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The study of shadows—Kepler's 'light figures' and pinhole imaging

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Abstract

Kepler's theory on pinhole camera imaging is still valid today, its development is well documented and provides an exciting context for optics lessons. Kepler presented a generalised concept of 'light figures,' describing the formation of soft shadow images through the interaction between extended apertures and extended light sources. The work marks the culmination of Kepler's extensive engagement with the 'Moon Puzzle.' In this paper, we examine Kepler's theory and depiction of 'light figures' from both historical and experimental perspectives. We provide an overview of Kepler's theory and its historical context, and present experiments that illustrate Kepler's theoretical insights, specifically designed for educational use. In this way, a generalised concept of soft shadow imaging can be integrated into optics education, drawing on an authentic historical context.

Keywords: pinhole camera, Kepler, light figures, shadow imaging

Supplementary material for this article is available online

1. Introduction

In 1604, Johannes Kepler published *Ad Vitellionem Paralipomena*, a part of his treatise *Quibus Astronomiae Pars Optica Traditur*. In the second chapter, *On the Shaping of Light*, he presented the first correct theory of pinhole camera imaging in the Western world [1]. His research was driven by an unusual observation during the solar eclipse of 10 July 1600: in pinhole projections, the Moon's shadow appeared smaller than expected [2, 3]. To resolve the inconsistencies between direct observation and pinhole projections, called the 'Moon Puzzle', Kepler analysed the imaging conditions of pinhole cameras with apertures of finite size. With his 1604 publication, he aimed to communicate his findings to the scientific community. At the heart of

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his theory lies a geometric principle describing how shadow images emerge from the interaction between extended apertures and extended light sources. He referred to these patterns as ‘light figures’ (’figurationes lucis’ in Latin), which are now understood as ‘soft shadow images’. – They arise between the extreme cases of a point light source on the one hand, generating a sharp projection of an extended aperture (*hard shadow*) and an approximately expansionless aperture on the other hand, imaging an extended light source (*pinhole image*), i.e. *soft shadow images* always show a mixture of the geometry of the aperture and the light source [4].

The aim of the present work is to historically and experimentally explore these ‘light figures’ in the context of optics education. Kepler’s theory of pinhole imaging offers new opportunities for a broader treatment of imaging phenomena in the classroom. While standard presentations often focus on the ideal pinhole camera scenario with an aperture that does not expand, Kepler’s work delves into the effects of expanded apertures and light sources. These effects are typically overlooked or considered mere technical imperfections in the image-formation process. However, Kepler’s approach presents them as the result of a dynamic interaction between the imaging and imaged objects, in which the principle of optical convolution can be easily recognised. The experimental reproduction of Kepler’s principles allows us to uncover shadow phenomena in everyday life that were previously unnoticed and which can sometimes be surprisingly beautiful. These include shadow images that can only be fully understood if Kepler’s classification is extended by replacing the imaging aperture with a geometrically isomorphic obstacle.

The structure of this paper is as follows. The first part outlines Kepler’s theory of ‘light figures’ and examines its historical context, with emphasis on its connection to the ‘Moon puzzle.’ The second part presents a selection of illustrative experiments that are historically informed and designed for classroom use. Extensions of these experiments are showcased in two videos (’Curious Shadow Phenomena’ and ‘Kepler’s ‘Light figures’ and Beyond’), which are available in the *Supplementary Material* of the online version. The final part highlights the significance of historical insights in expanding contemporary theoretical frameworks, demonstrating how Kepler’s principles can be applied to the development of shadow images. We conclude by showing how inverting the aperture results in complementary ‘light figures,’ thereby offering a broader understanding of the formation of soft shadow images.

2. Keplers ‘light figures’ in *Ad Vitellionem*

In the solution to the Moon puzzle in Kepler’s notebook from July 1600, the idea for the first generalised theory of pinhole imaging in the Western World shines through [5]. His chapter *On the Shaping of Light* (1604) is a direct continuation of this earlier exploration. The Moon puzzle sets the narrative framework for the chapter: it sets the problem, and its solution serves as the first example of applying the new theory. Near the beginning, Kepler writes [1]:

> For however many eclipses were observed in this way [pinhole camera method], they all had come out much greater in the sky than it appeared in the ray [image]: all showed a much greater lunar diameter in the sky than in the ray [image]. Hence it is that that Phoenix of astronomers, Tycho Brahe, in his wonder, was driven to such straits as to pronounce that the lunar diameter is always a fifth part smaller in conjunctions than it appears to be in oppositions, even though it is the same distance from us in both instances.

