Sunlight and the monochrome linear relief

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The paper focuses on the visual impression of a modern linear relief illuminated by sunlight. It starts with the reference to the ancient stone reliefs from Egypt and Persia and discusses the typology of stone relief: sunk, mid and high relief. Then modern Norwegian architectural examples of wall relief are shown, including the oak wall in the Opera House in Oslo and works of contemporary fine artist Edith Lundebrekke. The method of developing modern reliefs is totally different, most often it is based on the fastening of wooden slats to the wall and consequently the relief shape is dominated by linear elements that may differ in regard to thickness, width, length and colour. A series of parameters influencing perception of modern linear reliefs have been examined with the help of calculations of the sunlit part of a relief and with visual studies of previously prepared coloured relief plates that were illuminated by an artificial sun in the Daylight Laboratory at the Norwegian University of Science and Technology (NTNU), Light & Colour Group. The common opinion saying that the lightness (perceived luminance) of a relief depends mostly on its depth has been challenged. The depth is of course very important, but for observation angles close to the incidence angle of the sunlight the relief lightness is high even for very deep reliefs and for angles opposite to it the only essential parameter is the relation between the widths of the outer and the inner surfaces. The main conclusion is that in addition to the design of the relief itself, i.e., its colour and the widths of the inner, outer and side surfaces, there is a combination of the light direction and the observation direction that decides how much of the relief image (as seen from the observer) is illuminated by the sun and consequently how light the relief appears.

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Introduction

According to Merriam Webster dictionary [1] and the Penguin Dictionary of Art & Artists [2], the word relief is connected to the sculptural technique. It stems from the Middle French, and Italian rilievo or relievo and means: a) mode of sculpture in which forms and figures are distinguished from a surrounding plane surface b) sculpture or a sculptural form executed in this mode c) projecting detail, ornament, or figures.

The traditional relief has been created by cutting in from a flat surface of stone or wood and lowering of the background field, leaving the unsculpted parts seemingly raised. The technique involves substantial chiseling away of the background, which is a very time-consuming exercise. Traditional reliefs have often narrative motives and give an impression that the sculpted motive has been raised above the background plane.

Figure 1: A sunk-relief depiction of Pharaoh Akhenaten with his wife Nefertiti and daughters. Wikipedia, https://en.wikipedia.org/wiki/Relief, file:Qajari relief.jpg, author: Zereshk.

Figure 2: A Persian mid-relief from the Qajar era, located at Tangeh Savashi in Iran. Wikipedia, https://en.wikipedia.org/wiki/Relief, file:Qajari relief.jpg, author: Zereshk.

Over the passage of years different types of relief have been developed. A typical for ancient Egypt sunk-relief is exemplified in Figure 1, in Figure 2 a Persian mid-relief from the Qajar era, which might also be described as two stages of low-relief, and an example of high-relief is shown in Figure 3.

Figure 3: High-relief metope from the Classical Greek Elgin Marbles. Wikipedia, https://en.wikipedia.org/wiki/Relief, photo by Adam Carr.

In this paper the notion of relief refers to all types of building surfaces having rising and falling surface geometry. As the depth of a relief is rather small compared to the size of the surface, the 3D-shape of a relief can be described as small movements in between two surfaces, the outer and the inner surface.

Reliefs developed in one material of a given colour have the colour, and colour nuances, unique for it. The impression of three-dimensionality is underscored by the shadows. Both, the direction and the intensity of light, have a huge impact on the image of the relief wall.

Can we find examples of relief-like works in modern architecture? Two well-known but very different examples are the outside wall of the Bibliotheca Alexandrina and the wall in the main core of the Opera House in Oslo, both designed by Snøhetta [3-4]. The first one is made by carvings in stone employing local stone cutting method and resulting in a sunk-relief not very different from sunk-reliefs preserved from ancient Egypt (Figure 4). The second one is a curved wall surface covered with wooden sticks assembled together, as shown in Figure 5. Here only one material is used resulting in colour nuances that are genuine for this specific material, namely oak. Instead of chiseling away a material, the tectonic variation on the surface is made by using profiles with different cross-sections, see the right hand photo in Figure 5. This method invites creation of abstract linear compositions rather than figurative motives.

The best-known artist working with this technique in Norway is Edit Lundebrekke from Trondheim [5]. She made artistic decoration projects in numerous buildings. Three of her relief projects are presented in Figures 6-8. She divides wall surfaces into rectangular areas and is playing with the length and the thickness of the sticks, the distance between them, and, something that was impossible in the chiseled relief, the colour of the background. The degree to which the background colour is visible depends very much on the observation angle, resulting in considerably different colour compositions; please compare right hand and left hand photos in Figures 6 and 7.

