Magnifying Grains of Sand, Seeds and Blades of Grass: Optical Effects in Robert Grosseteste's *De iride* – *On the Rainbow* (c. 1228-30)

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Abstract

In his treatise *On the Rainbow* (De iride), composed nearly 400 years before the first known telescope, the English polymath Robert Grosseteste identified three striking optical effects: distant objects can be rendered close by; close by large objects can be rendered small; and distant small objects can be rendered large. In the context of the history of optics, the first effect is especially striking. Grosseteste did not give details of the mechanisms underlying these effects, but did mention the passage of the ray through refraction in 'diaphanous' or transparent bodies. While making no final claim that Grosseteste himself necessarily knew of or used lenses, this paper examines the coherence between the three optical effects described in Grosseteste's treatise, and two candidate proposals for the deployment of a single convex lens. A convex lens, deployed in different ways, is shown to produce all three of Grosseteste's optical effects, in a manner strikingly aligned with the language that he uses to distinguish changes in the location and size of objects. The implications of this coherence for interpretations of *On the Rainbow* are discussed throughout the paper.

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In *On the Rainbow* (De iride), a treatise most likely composed c.1229, and so pre-dating the first known telescope by nearly 400 hundred years,[1] Grosseteste described three striking optical effects. The passage appears in a long preliminary discussion of *dioptrics* (refraction), before the rainbow is addressed directly. The three effects are: (1) distant objects appear as though close by; (2) large things placed close by appear small; and (3) small things placed far away appear large. In his words:

> the passage of the ray is through several diaphanous [things] of different kinds, at whose point of contact the visual ray is refracted and makes an angle, and the ray arrives at the thing seen not by a straight progression, but by a route consisting of several straight lines connected at angles. ... if known perfectly, this part of optics shows us the way in which we may make things very far away appear as though placed very close by, and in which we may make large things placed close by appear very small, and in which we may make small things placed far away appear as large as we please, so that it becomes possible for us to read very small letters at an incredible distance, or count [grains of] sand, or seeds, or [blades of] grass, or whatever you might want.[2]

The aim of this investigation is to evaluate Grosseteste's description of optical effects against a series of modern demonstrations with lenses, which are found to be entirely coherent with the effects described. We will show that just a single convex lens can be deployed in different ways to produce optical effects that are consistent with Grosseteste's description. In such a scheme, the first and second optical effects are consistent with a distant (effect one) or close by (effect two) object viewed through a convex lens held at arm's length (or mounted on a sighting pole); and the third optical effect is consistent with a small object positioned within one focal length of a convex lens, viewed through the lens from a distance. The implications of this are debated throughout the paper and raise significant questions for the possible existence of medieval lens-like objects predating the current archaeological record. The coherence between Grosseteste's description and the modern demonstrations suggest that the possibility cannot be discounted.

This needs to be explored alongside the historical and textual contexts, however. Whether Grosseteste himself had seen such objects and their effects or heard of them through intermediaries must remain an open question. His treatise draws on a range of identifiable authoritative sources, however, especially Euclid and Aristotle, whose thought, mediated to Latin Europe in different ways, forms the structure and conceptual framework of the treatise.[3] Of special interest are the sources for the study of optics with which Grosseteste was familiar, and what his understanding of optics in the late 1220s was therefore likely to have been. In particular, he does not appear to have had access to the optical works of Ptolemy or Ibn al-Haytham.[4] al-Haytham would have considerable influence on later thirteenth-century thought on optics, including a more sophisticated understanding of refraction, and his influence on Roger Bacon was to be particularly great.[5] Grosseteste makes use rather of Aristotle's *Posterior Analytics*, on which he wrote the first medieval commentary, and *Meteorology*, both of which had been available to Latin authors since the mid-twelfth century.[6] To that should be added a general knowledge of al-Kindi's *On Sight* and Euclid's *Optics*, and a text *On Mirrors*, attributed by some, including its most recent editor, to Euclid.[7] Although *On Mirrors* deals with *catoptrics,* the study of reflection, it is cited in *On the Rainbow* as the source for Grosseteste's illustration of refraction with an object, water and a cup. A source-text for the description of Grosseteste's three optical effects is not easily identified; elements can be found in Aristotle, Euclid and Seneca, though never in directly-quoted form.

While there is, strictly speaking, no evidence to suggest that Grosseteste's statements are drawn from practical use, it is nevertheless instructive to explore Grosseteste's three optical effects from this perspective. How he might have derived his thinking on these phenomena is a matter of interpretation, in which an assessment of the practical possibilities, and their implications, has an important place, all too often overlooked. In what follows, two proposals are advanced which explore possible ranges of inference for Grosseteste's remarks. An important caveat running through this investigation is that the way in which we use a modern understanding of optics in our analysis does not imply that this was in any way familiar to Grosseteste. The interdisciplinary methodology of this investigation deploys the interpretative frameworks of both medieval studies and modern science to elucidate Grosseteste's writing, while in no way imposing anachronistic readings onto the thirteenth-century material.[8] In this case, modern scientific optics are used to determine what optical effects might, in principle, have been observed using lensing materials available at that time, irrespective of any contemporary optical theory. Before turning to the proposals connected to Grosseteste's treatise *On the Rainbow*, some preliminary comments are necessary on its language and terminology, as well as the material use and availability of lenses in the medieval period.

