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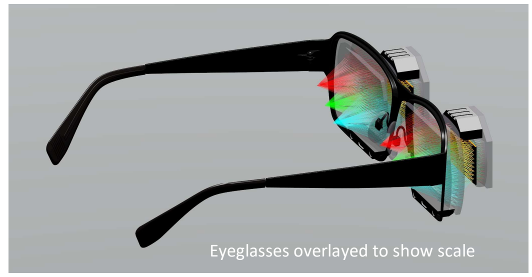
Next Generation Wearable VR Displays using Modulated Subpupil Lighting



Leveraging eye pupil tracking to turn off light missing the eye pupil center dramatically increases edge-to-edge image clarity and contrast, reduces power usage and heat by over 99%, and increases depth of focus for decreased vergence accommodation conflict.

WHITE PAPER

Shawn L. Kelly, CEO, Panamorph, Inc.
shawn@panamorph.com, as of December 9, 2022

The following is a summary of the basic principles of Modulated Subpupil Lighting (MSL) - a new near-eye display lighting technology more thoroughly explained in US Patent 11493773B2 and other related pending patents (all rights reserved). This white paper is not intended to be an exhaustive examination of all aspects of MSL, but rather to focus on basic principles as may be confirmed by the reader through simple experiments herein described.

A conventional near-eye display system includes a magnifier lens which collects and directs light from a flat panel array of self-emitting or backlit display pixels toward the eye of a user whose eye pupil and eye lens thereafter intercept a portion of that light to form a real image on the eye's retina for interpretation as a distant virtual image. Problems with such conventional near-eye displays include a) most of the light from the display panel misses the relatively small eye pupil, representing a significant waste of energy and a source of scattering which reduces image contrast; b) the light entering the user's eye includes optical aberrations both from the magnifier lens and the user's eye lens which reduce clarity; and c) disparity between the user's eye lens focus and the user's binocular interpretation of the distance to content within the virtual image leads to vergence-accommodation conflict (VAC).

The above problems can be substantially reduced by turning off the roughly 99% of light through a conventional near-eye display system that misses the center of the eye pupil, exploiting Maxwellian optical principles to reduce optical aberrations and to increase depth of focus. This is achieved through two cooperating imaging systems. The first imaging system is simply the conventional magnifier such as a pancake lens forming a virtual image of a transparent display panel. The second imaging system, effectively the lighting system, includes an array of light sources which is imaged through the display panel as the aperture stop of that second imaging system, then through the magnifier to form a real image of that array of light sources at an exit pupil where the user's eye is located. Each light source therefore corresponds to a small region or "subpupil" of the exit pupil, with all subpupils corresponding to their respective light sources therefore making up the entire exit pupil. Operationally, as a simplest implementation, that subpupil corresponding to the user's eye pupil center location as determined by eye pupil tracking is turned "on" by turning on the corresponding light source while the remaining light sources are turned off.

The primary challenge of such a near-eye display architecture is to form reasonably well-focused subpupils at the location of the user's eye pupil. The smaller the subpupil, especially achieving a size smaller than the user's eye pupil, the more Maxwellian the system becomes for improved image quality as well as depth of focus supporting a reduction in VAC. At the same time, such properties must be provided by a compact arrangement of components to be commercially viable. Accordingly, we select a catadioptric or "pancake" lens for the magnifier, creating a virtual image of a transmissive LCD display which is illuminated by a waveguide