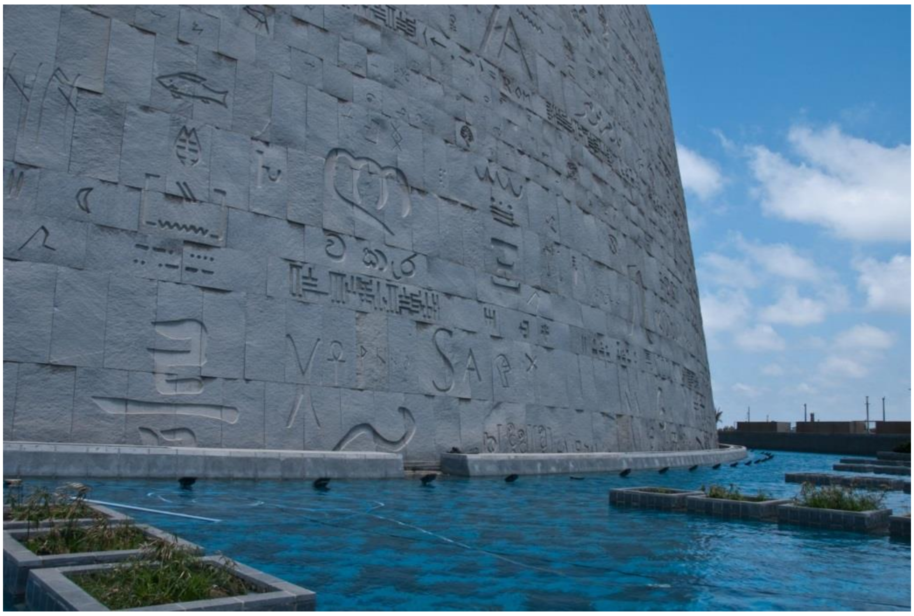


Figure 4: Outside wall of the Bibliotheca Alexandrina. Wikipedia, photo by Kostas Kokkinos, https://upload.wikimedia.org/wikipedia/commons/9/98/Words_on_a_Wall.jpg.

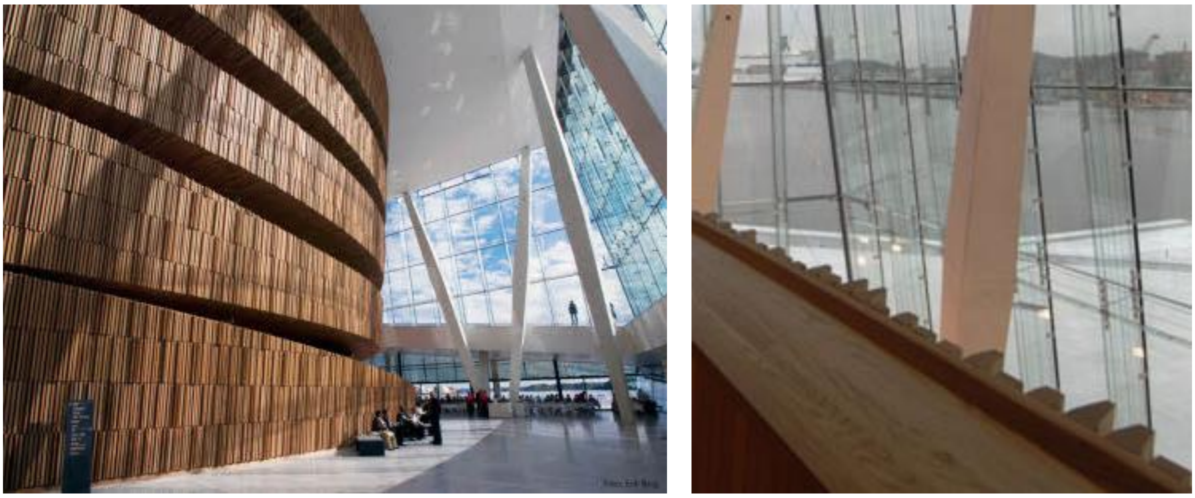


Figure 5: Wooden relief wall, also called the waving wood wall (left) and the railing (right), in the foyer of the Oslo Opera House by Snøhetta Architects. Photos B. Matusiak 2010.

Figure 6: Wall installation in the auditorium of St. Olav Hospital by Edit Lundebrekke. Collected from: edith.no/project/st-olavs, Women and Children Centre auditorium.

Figure 7: Wall installation in St. Olav Hospital in Trondheim by Edit Lundebrekke, hall in the knowledge center to the left and canteen to the right. Photo B. Matusiak, 2015.

Figure 8: Wall installation at Sandmoen fire station, Trondheim, by Edith Lundebrekke. Collected from edith.no/project/fire-station-trondheim.

For architects and interior designers considering a modern relief wall, one of the relevant questions concerns the walls' ability to reflect light, specifically to the average reflectance of a relief wall, as compared to a flat surface made of the same material or painted in the same colour. This question is important for the designer selecting colours and materials of other elements of the environment, and from the light-technical point of view since a lower reflectance has to be counterbalanced by a higher intensity of illumination, meaning also higher energy consumption.

A study dealing with this issue is presented at AIC 2016 Interim Meeting in Santiago de Chile [6]. This study is limited to single colour linear reliefs, see Figure 9. The study confirmed that the average reflectance decreases with the depth of the relief and that the average reflectance of the relief wall can be calculated with the Sumpner's Equation [7- 9] with the accuracy of about **5%** for red (ρ=17%), blue (ρ =30%) and green (ρ =31%) and with accuracy of about **10%** for yellow (ρ =70%).

As it can be observed in Figure 9a, the lightness of the relief decreases with its depth. However, all four plates appear almost equally bright in Figure 9b. In Figure 9c the three relief plates appear equally bright, while the flat plate stands out as much brighter. This intriguing observation motivated the author to study the relief image from different observation angles and in different lighting conditions.

