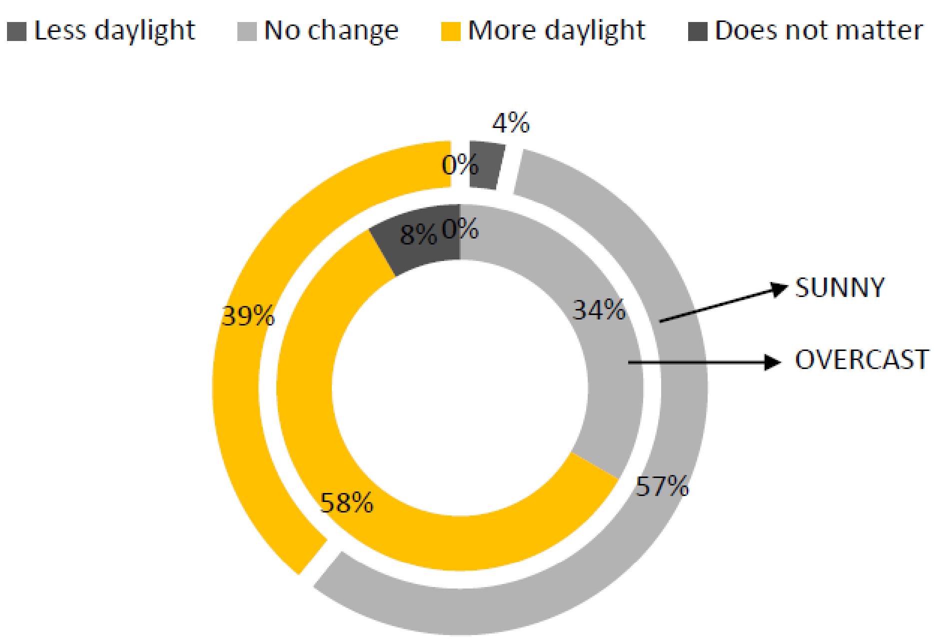
Appendix A

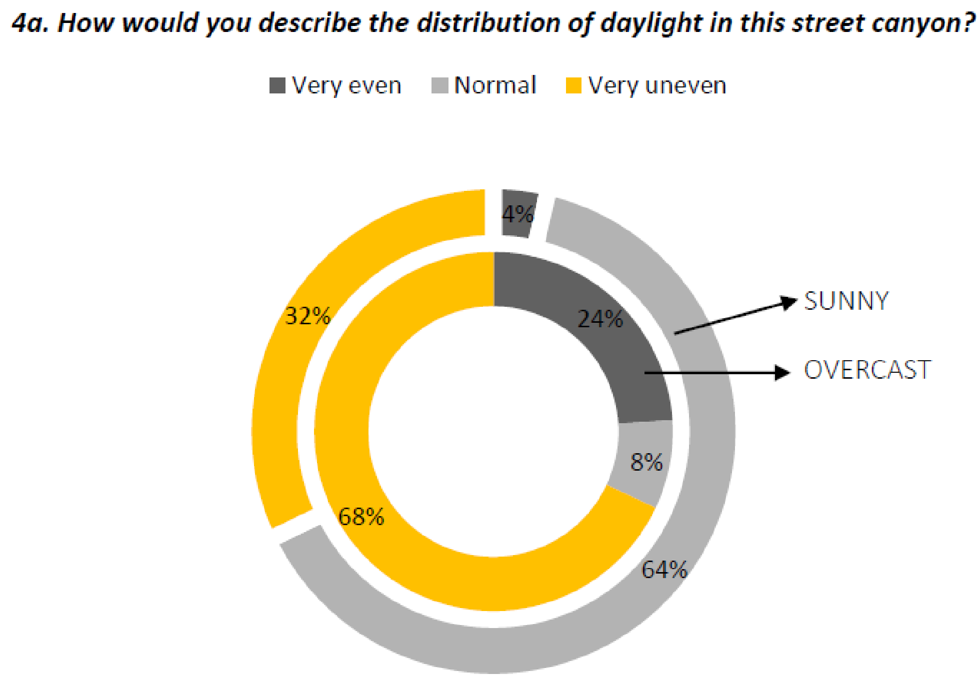
Canyon O – Østergade

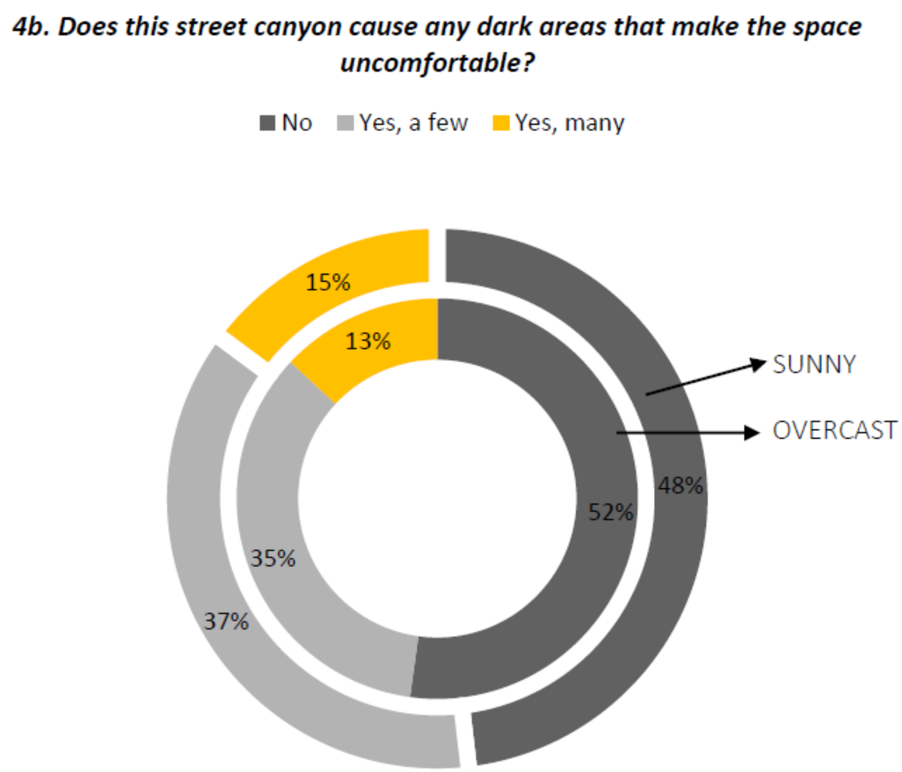
3a. How would you describe daylight in this street canyon?