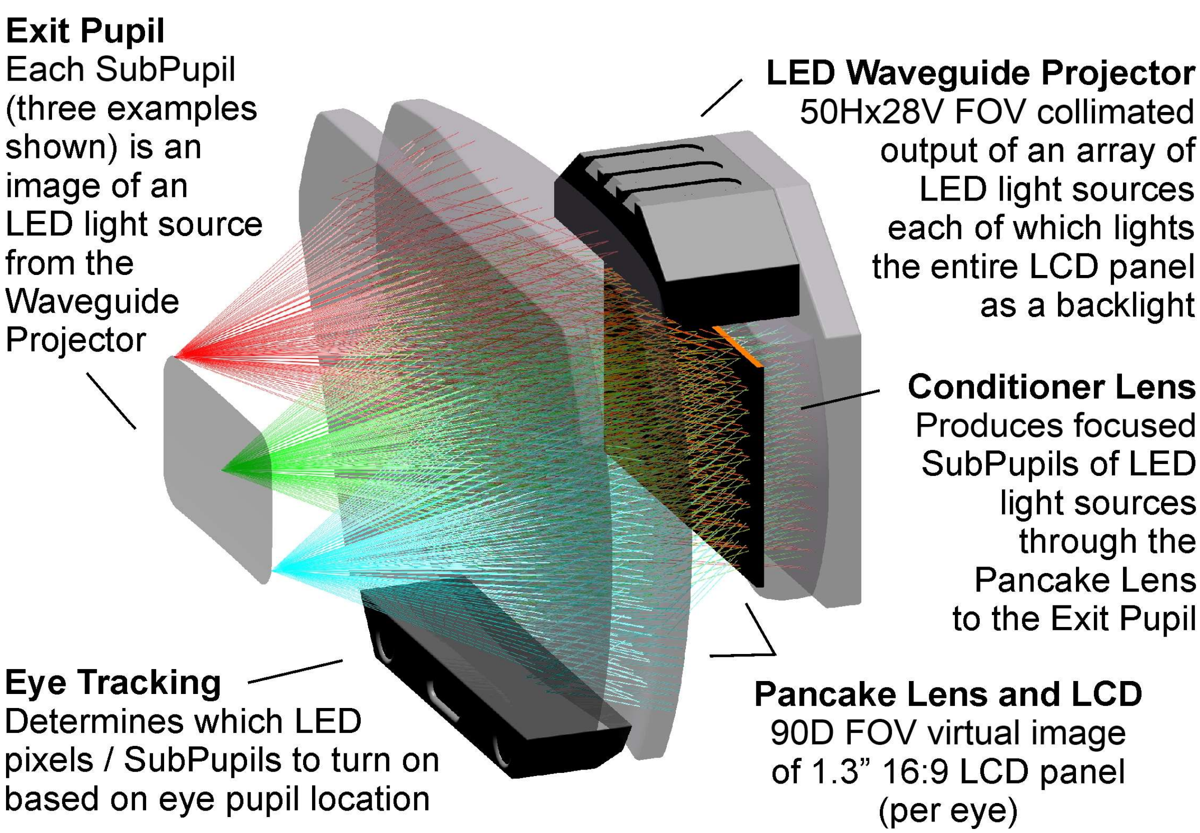


Figure 1. Primary display components of a near-eye display using Modulated Subpupil Lighting (MSL).

projector, the collimated light from which is "conditioned" by an intermediate conditioner lens to support a best focus of the light sources projected through the waveguide and thereafter propagated through the pancake lens to the exit pupil, all as shown in assembly and in operation using actual optical ray tracing through three example subpupils in Figure 1 (Zemax used in all ray tracing examples).

To illustrate these optical concepts in more detail, Figure 1a shows a plan view model of a typical pancake lens with rays traced in reverse from a virtual image (not shown) at a 2500mm distance, having a 77 degree horizontal by 47 degree vertical (90 diagonal) field of view, through a 20mm diameter system exit pupil (the entrance pupil in this case) with 16mm eye relief and then through catadioptric or "pancake" lens components to a rectangular flat panel display. To minimize pupil swim, these components were optimized for best image quality through the entire optical system pupil so that the image is relatively stable regardless of eye pupil location. However, note that no consideration of the eventual lighting system has been factored into this optimization. All efforts were simply dedicated to provide the best pancake lens design which is identically that shown in Figure 1.

