Zograscope viewing

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Abstract. The “zograscope” is a “visual aid” (commonly known as “optical machine” in the 18th century) invented in the mid-18th century, and in general use until the early 20th century. It was intended to view single pictures (thus not stereographic pairs) with both eyes. The optics approximately eliminates the physiological cues (binocular disparity, vergence, accommodation, movement parallax, and image blur) that might indicate the flatness of the picture surface. The spatial structure of pictorial space is due to the remaining pictorial cues. As a consequence, many (or perhaps most) observers are aware of a heightened “plasticity” of the pictorial content for zograscope as compared with natural viewing. We discuss the optics of the zograscope in some detail. Such an analysis is not available in the literature, whereas common “explanations” of the apparatus are evidently nonsensical. We constructed a zograscope, using modern parts, and present psychophysical data on its performance.

Keywords: zograscope, viewboxes, monocular stereopsis, plasticity, psycho-optics, synoptic viewing.

1 Introduction
This paper is conceptually divided into two parts. The first part (Section 2) deals with the optical properties of “zograscopes.” The second part (Section 3) is an account of a psychophysical enquiry into the visual effects of such instruments.

2 Optics of the zograscope

2.1 Optical viewing aids
“Optical viewing aids” are a fuzzily defined subset of optical devices designed to be used by the human observer. “Used by the human observer” means that the retinal image is the final stage in the optical pathway of imaging instruments. The actual “output” is the visual awareness of the user of the instrument, not some physical illuminance distribution. “Imaging instrument” implies that we ignore such things as gun sights (at least “iron sights” and the like), the theodolite and other surveying instruments, and so forth. We also ignore microscopes and telescopes as specialized areas: we roughly aim at what could also be seen with the unarmed eye. Another—huge—area that we ignore are spectacles. We mainly aim at vision aids for viewing pictures of “normal”—postcard to folio, say—size. Typical examples of “viewing aids” then are hand magnifiers (reading glasses), viewboxes (Guckkasten), and so forth. The zograscope (Figure 1; see note 1 with a typical erroneous explanation of the function) is a generic case (see Chaldecott, 1953; Keyser, 1962; von Rohr, 1936).

The hand magnifier, often used by elderly people to read or younger people to view smallish items like postage stamps, is a good example to introduce a few key issues. It is such a good example because it is treated in virtually any book on introductory physics that has a chapter on optics (Halliday, Resnick, & Walker, 1996). In the conventional account, the glass is held closely in front of the (single?) eye, the object being placed in the focal plane of the (positive) lens (Figure 2, left). “The” magnification of the hand magnifier is usually defined as 250 mm divided by the focal length in mm. Here, 250 mm is the conventionally designated “normal reading distance.” The magnification is then defined as the ratio of the angular size subtended by an object with the glass in normal use, and the
same object at normal viewing distance. So far so good. However, if you watch people actually using a hand magnifier, you will notice that they hold it at quite a distance, and look through it with both eyes open (Figure 2, right). They move the glass back and forth, rarely having the object in the intended focal plane. Some experimentation will soon teach you that a single hand magnifier can yield quite a range of “magnifications.” Thus, the use is different from that assumed by the textbooks, and the effect (the magnification) is different too. The reason is that optics texts fail to take the actual eye use, and the relation between visual awareness and optical input, into account.

These informal observations are fairly typical of the way viewing aids are treated in conventional optics (Hecht, 2002). Their actual use tends to be ignored, and replaced with an idealized account that may be arbitrarily far from reality. As a matter of course, observers make eye movements, including differential ones, change accommodation state and pupil diameter (important for depth of field). Moreover, the effect of the instrument, which is the visual awareness of the user, is not at all recognized for what it is. For instance, binoculars are usually stamped with their so-called “magnification,” whereas the user notices no magnification at all, but an apparently diminished distance instead. There are many instruments for which no such convenient number is available. Examples are the Zeiss Variant and Synopter (note 2). The zograscope is another instance. These instruments have disappeared

Figure 1. A typical specimen of the zograscope with original zograscope picture.