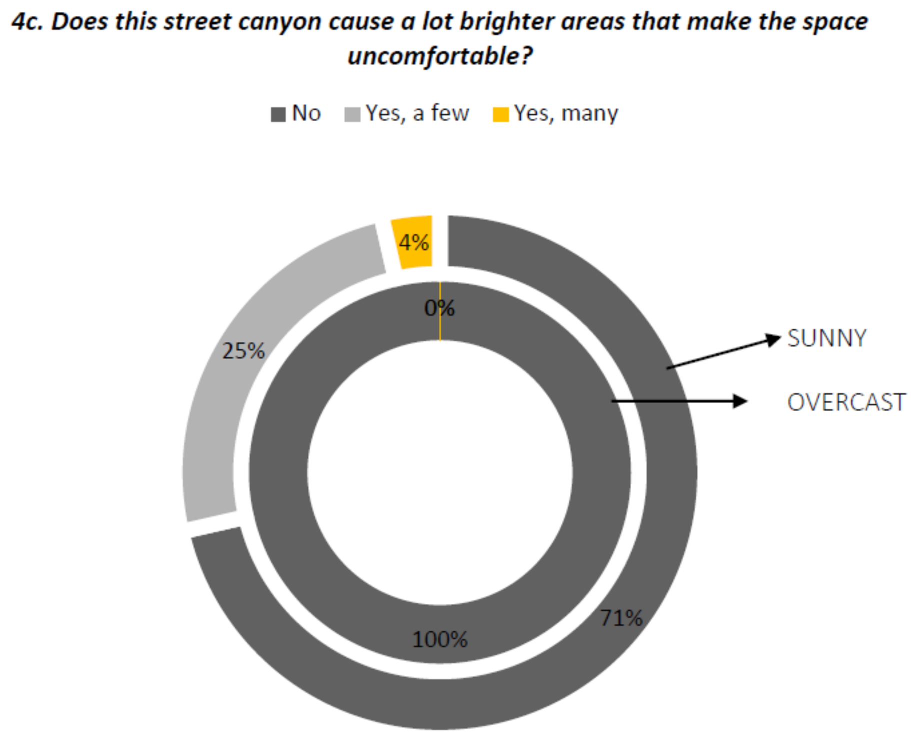


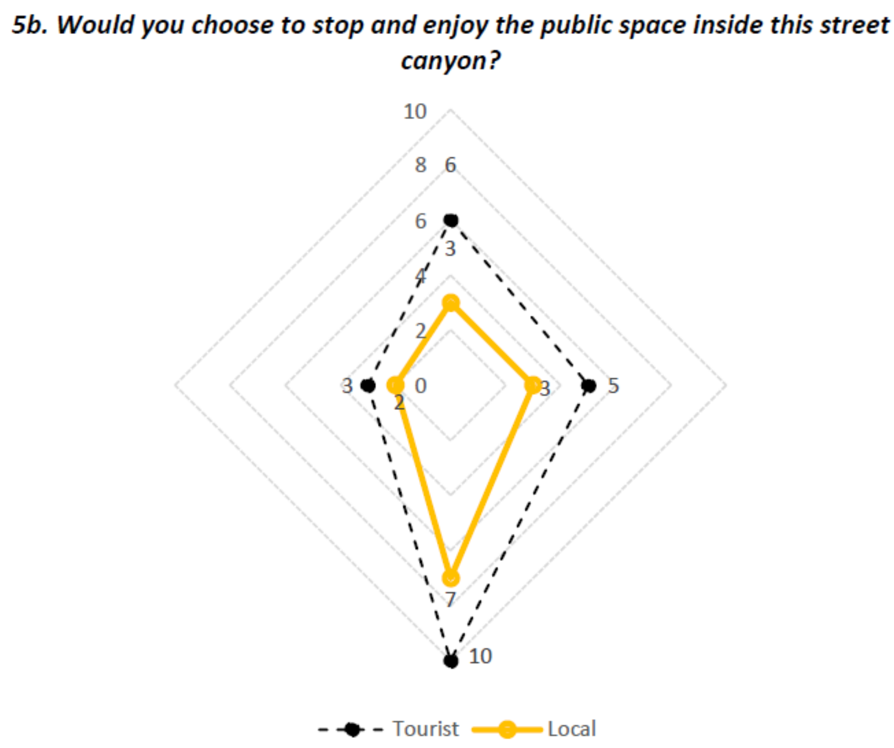
3b. How would you wish to change daylight in this street canyon?




4a. How would you describe the distribution of daylight in this street canyon?
Very even
Normal
Very uneven
4%
32%
24%
SUNNY
OVERCAST
8%
68%
64%

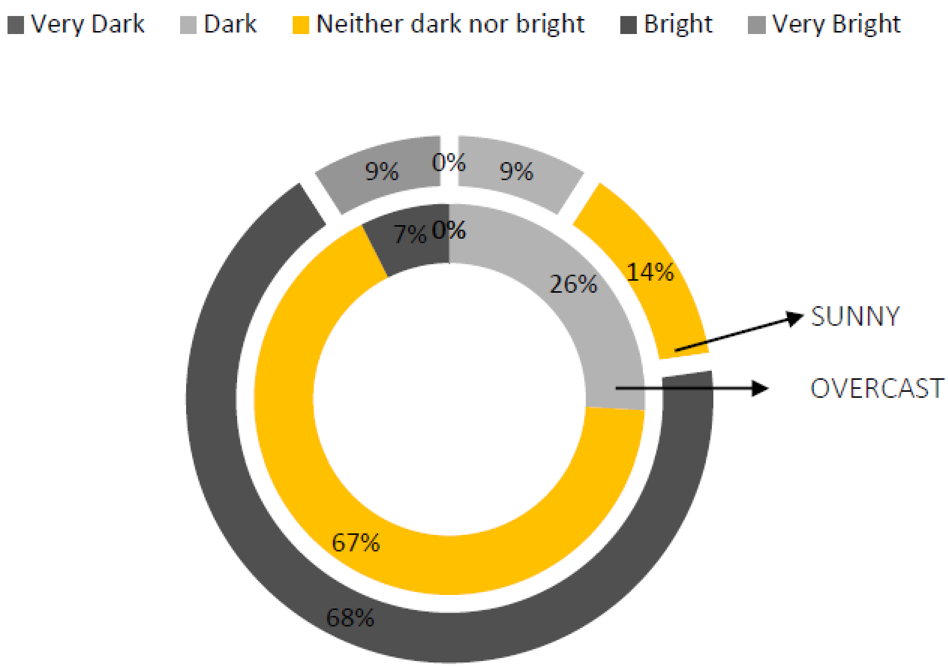

4b. Does this street canyon cause any dark areas that make the space uncomfortable?
No
Yes, a few
Yes, many
15%
13%
SUNNY
OVERCAST
48%
52%
35%
37%