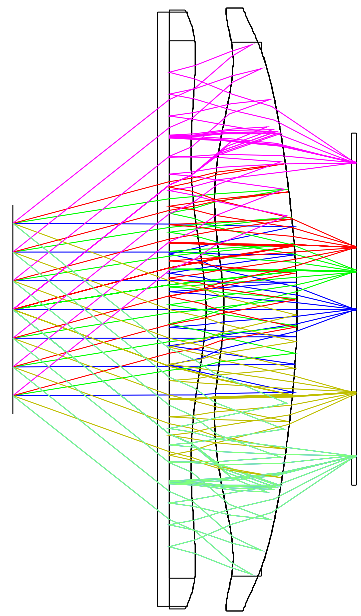


Figure 1a. Typical pancake lens magnifier shown in Figure 1 showing ray traces of a wide field virtual image (not shown) of a transparent display panel through a large exit pupil.

Without changing the pancake lens design and display arrangement of Figure 1a, Figure 1b now traces light rays originating from a number of points in the exit pupil representing locations where a user's eye pupil center may be, those rays then propagated through the pancake lens and through the full display panel, now acting as an aperture stop, and then continuing on unmodified to an arbitrary surface, in this case about 80mm away. The interesting result of this exercise is that optical rays from any given pupil location and propagated through the pancake lens

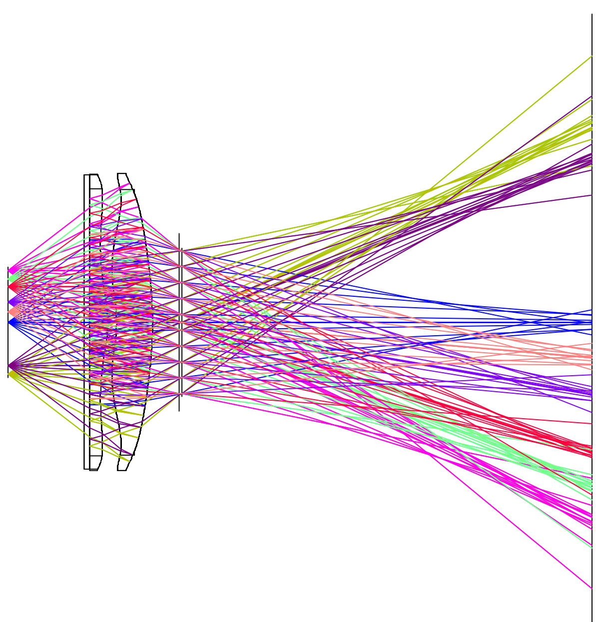


Figure 1b. Pancake magnifier of Figure 1a now showing rays traced from points in the exit pupil to illustrate lighting paths from possible eye pupil locations and through the pancake lens and transparent display panel to show relative convergence of rays from pupil locations to distant images of those locations.

and display naturally converge, albeit poorly, to form an “image” of that pupil location beyond the display panel. Due to reciprocity, if one were to place a small light source at such an “image” location, the light from that light source would propagate in reverse, flooding the entire display panel and then passing through the pancake lens to form a corresponding image of the light source, again albeit a poor one, in the exit pupil. This “image” of a small light source therefore represents a relatively small bundle of light or “subpupil” which forms the entire display image on the user’s retina when such light passes through the eye pupil and eye lens, effectively eliminating the need for light passing through other locations of the optical system exit pupil, in other words through other subpupils corresponding to other light sources, until the eye rotates to those locations. Those other light sources can therefore be left off until the eye pupil location changes, where a more optimum subpupil is activated by turning on its corresponding light source while turning off the previous light source.

Of course, an array of physically distant light sources each flooding the display panel does not support a compact display device and, of course, it is desirable that each such light source forms as focused a subpupil image as possible at the eye pupil location to maximize the benefits of Maxwellian optics. A more compact approach to filling the entire display panel with the light from each of an array of light sources is to use a waveguide projector very similar in form to those developed for augmented reality displays, but in this case to apply the waveguide projector as a backlight for the display panel.

