Scanned for the Undersea and Hyperbaric Medical Society by The Rubicon Foundation
in cooperation with Global Underwater Explorers. (http://rubicon-foundation.org)

Undersea Biomedical Research, Vol. 1, No. 4, December 1974

Linear polarizing filters and underwater vision

S. M. LURIA and JO ANN S. KINNEY

Naval Submarine Medical Research Laboratory
Groton, Connecticut 06340

Luria, S. M., and J. A. S. Kinney. 1974. Linear polarizing filters and underwater vision. Undersea Biomed. Res. 1(4):371-378.–The effectiveness of linear polarizing filters in improving resolution acuity and detection thresholds under water was measured both in sunlight and under polarized artificial light. The magnitude of natural polarization of sunlight is enough to affect the thresholds as the observer's polarizing filter is rotated, but vision with the filter is not reliably superior to that without the filter. In dimmer artificial light, the reduction in the amount of light reaching the eye through the filter outweighs any beneficial effects of the polarization phenomenon and visibility is decreased.

underwater vision
linear polarizing filters
visibility

Natural light is polarized. This phenomenon is clearly observable with the polarizing filters found in many sunglasses. The degree of polarization depends on the angle formed by the observer's line of sight to a point in the sky and the line from that point to the sun–the angle of scatter as it is called. As illustrated in Fig. 1, direct sunlight is unpolarized, but the light reflected from molecules of air is partly polarized.

Skylight entering the water also exhibits various degrees of polarization, again depending on the angles of scatter (Mertens 1970). This is also readily observable. Consequently, it is believed that the polarization of light is used as a navigational aid by both airborne and marine animals (Waterman 1955).

The question of whether the polarization of light in the water can be used to improve the vision of divers has been raised by several investigators. Theoretically it can, because light reflected from large objects maintains its polarization, but light reflected from the tiny particles suspended in the water does not. Thus a polarizing filter should be able to transmit the light from the large objects while screening out much of the veiling light present in the water. It is not certain if this is a practical proposal, however, because the ambient light in the water is not polarized very much. Nevertheless, Lythgoe and Hemmings (1967) have reported increasing the range at which targets became invisible with the use of polarizing filters.

It would appear, however, that using polarizing filters in conjunction with artificial light which has itself been polarized would hold far more promise of success. And, indeed, Briggs and Hatchett (1965) as well as Gilbert and Pernicke (1966) have reported improving visibility by this method, the latter by a substantial amount. This study was carried out to check these findings. It sought to determine whether or not there is a difference in the distance at which a target can be seen (1) as a function of the axis of the polarizing filter

Scanned for the Undersea and Hyperbaric Medical Society by The Rubicon Foundation
in cooperation with Global Underwater Explorers. (http://rubicon-foundation.org)