4c. Does this street canyon cause a lot brighter areas that make the space uncomfortable?
No
Yes, a few
Yes, many
4%
0%
25%
SUNNY
OVERCAST
71%
100%

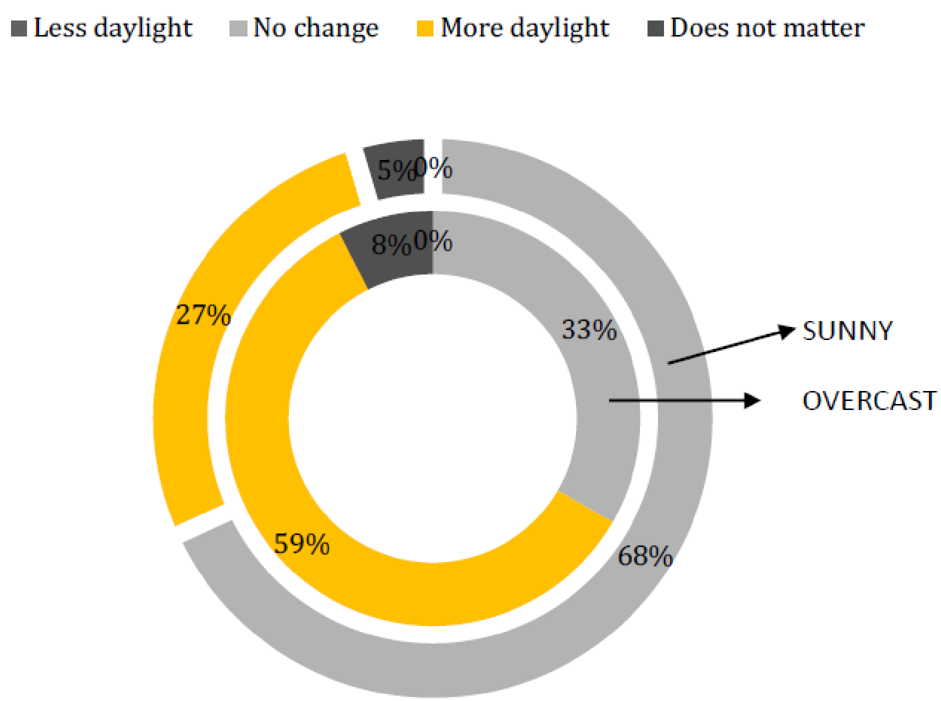

5b. Would you choose to stop and enjoy the public space inside this street canyon?
10
8
6
4
2
0
6
3
3
2
3
5
7
10
Tourist
Local

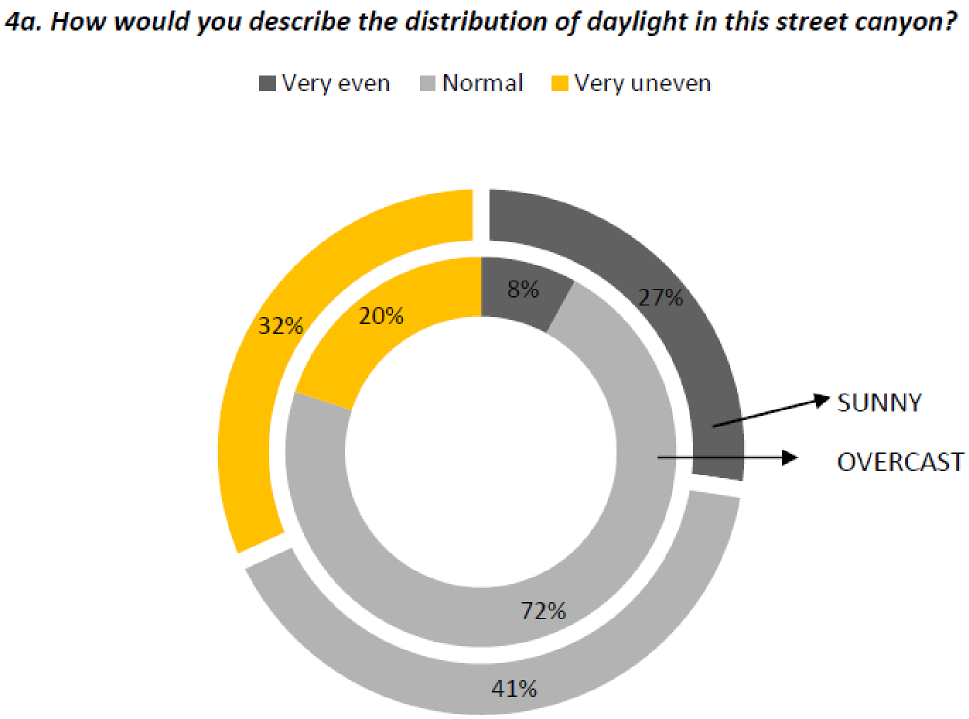
Canyon K – Krøyers Plads

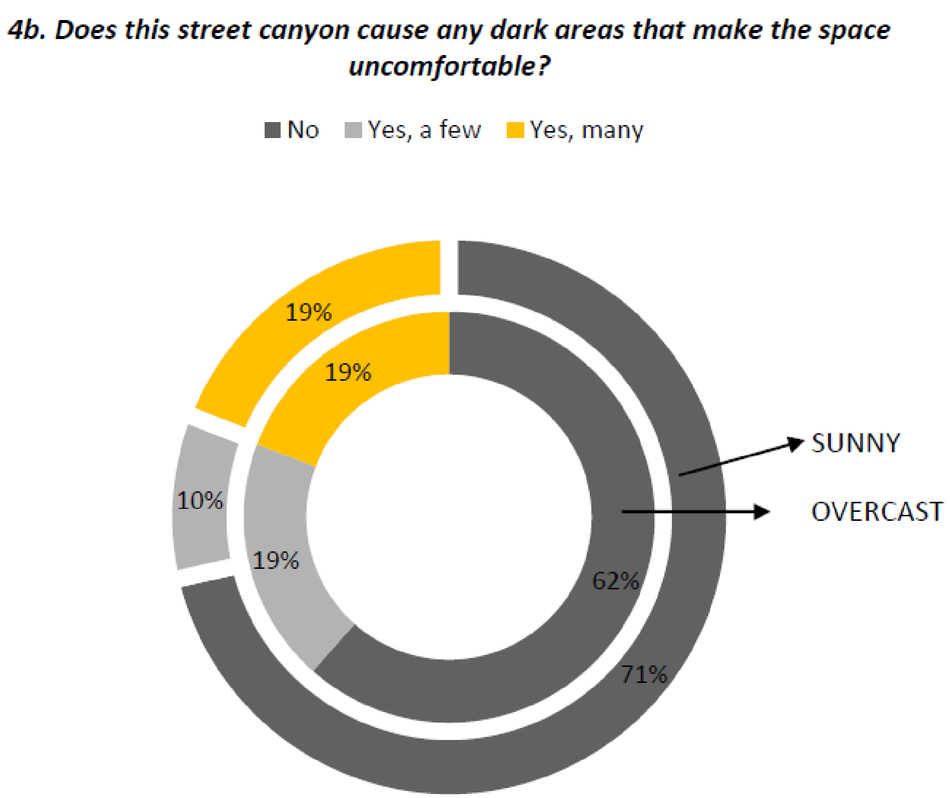
3a. How would you describe daylight in this street canyon?