Lenses: Meaning, Manufacture, and Manipulation

A semantic point is worth raising. The Latin word used in the Middle Ages for lens in the modern sense is *perspicuum*, and its earliest attestation with this meaning dates from the later thirteenth century in Roger Bacon's alchemical treatise *On the Vanity of Magic*.[9] There it is found in a plural form connected with mirrors, as *perspicua specula*, and on its own, again in a plural form *perspicua* to indicate media that allow magnification, which implies something like a lens.[10] The other medieval meaning for *perspicuum* as a noun is 'a transparent thing that can be seen through'. This is important to note. Grosseteste uses the term *perspicuum* in *On the Rainbow* only towards the end of the section on dioptrics. He also uses the term *diaphanum* in the same treatise synonymously with *perspicuum*. While this word may similarly have the possible meaning of lens in Bacon, there is no comparable record of the use of *diaphanum* in this sense at the time of Grosseteste's writing. His interchangeable use of the terms presents an interpretative problem not easily resolved, namely that not only does he make no unambiguous mention of a lens, but that even had he wanted to, it is not entirely clear what Latin term was available for him to use at the time of writing.

The term *perspicuum* also features in Grosseteste's treatise *On Colour* c.1225, though not in a form that could confidently be described as referring to a lens. Colour, Grosseteste states, is light embodied in a *perspicuum*.[11] The treatise *On Colour* ends with an observation that those who are skilled in optics can manipulate the *perspicuum* and so create all the colours they desire.[12] A similar statement is made with respect to the three optical phenomena under scrutiny here, at the end of the first half of *On the Rainbow*:

> ...It is also evident to these same [sc. the perfect] how to shape diaphanous [objects] so that these diaphanous [objects] will receive the rays emitted from the eye according to an angle, made in the eye, of whatever size they want. And they will refract the received rays, to whatever extent they like, on visible things, regardless of whether these visible things are large or small, and placed close by or far away; and in this way all visible things will appear to them [sc. the perfect] in the place they would like and the size they would like, and they could make the largest things appear to be very small, and inversely they could make the smallest and most remote objects appear large and perfectly perceptible by sight.[13]

While this may suggest a lens being ground, shaped and deployed, caution should still be counselled. Grosseteste's fullest exposition of transparency, *perspicuitas*, comes in his

Hexaemeron, the commentary on the six days of creation, written in c. 1235, in which he develops his earlier thoughts from the treatise *On Colour*. Transparency is, for Grosseteste, connected to the two elements of water and air. These elements mix with earth (non-transparent) and are material constituents by which natural bodies can be made transparent to whatever degree is possible.[14] Potential transparency requires light in order to attain actual transparency; a transparent body is therefore a body containing light, and transparency itself a property of some natural bodies, rather than a description of a particular object. Nevertheless, that a glass lens might be conceived of as a *perspicuum* or *diaphanum* should not be overlooked either. At the very least, these unresolved linguistic puzzles point to the need for evidence from other quarters, such as the technical discussion of this work, if the question of availability of imaging lenses in the early thirteenth century is to be resolved.

The evidence for the material production of lenses at the time of Grosseteste's rainbow treatise is similarly patchy at best. The uses of ancient examples of lens-like objects are debated, typically between the poles of decorative and functional purposes; the former is straightforward to demonstrate, the latter can only be suggested.[15] An explicit description of *magnification* was however provided by Seneca the Younger (c.45BC-65AD) in his *Natural Questions*, familiar to Grosseteste, as part of a longer discussion of the rainbow. Seneca noted that 'letters, however tiny and obscure, are seen larger and clearer through a glass ball filled with water'.[16] In the ninth century, reading stones (glass or crystal hemispheres, akin to plano-convex lenses) seem to have made an appearance, the invention credited to Abbās Ibn Firnās (810–887).[17] Closer to Grosseteste's lifetime, quartz lenses discovered in several Viking graves on the island of Gotland, Sweden and dated to the twelfth and thirteenth centuries, the so-called Visby lenses, offer more possibilities for lens production. Although some are mounted in silver, suggesting ornamental use, others are unmounted. The evidence for their deliberate manufacture seems clear.[18] Where these objects lie on the decorative-functional axis is not possible to establish, but their existence allows at least the suggestion that lenses may have been available at the time of writing *On the Rainbow*. Contacts between England and Scandinavia in the eleventh, twelfth and thirteenth centuries were commonplace.[19]

Grosseteste's Optical Effects

Grosseteste's account of various optical effects that are produced with the passage of rays through diaphanous bodies is strikingly selective, on close examination. He does not present an exhaustive account of the types of optical transformations that might be possible, but rather focuses on three specific effects, all produced by *refracted* rays of light: distant things rendered close by, close by large things rendered small, and distant small things rendered large. Other permutations – none of which can be produced using a single convex lens (see cells with an asterisk in Table 1) – find no mention. This is with the exception of the case of close by small things rendered large, but as we will go on to demonstrate, this effect is implicit in Grosseteste's third effect (distant small things rendered large), if the single convex lens is deployed in the manner suggested in the second proposal.

Table 1. *Grosseteste's three optical effects are presented in a table depicting all combinations of optical manipulations to the location and size of objects and images of those objects. Optical effects that are not mentioned by Grosseteste are indicated with an asterisk.*

<table>
<tr><td colspan="3" rowspan="3"></td><td colspan="4">Object</td></tr>
<tr><td colspan="2">Close by</td><td colspan="2">Distant</td></tr>
<tr><td>Small</td><td>Large</td><td>Small</td><td>Large</td></tr>
<tr><td rowspan="4">Image</td><td rowspan="2">Close by</td><td>Small</td><td></td><td>Effect Two</td><td colspan="2" rowspan="2">Effect One
Note that Grosseteste's statement – things placed very far away appear as though placed close by – does not make mention of the size of the original object nor the rendered object. If using a single convex lens held at arm's length, the size of the rendered object [image] depends on the observer's near point.</td></tr>
<tr><td>Large</td><td>Implicit in Effect Three according to the Second Proposal</td><td></td></tr>
<tr><td rowspan="2">Distant</td><td>Small</td><td>*</td><td>*</td><td></td><td>*</td></tr>
<tr><td>Large</td><td>*</td><td>*</td><td>Effect Three</td><td></td></tr>
</table>

An important consideration is the interpretation of 'close by' in Grosseteste's 'things [placed] very far away *appear as though placed very close by.*' An object, viewed through a lens, can appear as though close by for different reasons. First, the image of the object may be magnified. Retinal image size influences judgements about an object's location. An object may appear as though placed close by because the magnified image subtends a large angle at the eye, and therefore produces a larger image on the retina. Second, a real image of the object may be created on the same side of the lens as the observer (that is, on the opposite side of the lens to the object), so that the real image of the object is closer to the observer than the object itself (potentially very much closer). In this case, the perceptual information contributing to a judgement of distance is the focal distance to which the observer's eye accommodates to view the real image, and potentially also parallax between the object and the image. When there is no magnification at all, or even a reduction in apparent size, the real image to which the observer focuses in this case is 'close by'.