Figure 2. Left: use of lens magnifier according to the optics texts; right: lens magnifier as actually used by most people.
from the optics textbooks because they really belong to *psycho-optics* (a term framed by analogy with “psycho-acoustics”), a field that has no official standing. Yet an instrument like the zograscope was in use for at least two centuries to the full satisfaction of its users.

The zograscope was apparently invented in the mid-18th century (or possibly earlier), and was in common use to at least the conclusion of the 19th century. Perhaps unfortunately, the etymological origin of the term remains unclear. It was a popular instrument for the well-to-do classes, much like the stereoscope was in Victorian times. At the turn of the century (19th to 20th), one had even combined stereoscopes–zograscopes (various examples can easily be found on the Internet), each having its specific use. Like stereo pairs, prints meant to be looked at with the zograscope are common enough on the antiques market. They are easily recognized by their size, and especially the title, which always appears in mirror reversed print.

### 2.2 Principle of the zograscope

The principle of the zograscope appears simple enough (Figures 3 and 4), although the explanations offered in various places are frequently nonsensical. The observer views a picture through a large lens of positive power. The picture is placed at the focal plane of the lens. The observer looks through the lens with both eyes. The picture is scrutinized via eye movements. Eye movements are necessary because the field of view is quite large, about 30°–40°. Because the picture is at the focal plane, the observer neither has to adjust vergence nor accommodation, as the fixation point is changed. The two eyes receive identical images. This removes effectively the physiological cues (Graham, 1965; Helmholtz, 1856), eg, binocular disparity, vergence, monocular movement parallax, head movement

![Figure 3.](image-url) The principle of the zograscope. Both eyes obtain the same input. The “object” is at infinity. There is no vergence and no disparity. In these drawings we use an “ideal” zograscope, the lens is infinitely thin, and ray tracing uses the paraxial approximation. At left, the center of the picture is seen at infinity for both eyes. There is no vergence and no accommodation. At right, notice that the two eyes receive identical images of the (grating) picture. This illustrates the principle very well: the zograscope renders the viewer “cyclopic.”

![Figure 4.](image-url) A 3D rendering of the beams involved in zograscopic vision. In this figure, the eyes are viewing in parallel directions for each pair of beams, thus revealing field curvature. However, such aberrations are easily corrected by way of minor adjustments of the human visual system. The figure has been drawn for 4-mm pupil sizes. Notice the horizontal–vertical asymmetry of the system.
parallax, accommodation, and blur, which might reveal that the picture is actually a flat surface covered with pigments in a particular simultaneous arrangement. As a result, pictorial space develops in “monocular stereopsis,” which results in a vivid impression of markedly increased “plasticity” as compared with viewing the picture binocularly without the instrument. Monocular stereopsis is due to so-called “pictorial cues.” The effect is somewhat similar to viewing a large painting from a distance with one eye closed, a case familiar from the literature on the visual arts. In the 20th century, Moritz von Rohr (note 3), an optics engineer working at the Zeiss optical factory (note 4), developed “syn-opters” (note 5) that essentially achieved the same effect, although with (much) better optical quality. Von Rohr’s designs were apparently inspired by his collaboration with Alvar Guullstrand (note 6), a Danish ophthalmologist with a keen interest in optics. Guullstrand frequently visited the Zeiss factory, his native country Denmark lacking an important optical industry.

Another design with superior properties was the Doppelverant (again by von Rohr with input from Guullstrand), essentially a high-quality stereoscope, used with two copies of a single image instead of a stereo pair. The plasticity achieved by the Doppelverant was frequently rated better than what could be achieved via the usual disparate images. The disparate images suffer from a marked “coulisses effect,” that is, they tend to yield a depth stack of flattish, silhouette forms, instead of neatly rounded, volumetric pictorial shapes. In contradistinction, the Doppelverant yields pleasantly articulated (“plastic”) pictorial reliefs.