Kepler had recognised that the apparent shrinkage of the Moon in pinhole camera images was due to the geometric effects of the imaging aperture (figure 1), not to astronomical causes as Brahe had believed. The text continues by describing Kepler’s journey to solve the Moon puzzle and his almost desperate struggle with existing solution attempts. His conclusion that studying Pecham’s theory of the pinhole camera was not helpful led him to propose a tangible model of pinhole camera imaging (lat. ‘confugi at $\alpha\upsilon\tau\omega\psi\iota\alpha\nu$ in solido’ [7], engl. ‘I had recourse to seeing with my own eyes in space.’[1]). This approach was possibly inspired by Albrecht Dürer’s techniques

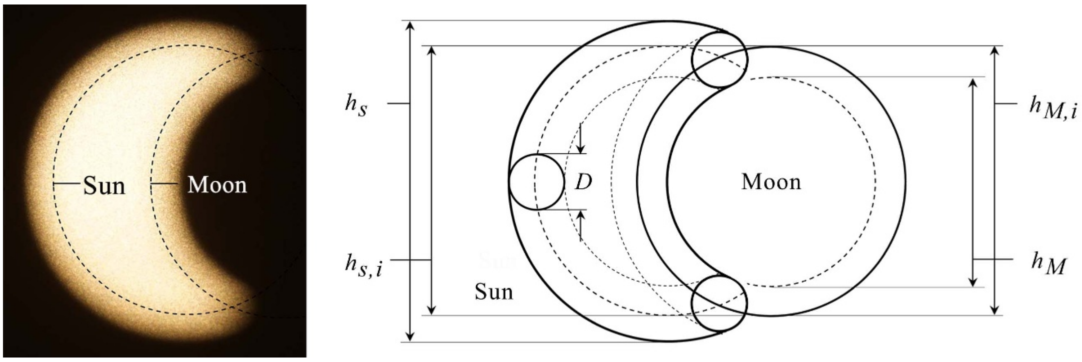

Figure 1. The Moon puzzle: in contrast to direct view, where Sun and Moon appear to be about the same size ($\alpha_{\text{Sun}} = \alpha_{\text{Moon}}$) the pinhole image of the Sun h_{S} appears enlarged, and the diameter of the Moon h_{M}, derived from the radius of the obscured part of the Sun, is reduced (left). Kepler recognised that the solution lay in the imaging conditions of the aperture and had no astronomical causes. By convolving the image of the partially occulted Sun with the imaging aperture D, the solar image $h_{\text{S},i}$ appears enlarged by the aperture diameter and the lunar image h_{M} reconstructed from the concave edge appears reduced by the same amount (right) [6].

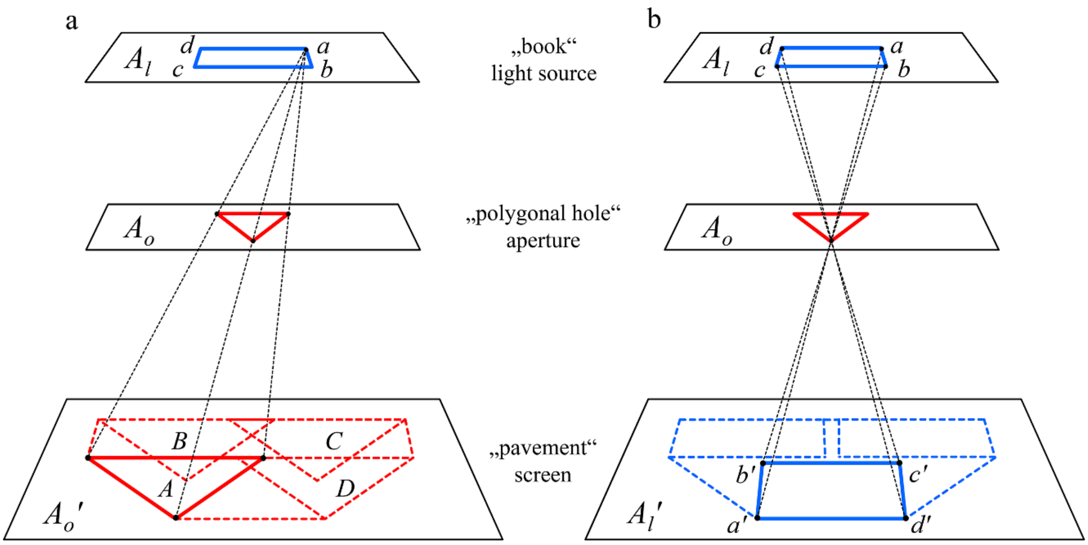

Figure 2. Illustration of Kepler's quoted model for the formation of 'light figures', i.e. soft shadow images as superimposed projections of the aperture (a). Kepler's geometrically equivalent explanation of soft shadow images as superimposed pinhole images of the extended light source (b) [1].

for constructing perspective views [8]. Kepler writes [1]:

> I set a book in a high place, which was to stand for a luminous body (figure 2(a)). Between this and the pavement a tablet with a polygonal hole was set up. Next, a thread was sent down from one corner of the book through the hole to the pavement, falling upon the pavement in such a way as to graze the edges of the hole, the image of which I traced with chalk. In this way a figure was created upon the pavement similar to the hole. The same thing occurred when an additional thread was added from the second, third, and fourth corner of the book, as well as from the infinite points of the edges. In this way, a narrow row of infinite

> figures of the hole outlined the large quadrangular figure of the book on the pavement.