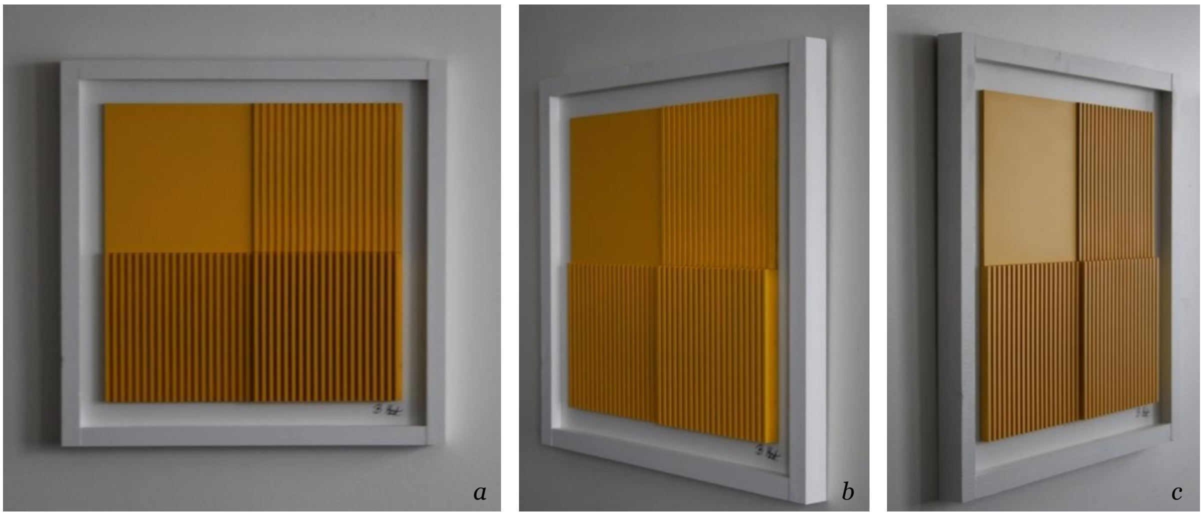


Figure 9: Relief composition designed by the author. It is assembled of a flat plate (upper left) and three linear relief plates that have a depth of 0.5 (upper right), 1.0 (lower left) and 2.0 (lower right) of the module, which is the width of the strips. Photos B. Matusiak, 2015.

The visual impression of a modern relief, i.e., one with a repetitive geometric design, seems to be strongly dependent on the presence of direct light of high intensity. As can be observed in Figure 10, the presence of direct sunlight on the relief surface creates strong luminance contrasts that attract the eye and dominate the image such that the importance of the background colour is strongly reduced; please, compare the right and the left hand photo in Figure 10. Consequently, the visual impression of a sunlit relief may change considerably depending on the incidence angle of light and the observation direction. The research question for this study is:

*What are the important parameters influencing perception of a **sunlit** modern linear relief and how are they influencing it?*

Figure 10: A relief wall in the detached house, Steinåsen 44b in Trondheim, designed by the author. Pictures taken with sunlight and clear sky to the left, and overcast sky to the right. Photos B. Matusiak, 2015.

A sunlit relief

When the relief surface is illuminated by a strongly directional, high-intensity light, e.g., sunlight, the visual impression and the average reflectance of the relief vary with the light incidence angle and the observation angle. Both angles are defined in relation to the normal of the outer surface of the relief.

Sometimes the observer's view direction nearly coincides with the direction of the sunlight; the observer sees only fully illuminated surfaces, no cast shadows. In this case the lightness of the relief depends on the luminous intensity of the light, the colour of the relief surface, its specularity and the adaptation of the eye.

Most often the observer's view direction does not coincide with the direction of the sunlight; the observer sees parts of the relief as being in shadow, the rest being excessively illuminated. The huge luminance contrast between light and shadow dominates and small luminance variations in the shadowed areas may be considered negligible. Since the surfaces of linear reliefs are oriented differently (by 90° in cross-section), the incident angle of sunlight differs and consequently, the visual image of the relief consists of very dark shadow strips and very bright sunlit strips, i.e., having very high luminance. To be precise, quite often the observer sees two types of sunlit strips having slightly different luminance, which is a result of slightly different incidence angle of light.

To make the analysis simpler, we may assume that the image of a linear relief consists of two components or aspects only: sunlit and shadowed strips. This makes it possible to reduce the image of a 3D linear relief to an image of a 2D pattern of light-dark strips. Obviously, the relation between the width of dark and light strips has an impact on the mean lightness of the relief.

In the next section the sunlit part of the relief image will be calculated for different relief geometries combined with diverse incidence and observation angles. As we limit our study to linear reliefs, the analysis of the light-shadow relation can be carried out on the cross-section plane.

Calculation of the sunlit part of the relief as seen by an observer

Let us consider a linear relief made of one material or painted in one colour and having repetitive design with each surface oriented by 90° relative to the next one; see the cross-section in Figure 11. The width of the outer surface is a, the width of the side surface b and the width of the inner surface c. The relief angle β is defined by the relation between b and c and can be easily calculated from the arctangent function as:

$$\beta = \arctan (c/b) \qquad (1)$$

The incidence angle of light is smaller than the relief angle $\alpha < \beta$

Let us consider that the relief is illuminated by sunlight, the incidence angle of the light is α, and the light hits the inner surface, i.e., one of the side walls is in shadow, the other one is sunlit.