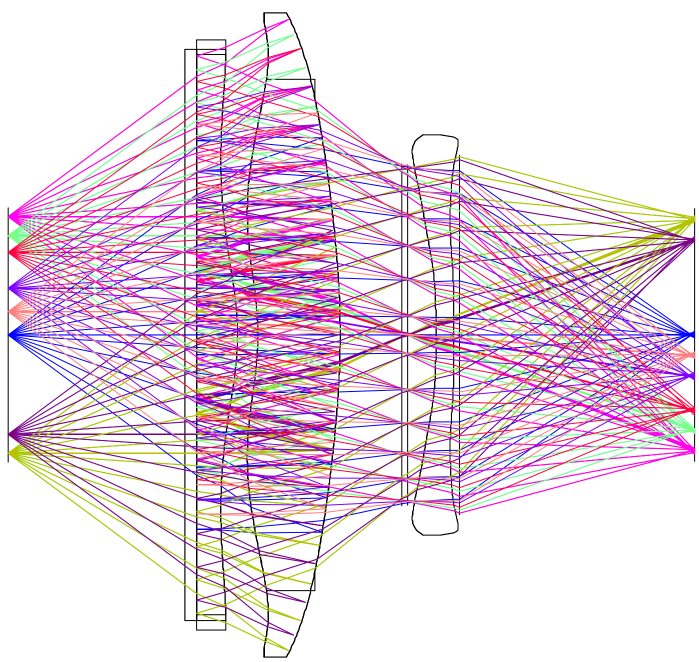


Figure 1c. Rays traced from exit pupil locations shown in Figure 1b but now collimated by a conditioner lens after the transparent display and projected through a waveguide projector modeled as a paraxial lens to illustrate a reciprocal imaging relationship between light sources of the waveguide projector and subpupils in the system exit pupil.

A fundamental property of a waveguide projector is that the waveguide output represents beams of angularly-differentiated but collimated light from each of those light sources. Accordingly, in Figure 1c a “conditioner” lens is added to collimate those rays from the pancake lens after having passed through the display, knowing again that due to reciprocity such a conditioner will take the collimated rays from the waveguide and modify them for forming a best focus at the subpupil locations. For modeling and analysis, we then add an ideal paraxial lens representing the waveguide after the conditioner lens and trace the rays to the focal plane of that paraxial lens to simulate points representing the light sources of the waveguide projector. While again such imaging result is not perfect, and further allowing that the waveguide projector is also not perfectly modeled with a paraxial lens, we still see that there is a very good imaging relationship between each subpupil and its corresponding light source of the waveguide projector. This suggest that each of such waveguide projector light sources will form a fairly focused image at the optical system exit pupil, therefore forming an array of subpupils from which to select that subpupil or group of subpupils best directed to the eye pupil location from eye pupil tracking inputs.

At this point one may ask that if a waveguide projector is used as a backlight for a display panel in this case, then why not just use the waveguide projector as the near-eye display system itself? First the "field of view" of the waveguide projector output need only be approximately 50 degrees by 28 degrees to support the larger 77 by 47 degree actual field of view of the resulting virtual image through the pancake lens, resulting in a much greater field of view than is possible with current waveguide technology. Second, the resolution and image quality provided by the waveguide projector can be much lower than that required by current augmented reality displays since the goal is more simply to create subpupils smaller than the user's eye pupil rather than an actual high resolution visual image. Any diffraction effects and other anomalies typical of waveguide displays therefore become artifacts in the subpupils rather than in the visual image itself. Third, the waveguide in this case is located proximate the conditioner lens and display, obviating the need for significant "eye relief" from the waveguide to fully illuminate the display panel. And of course, in this case the waveguide does not need to be transparent to an external environment, allowing for greater efficiency in directing the light from the array of light source through the display panel.

