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Window geometry and its effect on the experience of illuminated spaces – a study of three daylit architectural cases

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Abstract Looking at the architecture of modern housing in Denmark, it seems to express an understanding that equals more daylight with good daylight. With coated energy glass, the windows have increased in size, making glass into a façade material. This means that windows are no longer just holes in the façade but rather make up the entire façade itself. This changes the spatial relationship between the window design and distribution of daylight within the interior space, though we seldom address this lacking a vocabulary and methods. This paper sets out to investigate and experiment with how we can describe and document this change in daylight conditions and how these influence our visual environment, using photographs to record this. The methodology focusses on observations of daylit spaces in three different housing examples in Copenhagen from the 1800s to today. By observing the three daylit spaces, it becomes clear that differences in the size, shape, and position of window apertures influence the qualities of light in a space significantly. Considering that when it comes to window apertures different designs affect the experience of light in a space significantly, it is important to take this into account when designing with daylight. It is also important from a sustainability point of view to include this awareness in future design approaches.

1. Introduction: experiencing a daylit room

The geometry of a window determines the character of the daylight in a room. Size, shape and position of a window have a significant influence on the illumination of a room with daylight [1]. This can be explained through the physics of light, where light is defined as radiation which travels in straight lines and interacts with the surfaces it meets, thereby allowing light to penetrate a room based on the design of the aperture. The illumination of a space is therefore directly related to the *geometry of the window*.

Light in a space is traditionally measured on a horizontal plane 0.85m above the floor, described through the daylight factor (DF). The DF indicates the relationship between the exterior and interior light as a measure of the illuminance within a room relative to the outdoor illuminance incident on a horizontal plane from an unobstructed overcast sky. The DF is expressed as a percentage for various points in a room, indicating the amount of light and thereby also the variation of light throughout the space. [2]. This is one of the main properties of illuminated spaces, a property which is relatively easy to register if these spaces can be simulated and measured using well-known units of light. The DF is one of the most often used measures of light in a space even though it has its limits, as it does not provide any information regarding the climate, latitude or orientation of the room in question.

Apart from being measurable, light-filled spaces are also perceived by humans, the inhabitants of the space. Engineer R.G. Hopkinson (1913–1994) also stated this in his book *Daylighting* [3]: *Light is the visual manifestation of radiant energy and, consequently, is intimately related to human sensations*. When daylight openings vary in size, shape and position, illuminated spaces vary in appearance. This paper is investigating the impact of different aperture designs on the illumination of spaces and how they are perceived. This paper is thereby centred on the experience of visual environments, more specifically, the qualitative aspects of daylit spaces. In order to provide a focussed study on the qualitative aspects of light, the quantitative aspects are intentionally left out. A future study could benefit greatly by looking at both the quantities and qualities of light.

At present daylight design is often described through quantitative aspects, such as efficiency, energy consumption and climate conditions, for good and unignorable reasons. Advanced computer-aided design techniques allow daylight situations of a building to be simulated in 3D programs, providing information on energy consumption and indoor climate. Simulations carried out in relation to specific climate conditions [4] can predict the daylight levels and distribution in a particular space [5]. Information which relies on quantitative data to ensure that standards, guidelines, or certifications are met, all important to support sustainable development and to decrease energy consumption of our build environment [6]. However, these simulations often leave out the aspect of how the illuminated space may be perceived. Aspects that support our vision and could thereby potentially diminish the use of energy. These qualitative aspects are often highlighted for different user groups, e.g. visually impaired people, for whom they are essential [7].

Qualitative aspects of daylight design are difficult to measure, but they are undoubtedly experienced and of importance to people occupying the space [8]. Acknowledging the importance of the qualitative aspects of daylight, this paper investigates systematic methods to register them. Through three cases, the visual impact of the design of daylight apertures in relation to illuminated spaces is studied.

2. Objectives and research question

The focus of the paper is on how daylight, window aperture and space interact and create the perceived light *in the space* and *on the objects*. Through the interplay of light penetrating the geometry of a window aperture, surface reflectance and space boundaries, the visual environment of the space is created. The three cases represent three different designs of daylight aperture that are commonly known and differ significantly.

The objective is to describe the relationship between the geometry of the aperture and the perceived effect of the light in the interior space. The experience of light is studied in relation to both the overall illumination of the space and how a three-dimensional object is perceived in the light.

The aim of systematic registration is to gather knowledge on the perceived light, which potentially can qualify architects' daylight design process and give building clients a more specific vocabulary for the spatial qualities of daylight.