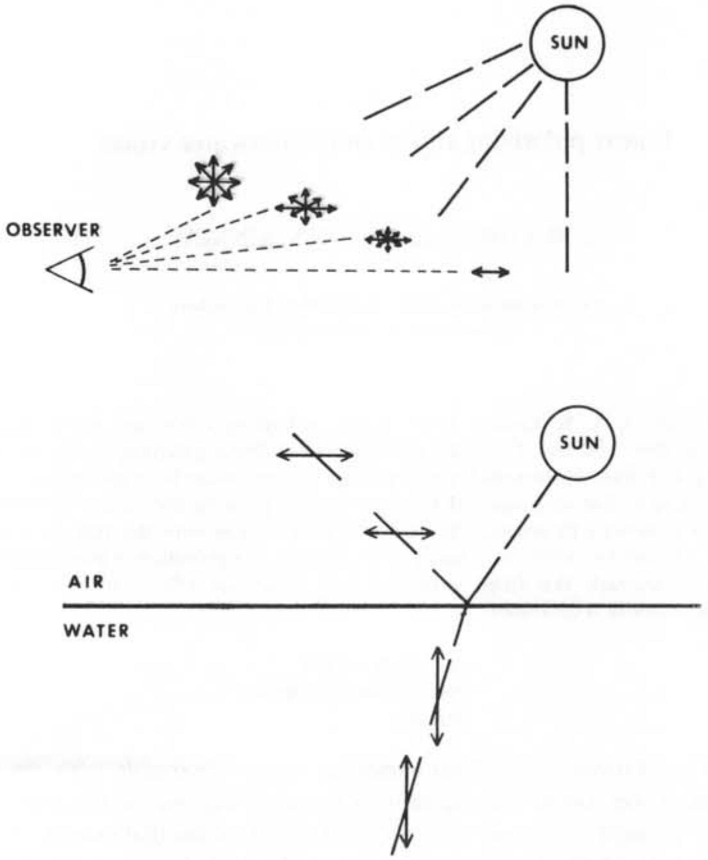

Fig. 1. The degree of polarization depends on the angle formed by observer's line of sight to a point in the sky and the line from that point to the sun (top).

Reflection from the surface of the water (bottom) produces polarization in both the reflected and refracted rays, but in planes which are perpendicular to each other.

before the observer, and (2) whether visibility with optimal filter-orientation is better than that with no filter at all. Measurements were carried out in three bodies of water with different levels of turbidity. Both resolution acuity thresholds and detection thresholds were obtained. Measurements were taken both in natural light and under artificial polarized illumination.

EXPERIMENT I – NATURAL LIGHT

The first experiment was carried out in two turbid lakes with somewhat different degrees of turbidity. The attenuation coefficient, α, in the equation describing the transmission of energy[1] was around 4 for the clearer lake and around 8 for the more turbid lake. All measurements were made on sunny days within 90 minutes of noon. Thresholds were

---

[1] $P = P_o e^{-\alpha d}$ where P_o is the radiant power at the initial point, e is base of natural logarithms and d is the distance.

Scanned for the Undersea and Hyperbaric Medical Society by The Rubicon Foundation
in cooperation with Global Underwater Explorers. (http://rubicon-foundation.org)

obtained for four subjects in the clearer lake and two subjects in the more turbid lake. Measurements were taken for three orientations: looking away from the sun, toward the sun, and with the sun's rays perpendicular to subject's line of sight.

METHOD

Polarizing filters. Linear polarizing filters, 18 cm square, made by the Polaroid Corp. were used. Each filter transmitted 40% of the incident light through the horizontal axis and 20% through the vertical axis. When crossed, the pair transmitted about 4% of the light.

Targets and apparatus. Three targets were used in this experiment to measure resolution acuity thresholds and detection thresholds for both white and black targets. All were 18 cm square. One was a grid with alternating black and gray stripes 3 cm wide. The contrast was .48, calculated by the formula $(L_H - L_L)/(L_H + L_L)$ where L_H is the greater amount of light and L_L is the lesser amount of light reflected from the gray and black bars of the target. The light was measured in foot-lamberts by a Spectra Brightness Spot Meter. The other targets were a white square and a black square.

The targets were presented to the subject in a holder which could be moved back and forth along a graduated horizontal rod. The rod was attached to a heavy tripod which supported the subject's chinrest. The distance of the target from the subject could be read from the rod.

Procedure. Observations were made in water 4 ft deep with the subject wearing a standard scuba facemask (Luria, Ferris, McKay, Kinney, and Paulson 1972) and snorkel. He knelt with his chin in the chinrest and looked along the horizontal rod while holding the polarizing filter against his scuba mask. (The subject did not know the axis of the filter.) Thresholds were measured with the method of limits. The target-holder was moved slowly away from the subject until he signaled that he could no longer see it (in the case of the white or black target). It was then moved slowly toward him until he signaled that it was again visible. Four to eight such measurements were taken for each threshold, depending on the subject's variability. In the case of the grid target, he was required to indicate the orientation of the stripes (horizontal or vertical). Each orientation was presented half the time, in random order.

Subjects. All subjects were staff members of the Laboratory.

RESULTS

The first question was whether or not there is enough natural polarization of sunlight to produce differences in threshold as a linear polaroid filter is rotated before the eyes. Table 1 gives the mean distances at which four subjects in the less turbid lake and two subjects in the more turbid lake could correctly indicate the orientation of the grid target. The results are quite clear. Visibility thresholds were appreciably better when the axis of the polarizing filter was vertical irrespective of the subject's orientation with respect to the sun. For example, in the less turbid lake with the sun in back of the subject, the grid target could be resolved at a mean distance of 95.3 cm with a vertical filter but only 83 cm with a horizontal filter. This effect occurred for every subject in every condition (paired $t = 4.56$, df = 17, $P < 0.01$). The difference in turbidity between the two bodies of water is evident in the two sets of threshold distances, but the pattern of results was the same in both cases.