Whether rays from an object refract to create an image on the same side of the lens as the observer (real image) or rays refract such that they appear to have originated from the same side of the lens as the object (virtual image), depends on the distance between the object and the lens. Figure 1 provides a pictorial summary, using the example of a single convex lens. The distance between the object and the lens decreases in successive columns of the Figure.

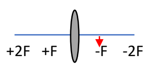
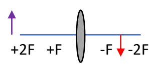
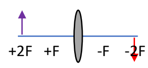
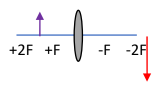
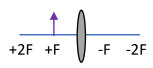
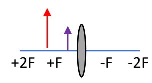
	a 	b 	c 	d 	e 	f 
Object Location ↑	Infinity	More than 2F	2F	Between F and 2F	1F	Closer than 1F
Image Location ↑	-1F	Between -1F and -2F	-2F	More than -2F	Infinity	Between +1F and +2F
Image Type	Real	Real	Real	Real	Real: At infinity Virtual: At infinity	Virtual
Orientation of Image	Inverted	Inverted	Inverted	Inverted	Real: Inverted Virtual: Upright	Upright
Size of Image	Smaller	Smaller	Same size	Bigger	Bigger	Bigger

Figure 1. Image location (same [+] side of lens as object, opposite [-] side of lens to object), type, orientation, and relative size, as a function of the location of the object relative to the convex lens. F is the focal length of the lens.

A Preliminary Note on Refracting Two-Lensed Telescopes

A review of the optics behind refracting two-lensed telescopes – which may be familiar to readers – provides a useful pedagogical starting point for illustrating the less-familiar optical effects that can be produced using a single convex lens (see Figure 2 a, b and c). In doing so we stress that although a two-lens (Keplerian) telescope could have yielded some of the effects Grosseteste describes, there is absolutely no evidence, textual or material, to support the idea that he or anyone else in the Middle Ages knew that such an arrangement of lenses could yield clear magnification. Specifically, we note that the first reported two-lens magnifying telescope was devised by Lippershey in 1608[20].

Summarising the way that light is gathered and focussed in a two-lensed telescope: the larger *objective* lens is positioned at the far-end of the telescope, and the smaller *eyepiece* lens is positioned close to the observer's eye. The objective lens gathers and focuses rays of light from a distant object, to form a real image inside the telescope (Figure 1a). The eyepiece lens – placed one focal length from the real image (Figure 1e, where the real image is the object) – magnifies the (typically small) real image so that it subtends a larger angle at the eye, and therefore produces a larger image on the observer's retina (Figure 2a). Magnification is determined by the ratio of the focal length of the objective lens to the focal length of the eyepiece lens, and is therefore limited by the size of the telescope and the ability to make long- and short- focal-length lenses; both of which are technologically demanding.