In the passage quoted, Kepler conceptualises the extended light source as being decomposed into point light sources that project sharp images of the aperture onto the image plane (figure 2(a)). The resulting shadow image emerges from the sum of these overlapping aperture projections. This method of image construction is essentially the same as that commonly taught in schools today. However, Kepler does not further elaborate on this construction principle in his text. Instead, he describes a second, geometrically equivalent scenario that forms the basis for further reasoning. In this second principle, the shadow image is formed by the sum of superimposed pinhole images of the light source (figure 2(b)). Each point on the edge of the aperture is treated as a point like pinhole, which creates a point-symmetrically mirrored image of the light source on the screen. The aggregate of these pinhole images outlines the resulting shadow image (or 'light figure'). In Kepler's words [1]:

> The shape of a ray [image] on the wall is a mixture of the inverted shape of the luminous surface and the upright shape of the window, and it corresponds to them in position in this way.

Both methods allow for a generalised construction of shadow images when light from an extended source passes through an aperture of significant size. The dominance of either the light source's shape or the aperture's shape in the resulting shadow image is determined by the size ratio of their respective projections onto the screen. Kepler now identifies three cases by comparing the size ratios of the projections and analyzing their effects on the shadow image. To clarify these distinctions, we denote A_l and A_o as the areas of the light source and the aperture, respectively, and A_l' and A_o' as the areas of their projections onto the screen. Although Kepler primarily demonstrates the cases for the second construction principle (the sum of ideal pinhole images of the source), we also explore the alternative construction (the sum of projections of the aperture) (figure 3).

If the projected aperture A_o' on the screen significantly exceeds the size A_l' of the pinhole image of the light source, for example because the aperture is very close to the screen, then the resulting shadow image will more closely resemble the aperture A_o (figures 3(a) and (d)). In contrast, if the projection of the aperture A_o' becomes very small compared to the pinhole image A_l' of the light source, the conditions are reversed. In this case, the shape of the light source A_l will dominate the shadow image (c and f). Between these two extremes, there exists a stage where the shadow image exhibits a balanced interplay between the shapes of the light source and the aperture, making it impossible to discern which shape predominantly influences the resulting 'light figure'. In this scenario, the projections of the light source A_l' and the aperture A_o' are approximately the same size (b and e). In summary:

(i) $A_\mathrm{l}' < A_\mathrm{o}'$: the image of A_o predominates $\rightarrow$ *projection of the aperture*
(ii) $A_\mathrm{l}' \approx A_\mathrm{o}'$: the image shows a balanced mixture of shapes A_l and A_o $\rightarrow$ *soft shadow image*
(iii) $A_\mathrm{l}' > A_\mathrm{o}'$: the image of A_l predominates $\rightarrow$ *pinhole image of the light source*.

By distinguishing these cases, Kepler characterised the full range of possible soft shadow images as combinations of both light source and aperture shapes. From this generalised pinhole camera theory, we can derive several lessons for teaching optics. Contrary to widely held belief, shadow images are not simply projections of the aperture (i.e. the shadow caster)[9]; instead, they result from the geometric relationship between the imaging and the imaged object. What is commonly referred to as 'blurring' actually represents an increase in geometric image information about the light source within the shadow image (as A_l' increases relative to A_o'). The shadow image thus contains the whole information about the spatial conditions that lead to its formation. Learning to see shadows as images means recognizing the overall context of these conditions in the actual shadow. The distinction between umbra and penumbra proves to be too simplified against this background; it ignores the fact that the penumbra is the 'image zone of the light source', just as the umbra is the 'image zone of