The results with the white and black targets were not so clear-cut. All of the subjects reported the appearance of the white target at a farther distance through the vertical filter

Scanned for the Undersea and Hyperbaric Medical Society by The Rubicon Foundation
in cooperation with Global Underwater Explorers. (http://rubicon-foundation.org)

TABLE 1

Mean resolution threshold distance (cm) for grid target seen through a horizontal or vertical polarizing filter for various orientations of S with respect to sun

	Less turbid lake (n=4)		More turbid lake (n=2)	
	Horizontal	*Vertical*	*Horizontal*	*Vertical*
Sun at back	83.0	95.3	36.4	39.0
Sun at left	69.8	74.0	25.5	25.9
Looking toward sun	59.1	69.9	17.3	21.8

when the sun was either in back of them or to their side. But when looking toward the sun, they were not consistent ($P < 0.10$). The data from the two lakes have been combined in Table 2. The distances are relatively large because more subjects were tested in the less turbid lake and because the detection distances for the white target were much greater than the distance at which the grid target could be resolved.

With the black target, there was no consistency under any of the conditions; under each condition, one subject showed better visibility with the horizontal filter ($P < 0.60$). In addition, the differences in threshold between the horizontal and vertical filters were very small. The data from the two lakes are again combined in Table 3.

TABLE 2

Mean detection threshold distances (cm) for a white target seen through a horizontal or vertical polarizing filter for various orientations of S with respect to the sun

	Horizontal	Vertical
Sun at back	100.8	109.0
Sun to left	58.5	61.3
Toward sun	68.2	67.8

TABLE 3

Mean detection threshold distances (cm) for a black target seen through a horizontal or vertical polarizing filter for various orientations of S with respect to the sun

	Horizontal	Vertical
Sun at back	69.8	70.4
Sun to left	69.8	68.6
Toward sun	66.0	68.0

The improved visibility of the grid and the white target through the vertical filter indicates that the polarization phenomenon was effective. Since light is polarized vertically in the water, the vertical filter should pass the light from the target while screening out the more unpolarized radiation in the background. Moreover, the polarization effect would seem to be substantial, since more light is actually transmitted through the horizontal axis, and yet visibility was greater through the vertical axis.[2]

---

[2] To demonstrate further the polarizing effect, the acuity of four subjects was measured in air through the filter. Resolution thresholds were measured with a set of high-contrast grids of varying bar-widths using the method of constant stimuli. In air, mean acuity was better through the horizontal filter (1.75) than through the vertical filter (1.67), the opposite of what was found in the water.

Scanned for the Undersea and Hyperbaric Medical Society by The Rubicon Foundation
in cooperation with Global Underwater Explorers. (http://rubicon-foundation.org)

These results show that the degree of natural polarization of light is sufficient to produce differences in visual thresholds as a result of the orientation of a linear polarizing filter. The vertical orientation of the filter is better in the water.

The next question was whether or not the polarizing filter in its optimal orientation improves visibility compared to no filter at all. This was tested only in the less turbid water with the subjects looking away from the sun. The results are given in Table 4. The use of the filter clearly did not result in much improvement in visibility. Only with the white target was the mean visibility threshold better with the filter, and that difference was trivial. A paired *t* test showed that the differences were not statistically reliable.

TABLE 4

Mean threshold distances (cm) for various targets viewed through either a vertical polarizing filter or no filter with *S* facing away from the sun

Target	Vertical	No filter
Grid	85.5	88.0
White	109.0	108.0
Black	94.0	96.0

EXPERIMENT II – ARTIFICIAL LIGHT

We next tested whether visibility through a polarizing filter would be significantly improved if the source of illumination were also polarized. It is no trouble, of course, to produce artificially a magnitude of polarization which far exceeds that found naturally. This experiment compared visibility through a polarizing filter with visibility through no filter when the ambient illumination was artificially polarized.