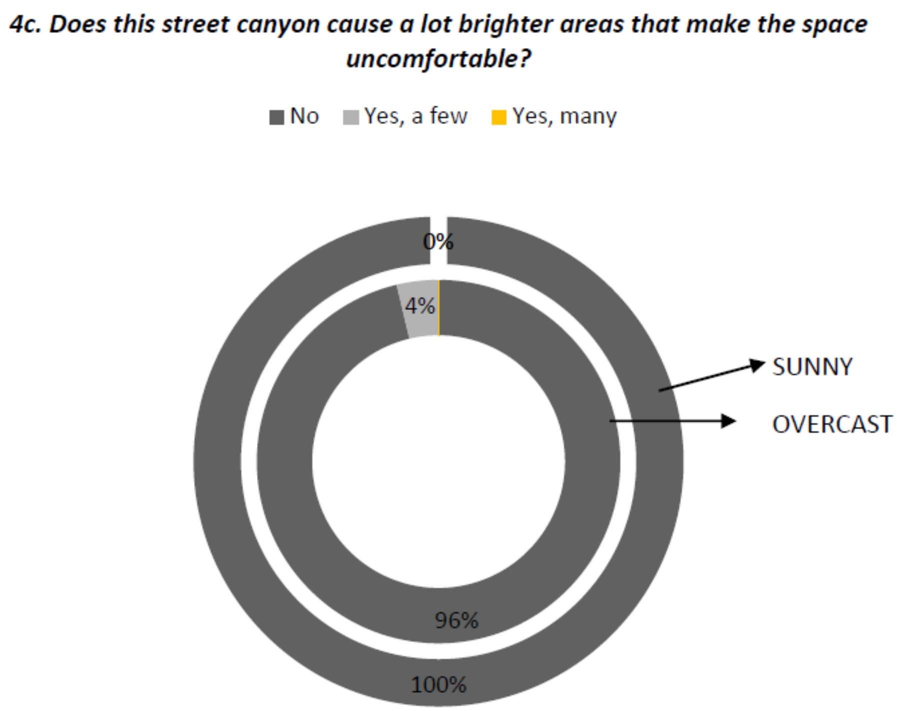


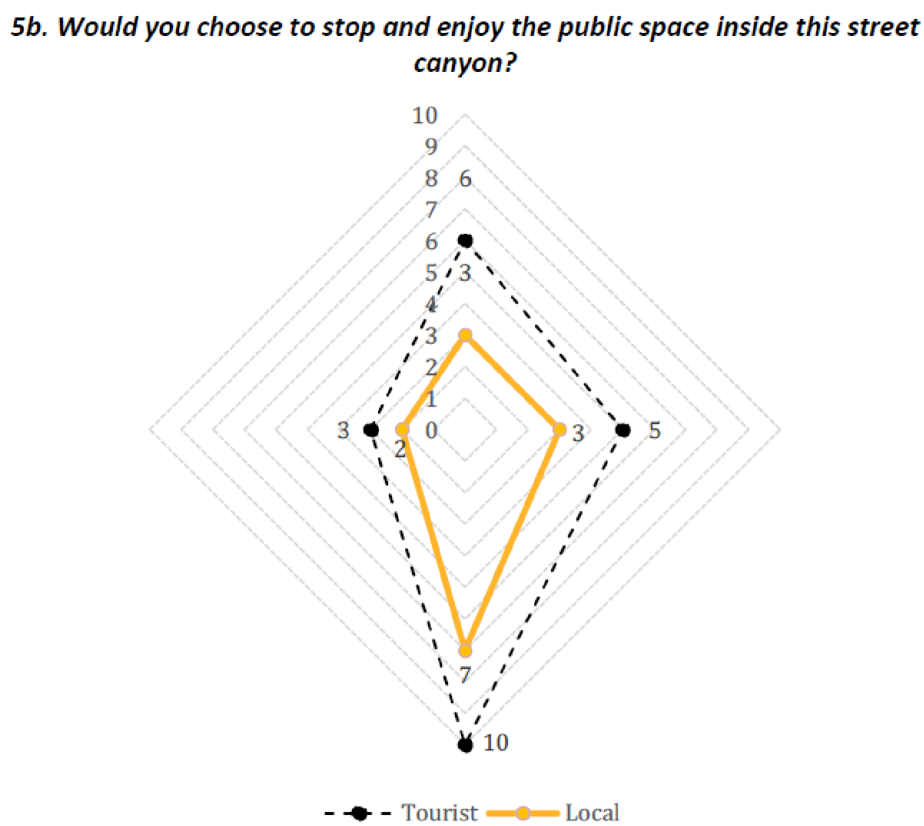
3b. How would you wish to change daylight in this street canyon?