Focusing on the visual environment of the daylit space, the main question is: *How do various aperture designs affect the way light is perceived in the space?*

To answer the question, the following sub-questions have been posed: Firstly, *how do the different designs of daylight aperture determine the overall light distribution, and how is this perceived?* Second, *how does the framing of the window affect the way daylight is perceived in the space?* And thirdly, h*ow is a three-dimensional object perceived when exposed to light emerging from different daylight apertures?*

Figure 01. Daylight penetrating a traditional cross-window on an overcast day.

3. Theory

This project draws on the Nordic tradition of both studying and acknowledging the impact of daylight qualities in architectural design. The Norwegian architect and Professor of Architectural Theory and History Christian Norberg-Schultz (1926–2000) described how the local environment has an impact on traditional architecture [9] and argued that daylight is one of the most significant elements of space and place [10]. In Sweden, architect Sven Hesselgren (1907–1993) focused on how people perceive light [11].

This is pursued by architect Professor Anders Liljefors, who establishes a precise vocabulary on light with a clear distinction between measurable and perceived light [12]. In Denmark, lighting design research has focused on the "*geometry of light"* [13] both as a tool of design and of understanding. Architect Poul Henningsen (1894–1967) designed the PH-lamp with the ambition of making lamps that reflected rays of light and created a lighting design without glare and with a balanced shadow pattern based on this geometric understanding of light [14]. This approach was developed further at the School of Architecture at the Royal Danish Academy of Fine Arts and taught by architect Mogens Voltelen (1908–1995), who worked with Poul Henningsen. The colleague of Mogens Voltelen architect Sophus Frandsen (1927–2013) transformed the geometric understanding of light from artificial light in the field of daylight design. He studied how to describe daylight that penetrates windows systematically, including the spatial and qualitative effects. His studies were done in spaces/labs designed for the purpose. The advantages of studying light in a lab is that it is possible to control and change the surface reflectance and size and position of the daylight apertures. His theory and results were published in the article: "*The Scale of Light*" [15], which has been the inspiration for the study presented in this paper regarding the overall impression of the spaces and the details of the shadow patterns.

With the point of departure within architecture and the subsequent attention on spaces and being in spaces, this paper focuses on how light is perceived in a space, in other words, it focuses on spatial light distribution, surface texture, the form of three-dimensional objects and shadow patterns. Computer simulations and calculations can be extremely useful, but the subtle and delicate surface texture and shadow pattern on three-dimensional objects are still difficult to reproduce in computer simulations. By referring to the Nordic theory on daylight and architects' attention to the way light is perceived, the aim is to (re)introduce useful tools to describe qualitative properties of daylight.

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4. Methodology

The study is based on case studies performed as onsite observations [16] of the daylit spaces in three housing examples in Copenhagen from the 1800s to today. Each case involves a sidelight, but the designs of the daylight apertures differ significantly, from the traditional cross-windows to a bay-balcony window and a curtain wall, presenting different relationships between the design of the aperture and the daylight in the interior space.

All three cases are located within a building complex in an urban setting in Copenhagen, Denmark. All three have an unobstructed view of pleasant surroundings and open sky. The oldest case, with classical cross-windows, is oriented towards the east and has a view of a historical square in the centre of Copenhagen; the case with a bay-balcony window is in a modern movement apartment building oriented towards the west and facing the lakes of Copenhagen; and the newest building with triangular balconies is oriented towards the south and overlooks a preserved national park. Except for the case with the cross-window, the cases have balconies. Though the balconies influence the daylight penetration, they are not discussed in this study. The interiors of all three cases have been painted with white matte paint with approximately 80% reflectance. They have light-coloured wooden floors.

The observations have been made onsite by the authors, focusing on three themes: 1) the overall light distribution, 2) the mediation of light from the exterior to the interior, focusing on the design of the window framing and 3) the form-enhancing effects of the light on a three-dimensional object in the space.

As the three cases are oriented differently, the observations have been made without direct sunlight penetrating the spaces. The inhabitants of the apartments have kindly given access to their private homes, but it was not possible to visit Case 2 on a day where there was an overcast sky, hence the study of the three-dimensional objects was only conducted for Cases 1 and 3.

The three cases have been documented through a series of systematic photo registrations. Recorded with the following camera: Canon EOS 5D Full-frame DSLR / Objective: EF 24-105mm f/4L IS USM. Each photo series relates to one of the three themes mentioned above, described respectively in subchapters 6.1., 6.2. and 6.3. (See fig. 03, 04, 05).