The foregoing discussion therefore summarizes the basic principles of a new near-eye display architecture for limiting the spatial extent of the beam of light entering the user's eye for dramatic power savings and improved image quality. One will note that there are a number of refinements and considerations beyond the scope of this summary, including especially how to best position the user's eye relative to such subpupils, or otherwise how to position those subpupils to the user's eye, as well as how to best choose or modulate the intensities of the light sources for a best user experience in response to eye pupil tracking, and further how such implementation will insure perceived uniformity of image brightness throughout the exit pupil. Nonetheless, it is instructive to introduce a number of simple experiments to achieve first-hand experience of these basic principles as a basis for future discussion and developments.

SUGGESTED EXPERIMENTAL CONFIRMATION OF BASIC PRINCIPLES

The fundamental premise of this new near-eye display architecture is that an array of light sources each with individually modulated intensities can be implemented to selectively control the light passing through an array of corresponding subpupils which together make up the entire optical system exit pupil of a conventional magnifier, and that by turning off all but one or a few of such light sources corresponding to subpupils at the eye pupil location as determined by eye pupil tracking there is a substantial reduction in power required as well as a substantial increase in both contrast and ultimately in image clarity and depth of focus. It is an objective of the following experiments to provide the reader with first-hand experiential proof of the basic principles stated herein as simply as possible without the need for more customized components such as a specific magnifier, display, conditioner lens, waveguide projector, eye pupil tracking technologies and subpupil modulation algorithms. Therefore …

For simplicity, we first assume that if a single light source can be used to demonstrate the benefits stated herein through a single corresponding subpupil, and if laterally moving such a single light source also laterally moves the subpupil within the optical system exit pupil, then it is fair to conclude that an array of individually controllable, laterally displaced, single light sources can be used to produce an array of laterally displaced, single subpupils so that these benefits can be achieved throughout the exit pupil if such an array of light sources is implemented.

Second, we assume that, especially for a near-eye display system with a reasonably large field of view, a reasonably small subpupil or group of subpupils used to provide light to the eye pupil represents less than 1% of the total available subpupils making up the exit pupil, and therefore that turning off those remaining available subpupils reduces the power required to illuminate the entire exit pupil by a corresponding amount.

Third, we assume that current methods of eye pupil tracking are sufficient to determine the location and preferably even size of the eye pupil and its distance from the near-eye display system as it rotates relative to the near-eye display system and therefore to determine the best one or more subpupils and therefore the best one or more corresponding light sources to provide light through that eye pupil location; that electronic processing and appropriate algorithms are sufficient to modulate the intensities of those light sources without noticeable lag in response to eye movement; and that such algorithms, the arrangement of components and other display system features are sufficient to provide the perception of a uniformly illuminated exit pupil as the eye rotates.

Fourth, we assume that if the following first-hand experiments satisfactorily demonstrate the basic principles of this new near-eye display architecture even without the implementation of optimized components for improved subpupil images, then such optimized components should provide results at least as good as those without them.

Finally, we assume that an increased depth of focus as one benefit of subpupils smaller than the eye pupil will lead to a decrease in vergence-accommodation conflict. If virtual image clarity remains high over a large range of eye lens focus then such focus can be more relaxed to allow a focus at a different focal plane suggested by the vergence of objects in the virtual image. In other words, if the image clarity remains high when the eye lens is focused at the vergence distance then the eye lens will struggle less to change accommodation from the virtual image to focus on that vergence distance. Therefore …

While generally any optical magnifier can be used for such experimentation, it is most instructive to use a pancake lens since such a magnifier is popular among the latest virtual reality wearable displays and further often naturally provides optical rays through the display panel that ultimately converge. As initial preparation, mount or position the pancake lens to form a virtual image of a transparent object such as a transparent display, film image or transparent resolution test pattern as one would typically use such a lens. All experiments to follow involve this same arrangement of lens and transparent object, varying only in how light is directed through it and to the eye.