When this relief is observed from the direction making larger angle with the relief normal than the sunlight, as shown by the yellow arrows in Figure 11, the shadowed parts of the relief are not visible, the whole relief appears as sunlit, so the sunlit part of the relief S:

$$S = 1.0 \text{ or } 100\%. \qquad (2)$$

When the relief is observed from the direction making smaller angle with the normal than the sunlight, as shown by red arrows, a small part of the relief image will be in shadow. Let us calculate the sunlit part, as the relief has repetitive shape, the calculation can be limited to one cycle, i.e., the space between red lines in Figure 11. The width of the image *W(i)* is:

$$W(i) = (a+c)\cos\gamma \quad (3)$$

And the width of the sunlit part *W(s)* is:

$$W(s) = (a+c)\cos\gamma - b\,(\tan\alpha - \tan\gamma)\cos\gamma \quad (4)$$

$$S = W(s)/\,W(i) \quad (5)$$

$$S = 1 - b\,(\tan\alpha - \tan\gamma)/(a + c) \quad (6)$$

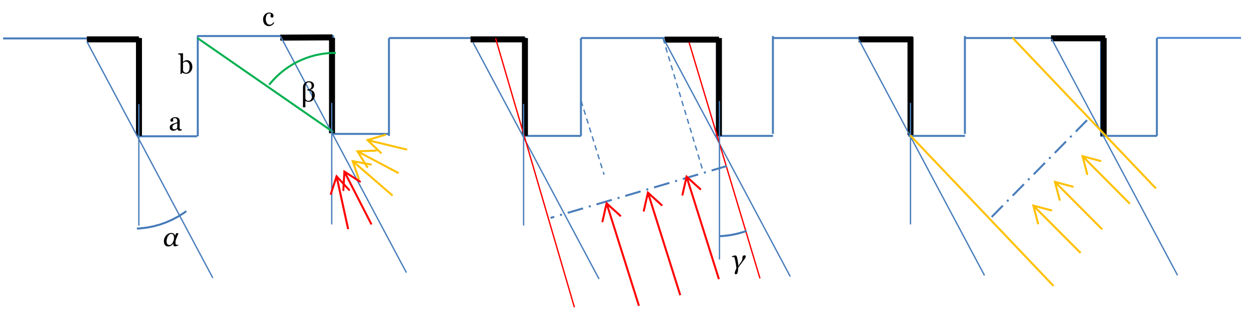


Figure 11: The cross-section of a linear relief illuminated by sunlight. The observation direction varies from 0 to 90° on the same side of the relief normal to the sunlight. An observation angle smaller than the sunlight incidence angle is exemplified by red arrows, larger by yellow arrows.

Equation 6 testifies that *b* (the depth of the relief) has negative impact on *S* as well as the difference between *tan α* and *tan γ*.

If the observer sees the relief from the normal direction, i.e., the view angle $\gamma = 0°$, $\tan\gamma = 0$, consequently:

$$S = 1 - b(\tan\alpha)/(a + c) \quad (7)$$

In the very special case when in addition $\alpha = 0°$, so $\tan\alpha = 0$ giving, as expected:

$$S = 1.0 \quad (8)$$

When the relief is observed from the opposite side of the relief normal, see Figure 12, the important question is: How much of the sunlit inner surface can the observer see? The green line marks this border and it is defined by the angle *υ*, where:

$$\upsilon = \arctan(\tan\beta - \tan\alpha) \quad (9)$$

If the same relief is observed from an angle larger than υ, marked by yellow arrows, the sunlit part of the relief is:

$$S = a/(a+c), \quad (10)$$

That means it is independent on the depth.

For directions marked by red arrows the sunlit part will be:

$$S = [a \cos \gamma + (c - b \tan \gamma - b \tan \alpha) \cos \gamma]/(a + c) \cos \gamma \quad (11)$$

$$S = 1 - b (\tan \gamma + \tan \alpha)/(a + c) \quad (12)$$

Equation 12 testifies that b (the depth of the relief) has negative impact on the size of S as well as the size of both angles, α and γ.

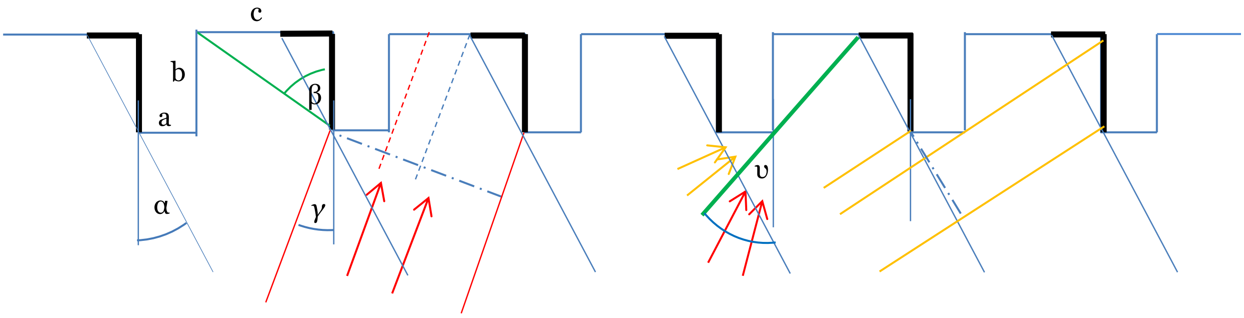


Figure 12: Cross-section of a linear relief illuminated by sunlight. The observation direction varies from 0 to 90° and is on the other side of the relief normal to the sun.