Figure 02. Three cases, exterior view. Left to right: *Gråbrødre Torv*, *Vestersøhus* and *VM house.*

5. Cases: three window typologies

The window designs included in the study vary in size, shape and position. The windows have been selected due to their design, though they also represent three different periods of architectural history. The window typologies are the cross-window, the bay-balcony window and the curtain wall, representing an increase in window size. Each of the window typologies are well known and common in a Danish context, though the details and execution can vary greatly.

5.1. *Cross-window*

The cross-window has a four-light casement with a mullion and a transom forming a cross. The casement window opens on hinges like a door with a closing mechanism (fastener). The two lower casements are about twice the height of the top sashes. The mullion and transom form a cross, and the window is therefore usually called a "cross-window". This window has secondary glazing. This type of window is very common in Danish residential housing from the 18th and 19th centuries. [17].

Case 1 *Ildebrandshuset* on Gråbrødretorv was built in 1729 and is part of some of the very old residential buildings in Copenhagen. They are named Ildebrandshusene – the Firehouses – as they were constructed after the first Great Fire of Copenhagen in 1728. The existing window is not the original window, as the cross-window was not introduced until the late 18th century due limitations in the production of glass. Developments in the production of glass in the late 18th century meant that after the second Great Fire of Copenhagen in 1795 cross-windows became widespread. In 1729 it was not possible to produce as large panes of glass as needed for the four-light casement window [18]. Therefore, the original window would probably have been a multiple-light casement window, and the glassed area might also have been smaller [19].

5.2. *Bay-balcony window*

The bay-balcony window is a window that integrates a balcony and has corner windows letting light in from two sides. The window area is larger than the traditional cross-window, meaning there is often only one large bay-balcony window in a living room compared to cross-windows, where there are typically several.

Case 2 *Vestersøhus* by the lakes of Copenhagen was designed by architects Kay Fisker and C.F. Møller and was built in 1936 as one of the first and most excellent examples of the bay-balcony houses [20]. This type of residential housing was very popular during the heyday of Danish Functionalism. The focus on light and fresh air promoted building structures that included balconies with easy access to the exterior [21].

5.3. *Curtain wall*

The curtain wall is a façade concept where the façade does not carry any structural load, as opposed to traditional façade systems, where the façade is load bearing [22]. This allows freedom with regard to designing the façade and opens up the possibility of constructing the whole façade entirely from glass. However, in a Danish context it must shield from various weather conditions, including intense sunlight during the summer and cold weather during the winter. Hence to provide the spaces with a comfortable indoor climate, special glass that can create a balance between heating and cooling must be used. This glass technology often lowers the light transmission.

Case 3 *VM Houses* designed by Plot was built in 2005. The building was one of the first housing complexes in Ørestaden, a newly developed environment on the outskirts of Copenhagen. The playful building was constructed using concrete, steel and glass. The housing complex consist of 80 different apartment types, most of them with more than one level. Each apartment has been designed as one open space, allowing the inhabitants to subdivide it into more spaces as they wish. The façade is entirely made of glass subdivided into smaller areas, allowing for doors to the balcony. The glass façade allows light to penetrate the apartments unhindered and offers the inhabitants an undisturbed view of the outside.

6. Findings: the interrelation between window and the experience of a daylit space

The following three subchapters present the findings from the study, focusing on 1) how the different designs of the daylight apertures determine the overall light distribution, 2) how the framing of the windows affects the perceived daylight in the space and 3) how a three-dimensional object is perceived in light coming from different daylight apertures.

Figure 03. Three cases, interior view of the overall light distribution. The photos represent different experiences of the spaces according to different positions in the space. Top to bottom: cross-window, bay-balcony window, and curtain wall.

6.1. Illuminated space

The experience of the overall light distribution of the three spaces varies (Fig03). In Case 1, the light level is experienced as generally high and evenly distributed even though the façade wall is darker than the sidewalls, as it only receives reflected light from the space. Light from the window on an overcast day is scattered softly onto the sidewalls, where a significant pattern of brightness reflects the design of the window. These variations in light level are stimulating and apply a character to the space. The areas of brightness are also experienced on the floor and ceiling, which entails a pattern of bright and less bright areas. The brightness fades further away from the window, creating an experience of a soft shaded environment with a myriad of grey tones, which are especially visible on the walls. Furthermore, the semi-gloss surfaces on the wooden panels around the daylight apertures create reflections which are especially visible at a short distance.