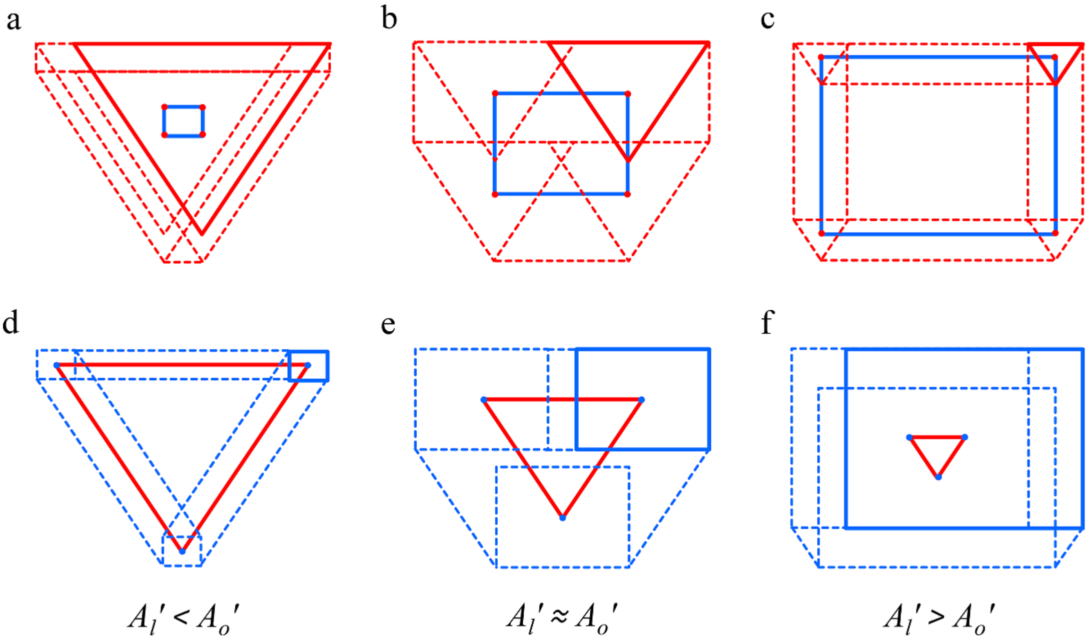

Figure 3. Kepler's case distinction for the two equivalent construction methods in figure 2 in overview. The upper row shows a series of soft shadow images, built up from the sum of the projections of the triangular aperture (a)–(c). The bottom row shows the same series, resulting from the sum of the pinhole images of the rectangular light source (d)–(f). The theoretical limiting cases are given for expansionless aperture and point light source respectively.

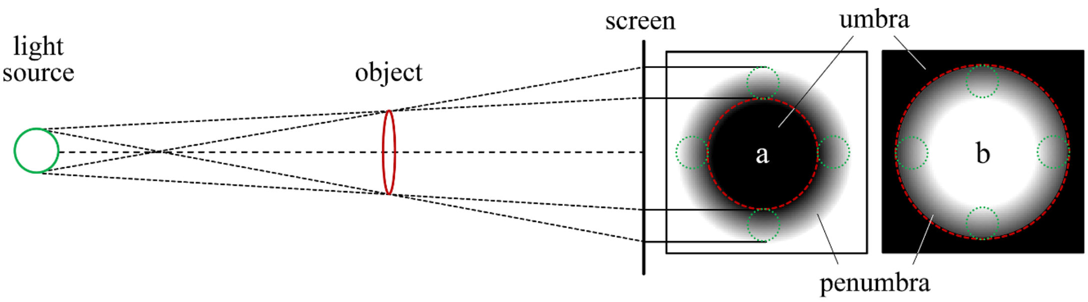

Figure 4. The shape of the umbra is determined by the shape of the object; the umbra is therefore the *image zone of the object*. The shape of the penumbra is determined by the shape of the light source. The penumbra is therefore the *image zone of the light source*. Inverse objects (aperture/obstacle) lead to complementary shadow images (a), (b); see section 4).

the aperture' (figure 4). In this way, Kepler's generalised pinhole camera theory also provides a graphical representation of the principle of optical convolution [10].

At the conclusion of the chapter, Kepler revisits the solution to the Moon puzzle. Brahe never witnessed this resolution, as he had passed away in October 1601.

3. Experiments on 'light figures'

If we follow Kepler's example and play with differently shaped light sources and apertures, the result is a surprisingly diverse, aesthetically pleasing spectrum of shadow images (i.e. 'light figures'), the different types of which can also be discovered in everyday life. Most direct and

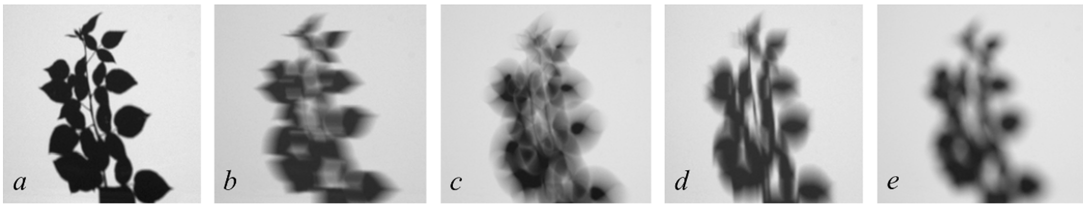

Figure 5. Shadow images of a raspberry spray. What shape does the respective light source have? [12] .

indirect light sources in our everyday environment are extended and change shape depending on perspective, producing surprising effects such as the *hole in the shadow* or the *bright shadow* [4]. Studying this in more detail in physics lessons seems worthwhile for at least the following reasons: It turns out that the field of shadow phenomena is much larger and more varied than the conventional definition of shadows suggests. Shadow phenomena can be realised with simple equipment in a variety of ways and at low cost and offer space for individual activity and creativity. Shadow images are a very simple, easy-to-understand visualisation of the fundamental principle of optical convolution, i.e. how imaging and being imaged depend on each other. Finally, shadow images reveal a high aesthetic quality that can sensitise students' visual experience. Similarly to deduce the diffracting structure from diffraction images, one can visually reconstruct the shape of the light source from the alienated shadow image of a known object (figure 5) [11].