The incidence angle of light is larger than the relief angle α < β

Let us now consider the case where the sunlight incidence angle α is larger than the relief angle β and resulting in the inner surface being in shadow for any observation angle.

In the case the observation angle γ is larger than the sun angle α (Figure 13, yellow arrows) the sunlit part of the relief image S is independent of the relief geometry, i.e., a, b and c, not on the view angle either:

$$S = 1.0 \text{ or } S = 100\% \quad (13)$$

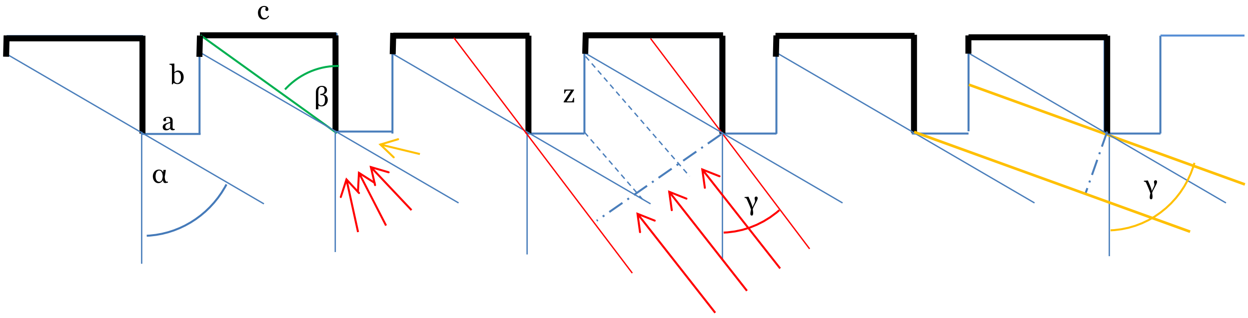


Figure 13: Cross-section of a linear relief illuminated by sunlight. The observation direction varies from 0 to 90° on the same side of the relief normal to the sun. Observation angles smaller than the sun angle are exemplified by red arrows, larger by yellow arrows.

In the case the observation angle γ is smaller than the sun angle α (red arrows) the sunlit part of the relief image S is:

$$S = (a \cos\gamma + z \sin\gamma)/(a+c)\cos\gamma \quad (14)$$

where:

$$z = c/\tan\alpha \quad (15)$$

That is:

$$S = (a/a+c) + c\,(\tan\gamma)/(a+c)\tan\alpha \quad (16)$$

Equation 16 shows that the sunlit part of the relief image S depends very much on the relief geometry, e.g., the size of a is decisive for the first term of the equation, c for the second one. The view angle γ has positive impact and the incidence angle α has negative impact on the second term of the equation.

In the case the observer views the relief from the normal direction, i.e., the view angle $\gamma = 0°$, $\tan\gamma$ is also 0 resulting in:

$$S = a/(a+c) \quad (17)$$

In this case the inner surface c is in shadow and the size of the relief depth b does not matter, the most important parameter that has a positive impact is the size of the outer surface a.

The same Equation 17 is to be used for observation angles on the opposite side of the relief normal to the sunlight direction. Due to the inner surface c and side surface b, both being in shadow, the size of the sunlit part S is not dependent on the observation angle, only on the proportion between a and c.

Let us illustrate how the sunlit part of a relief changes with the observation angle using two examples of a linear relief with a very simple design:

Relief 1, the shallow one: $a = c = 1$, $b = 0.5$

Relief 2, the deep one: $a = c = 1$, $b = 2.0$.