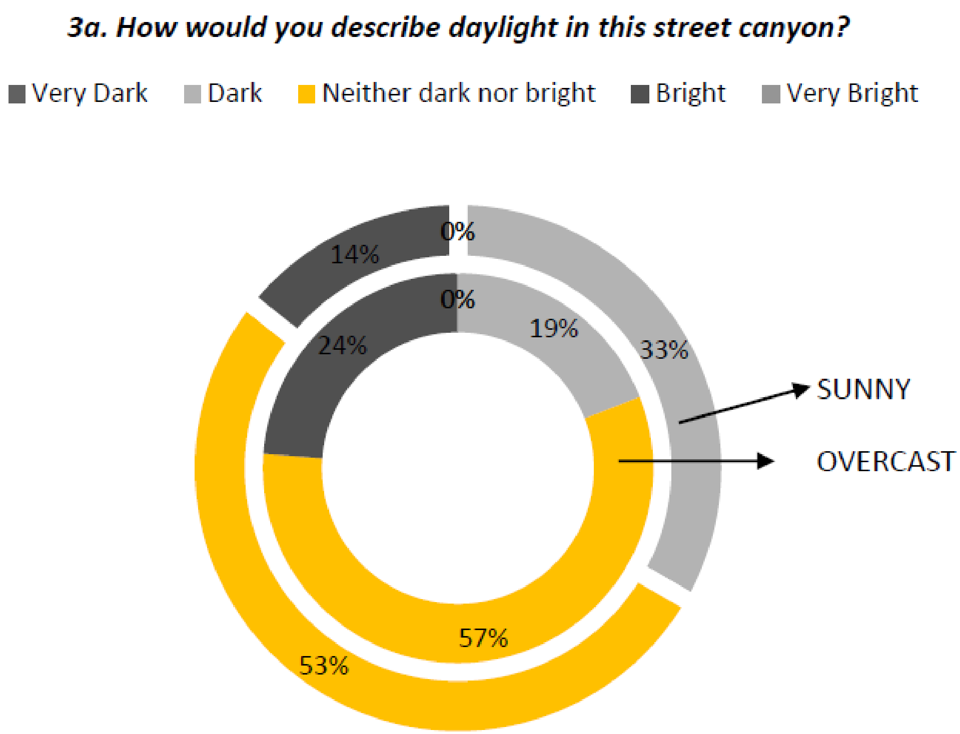

4a. How would you describe the distribution of daylight in this street canyon?
Very even
Normal
Very uneven
8%
27%
32%
20%
72%
41%
SUNNY
OVERCAST

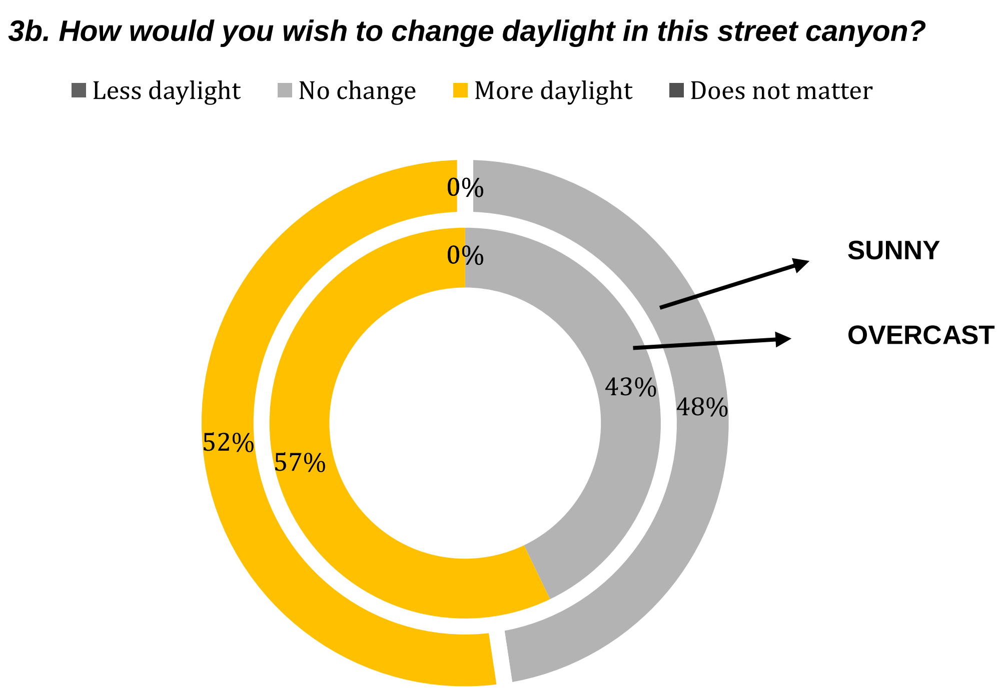

4b. Does this street canyon cause any dark areas that make the space uncomfortable?
No
Yes, a few
Yes, many
19%
19%
10%
19%
62%
71%
SUNNY
OVERCAST


4c. Does this street canyon cause a lot brighter areas that make the space uncomfortable?
No
Yes, a few
Yes, many
0%
4%
96%
100%
SUNNY
OVERCAST

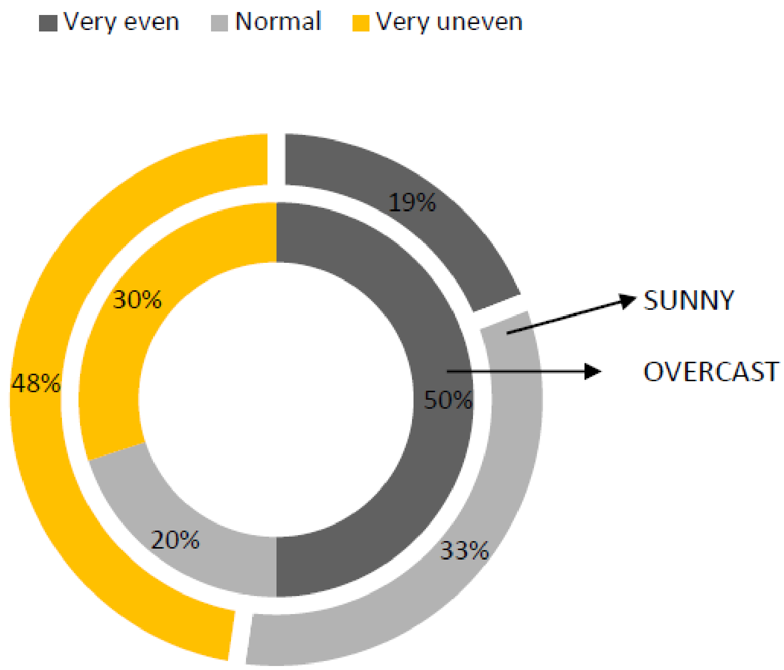

5b. Would you choose to stop and enjoy the public space inside this street canyon?
10
9
8
7
6
5
4
3
2
1
0
6
3
3
5
3
2
7
10
Tourist
Local