The appreciation of the plasticity resulting from monocular stereopsis has largely disappeared from the literature in the standard contemporary textbooks (Palmer, 2001; Vishwanath, 2001). In fact “stereopsis” is nowadays commonly defined as “binocular stereopsis” (note 7), and even the term “monocular stereopsis” is taken to be self-contradictory (Enright, 1991; Pollack, 1955; even as early as 1904, Claparède (1904) mentions “paradoxical monocular stereopsis”). This is perhaps somewhat surprising, as the viewing of single images is still common enough, and one may hardly assume that the viewers of holiday postcards (say) have no impressions of pictorial space, but are only aware of planar patterns of colored patches. But the appreciation of the special charm of monocular pictorial space appears to have been lost. The remarkable plasticity in such awareness was still common knowledge in the early 20th century.

2.3 Analysis of specific zograscope designs

The zograscope is a typical “historical” instrument, in that the design was not changed since its invention in the 18th century. This is understandable for technical reasons: the need for a large lens with comparatively short focal length does not lend itself to a manageable design. Occasionally one finds zograscopes that use a concave mirror instead of a lens. This at least removes a major defect of the lens, which is chromatic aberration. We have only seen such mirror devices for smallish pictures (less than postcard format), again, an understandable constraint. A modern version of the zograscope might use a (plastic) Fresnel lens, this would indeed be an advantage. Here we only analyze the classical design though.

At first blush, judging from some familiarity with traditional optical design principles (Hecht, 2001; Herzberger, 1958), the zograscope appears to be a rather unlikely design. A single lens of that aperture (ca. 1:3 to 1:4) is certain to have a large degree of spherical deviation on axis, and huge amounts of astigmatic and comatic aberrations at 20º off axis. Moreover, the Petzval field curvature (note 8) has to be appreciable. Apart from these aberrations, there will additionally be a huge chromatic aberration for the typical glasses (standard crown) used for the lens. However, we propose that such notions are not appropriate, because they implicitly assume that the image-forming bundles are limited by the outer diameter of the lens. However, the pupil diameters of the user’s eyes, rather than the outer diameter of the lens, limit the beams. Thus, one needs to consider a combination of two narrow beams, separated by the interocular distance, instead of a single wide one.

Moreover, the optics of the zograscope should take the eye optics into account, including the motility of the eyes. Thus, the optical system is not fixed, but changes as the observer changes fixation. Observers typically make minor corrective eye movements, and (depending upon age) accommodation changes, small enough not to count as physiological cues, but enough to cancel various imperfections of the optical system. This renders the full analysis of the zograscope a surprisingly complicated problem, rather more complicated than that of many sophisticated, multicomponent optical systems such as camera lenses.
In order to obtain a feeling for what is implied here, we discuss two simple cases. The first involves the (indeed very significant) spherical aberration (note 9) of the lens, and the second involves the influence of (again very significant) field curvature (note 8).

Consider spherical aberration (Figure 5, top). This is a serious on-axis aberration. The so-called “focal length” of the lens is the point at which rays parallel to the axis and, running at a short distance from it, converge. A ray parallel to the axis that enters the lens at some distance from the axis will meet the axis at some distance from the focal point, toward the observer. For a ray that meets the lens near its boundary, this distance can easily amount to a few centimeters for the generic zograscope. Thus, one is perhaps led to take the spherical aberration very seriously. However, consider the case of the two eyes looking into the direction of the axis (“straight ahead”). The beams defined by the pupils will converge at some point on the axis, away from the focal point. Is this at all problematic? We propose that it is not a problem. For you may simply place the picture at the point where the beams cross the axis, and you end up with an almost perfect system. The remaining spherical aberration is actually quite small, because the beam diameter is the pupil diameter (say, 4 mm) instead of the lens diameter (say, 10 cm). This is a first example that illustrates that the standard insight into lens aberrations is of no use here.