The following section presents several qualitative experiments that illustrate key aspects of Kepler's 'light figures' within their historical context. They can be carried out with simple equipment and are also suitable for middle school physics lessons. We will demonstrate the generation and transformation behaviour of 'light figures' and experimentally illustrate the two construction rules introduced by Kepler. Extensions are given in the online supplementary material.

3.1. Exploring the generation of 'light figures'

To create 'light figures' (i.e. shadow images) and to qualitatively study the influence of extended light sources on the shape of shadows, we use all kinds of commercially available extended lights in different sizes. Examples of creating shadow images with a ring lamp, a rod lamp and a filament are shown in the first video ('Curious Shadow Phenomena'). In this way, we gain a sensitivity for how the geometry of the light source is shaped in the alienation of the aperture's shadow. We are thus reproducing Kepler's central observation: Shadow images are generally 'mixed patterns', as they contain not only the geometric information of the aperture, but also that of the light source. We suggest referring to the umbra as the *image zone of the object* and the penumbra as the *image zone of the light source*. The multiplicative linking of the shapes in the image plane can be characterised by imagining the resulting shadow image as having been created by drawing the aperture's outline with a pencil whose tip has the shape of the light source geometry [13].

In order to optimise and systematically vary the conditions for generating Kepler's 'light figures', we use the setup shown in figure 6. The light source consists of a hemisphere (Ø = 30 cm) whose interior is coated with a highly matte white surface and illuminated by four 500 W halogen lamps, creating an almost homogeneous luminance. The maximum aperture is 20 cm. Circular panels made of sheet steel with differently shaped openings of various sizes can be placed in front of the opening and set in adjustable rotation with an electric drive. This allows the influence of the geometry of the light source in the shadow image to be enhanced by movement. The illuminated aperture A_o is realised by differently shaped paper windows, which are glued to glass panes and can be moved between the light source and the projection screen. The shadow images are projected onto a semi-transparent screen, which we observe from behind.

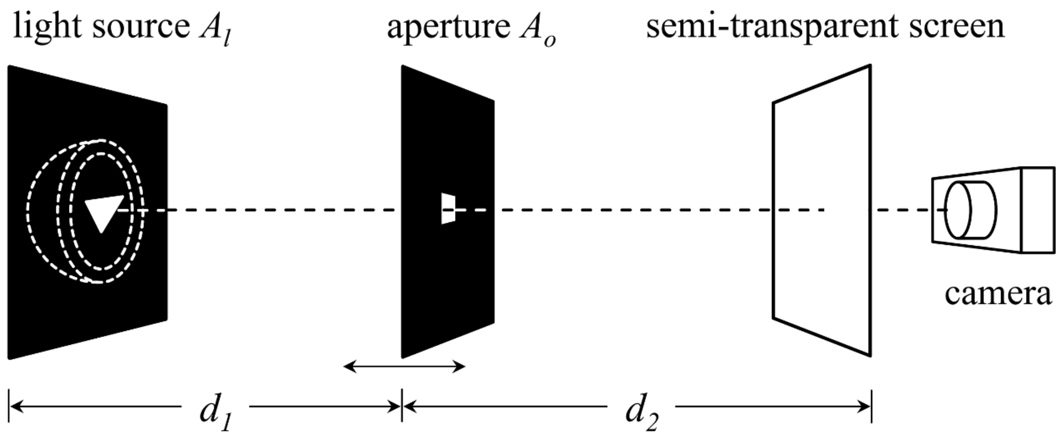

Figure 6. Setup for generating Kepler's 'light figures'. The position of the aperture A_o is specified by the distance ratio $\gamma = d_2/d_1$.