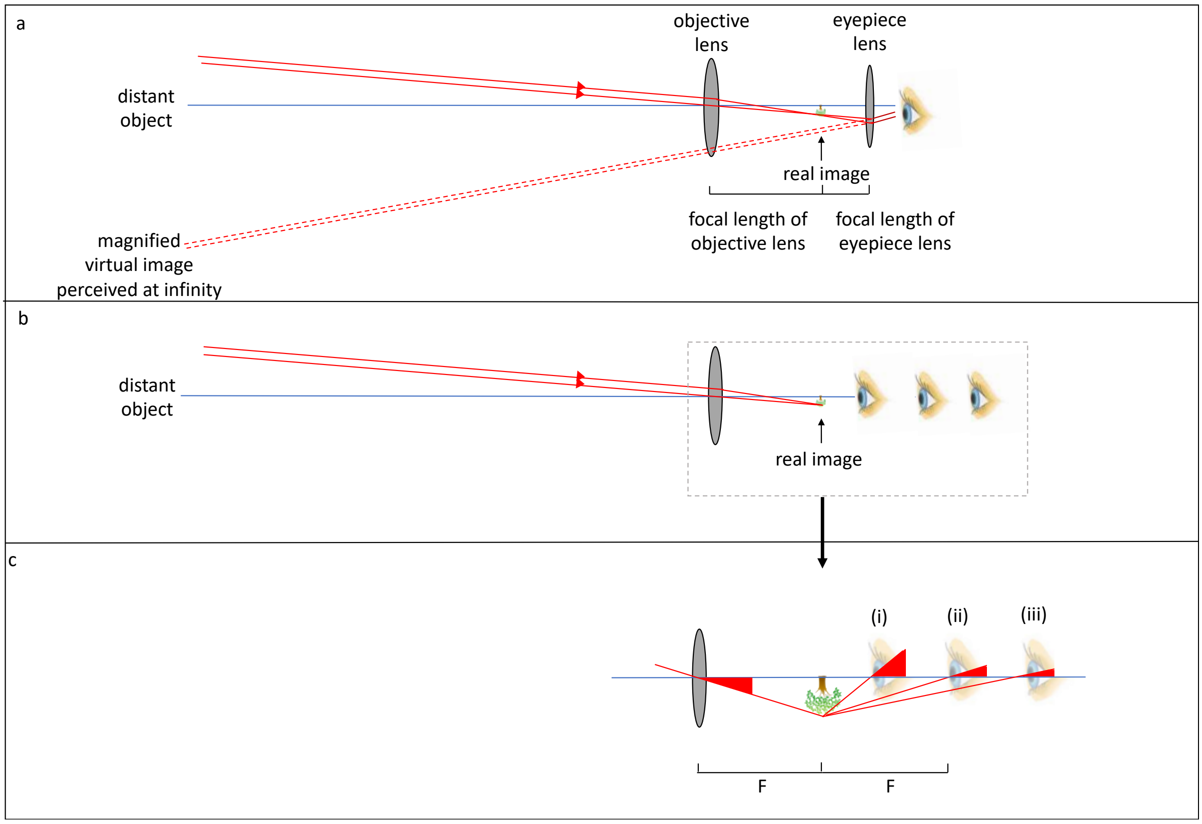


Figure 2. (a) Magnified virtual image of an object at infinity viewed through two convex lenses. The parallel rays of light from the object converge between the two lenses, at a point that is both one (objective-) focal length from the objective lens and one (eyepiece-) focal length from the eyepiece lens. The rays then enter the eyepiece lens at an angle and exit the lens in parallel. The lens of the observer's eye converges the parallel rays, and owing to their parallel nature, perceives them as having come from a point at infinity. The image that is produced is magnified (because the eyepiece allows the eye to focus on a very nearby real image) and virtual (formed where parallel rays emerging from the eyepiece *appear* to have originated). Magnification is determined by the ratio of the focal length of the objective lens to the focal length of the eyepiece. (b) Real image of an object at infinity viewed through a single convex lens. Note different possible positions of the observer's eye relative to the real image. These differences depend on the near point, which is the closest distance at which the eye can focus. Magnification of the real image is determined by the ratio of the focal length of the objective lens to the observer's near point. (c) The perceived angle of the real image and the associated angular magnification for conditions in which (i) the focal length of the objective lens is larger than the observer's near point, (ii) the focal length of the objective

lens is equal to the observer's near point, and (iii) the focal length of the objective lens is smaller than the observer's near point.

Some scholars have argued that two-lensed telescopes may have predated the early seventeenth century[21], but there is no substantial historical evidence to support this assertion. A two-lensed telescope *can* be used to produce the optical effects that Grosseteste described, but nuances in the text suggest that, even if a two-lensed telescope had been available to Grosseteste, this is not the configuration that he had in mind. Grosseteste's choice of example stimuli 'at incredible distance' that can be viewed as if at very close proximity include letters, grains of sand, seeds, and leaves of grass, rather than distant objects that cannot be viewed up close. He did not mention the inversion that would occur if these distant objects were viewed through two convex lenses; this would be particularly problematic for letters. Moreover, whereas Grosseteste explicitly separated out his first optical effect (distant objects appearing close by) and his third optical effect (distant small objects appearing large), a telescope with two convex lenses would result in things placed far away appearing close by *due to* the change in retinal image size (small things appearing large) and so would not permit or suggest the distinction he draws.

Two Interpretive Proposals for the Arrangement of a Single Convex Lens

There follows an exploration of two proposals for the arrangement of a *single convex lens* that each produces the optical effects described in *On the Rainbow*: (1) a single-lens telescope; that is, a single lens in a fixed position (relative to the observer), and (2) a single lens deployed differently to produce the different effects.

First Proposal: A Single-Lens Telescope

An intriguing suggestion with respect to the optical effects in Grosseteste's rainbow treatise is their consistency with telescopic observations that may be made using a single convex lens held in a fixed position relative to the observer. Practically speaking, this would be a lens held at arm's length or on the end of a rigid pole. Here, it is helpful to think of the single lens as analogous to the objective lens positioned at the far-end of the two-lensed telescope, but without an eyepiece. In a telescope, the purpose of the objective lens is to gather and focus rays of light from a distant object, forming a real image that in turn becomes the object of the eyepiece lens. The eyepiece lens, acting as a magnifying glass for the real image, has a short focal length (e.g., 50 mm) to achieve magnification, and to allow the observer's eye in a relaxed state of accommodation to be focussed on a virtual image at effectively infinite distance (Figure 2a).

The term *single-lens telescope* is herein used to refer to a telescope with only an objective lens (Figure 2b). In the absence of an eyepiece lens, an observer with normal vision is nevertheless able to focus on the real image at distances as close as approximately 250 mm. This distance represents the *near point* for normal vision: the closest point at which rays of light from an object can be converged by the lens of the observer's eye and brought to sharp focus on the retina. An eyepiece is therefore not necessary providing that the real image can be brought into focus by the observer's eye. Furthermore, if the real image is large enough and close enough to the eye, its resultant retinal image may be larger than when the physical object is viewed from a distance by the naked eye – a telescopic effect. A geometric argument shows that a single-lens telescope can be used to magnify distant objects if the focal length of the objective lens is longer than the distance between the (focused) real image and the observer's eye (Figure 2c).[22]

When compared to an observer with normal vision, an observer with myopia (or near-sightedness) may achieve focussed images with even greater magnification, due to myopes having a closer near point. The way this arises is illustrated in Figure 2c, illustrating the same real image viewed at different distances. The observer depicted in (i) has a very close near point (that is, myopia) with the result that the real image subtends a large angle at the eye and is magnified relative to the object itself. In Figure 3a, we model the magnification that would be produced with lenses of different focal lengths as a function of the observer's near point.