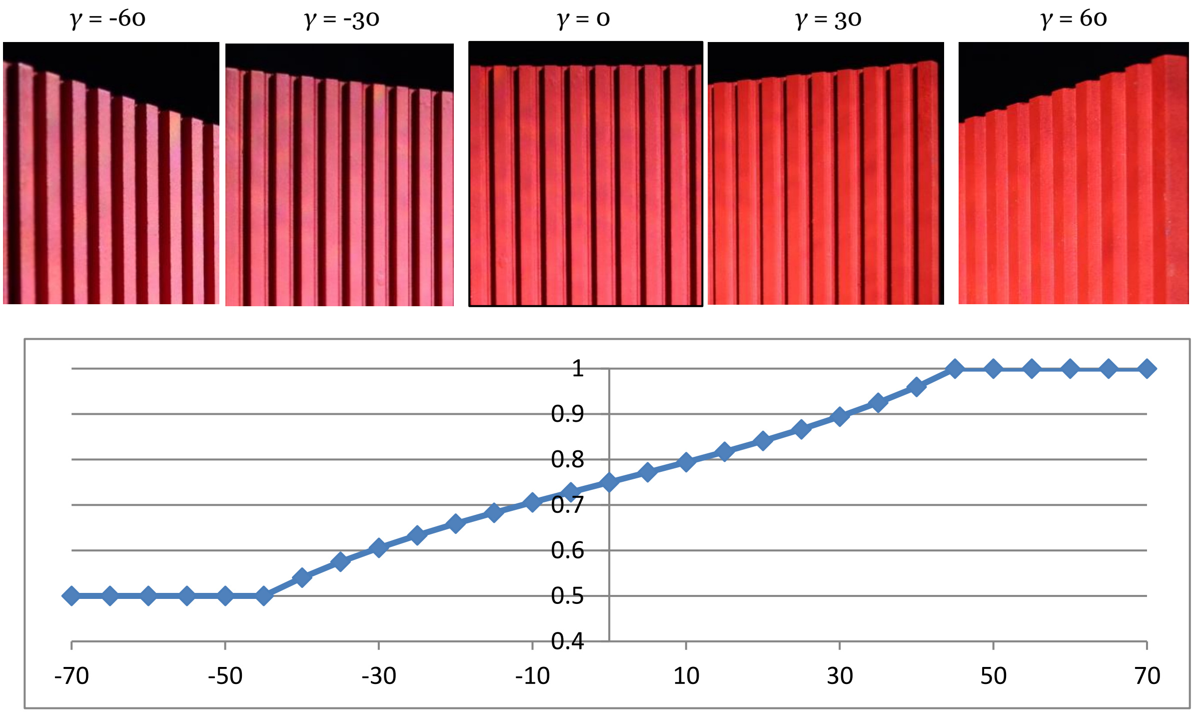
Both reliefs were illuminated with sunlight coming from the incidence angle of about 45°.

The sunlit part of those reliefs S was calculated using Equations 6 and 10 for the shallow relief and 16 and 17 for the deep relief.

The red relief plates like the ones used in the relief composition shown in Figure 8, were photographed in the Daylight Laboratory [10] while illuminated by the artificial sun. The following five observation angles were chosen: $\gamma = -60°$; $\gamma = -30°$; $\gamma = 0°$; $\gamma = 30°$; $\gamma = 60°$, where negative angles refer to the opposite side to the sun.

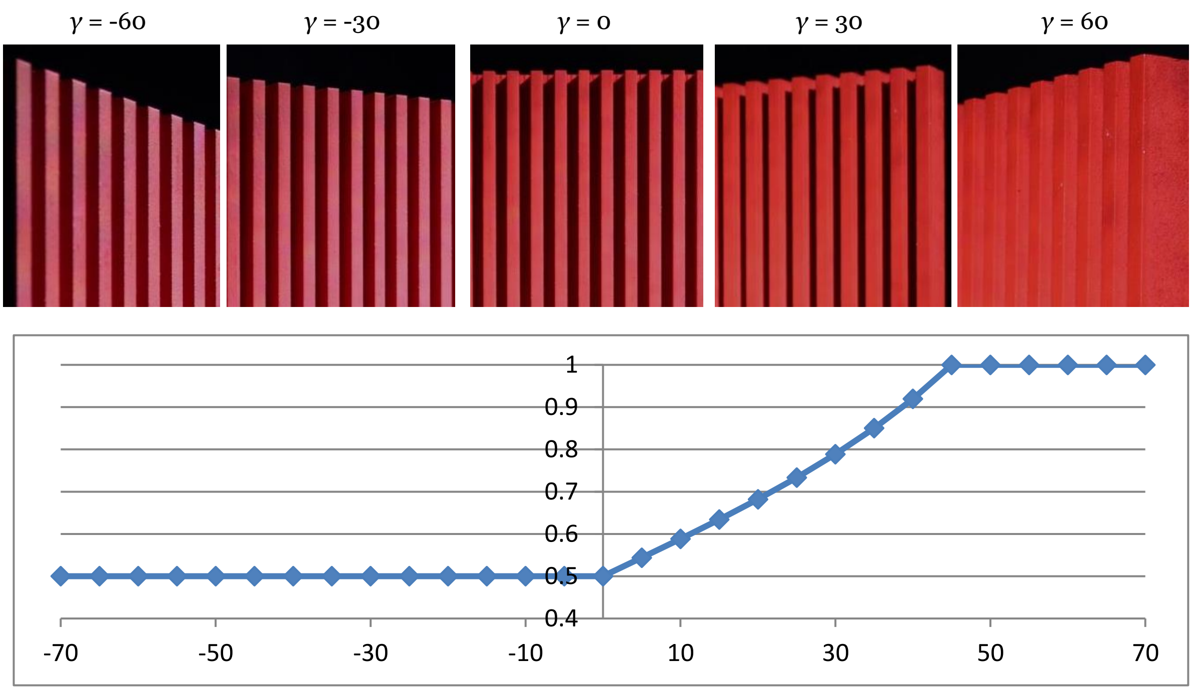
All photos as well as graphs showing calculation results are presented in Figure 14.

Relief 1: *a* = *c* = *1,0; b* = *0,5;* photographed from different observation angles *γ*



Calculated sunlit part S

Relief 2: *a* = *c* = *1,0; b* = *2,0;* photographed from different observation angles *γ*



Calculated sunlit part S for relief 2

Figure 14: The sunlit part S of a shallow relief (top) and a deep one (bottom).

How to estimate the average luminance of a sunlit relief?