Next, consider the case of the Petzval field curvature (note 8; Figures 5 bottom, and 6). Suppose you have correctly “focussed” the zograscope, that is to say, rays parallel to the axis at a distance of half an interocular distance from the axis meet the axis at the plane where the picture is. Now fixate a point of the picture away from the axis. When the two eyes do not change vergence, field curvature will make the two beams meet at some distance in front of the picture. Is this a problem? Again, not at all, for the observer easily rectifies this with a minor vergence adjustment. The vergence needed is too small to act as a depth cue, but the field curvature has been “corrected.” Notice that each of the two beams converges to a point somewhat in front of the picture plane. Is this a problem? Again, no, for a minor accommodation change (too small to act as a depth cue) easily takes care of that. This case is evidently more complicated than that of the spherical aberration, where no vergence or accommodation changes were needed at all. It is harder to analyze in full detail.

Figure 5. The upper figure illustrates spherical aberration, the lower pair field curvature. At top one notices that rays that enter parallel to the optical axis fail to meet the axis at a single “focal point.” Instead, one obtains a cuspidal caustic. At bottom left the eyes look perfectly parallel. At bottom right, a minor vergence “corrects” the effect of field curvature.
In order to study the actual performance of zograscopes, one needs to take the possible corrective actions of the observer’s oculomotor system into account. This renders such a study complicated. It is very different from the regular analysis used to design conventional optical imaging systems.

We studied the zograscope through ray tracing. We implemented the well-known ray-tracing algorithm of Herzberger (1958) in Mathematica code (note 10). This allows us to implement various nonstandard methods with reasonable ease. We studied the zograscope with symmetrical biconvex, plan-convex, and convex-plan lenses (the latter differ only in orientation). Somewhat different from intuition (we put our money on the biconvex lens based on our experiences with standard optical designs), the best setup is the plan-convex lens (planar side at the observer side). Although the various cases show up significant differences in quality, all are “good enough,” thus suitable for zograscopic use. We discuss only this best case here (plan-convex with planar side to the observer). The reverse design (convex side to the observer) is not much worse. The zograscopes we could examine had convex curvatures facing the observer, but we were in no position to examine the other side. Judging from other historical instruments we guess that most lenses were biconvex. They must have been a little inferior (though still serviceable) to our implementation.

We analyzed a design with a 120-mm diameter plan-convex lens, made of borosilicate crown (BK7) glass, refractive index at λ = 546.706 nm being n = 1.518872 (at λ = 404.66 nm, n = 1.53024, and at λ = 706.52 nm, n = 1.51289), radius of curvature 120 mm. We assume an interocular distance of 65 mm and a pupil diameter of 4 mm. The “effective focal length,” defined by the axis crossing of a ray at half the interocular distance from the axis, is 271 mm, reckoned from the front of the lens. It is more than 20 mm closer to the lens than the paraxial focal plane. We consider a picture of 200 mm wide.

The field curvature (radius of curvature 202 mm) is not very extreme (this is one aspect on which the plan-convex configuration beats the convex-plan and biconvex ones), and is easily corrected for by very minor vergence movements. At an eccentricity of 20º, a vergence of 1º is needed, at 10º less than 0.3º. We find that the system has a number of aberrations that do not really fit the conventional taxonomy very well. The blur regions for the left and right eyes are different (Figure 7), and may be astigmatic “lines” of rather different length that meet at an angle. Then what is the relevant size of “the” blur circle? In our view, most likely the smallest one, as one easily checks by defocussing one branch of a stereoscope loaded with identical pictures. For the system analyzed here, the blur circle then does not exceed a quarter of a millimeter at the far out corners of the image. For most of the picture, it is less than a tenth of a millimeter. This implies that the zograscope performs fine with respect to resolution.

We encounter two aberrations that might possibly limit the zograscope’s performance. One is differential distortion and another (most serious) is chromatic aberration.