Canyon M – Magstræde

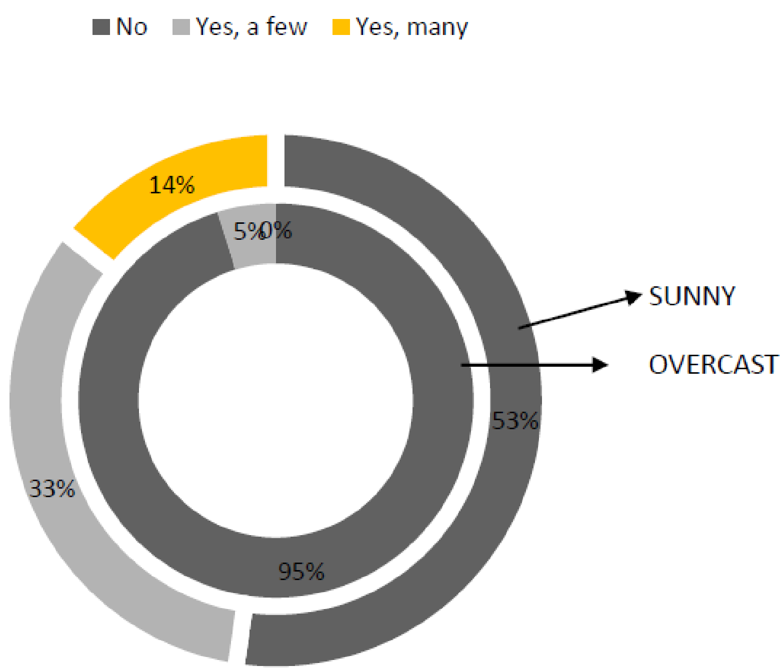


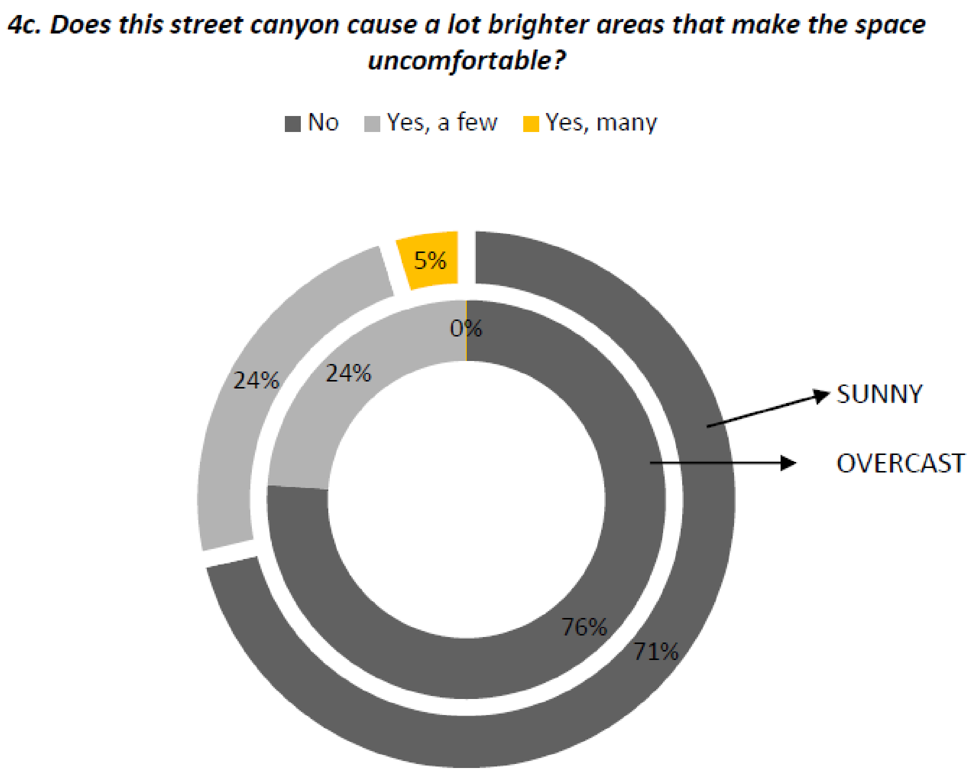


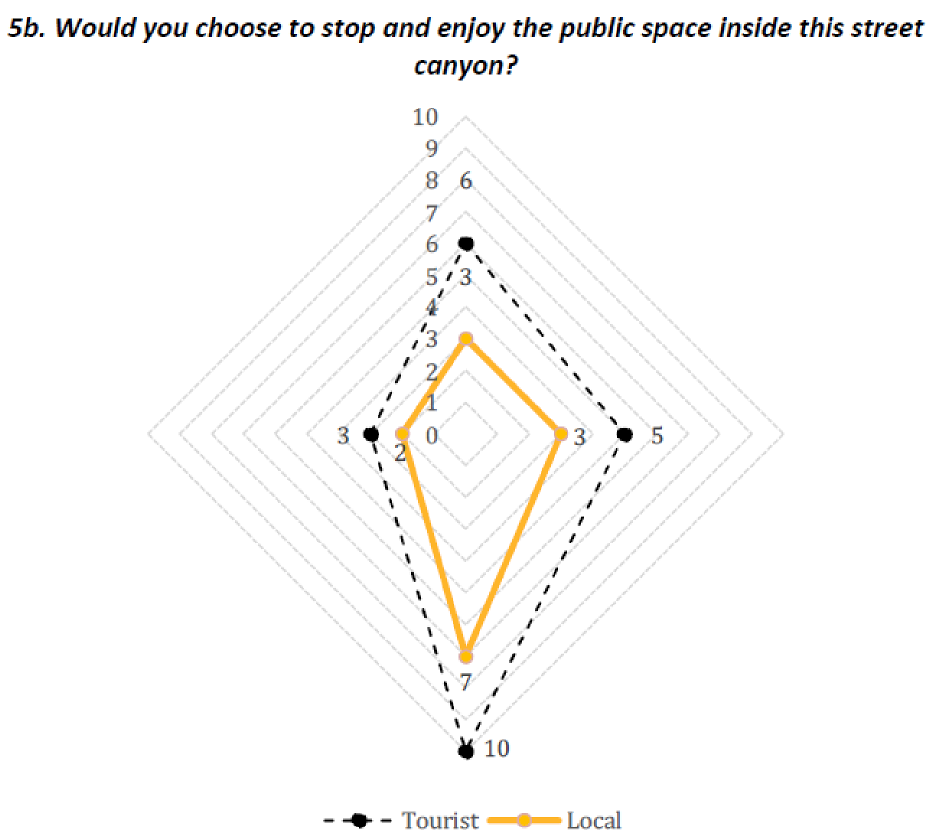
4a. How would you describe the distribution of daylight in this street canyon?