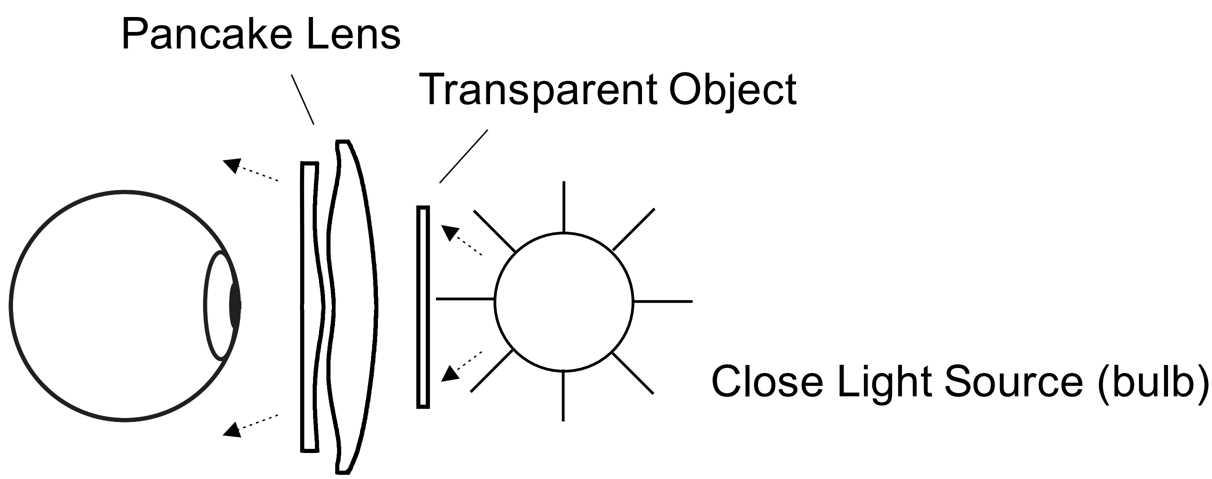


Figure 2a. Experimental demonstration of relatively low image contrast, low full-field image clarity and substantial wasted light missing the eye provided from an extended close light source such as a conventional backlight through a conventional pancake magnifier.

First, view the transparent object through the pancake lens with a relatively extended light source such as a frosted light bulb relatively closely positioned behind the transparent object, with other ambient light sources turned off. This first experience should fully fill the display and exit pupil, representing the image quality, both clarity and contrast, of a conventional near-eye display system. As long as the light bulb is close enough to the display panel so that it is sufficiently extended, you will be able to look around the entire image by rotating your eye without the image disappearing (i.e. without vignetting) because the closely located light bulb is creating an exit pupil significantly larger than your eye (assuming the pancake lens is of sufficient size relative to the transparent object).

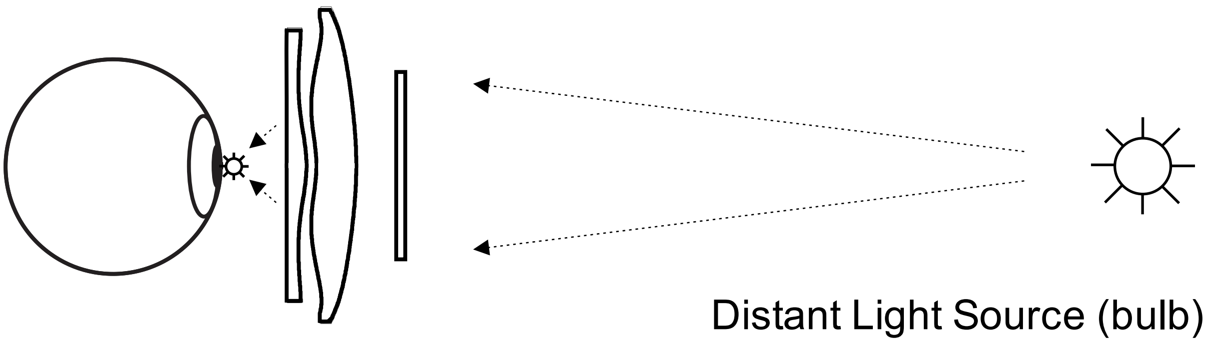


Figure 2b. Experimental demonstration of increased image contrast and image clarity due to light forming a relatively small subpupil image of a distant light source at the eye pupil.