The plan-convex configuration minimizes distortion as compared with convex-plan or biconvex. Distortion in itself is not a major defect (except when one places an extreme weight on projective structure), but the problem is that the left and right eyes receive mutual mirror-reversed versions of laterally asymmetrical distortion (Figure 8). This is something that never occurs in the conventional optical systems. Is this a problem? We propose it is not, because most of the difference can be “corrected” via a minor vergence movement. What rests is a small disparity field about the present fixa-
tion point. For a point at the edge of the field of view (really worst case), looking 45º upward (again: worst case), we find a differential cyclorotation of 2º, a differential magnification of 3%, and a differential deformation (magnification anisotropy) of 3%, the last perhaps suggesting a 14º obliquity of the apparent frontoparallel plane. These numbers are really minor. The differential magnification and cyclorotation will be fully unnoticeable. The differential deformation might be, but probably will not. Over most of the visual field, the deviations are even much less than this. This might perhaps induce the impression of a faintly curved picture plane. In practice (pictures of articulated scenes) one does not see this at all. Perhaps one might notice it if one used checkerboard patterns as pictures though.

The chromatic aberration (note 11) is a major flaw of the system. The problem is that lateral chromatic aberration occurs mirror reversed in the two eyes. Thus, it leads to a significant chromatic disparity signal (Figure 9). This is indeed quite noticeable in a “TV test image” with vividly colored lines and squares. We do not really notice it in structured images, and we do not notice chromatic fringes in monochrome images. That is to say, any chromatic fringing is much less noticeable than in (even quality) consumer camera digital images taken at moderate “wide angle” settings. (In our experience these are often objectionable.)

Because of the horizontal separation of the eyes, the zograscope is not rotationally symmetric about the axis. There is a minor magnification difference of 3.25% between the vertical and horizontal directions. All aberrations depend not only on the distance from the axis but also on the azimuthal location (angle with the horizontal). The numbers given above are all worst case.

The zograscope is even more complicated when one considers minor head movements (translations and rotations), as are certain to occur in actual use. Longitudinal translations change the eye

Figure 7. Here we show two extreme cases, the fixated point being at the boundary of the field of view. At left the fixation point is in the top right corner, at right at the top center. The blurring ellipsoids (containing two-thirds of the traced rays) for the two eyes (drawn in red and blue) are very different. The smaller one dominates awareness. Notice that the “blur size” is quite small, even at the edge of the field. All measures are in millimeters. Pupil sizes of 4 mm were assumed. We did not take the Stiles–Crawford effect (Stiles & Crawford, 1933) into account, which will have a beneficial influence on resolution.

Figure 8. Distortion is noticeable. What is really relevant is that it occurs mirror reversed in the two eyes. What really counts is the difference modulo shift and size. It is only minor.
relief, and thus the lateral locations of the entrance beams in the case of off-axis fixations. Lateral translations affect the locations of the entrance beams even for straight ahead fixations. Thus, the zograscope is a remarkably complicated, dynamic optical system. In practice head attitude and location, as well as fixation directions (including vergence and cyclovergence movements), and states of accommodation are unknown. Pupil sizes will probably vary too, affecting the depth of field. The characterizations discussed above allow a reasonable insight into the performance of the system, but are in no way exhaustive.

3 Psychophysical investigation of the effect of the zograscope
It is of some interest to compare measurements of pictorial relief evoked by pictures viewed directly (with both eyes) with those viewed zograscopically. Is there any evidence that zograscopic viewing promotes “plasticity”?

If there is any effect it has to be due to the removal of all but purely pictorial cues. That this has an important effect was widely known until the early 20th century, whereas this insight somehow became lost even before WW II. Thus, writing in 1941, Harold Schlosberg remarks on the first page (opening sentences of the paper):

In the period around 1910, when interest in stereoscopy was high, it was widely known that the “plastic” effect could be obtained almost as well by viewing a single picture through a lens as by the use of disparate pictures in the binocular stereoscope. The phenomenon has been largely forgotten during the last two decades, and does not seem to be mentioned in any of the standard introductory texts of psychology. … A surprisingly large proportion of psychologists are unaware of the phenomenon, and somewhat at a loss for an explanation. … the plastic depth that can be obtained monocularly is very striking, and must be seen to be appreciated. … To summarize: the phenomenon of monocular plastic depth is due to the release of certain monocular factors from overpowering cues, largely binocular, that