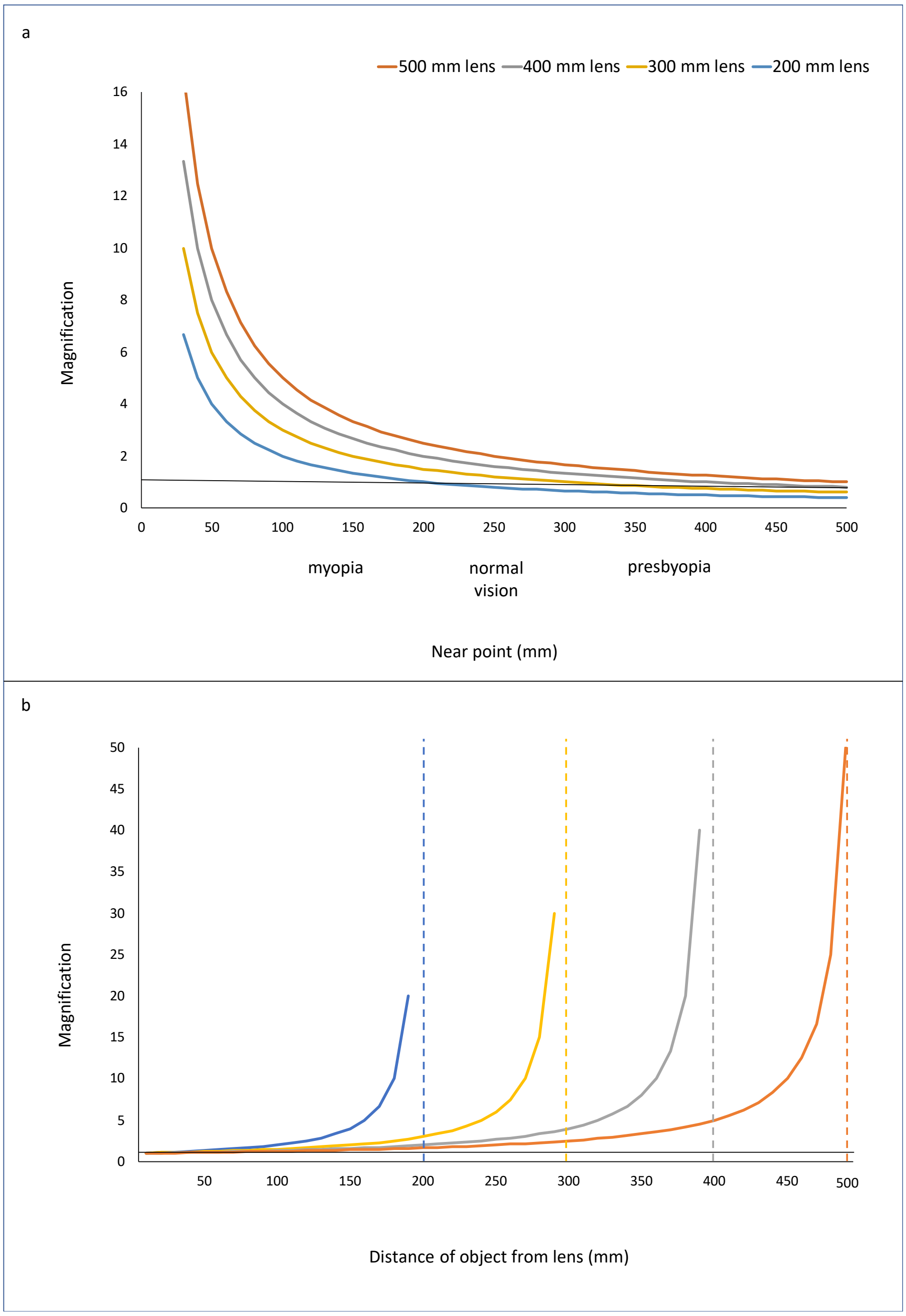


Figure 3. (a) Single-lens telescope: Magnification of an object (at infinity) achieved with four different lenses, as a function of the observer's near point. (b) Single-lens placed in front of 'distant' object: Magnification achieved with four different lenses, as a function of the distance of the object from the lens. The dashed lines, placed at the focal length of each lens, indicate a formal divergence of the magnification.

When an object is placed beyond the focal length, the image that is created is real and inverted (Figure 1a, b, c, d), and it may be smaller (Figure 1a, b) or the same size (Figure 1c) as the object. Note that the horizontal solid black lines indicate a magnification of one.

A single-lens telescope (a lens in a fixed position) is consistent with each of Grosseteste's three observations. To take the first: when a distant object is viewed through a convex lens, rays of light from the object converge in front of the lens, creating a real image that is close to the observer (Figure 2b). As to the second: a convex lens produces a diminished real image of a large object positioned more than two focal lengths from the lens (Figure 1a and b); whether this is consistent depends on our acceptance of this object as nearby. An alternative reading might place the emphasis on *distant* large objects being placed (or appearing) close by in the form of a small real image, rather than large *close-by* objects producing a small real image. The third effect is consistent with the action of a single-lens telescope, whose focal length is longer than the observer's near point (Figures 2b, 2c and 3a). With this set-up, the angle that the real image subtends on the eye is greater than the angle that the distant object subtends on the eye. In terms of actual observations, some practical points would warrant consideration. A person with normal vision (near point of 250 mm), would require a convex lens with a long focal length to achieve magnification; for example, a convex lens of 500 mm focal length would produce 2x magnification. No known early lenses have focal lengths of this magnitude. However, it is instructive to consider Gorelick and Gwinnett's suggestion that craftsmen from the Middle Ages produced intricate works without the aid of a magnifying lens as a result of having myopia and being able to focus on very nearby small objects.[23] Following this same logic, a myopic observer could achieve magnification of a distant object using a convex lens with a relatively short focal length (Figure 3a), as a result of being able to focus on a very nearby real image. For example, using a convex lens of 250 mm focal length, an observer with a near point of 50 mm would experience 5x magnification.