In Case 2, the light level is experienced as generally high and reaching rather far into the space. A larger bright area is experienced on the floor, ceiling and on the sidewall fading into the room but with less nuances than in Case 1. The visual environment is experienced as bright with few contrasts and easy to comprehend.

Case 3 on the contrary is experienced with large contrasts. The level of light is experienced as very high close to the window but decreases rather quickly further into the space, giving rise to contrasts that reduce the ability to see the space properly. The window occupies the whole façade, which further creates an intense backlight. Therefore, the experience of the space differs significantly depending on which way you are facing the curtain wall. Furthermore, the semi-gloss floor creates reflections and thereby glare that can be disturbing for vision.

Figure 04. How the design of the aperture modulates the daylight of the space. From left to right – Case 1: cross-window, Case 2: bay-balcony window, and Case 3: curtain wall.

To conclude, the three spaces differ regarding the variation of light in the space. In Case 1, there are areas of pure reflected light over the window and in the corners of the façade wall, creating a rhythm between precise direct daylight and soft reflected daylight and thereby producing different options depending on preferences. In Case 2, there is the same type of variation between the direct and the reflected light in the space, with direct light in front of the window and reflected light in the corners, though not as a rhythm as in Case 1. In Case 3, the direct light is evenly distributed along the curtain wall, with precise light that accentuates details on the ceiling and the walls, without variation.

6.2. Light transition

The framing of the window affects the perceived daylight in various ways (Fig. 04). In Case 1, the wooden framing of the window mediates the transition between the daylight level of the exterior and the interior. The framing modulated by panels with profiles softens and allows a gradation of light, diminishing the potential glare from the exterior light and thereby affecting the experience of the interior light positively. Though the framing in Case 2 has less detailed profiles, it still creates an effective gradation of light from the exterior to the interior and softens the experience of the light coming through the window. As Case 3 has no framing the transition between the light level of the exterior and the interior is very contrasted. Intense light settles on the sidewalls, ceiling and floor, creating a very bright area close to the window. Whereas Case 1 and 2 had a window framing with details mediating light, Case 3 has only the framing of the industrial window product without further architectural mediation between the exterior and interior light. The few but very functional elements of the window – the plastic joint and the ventilation opening – get all the attention, as the light accentuates them.

6.3. Form-enhancing shadow pattern

Three-dimensional objects are perceived differently depending on differences in daylight apertures (Fig.05). Whereas the two previous observations focused on light *in the space*, the last focuses on light *on an object* and thereby on the smaller shadow pattern that enhances form and details. To see light on a three-dimensional object, a sphere has been used. The sphere can also represent a human body or face. In Case 1 and 3, a sphere has been photographed and observed in 5 positions with 0.5 m in between on a straight line perpendicular to the middle of the window 0.85 m above the floor, starting as close to the window as possible. Observations up to a distance of 2.5 m inside the room from the window have therefore been made.

In Case 1, there is great contrast between the top and bottom of the sphere. In the position close to the window, the directionality of the light on the sphere differs depending on the position. Close to the window, the directionality of the light is very steep, but it lowers the further away from the window the sphere is positioned. The direct light from the sky is present close to the window and creates a very precise shadow pattern with a clear bright and dark side, enhancing the shape of the sphere. The reflected light takes over further away from the window, the sphere gets a softer shadow pattern where the roundness of the sphere disappears, and it becomes difficult to perceive the shape. These variations are

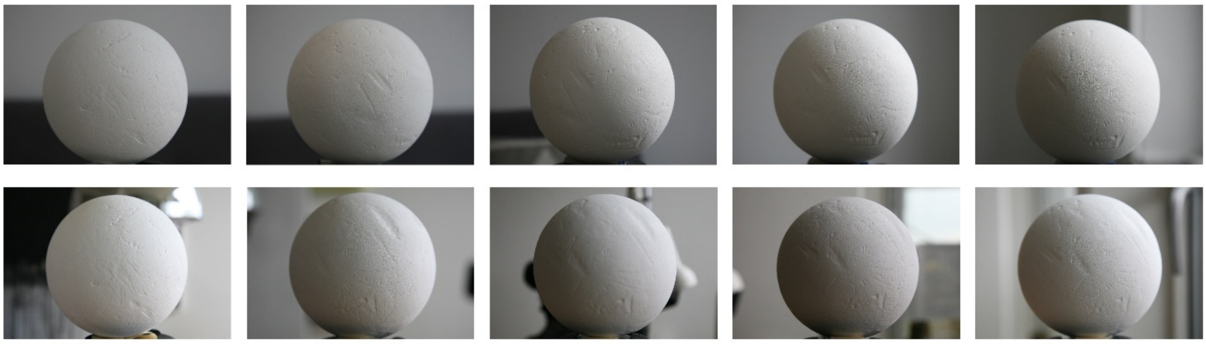

Figure 05. How a three-dimensional object receives light from a cross-window, Case 1 (top) and a curtain wall, Case 3 (bottom). The window is positioned to the right of the spheres.