Figure 9. Chromatic aberration is most likely the worst problem of the generic zograscope. Here are three blur ellipsoids (red and blue for the left and right eye) at the spectral limits (top 405 nm and bottom 707 nm), and the (dominant) spectral center (middle, 547 nm). All measures are in millimeters, whereas the effective viewing distance is (roughly) 20 cm. This is the worst case, 20º off axis at the top right. Even this aberration is manageable.
show the picture to be flat. (Schlosberg, 1941)

Perhaps unfortunately, the “proportion of psychologists” unaware of the effect, and clueless as to an explanation, has increased to probably over 99% (one in a hundred “in the know,” our informal sampling would suggest perhaps one in a thousand). No modern textbook known to us mentions these evidently important (indeed, crucial to a proper understanding of pictorial perception—or even perception as such) facts.

Judging from the contemporary literature on visual perception, one might well expect that 18th- and 19th-century observers were simply deluded. In such a view, the instrument is nothing but a nonsensical “Rube Goldberg” type of contraption (note 12).

Of course, this is simple enough to check through direct experiment. This might also yield a hint as to what one might mean by an ill-defined term like “plasticity.” In case the concept indeed is void, then the experiment should reveal this to be the case. Of course, the zograscope has such a venerable history that one would have to make a strong case in order to denounce it nonsense. The second part of our paper is devoted to such a study.

3.1 Methods

3.1.1 The zograscope used in the experiments
We constructed a zograscope from readily available (in any old laboratory that is) salvaged parts. The lens was a plan-convex element from a discarded epidiascope, which used to be powered by a carbon arc source. The lens has a 12-cm diameter and an effective focal length of 380 mm. The dimensions were just about right to use an iPad (note 13) as an image device (211 × 159 mm or 2048 × 1536 pixels). Both the iPad and the lens were mounted either on an optical bench (Figure 10) or in a wooden frame.

With the lens removed, observers could look through the empty aperture and view the iPad with both eyes without the optics. This made it very convenient to collect measurements with and without the zograscope.

3.1.2 Generic methods
We used the “gauge figure method” to collect data. The method has been described in detail at various places (Koenderink & van Doorn, 1995, 2003; Koenderink, van Doorn, & Kappers, 1992). It yields a pictorial relief map modulo absolute depth. Such depth maps are necessarily idiosyncratic. After all, monocular pictorial depth exists only in the mind of an observer. There is no obvious notion of “veridical depth.”

The implementation used in the experiments is written in MatLab, using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). The implementation is described by Wijntjes (2012).

Figure 10. The zograscope used in the experiments was constructed on the basis of a large plan-convex lens, salvaged from a discarded (carbon arc powered) epidiascope, and an iPad. These parts were mounted on a standard optical bench, making the instrument conveniently adjustable. Notice that we have omitted the diagonal mirror conventionally used in zograscopes. It is of no importance to our investigation.
Observers were the authors. They are well acquainted with the task. We know from many years of experience that “naive observers” yield similar results. The differences between the authors are easily as large as those we typically encounter in a group of naive observers.

The stimuli were two photographs of sculptures and one painting (Figure 11). The painting (by Modigliani) is very unlike a photograph, and would by many be considered “flat.” Of the photographs, one is technically “frontal” (actually taken downward, witness the floor tiles), the other “oblique.” The stimuli were selected because one might expect marked differences in pictorial relief.

4 Experiment

The raw settings of the observers were converted to a pictorial relief representation, a surface depth map modulo an arbitrary depth shift (we arbitrarily set the mean depth to zero). The conversion allows one to check the internal consistency of the data. Nothing extraordinary was detected in any case (either viewing condition, all observers, all stimuli). We will not report on this in detail, extensive discussions are available in the literature mentioned above. Here we start the analysis with the reliefs. They are illustrated for one observer, both viewing conditions, and all three stimuli (Figures 12a–c).