The calculation of the sunlit part of the relief gives a possibility for an estimated calculation of the average luminance of a relief illuminated by sunlight. The calculation is especially simple in the case of diffuse surface and the incidence angle of light of about 45°when both sunlit surfaces, *a* and *b*, have nearly equal luminance; the following well known equation can be used:

$$L = \rho E(\cos \theta) / \pi \qquad (18)$$

ρ is the reflectance of the relief surface
E is the illuminance measured perpendicularly to the light direction
θ is the incidence angle of light

The luminance of the shadowed surfaces depends on the intensity of the reflected light from the sunlit surfaces of the relief, something that depends on the relief design (*b* versus *c*), and on the ambient light level in the room. As mentioned in the introduction, in this study we make an important simplification, i.e., we reduce the visual image of the relief to two qualities sunlit and shadowed strips. We assume that sunlit parts of the relief have equal and very high luminance and that the shadowed parts have equal and very low luminance. According to estimate luminance measurements carried out in the daylight laboratory as well as outdoors, the luminance ratio may be in the range 1:5 – 1:50. This luminance ratio depends very much on the context, the highest contrast may be expected on the sunlit relief wall situated in a black room with a small window; the lowest contrast may happen, e.g., outdoors at a time close to sunset when the direct sunlight is weak in comparison to the light from the sky.

To calculate the mean luminance L_{mean} the following simple equation can be used:

$$L_{mean} = L_s S + L_d(1\text{-}S) \qquad (19)$$

L_s is the luminance of the sunlit part
L_d is the luminance of the shadow part

As the luminance of the shadow part of the relief is much lower than the luminance of the sunlit part, the size of the sunlit part S is decisive for the average luminance and consequently for the average lightness of a relief.

Visual stimulation

The human visual system is stimulated by the image of a linear relief in a very different way than by a flat surface having a luminance equal to the average luminance of the relief. The stimulating effect of a relief wall depends very much on the observation distance since the sensitivity of the human visual system for luminance contrast changes with the view angle. Similarly to the white-black patterns, see Figure 14, a wall composed of shadowed and sunlit strips may appear as very contrastful, Figure 15, from a short distance, and as dull and grey from a long distance. The spatial frequency is a decisive factor [11]. For the frequencies which our system is most sensitive to, that is, about 3 cycles per degree, the repetitive pattern of strong luminance contrasts can even cause visual nuisance and, after prolonged exposure, a headache [12].

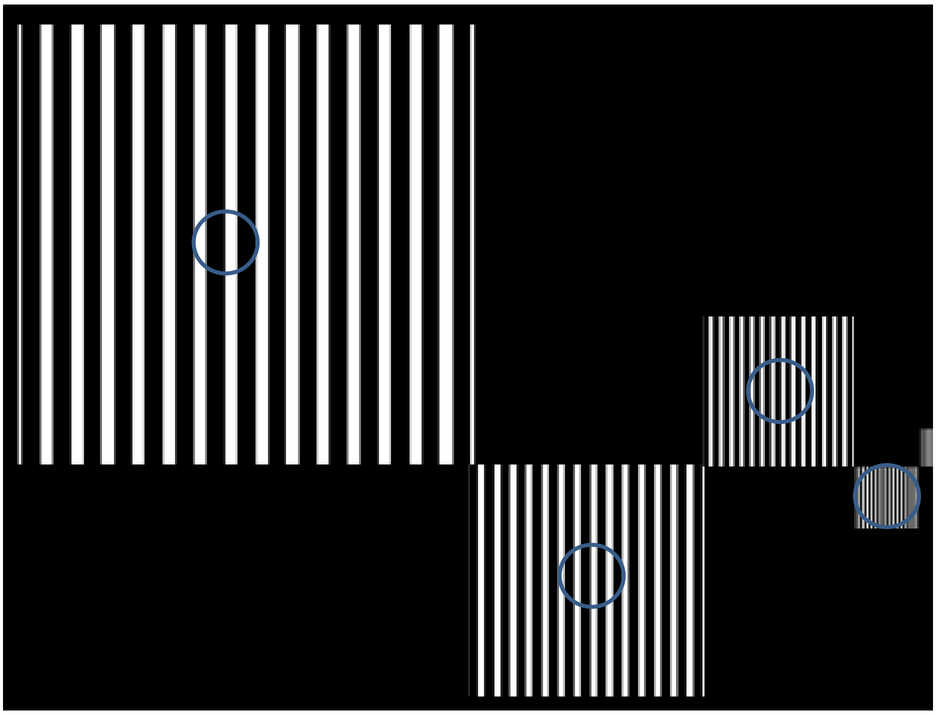


Figure 15: White-black stripes of different spatial frequency, the rings represent one degree.