This first proposal is consistent with Grosseteste's explicit separation of the first and third optical effects. With a single-lens telescope, distant objects appear close by as a result of the real image being produced between the lens and the observer; and distant small objects appear large when the observer positions their eye close to the real image. Importantly, resolution of distant small objects depends on the observer having a close near point, so that when they position their eye close to the real image, the rays of light from this image converge on (rather than behind) the retina. So, for an observer with normal vision, a distant object can appear near, without that distant object appearing large. Nearness occurs because of the way that the lens causes incoming rays of light to converge and produce a real image, whereas largeness occurs because of the way that the observer is positioned relative to the real image.

However, whilst the proposal makes sense of Grosseteste's explicit separation of the first and third effects, the single-lens telescope alone produces effects that are inconsistent with the language that he uses to describe changes in the size versus location of stimuli. Specifically, with regard to the third effect, in stating that '*small things placed far away appear as large as we please*', Grosseteste appears to describe a change in the size of the stimulus, but not a change in its location. However, to experience magnification of a distant object, the observer views the real image (produced between the lens and the observer) up close; a method invoking both a change in size and a change in location.

Finally, two problematic points apply as with the two-lens telescope: Grosseteste used as examples stimuli capable of being viewed close up, and therefore did not illustrate the potential of a single-lens telescope for viewing stimuli that are typically difficult to view due to their 'incredible distance', and he did not mention of the inversion of these stimuli (Figure 1a and b).

Second Proposal: A Single Lens, Deployed in Different Ways

A second proposal is that Grosseteste's remarks describe the effects of a single lens deployed in different ways. His first two effects can be related to the single-lens telescope detailed above. However, the third effect, that 'we may make small things placed far away appear as large as we please, so that it becomes possible for us to read very small letters at an incredible distance…', suggests a different configuration.

This proposal takes the 'incredible distance' to which the treatise alludes as the distance between the observer and a lens, rather than the viewed object and a lens. A small object placed far away can be magnified if the object is placed within one focal length of a single convex lens (Figure 1f), and the observer moves progressively further from the lens. With this arrangement, a virtual upright image is created on the same side of the lens as the viewed object (Figure 4a): this image is magnified, subtending a greater angle at the eye than the object itself (Figure 4b). This proposal explicitly captures the utility that lenses have in distant viewing conditions (that is distant objects appearing near and distant objects appearing large), and *implicitly* captures their utility in nearby viewing conditions. For a *distant* small object to be made large, a *nearby* small object is magnified, and then the observer moves from the lens to achieve distant magnification.

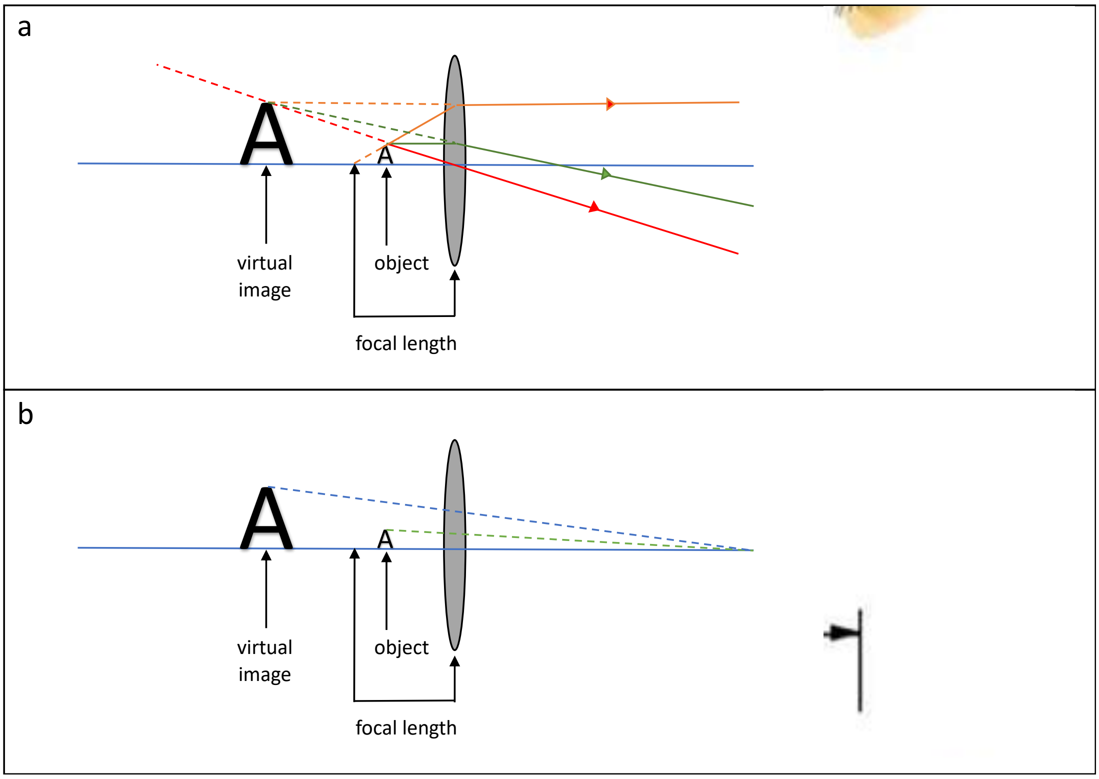


Figure 4. (a) Magnified virtual image of an object placed within one focal length of a convex lens. (b) The angle subtended by the virtual image at the eye (dotted blue line) is *larger* than the angle subtended by the object at the eye (dotted green line).

Figure 5 provides a demonstration. Three photographs present three distances (1m, 2m, 3m) between the observer and the lens. The text on the left side of the open book cannot be (easily) read at any of the three distances, yet through the convex lens, the letters on the right side of the open book are discernible at each distance. *Read*[ing] *very small letters at an incredible distance* is demonstrated.