Differences between zograscopic and normal viewing are readily detectable by eye. We analyze the data in more detail below.

The simplest analysis involves scatter plots of the depths of corresponding points in the two conditions (Figure 13). We find good correlations in the case of the Hermaphrodite image: coefficients of determination 0.97 for AD, 0.87 for JK, and 0.97 for observer MW, and also for the Danaid image: coefficients of determination 0.99 for AD, 0.96 for JK, and 0.99 for observer MW. For the Modigliani image, the correlations are much more variable over observers: coefficients of determination 0.70 for AD, 0.36 for JK, and 0.97 for observer MW.

The slopes of the regression lines indicate the depth of relief magnification for zograscopic relative to normal viewing. The values are collected in Table 1 and Figure 14.

The values for the Modigliani stimulus are not very useful, because the correlation is low (see below). In the other instances, we find a range of relief magnifications, ranging from only 4% to almost a factor of three. These magnifications apparently depend both on the observer and on the stimulus. In all cases of interest (the case of the Modigliani is discussed below), they are in the same direction though. Apparently, the zograscope tends to increase the depth of relief.

In the case of the Modigliani, it is evident that different parts of the image lead to different results. This is immediately obvious from a straight clustering analysis (using the k-means algorithm (Hartigan & Wong, 1979) with k = 2; see Figure 15). The overall coefficient of determination becomes 0.91 for AD, 0.75 for JK, and 0.98 for observer MW. Magnifications for the two clusters are {1.04, 0.94} for AD, {1.19, 1.12} for JK, and {1.06, 1.05} for MW. Thus, at least part-wise, the Modigliani case is not that different from that of the other stimuli. The existence of “parts,” which is very marked for observers AD and JK, is a phenomenon we have studied in detail before.

Overall, the depth relief magnifications are all expanding, with one exception (one of the clusters of observer AD for the Modigliani stimulus).
Figure 12. Pictorial reliefs for the (a) Hermaphrodite image, (b) Danaid image, and (c) Modigliani image. Observer JK. Bluish without, yellowish with Zograscopic viewing.

Figure 13. Raw depth plots of depths without (horizontal axis) versus with (vertical axis) zograscopic viewing for the Hermaphrodite image (left), Modigliani image (center), and Danaid image (right). Red observer AD, yellow observer JK, blue observer MW. Horizontal and vertical scales are the same.
5 Conclusions

Does the zograscope “work” as advertised, or were almost two centuries of satisfied users deluded? This is an interesting issue, because there never existed anything remotely like a “theory of the zograscope,” although the notion of “cue” was understood in the 18th century (Berkeley, 1709). The instrument was apparently “invented” by mere serendipity, starting from notions derived from experiences with view boxes, a fascination with lenses, and a desire to be able to use both eyes instead of looking through a single peephole. Nor is there much optical theory of modern origin. The ideas introduced by Moritz von Rohr that led to his development of the synopter at the Zeiss factory at the beginning of the 20th century, after the demise of the zograscope, are a first attempt at fundamental understanding. Roughly speaking, the zograscope works because it removes (at least to a large extent) the physiological cues that reveal pictures as being planar surfaces covered with pigments in some simultaneous configuration (as succinctly explained by Schlosberg, 1941, quoted above). Thus, its function is similar to that of the synopter, and, indeed, with very similar results (Koenderink, van Doorn, & Kappers, 1994). The effect is similar to that of closing an eye when looking at a painting, a technique that has served painters for centuries, and is still in widespread use. The zograscope is more convenient, in that it allows the conventional use of both eyes. Literature on “monocular stereopsis” (Ames, 1925a, b; Ciuffreda & Engber, 2002; Motokawa, Nakagawa, & Kohata, 1956; von Rohr, 1936; Schwartz, 1971; Streif, 1923) is generally in accordance with these findings. Thus, the “explanation” of the effect of zograscopic viewing is that it is a slightly complicated (due to the specific optical system) variety of synoptic viewing.