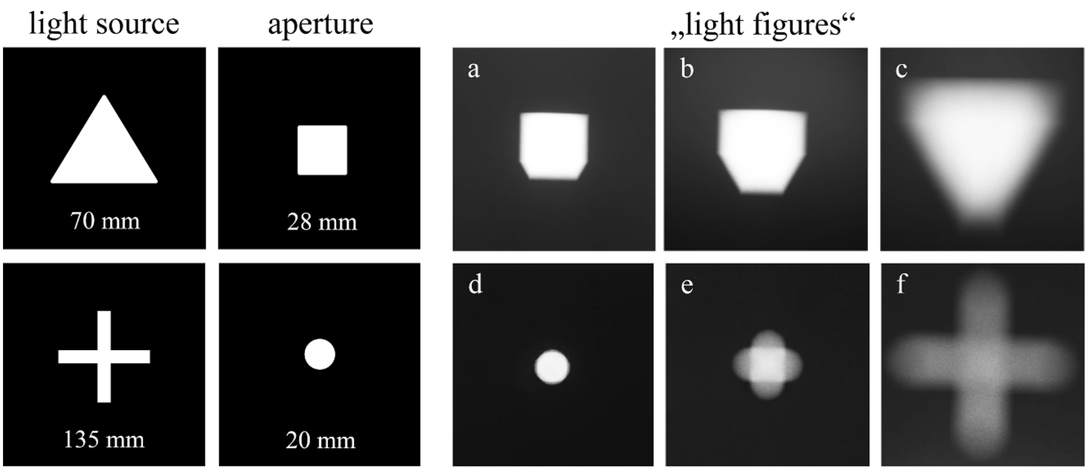

Figure 7. Kepler's case distinction from figure 3 with triangular (above) and cross-shaped (below) light source and square resp. circular aperture. The series a–c and d–f result from the increasing distance of the aperture from the screen with $\gamma = 0.1$ (a), (d), $\gamma = 0.3$ (b), (e) and $\gamma = 2.1$ (c), (f).

Figure 7 shows Kepler's case distinction for the 'light figures' in two variants, with which we modify the shapes of aperture and light source in figures 2 and 3. The dimensions of the respective areas A_l and A_o as well as the relative distances d_1 and d_2 are chosen to ensure that the cases i)–iii), namely the transition from the aperture image to the source image, can be realised. The distance $d_1 + d_2$ was 242.0 ± 0.1 cm. Further variants are given in the second video in the online supplement ('Kepler's Light figures and Beyond').

3.2. Constructing 'light figures'

As shown in the history section, Kepler outlines a generalised construction principle for soft shadow images in his Optics, which includes pinhole images as a special case and in which each point on the perimeter of the aperture produces an ideal pinhole image of the light source on the screen (figures 3(d)–(f)). To illustrate this way of thinking and to enhance the understanding of the concept in teaching, we again use the experimental setup in figure 6 and cover the square

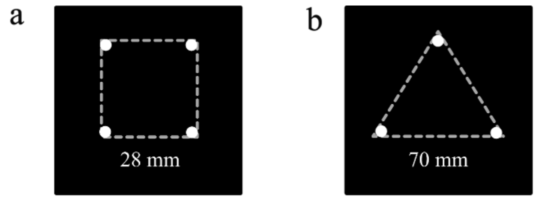

Figure 8. Apertures to illustrate Kepler's method for constructing 'light figures'.