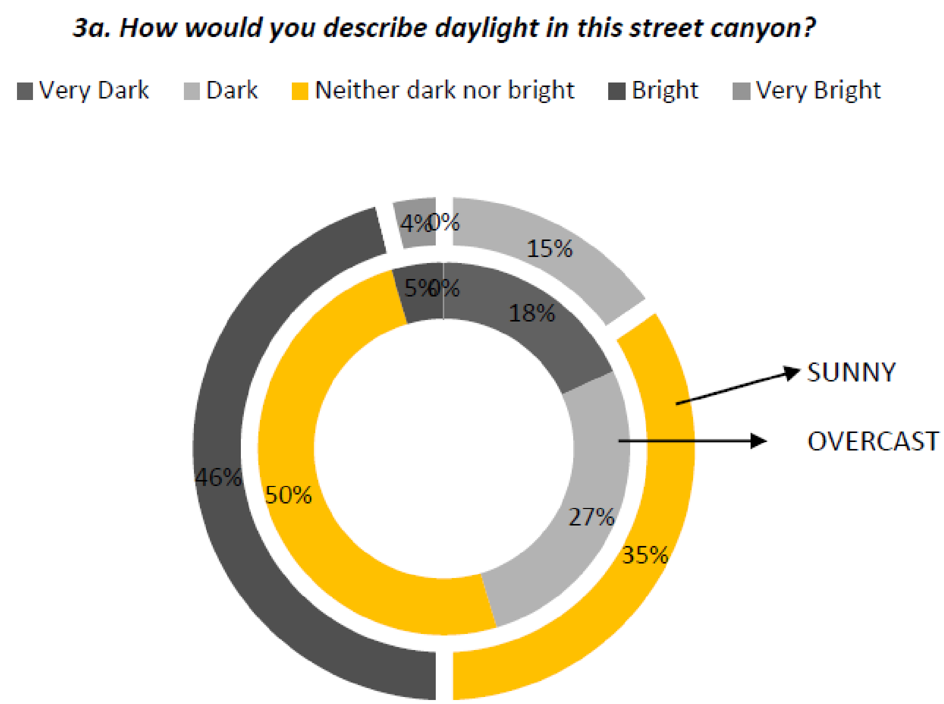
4b. Does this street canyon cause any dark areas that make the space uncomfortable?

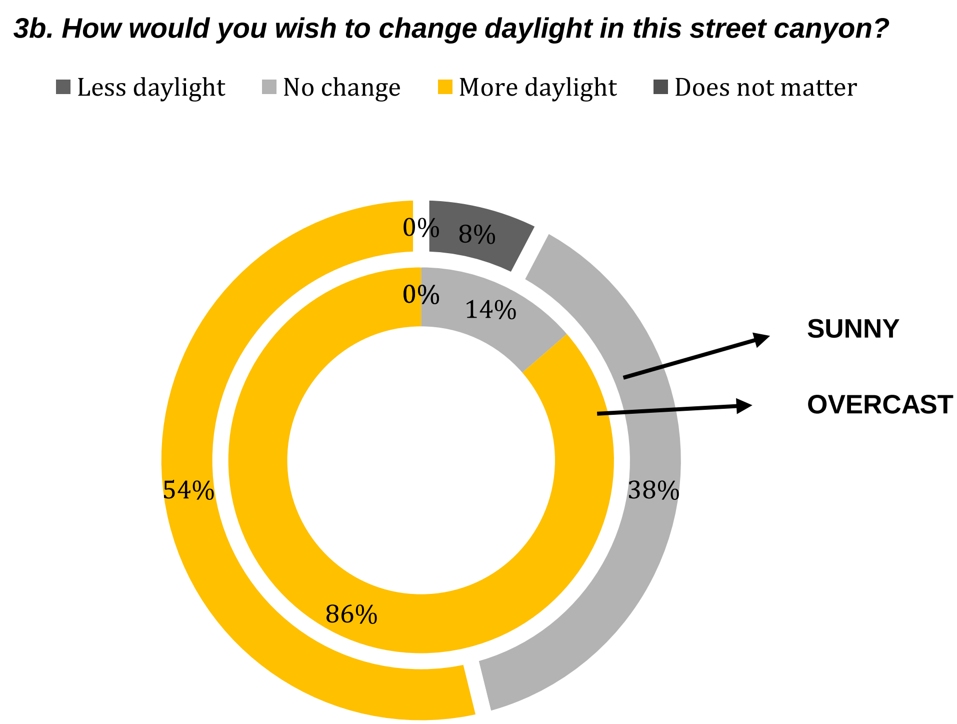



4c. Does this street canyon cause a lot brighter areas that make the space uncomfortable?
No
Yes, a few
Yes, many
5%
0%
24%
24%
SUNNY
OVERCAST
76%
71%

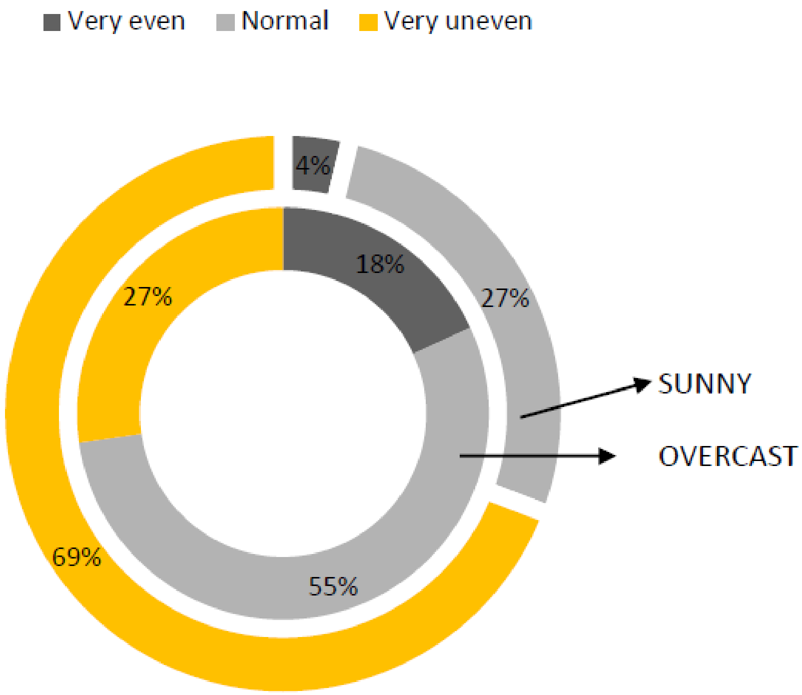

5b. Would you choose to stop and enjoy the public space inside this street canyon?
10
9
8
7
6
5
4
3
2
1
0
6
3
3
2
3
5
7
10
Tourist
Local