Figure 5. A single convex lens placed in front of text by its own focal length, viewed at distances of 1, 2, and 3 m, respectively.

In this configuration, magnification is a function of (1) the distance between the lens and the virtual image and (2) the distance between the lens and the object. This is fixed to 1F in the demonstration presented in Figure 5, therefore placing a virtual image at infinity, with an angular size that remains constant, whatever the position of the observer. The distance between the lens and the virtual image is a function of (1) the distance between the lens and the object and (2) the focal length of the lens. A small amount of magnification is observed when an object is positioned very close to the lens, and magnification increases with increasing distance from the lens, provided the object is positioned within one focal length. This is consistent with Grosseteste's statement that 'we may make small things placed far away appear as *large as we please*'. For a given lens, there is a limit in practice to the magnification that is possible, increasing for lenses of longer focal length (Figure 3b). Specifically, we can make things as large as we please if we use lenses of sufficiently long focal length. In an observation based on actual experience with lenses, the statement might also reflect the subjective impression of increasing image size as one moves from the lens. With reference to Figure 5, the reader has the impression of greater magnification of letters with increasing distance. This may be due to (1) the angular size of the *lens* decreasing, so that fewer words are framed by the lens, and/or (2) the angular size of the *image* remaining constant with increasing distance. In the example here, the image on the retina is the same size at different distances. The observer may therefore perceive the text as being larger with greater distance from the lens.

This second proposal necessitates the use of example stimuli that can be viewed up close, as the observer needs to be within one focal length of the object when s/he positions the lens. Moreover, stimuli are not inverted, which is particularly important if letters are to be read from 'an incredible distance.' A single lens deployed differently to produce the first and third effects is also consistent with the distinction that Grosseteste makes between making things appear closer and making things appear bigger. The first effect indicates a change in the location but not the size of the stimulus, consistent with a single-lens telescope rendering a distant object nearby in the form of a real image: a change in location but not size. The third effect indicates a change in the size but not the location of the stimulus, consistent with a single lens being placed within one focal length of a distant object to produce a magnified virtual image of the object on the same side of the lens as the object itself: a change in size but not location. One drawback to achieving magnification of distant objects by placing a convex lens in front of a distant object is the limited field of vision through the lens, but this is not a problem when the magnified stimuli are small. Here we might note, Grosseteste specifically mentions that *small* things placed far away appear as large as we please.

Grosseteste's effects are therefore consistent with a restricted account of refraction, and as we have illustrated, they are remarkably consistent with effects that can be achieved by a single convex lens. Whether it is possible that the three statements were based on observations that he (or someone known to him) had made using a single convex lens is a task for interpretation. To this end these technical considerations from optics complement the contributions from historical and philological analyses.

Conclusion

The question of whether Grosseteste, in *On the Rainbow*, or in earlier texts, reveals any familiarity with lenses is intriguing. The semantic difficulties presented by thirteenth-century thinkers' use of *perspicuum* are real, and glass which has been shaped for functional purposes does not occur often or unequivocally in archaeological contexts. Nevertheless, as this work has shown, there is a genuine coherence between Grosseteste's selective description of the three optical effects on which he focuses, and the results of demonstrations with a single convex lens deployed in various configurations. Consideration of Grosseteste's text and its coherence with an exploration of the optical effects of lenses provides a different perspective to traditional interpretations. While it is unlikely that we will ever know whether Grosseteste's account in *On the Rainbow* drew in any way on the experience of having extended the capacity for sight with a single lens, our investigation has sharpened an understanding of this hypothesis as a serious candidate for the source of the optical effects set out in *On the Rainbow*.

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[1] Cecilia Panti, 'Robert Grosseteste and Adam of Exeter's Physics of Light. Remarks on the Transmission, Authenticity and Chronology of Grosseteste's Scientific *Opuscula*', in John Flood, James R. Ginther and Joseph W. Goering, eds., *Robert Grosseteste and His Intellectual Milieu* (Toronto: Pontifical Institute of Mediaeval Studies, 2013), pp. 165-90, tabulated at p. 149.

[2] Robert Grosseteste, *De iride*, *On the Rainbow*, trans. Sigbjørn Sønnesyn from a new edition and translation forthcoming from the Ordered Universe project (www.ordered-universe.com): "transitus radii est per plura diaphona diversorum generum in quorum contiguitate frangitur radius visualis et facit angulum, pervenitque radius ad rem visam non secundum transitum rectum sed secundum viam plurium linearum rectarum angulariter coniunctarum….Hec namque pars perspective perfecte cognita ostendit nobis modum quo res longissime distantes faciamus apparere propinquissime positas, et quo res magnas propinquas faciamus apparere brevissimas, et quo res longe positas et parvas faciamus apparere quantum volumus magnas, ita ut possible est nobis ex incredibili distantia litteras minutas legere, aut arenam, aut granum aut gramina aut quevis numerare". All subsequent extracts are from this translation. The current critical edition, which the Ordered Universe is revising is Robert Grosseteste, *De iride,* ed. Ludwig Baur, *Die philosophischen Werke des Robert Grosseteste, Bishofs von Lincoln* (Münster i. W.: Ashendorff, 1912), pp. 150-241. An English translation based on Baur's text is available, Robert Grosseteste, *De iride*, trans. David C. Lindberg, in Edward Grant, *A Source Book in Medieval Science* (Cambridge, Mass.: Harvard University Press, 1974), pp. 388-91.

[3] For a general outline see David C. Lindberg, *The Beginnings of Western Science: The European Scientific Tradition in Philosophical, Religious, and Institutional Context, Prehistory to A.D. 1450*, 2nd edition (Chicago: University of Chicago Press, 2007), pp. 225-53.