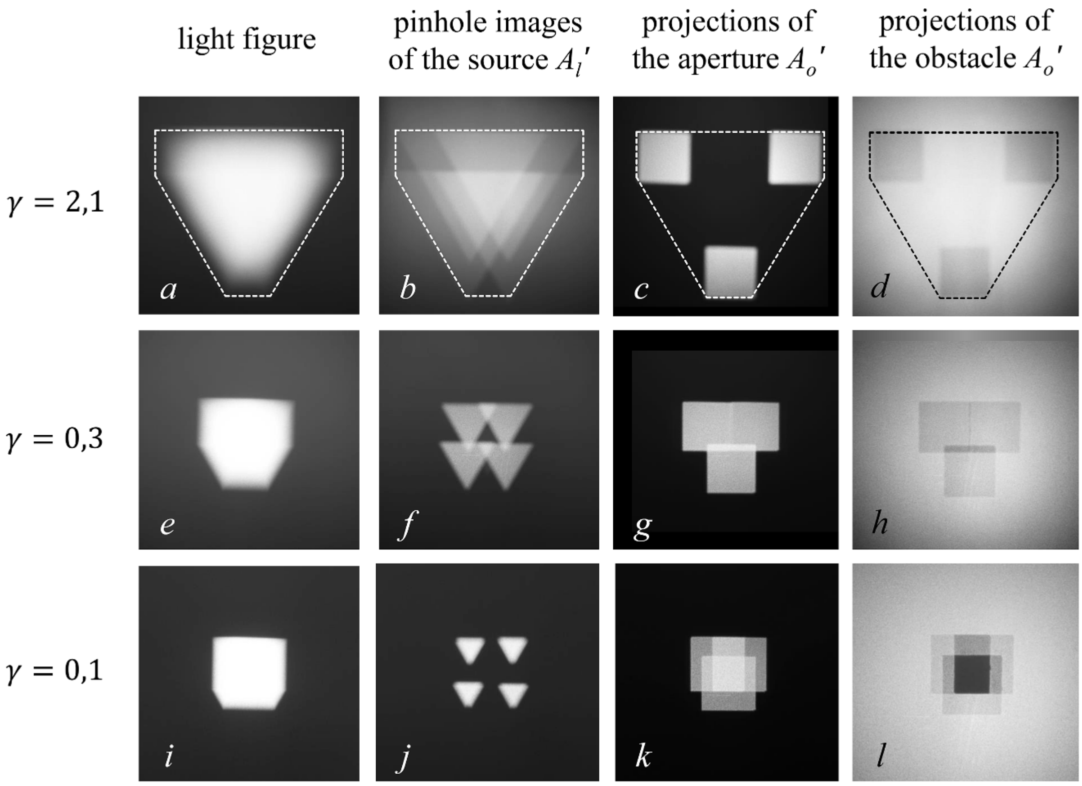

Figure 9. The matrix illustrates the composition of the 'light figures' of figures 7(a)–(c) (column 1) from selected pinhole camera images (column 2) resp. aperture projections (column 3). Replacing the opening with an obstacle of the same size leads to projections (column 4) that are complementary to those in column 3.

aperture with a thin sheet of aluminium in which four 4 mm holes have been drilled (figure 8(a)). These act as pinholes at the tips of the square and produce pinhole images of the light source onto the screen (figures 9(b), (f) and (j)). This reveals how the resulting 'light figure' can be thought of as the sum of the pinhole images of the light source imaged through the edge of the aperture.

As mentioned above, Kepler addresses in the book quote a second, geometrically equivalent construction principle without detailing it. In this approach, the light source is decomposed into imaginary point light sources, and the resulting shadow image on the screen is formed by summing the aperture projections (figure 2(a)). By covering the triangular light source with another aluminium sheet (figure 8(b)) in which three 3.6 mm holes are drilled, which act as point light sources at the tips of the triangle, we create three projections of the square aperture (figures 9(c), (g) and (k)). The outlines of these contours together form the light pattern again.

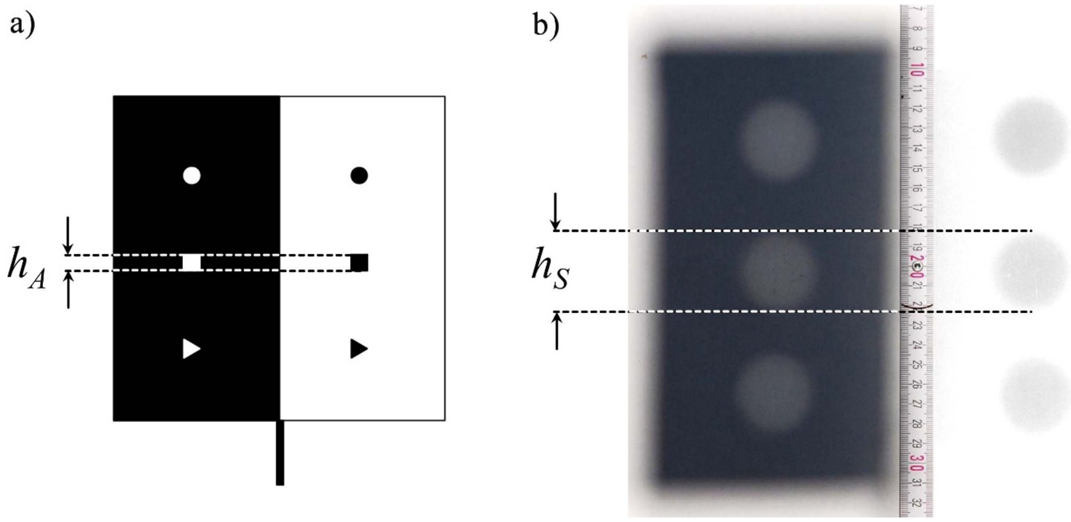

Figure 10. Inverse aperture geometries (circle, square and triangle) made of cardboard, glued to a pane of glass, create complementary images of the Sun on a sunlit wall. The extension h_A of the openings/obstacles is 8 mm, the size of the Sun images h_S is about 40 mm.

Comparing these two construction principles in the experiment confirms the formulation of the three imaging conditions (i)–(iii), since we can directly compare the area A_1' of the inverted pinhole images of the light source with those of the aperture projections A_o'.