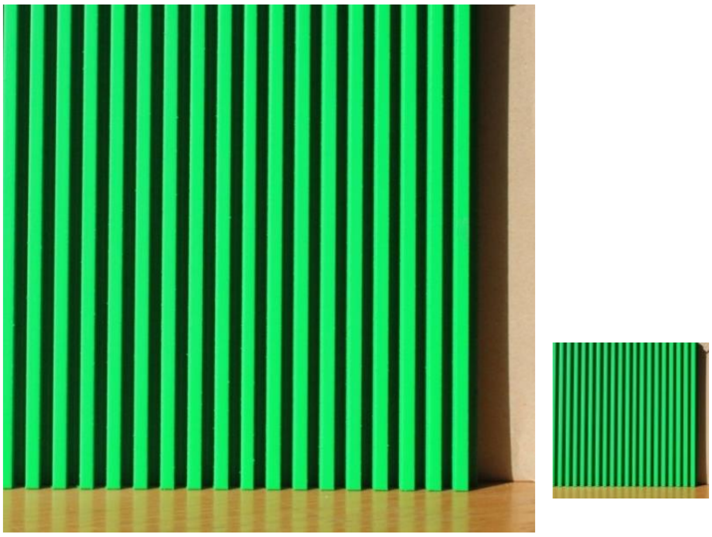


Figure 16: A green relief wall seen from a short and a long distance.

Discussion and Conclusions

With the calculations and visual studies of sunlit relief plates a series of parameters influencing perception of reliefs have been found, they are: width of strip–surfaces (a, b and c), colour, incidence angle of the light, and the observation angle.

The common opinion saying that the lightness (perceived luminance) of a relief depends mostly on its depth has been challenged. The depth is of course very important, its impact can be observed in Figure 14 by comparing the sunlit part S of the shallow relief (no 1.) with the deep relief (no 2.), for example for 0° observation angle (S = 0.75 for relief 1) and (S = 0.5 for relief 2).

The importance of depth is not always valid, for some observation angles (e.g. -60° in Figure 14) the only essential measure is the relation between the widths of the outer surface *a* and the inner surface *c*.

In the strong and direct illumination, e.g., sunlight, the observation direction is a very strong parameter. Generally we may consider two viewing situations. In the first one the observer's observation direction nearly coincides with the direction of light (for example 60° in Figure 14); the observer sees fully illuminated surfaces (no shadows). In this case the lightness of the relief depends on the illuminance, the incidence angle of light, the colour of the relief surface (reflectance) and the adaptation of the eye.

However, most often the observer's observation direction does not coincide with the direction of the sunlight; the observer sees parts of the relief being in shadow, the rest being excessively illuminated. The huge luminance contrast between light and shadow dominates and small luminance variations in the shadowed areas may be omitted as negligible. Since the surfaces of the studied reliefs are oriented differently (by 90°), the incident angle of sunlight differs and consequently, the visual image of the relief consists of strips of light and shadow. There is a combination of the light direction and the observation direction that decides how much of the relief image (as seen from the observer) is illuminated by the sun. New equations for calculation of the sunlit part of the relief have been developed and were used in calculations for two relief examples shown on graphs in Figure 14.

The photos in Figure 14 illustrate how the observer passing along the relief wall may perceive it. From the direction opposite to the direction of light (-60° in Figure 14) the strong light–shadow contrast dominates, the proportion between *a* and *c* are decisive for the size of the sunlit part *S* and consequently for the overall lightness of the relief; in our example there is not any difference between the visual image of the shallow and the deep relief. Starting from the observation angle when it is possible to see the light hitting the inner surface the sunlit part *S* for the shallow relief increases while it is still at the same low level in the deep relief and the difference between the two reliefs gets stronger (-30° and 0°) meaning that the shallow relief is getting lighter than the deep one. After passing the 0° the sunlit part *S* of the deep relief increases strongly (view angles 0° and 30°), this is because the partly sunlit side wall *b* becomes visible. Finally, from the observation direction close to the direction of light (60°) both reliefs appear without shadows, nearly as flat surfaces, again there is no difference between the shallow and the deep relief.

In addition to the changes of observation angle, which may happen very quickly, the incidence angle of sunlight changes continually, creating different light-shadow patterns over time. Depending on the location, orientation of the relief wall and the time, sunlight may illuminate the relief from one side underscoring its tectonic shape or from an angle close to the normal, making it more flat. The combination of the simultaneous changes of the sun incidence angle and the observation angle makes that many reliefs surprise us with a new image each time we see them, as such, they may be perceived nearly as mystic.

We may conclude that in addition to the design of the relief, i.e., it's colour and the widths of the inner, outer and side surfaces, there is a combination of the light direction and the observation direction that determines how much of the relief (as seen from the observer) is illuminated by the sun and consequently how bright the relief appears.

The discussion about the visual impression of the sunlit relief should not be limited to the overall lightness. Numerous examples of ancient reliefs can testify about using reliefs as an artistic decoration, often in combination with worship of deities and leaders and/or praises of military victories. The luminance contrast between light and shadow is especially strong in sunk-reliefs of ancient Egypt and modern stone reliefs done with traditional stone cutting method, e.g., of Bibliotheca Alexandrina. It was, and even today it continues to be, stimulating. Compared to ancient reliefs the modern reliefs made of wood sticks are often strictly repetitive resulting in even stronger stimulation, which can be compared to the stimulation caused by Op-art works [12]. The degree of stimulation depends on the spatial frequency of the relief combined with the contrast sensitivity of the eye. According to Valberg, the highest sensitivity of the human visual system occurs for surfaces with a luminance of about 300 cd/m^2 (a bit higher than a computer screen) and for a spatial frequency of about 3 cycles per degree. When designing modern reliefs in buildings, we should consider which level of visual stimulation fits the function of the space. We should also examine what happens when users are exposed to uncomfortable images for an extended period of time.

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