Now, still holding the lens and transparent object assembly to your eye, gradually increase your distance to the light bulb while maintain alignment from your eye, through the pancake lens and transparent object and to the light bulb, so you can constantly view the illuminated image. For example, simply walk backward (with a mind for safety) away from the light bulb. A real image of the light bulb will gradually form at approximately the exit pupil of the magnifier, representing a subpupil image of the light bulb. You will find that you will need to continuously positioning your eye pupil at that subpupil image of the light bulb to see the fully illuminated transparent object. As the distance to the light bulb increases you will see a very noticeable improvement first in the contrast and then in the clarity of the virtual image of the transparent object, albeit more dim because of increasing distance. This is because the optical arrangement is forming a subpupil image of the light bulb that is shrinking with distance to the light bulb. At first the shrinking subpupil image represents a smaller and smaller percentage of the exit pupil, thereby reducing stray light through the entire system to increase contrast. Then ultimately the subpupil image will become smaller than your eye pupil, thereby reducing aberrated light that contributes to image blur in the virtual image and therefore resulting in higher perceived clarity.

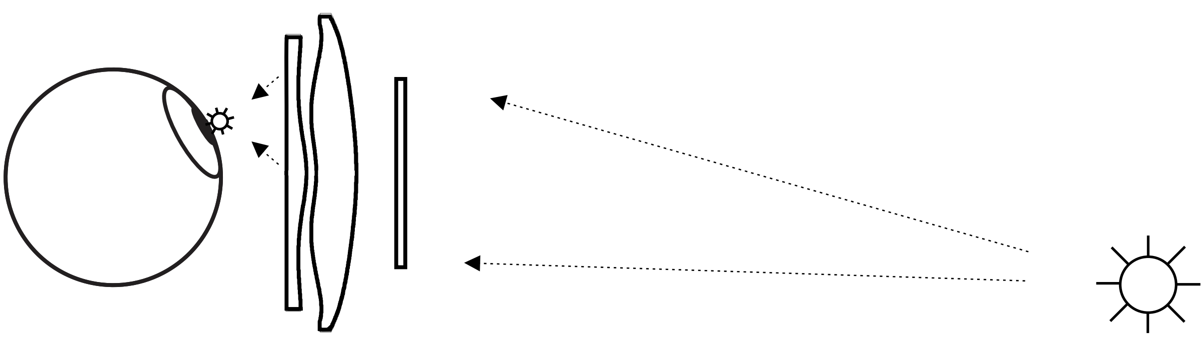


Figure 2c. Experimental demonstration of preserved increased image contrast and image clarity due to light forming a relatively small, translated subpupil image formed at a rotated eye pupil from a translated distant light source so that the complete virtual image of the transparent object is visible.

Next, note that rotating your eye to look at other regions of the virtual image will cause the image to disappear. This is because the subpupil image of the now distant light source is so small that rotating your eye forces those light rays to now miss your eye pupil. However, slightly rotate your head and the magnifier and transparent object all together in the direction of your eye rotation and you should see the image reappear. This is effectively creating a lateral shift of the distant light source which results in an opposite shift of the subpupil image to be reoriented with your eye pupil location.

The above very simple experiments not only demonstrate the benefit of Modulated Subpupil Lighting but also demonstrate that translating a light source also translates the subpupil image of that light source (although in opposite directions), thereby supporting the use of an array of individually controllable light sources to create an array of subpupils from which one or more can be turned on to illuminate the image through the eye pupil location.