We find that the zograscopic effect indeed occurs. The depth of pictorial relief is significantly larger with than without zograscopic viewing. As expected, the effect depends both upon the picture and on the observer. Thus—again, as expected—it is not possible to stamp the zograscope with a number “depth magnification such and so.” This is psycho-optics, not geometrical optics.

It is fairly obvious that a photograph of a brick wall in frontoparallel attitude is not going to reveal any “zograscopic effect.” The case of the Modigliani fits roughly in this ballpark, as Modigliani evidently painted in a way that preserves the awareness of the picture plane. Different from 19th-century academic painters, who conceived of the picture plane as a “window” opening up to a “pictorial world,” painters like Modigliani tried to preserve an awareness of the fact that pictures are actually flat objects, even when depicting volumetric objects in space.

### Table 1

|         | AD | JK | MW |
|---------|----|----|----|
| Hermaphrodite | 1.42 | 1.88 | 1.04 |
| Modigliani     | 0.72 | 0.72 | 1.08 |
| Danaid         | 1.4 | 2.96 | 1.36 |

Figure 14. The depth relief magnifications due to zograscopic viewing. Here the magnifications are specified as a percentage. (Thus unit magnification becomes 0%, a doubling becomes 100%, and so forth.) Red observer AD, yellow observer JK, blue observer MW.
That observers react differently on “synoptic viewing” (as also approximately achieved by the zograscope) is both empirically evident (Koenderink et al., 1994), and theoretically likely. For instance, observers with an amblyopic eye, or defective binocular depth vision, are likely to benefit little from such a viewing aid. This is an area in which empirical data are unfortunately scarce.

In summary, we analyzed the optics of the “zograscope,” constructed a functional implementation fit to work with the iPad, and presented psychophysical data for three observers. The function of the zograscope (different from the various explanations to be found in various places) is found to minimize the effect of physiological cues, and thus maximize the efficacy of the purely pictorial cues. From the experimental data, we conclude that the zograscope indeed (as shown earlier for the synopter; Koenderink et al., 1994) tends to magnify depth of pictorial relief, depending on the pictorial content and on the observer. These results perhaps suggest that the notion of a psycho-optics (after the generally recognized psycho-acoustics) is perhaps a useful one.

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Notes
1. Wikipedia http://en.wikipedia.org/wiki/Zograscope. (It is even suggested that the zograscope would generate horizontal disparities from a single picture!)
2. The contemporary Zeiss factory has a museum that contains such early visual aids, see http://www.optischesmuseum.de.
3. Wikipedia, http://en.wikipedia.org/wiki/Moritz_von_Rohr.
4. Wikipedia, http://en.wikipedia.org/wiki/Zeiss.
5. The patent description is Kaiserliches Patentamt Patentschrift Nr. 151312, Klasse 42h, 27 February 1903.
6. Wikipedia, http://en.wikipedia.org/wiki/Allvar_Gullstrand.
7. Wikipedia, http://en.wikipedia.org/wiki/Stereopsis.
8. Wikipedia, http://en.wikipedia.org/wiki/Petzval_field_curvature.
9. Wikipedia, http://en.wikipedia.org/wiki/Spherical_aberration.
10. Wikipedia, http://en.wikipedia.org/wiki/Mathematica.
11. Wikipedia, http://en.wikipedia.org/wiki/Chromatic_aberration.
12. Wikipedia, http://en.wikipedia.org/wiki/Rube_Goldberg_machine.
13. Wikipedia, http://en.wikipedia.org/wiki/IPad.
14. Wikipedia, http://en.wikipedia.org/wiki/Borghese_Hermaphroditus.
15. Wikipedia, http://en.wikipedia.org/wiki/Auguste_Rodin.
16. Wikipaintings, http://www.wikipaintings.org/en/auguste-rodin/danaid.
17. Wikipaintings, http://en.wikipedia.org/wiki/Amedeo_Modigliani.
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