4. Complementary 'light figures'

Kepler, primarily an astronomer, viewed the optical solution to the Moon puzzle as a stepping stone toward a deeper understanding of broader astronomical principles. His work on the theory of the pinhole camera led to a comprehensive understanding of the aperture's role and its geometric relationship with the light source. However, Kepler's research implicitly suggested a broader framework for exploring images formed by soft shadows. Inverting the aperture, i.e. replacing it with an obstacle of the same shape (effectively swapping transmissive and occluding regions) preserves the geometric imaging properties, resulting in complementary shadow images. This principle, when applied to Kepler's work, allows for the generation of complementary 'light figures': 'shadow figures'. It may seem strange to refer to these 'shadow figures' as *images*, they might also be called *missing images* for the following reason. We recall Kepler's construction principle in figure 2: If there is neither aperture nor obstacle between the light source and the viewing screen, the screen is filled with overlapping and thus indistinguishable images of the source. Since the aperture allows for the isolation of an image on the screen, an obstacle of the same size in the same position as the aperture prohibits that same image from reaching the viewing screen. Hence, what is 'seen' (the 'shadow figure') is actually what is not seen—a missing image. To illustrate this, several experiments are presented and shown as examples in the second video ('Kepler's Light figures and Beyond') in the online Supplement.

Figure 10 illustrates the concept by simultaneously creating light and dark 'Sun coins': the positives (circle, square and triangle), which were cut out of cardboard to create corresponding apertures, were glued next to them on a pane of glass.

Two more examples further illustrate this concept. Figures 9(d), (h) and (l) shows the construction principle for shadow images after replacing the aperture with an equally sized obstacle, such as a small cardboard square. Consequently, this approach yields 'shadow figures.' figure 11 illustrates the transformation of complementary

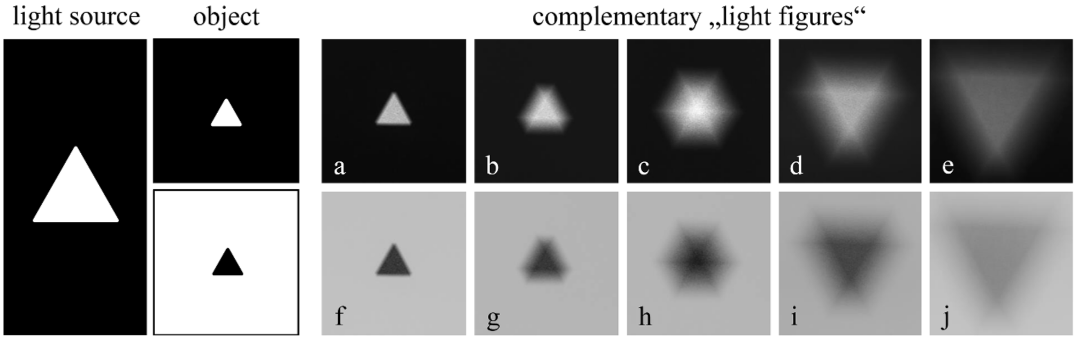

Figure 11. Inverse apertures produce complementary ‘light figures’. By varying the position of the aperture, series of ‘light figures’ are created which show the transformation of the aperture’s hard shadow (a), (f) into the mirrored pinhole image of the light source (e), (j), passing through a stage of mixed balance (c), (h). If the shapes of the light source and aperture rotate in opposite directions, e.g. in the aperture position for the mixed balance state of the shapes, a further, seemingly spatial dimension of Kepler’s ‘light figures’ becomes apparent (see the second video in the online Supplement).

shadow images in another interesting and aesthetic case, where a triangular object is illuminated by a similarly oriented triangular light source.

5. Conclusion

In this article, we delve into and experimentally explore Kepler’s ultimate pinhole camera theory, exemplified through his concept of ‘light figures’, which emerged from his solution to the Moon puzzle. Kepler’s principles for constructing these ‘light figures’ illustrate how generalised pinhole camera images arise from the dynamic interplay between luminous sources and the illuminated objects.

Within the historical narrative, Kepler’s depiction of ‘light figures’ is a product of scientific publishing, where the focus is on providing a clear, systematic, and compelling presentation of his findings to the scientific community. At the same time, the authenticity of Kepler’s documentation and the clarity of his reasoning regarding ‘light figures’ offer a valuable opportunity to expand the theory of the pinhole camera in educational contexts. Discussions typically centre around the ideal pinhole camera scenario, but deviations arising from finite-sized apertures, as opposed to point-like ones, are often dismissed as mere technical imperfections in image formation. In contrast, Kepler’s theory offers a universal and accessible treatment of pinhole camera images with finite-sized apertures and extended light sources. We have also shown how this interaction can be broadly described when discussing soft shadow images, providing a conceptual link from Kepler’s historical treatment of light figures to a generalised approach to soft shadow image formation. Additionally, we demonstrated that inverting the aperture leads to complementary ‘light figures.’

The history of pinhole camera theory, within the context of Kepler’s Moon puzzle and his theory of ‘light figures’, is a fascinating chapter in optics that integrates historical, technical, and epistemic perspectives, forming a comprehensive and unified understanding.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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[6] The picture on the left was taken from the semi-transparent screen in the experimental setup from figure 6 with a Sony alpha 7 III digital camera and the 28–75 mm F/2.8 Di III RXD objective from Tamron, as were the pictures in figures 5, 7, 9, 10 and 11.
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