[4] A. Mark Smith makes the tentative suggestion that perhaps Grosseteste knew al-Haytham's optical works in part in *From Sight to Light: The Passage from Ancient to Modern Optics* (Chicago: Chicago University Press, 2015), pp. 259-60. This is not accepted in Nader El-Bizri, 'Grosseteste's Meteorological Optics: Explications of the Phenomenon of the Rainbow After Ibn al-Haytham' in Jack Cunningham and Mark Hocknull, eds, *Robert Grosseteste: Religious and Scientific Learning* (New York: Springer, 2016), pp. 21-39, esp. p. 23.

[5] See A. Mark Smith, *From Sight to Light: The Passage from Ancient to Modern Optics* (Chicago: Chicago University Press, 2014), esp. chapters 5 and 6.

[6] The Latin Posterior Analytics that was used the most in the middle ages was by James of Venice (d.c.1147) see Aristoteles Latinus, IV.1-4, ed. L. Minio-Paluello et B.G. Dod, Brugges: De Brouwer, 1968. For Grosseteste's commentary see Robert Grosseteste, *Commentarius in Posteriorum Analyticorum libros*, ed. Pietro Rossi (Florence: Olschki, 1981).The *Meteorology* has a complex transmission. Henricus Aristippus translated book IV from the Greek in the twelfth century, and, somewhat later, Gerard of Cremona (d.1187) translated I-III from Arabic. These then circulated together, and Alfred of Sareshel (fl. c.1197-c.1222) commented on this hybrid. Gerard's translation of books I-III is edited by P. J. Schoonheim, *Aristotle's 'Meteorology' in the Arabic-Latin Tradition. A Critical Edition of the Texts, with Introduction and Indices* (Leiden: Brill, 2000).

[7] Ken'ichi Takahashi, *The Medieval Latin Traditions of Euclid's* Catoptrica*: A Critical Edition of* De speculis, *with an Introduction, English Translation, and Commentary* (Fukuoka: Kyushu University Press, 1992).

[8] The project, Ordered Universe: Interdisciplinary Readings of Medieval Science, is funded by the Arts and Humanities Research Council, UK, AH/N001222/1

[9] *Dictionary of Medieval Latin from British Sources*, 3 vols, eds. Richard Ashdowne, David Howlett, and Ronald Latham (Oxford, Oxford University Press, 2018) – consulted on the online version: http://www.dmlbs.ox.ac.uk/web/online.html, 13th October 2018.

[10] Roger Bacon, *De nullitate magiae*, in ed. J. S. Brewer (London: Longman, Green, Longman and Roberts, 1859), p. 534.
[11] Robert Grosseteste, *De colore*, ed. in Greti Dinkova-Bruun, Giles E. M. Gasper, Michael J. Huxtable, Tom C. B. McLeish, Cecilia Panti, Hannah E. Smithson, *The Dimensions of Colour, Robert Grosseteste's De colore* (Toronto: Pontifical Institute of Mediaeval Studies, 2013), pp. 16-19, at pp. 16-17.
[12] Grosseteste, *De colore*, pp. 18-19.
[13] Grosseteste, *De iride*, trans. Sønnesyn: "Et patens est eisdem modus figurandi diaphona ita ut illa diaphona recipiant radios egredientes ab oculo secundum quantitatem anguli quem voluerint in oculo facti, et refringant29 radios receptos quousque30 voluerint super res visibiles, sive fuerint res ille magne sive parve, sive longe sive prope posite; et ita appareant eis omnis res visibiles in situ quo voluerint, et ita in quantitate quo voluerint, et res maximas quam voluerint faciant apparere brevissimas, et e contrario brevissimas, et longe distantes faciant apparere magnas et optime visu perceptibiles".
[14] Robert Grosseteste, *Hexaemeron*, II.X.2, eds. Servus Gieben and R. C. Dales (Oxford: Oxford University Press, 1982), p. 99.
[15] D. Plantzos, 'Crystals and lenses in the Graeco-Roman world', *American Journal of Archaeology*, 1997, *101*: 451-64. G. Sines and Y. A. Sakellarakis, 'Lenses in Antiquity', *American Journal of Archaeology*, 1987, *91*: 191-6.
[16] Seneca, *Naturalium questionum libri*, Book 1.9, ed. H. M. Hine (Leipzig: Teubner, 1996); English translation from Seneca, *Natural Questions*, trans. Harry M. Hine (Chicago: University of Chicago Press, 2010), p. 146.
[17] J. Vernet, 'Abbās ibn Firnās' in *Dictionary of scientific biography*, ed. C.C. Gillispie (New York: Scribner, 1970-1980), vol. 1, p. 5; on the use of reading stones in the west see Vincent Ilardi, *Renaissance Vision From Spectacles to Telescopes* (Philadephia, American Philosophical Society, 2007), pp. 8 and 40.
[18] O. Schmidt, K. H. Wilms, and B. Lingelbach, "The Visby lenses", *Optometry and Vision Science*, 1999, *76*: 624-30.
[19] See Jonathan Adams and Katherine Holman, eds, *Scandinavia and Europe 800-1350: Contact, Conflict, and Coexistence* (Turnhout: Brepols, 2004).
[20] H. C. King, *The history of the telescope* (North Chelmsford, Ma: Courier Corporation, 2003) p. 30
[21] C. Ronan, 'Unidentified Elizabethan telescope', *The International Journal of Nautical Archaeology*, 1994, *23*: 250-250.
[22] Specifically, the expression for the magnification M of a single-lens telescope in terms of the focal length of the objective lens F and the (near point) distance from the real image to the eye, d, is $M=F/d$. Figure 3 is a graphical representation of this relationship. There is a direct similarity to the related expression for the magnification of a two-lens telescope $M=F/f$, in that the near point distance d substitutes for the focal length of the eyepiece, f.
[23] Gorelick and Gwinnett, "Close work without magnifying lenses", https://www.penn.museum/sites/expedition/close-work-without-magnifying-lenses/ (accessed 12.12.2019)