Canyon A – Århusgadekvarter

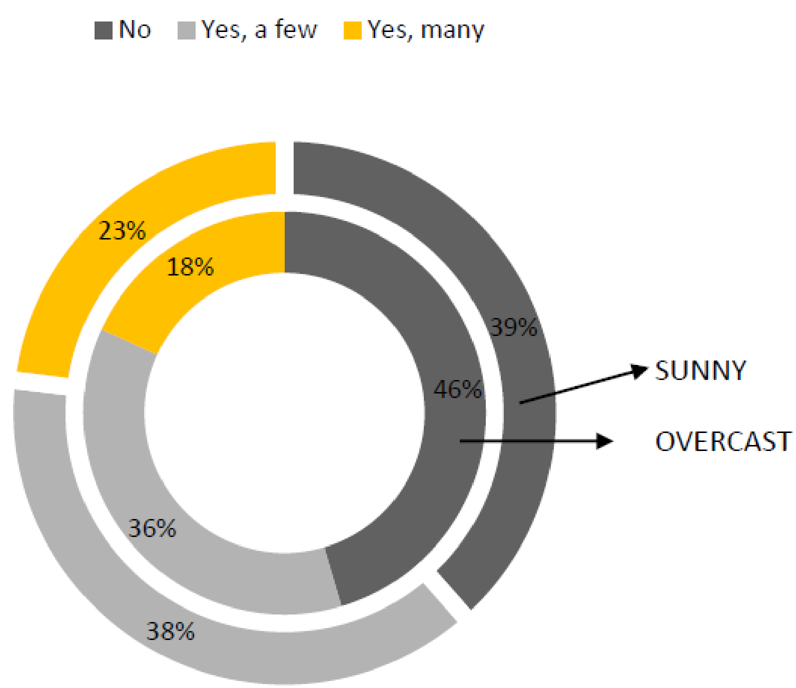


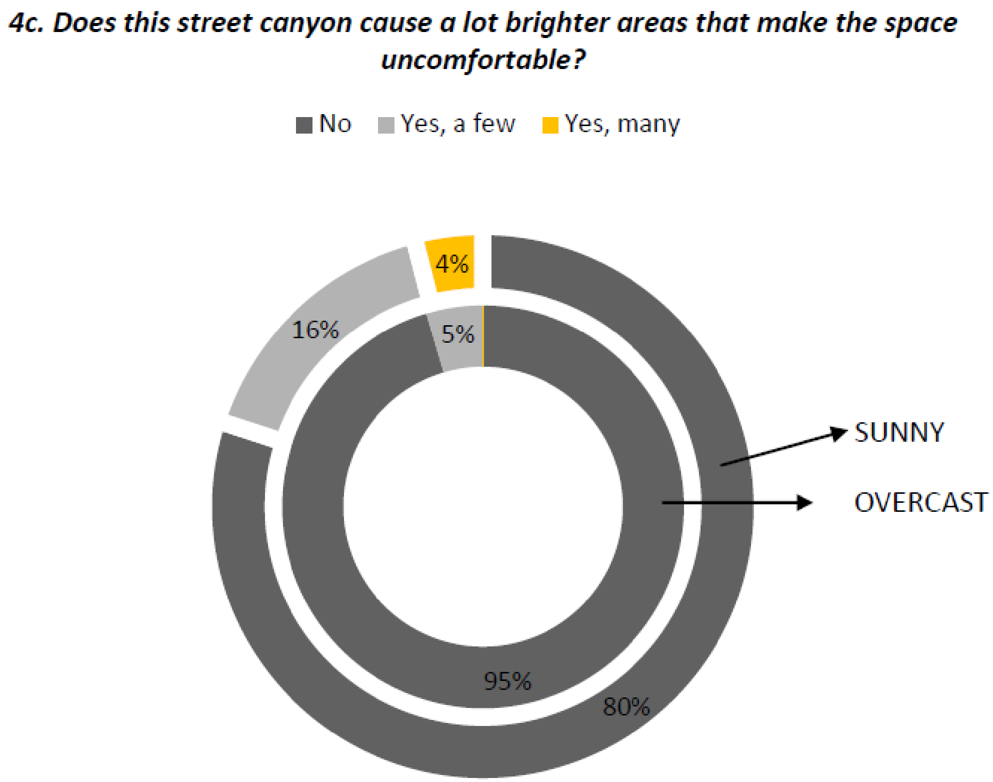


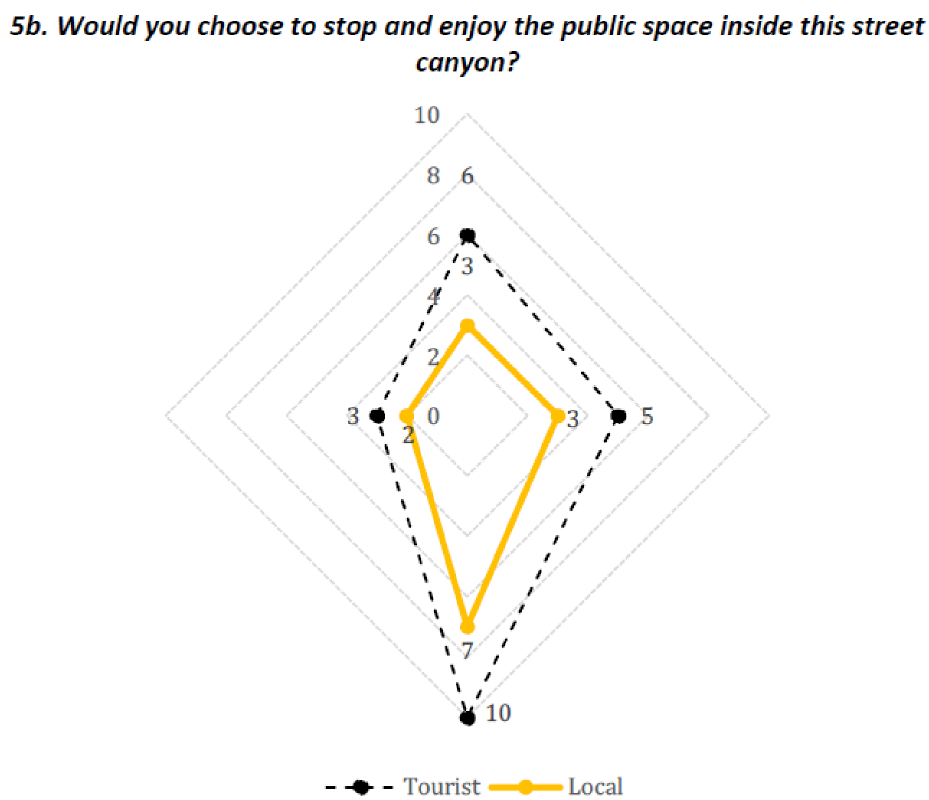
4a. How would you describe the distribution of daylight in this street canyon?



4b. Does this street canyon cause any dark areas that make the space uncomfortable?




4c. Does this street canyon cause a lot brighter areas that make the space uncomfortable?
No
Yes, a few
Yes, many
4%
16%
5%
95%
80%
SUNNY
OVERCAST


5b. Would you choose to stop and enjoy the public space inside this street canyon?
10
8
6
4
2
0
6
3
3
2
3
5
7
10
Tourist
Local

Dept of Architecture and Built Environment: Division of Energy and Building Design
Dept of Building and Environmental Technology: Division of Building Physics and Building Services