not only present from the façade and inwards but also parallel to the façade. As there are two windows, there will be a rhythm of direct light and reflected light depending on whether the sphere is in front of the window or between the windows.

In Case 3 the sphere is more evenly lit in the various positions. The light from the whole façade illuminates the whole sphere and makes it difficult to distinguish whether it is close to the window or further away from the window. Even though a vague highlight is noticed on the sphere closest to the window, there is very little variation in brightness and the shadow pattern on the sphere in general. Furthermore, varying the position parallel to the façade would not make the appearance of the sphere differ, as the curtain wall will light the sphere evenly. Whereas the appearance of the sphere in Case 1 varies from looking clear and round close to the window to looking more like a sponge deeper in the space, the appearance of the sphere in Case 3 is very much the same wherever it is placed in the room. That makes a large difference in experience of a three-dimensions object according to the design of the daylight aperture.

7. Discussion and conclusions: balancing the qualities of light in daylight design

Three different cases have been observed onsite in relation to the themes and theory developed by Nordic architectural lighting research primarily discussing and unfolding the qualities of light and the experience of the visual environment. Observing the three daylit spaces, it becomes evident that the size, shape and position of a window aperture influences the qualities of light in a space significantly.

When comparing the three different cases, we find a milder transition in Case 1 with the cross-window, which is both smaller and is a hole in the wall. The modulation of the daylight apertures and the surrounding wall soften the light and not least lessen the experience of glare when looking towards the daylight apertures, especially compared to Case 3 with the curtain wall, but also to some extent Case 2 with the bay-balcony window. The size of the daylight apertures in relation to the façade has significance: the larger the light aperture is, the greater the perceived contrast is in the space.

Likewise, the three cases are very different when it comes to variation in light. In Case 1, there are both areas of very direct and precise light close and parallel to the window but not in the areas opposite the window, between the windows and inwards into the space with soft reflected light. Though the space is small, there is variation in the light. In Case 2 there is less variation, but there are some areas with either precise and direct light and areas with soft reflected light. In Case 3 the wall-to-wall window results in very uniform light that accentuates details both at the ceiling and the walls.

How the details of the framing of the windows are done influences the experiences of glare. The perceived light becomes visible in the modulated transitions between outside and inside when these are designed and shaped by frames, profiles, and ornaments. These shaped transitions transmit light and reduce glare. Thus, details are highlighted, e.g. the profile in Case 1 & 2, and when there are not any transmitting details, as in Case 3, then the plastic joint is accentuated by the light.

Combining the observations of the sphere from Case 1 and 3, it can be concluded that the two different daylight apertures produce two very different light settings that produce very different visual appearances of objects. The light from the curtain wall creates an evenly lit environment without many nuances in the shadow pattern. On the contrary the light from the cross-window provides a space with very dynamic light. As there is variation in shadow pattern across different areas of the space, a variety of visual appearances of three-dimensional objects are produced.

In the study accounted for in this paper, the observations were made in real spaces. In real spaces, all minor and subtle details are visible and can therefore influence the evaluation of the experience of a daylit space. This is a preliminary study attempting to develop alternative ways to systematically register and observe aspects of the perceived light in a space. It is emphasised that this study has not yet developed a thorough vocabulary of the qualities of daylight. As most studies are carried out on computers, it is of course the future challenge to convert onsite experiences such as these into computer programs.

Having found that the various designs of window aperture affected the experience of light in a space significantly, it can be concluded that it is important to take such knowledge into account when designing with daylight, balancing window size, shape and position in relation to the intention of the space both when it comes to functionality and visual appearance. Unfortunately, these aspects are not in focus much, as present agendas mean that focus is on energy consumption. In a Danish context this is reflected in the guideline on daylight design in the Building Regulation which has gradually moved from an awareness of the importance of a comfortable visual environment to primarily supporting energy consumption [23]. By leaving out the experience of light, daylight design might end up disregarding the fact that people need to occupy spaces with a comfortable visual environment.

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