METHOD

Filters and light. The experiment was conducted in an indoor swimming pool at night. The water was quite clear. Divers could see the length of the 75-ft pool with the overhead illumination. To carry out this experiment, however, the overhead lights were turned out and illumination in the pool was provided solely by an underwater mercury light, Model L2B manufactured by the Oceanographic Engineering Corp. A linear polarizing filter with vertical axis could be attached to the lamp housing. A similar polarizing filter was positioned before the subject's facemask with the axis either horizontal or vertical. The lamp was located to the subject's left so that the angle formed by the lines of sight from the target to the lamp and from the target to the subject was about 30°.

Targets. Both acuity and detection targets were again used in this experiment, but the extreme clarity of the water made it necessary to use different sets of targets: very small acuity targets and a low contrast detection target. Acuity was tested with a set of high contrast (0.66) black and white grid targets whose bar-width ranged from 0.66 to 2.22 mm. Detection was measured with a dark gray circle of 8-cm diameter on a light gray square, 17 cm on a side; the contrast, calculated by the same formula as before for purposes of comparison, was 0.24.

Scanned for the Undersea and Hyperbaric Medical Society by The Rubicon Foundation
in cooperation with Global Underwater Explorers. (http://rubicon-foundation.org)

Procedure. The subject knelt in 4 ft of water with the mask, filter, and snorkel. The targets were presented at a distance of 12 ft. Resolution thresholds were measured by the method of constant stimuli. A set of about five targets was selected, which bracketed the subject's acuity. The targets were presented in random order, making certain that the vertical and horizontal orientations were each presented half the time. Each target was presented six times. The percentage of correct responses was plotted on cumulative probability paper and the point of 50%-correct responses taken as threshold. Thresholds were measured with the axis of the diver's polarizing filter in the same orientation as that before the lamp, with the axes crossed, and with no filter before the diver's facemask.

In addition, thresholds were measured with the low contrast circle using the method of the first experiment: the circle was slowly moved toward and away from the subject and its distance from him noted when it became visible or invisible.

RESULTS

Table 5 gives the acuity thresholds under the various conditions for two subjects. Acuity is defined as the reciprocal of the visual angle in minutes of arc subtended by the bars of the smallest target which could be perceived by the subject. Acuity was good without the filter, as would be expected in clear water (Kent 1966), and substantially better than when the targets were viewed through a polarizing filter. When the orientation of the axis of the diver's filter was the same as that before the lamp, acuity declined. When the axes of the two filters were crossed, acuity declined still further.

TABLE 5

Mean acuity thresholds for grid targets and distance thresholds (meters) for circle in artificially polarized light as a function of orientation of *S*'s polarizing filter

	Visual acuity		Distance (m)
	Subject: TP	*Subject: JK*	*Subject: MS*
No filter	1.45 ±0.16	1.11 ±0.12	2.74 ±0.15
Same axes	0.82 ±0.16	0.81 ±0.04	2.29 ±0.17
Crossed axes	0.70 ±0.40	0.70 ±0.20	1.98 ±0.20

In one final test, the detection threshold for the low contrast circle was measured under these conditions for a severely myopic subject. The mean distances at which he could detect the circle on three trials are also given in Table 5. The results conform completely with the resolution thresholds. With no filter before his mask, the diver could detect the circle at a mean distance of 2.74 m. When the axis of his filter was in the same orientation as that of the lamp filter, the mean detection distance was 2.29m; with the axes crossed, it fell further to 1.98m.

DISCUSSION

These results show, first of all, that the degree of natural polarization is enough to produce differences in target visibility as the axis of a diver's polarizing filter is rotated.

Scanned for the Undersea and Hyperbaric Medical Society by The Rubicon Foundation
in cooperation with Global Underwater Explorers. (http://rubicon-foundation.org)

Resolution thresholds were sensitive to this variable irrespective of the location of the sun in relation to the diver. Detection thresholds for white targets were better with the properly oriented filter when the sun was behind the diver or to his side. There was no difference, however, when looking toward the sun. Under this condition, of course, the *white* target was reduced to a black silhouette and the results were similar to those with the black target; the latter showed no threshold differences as a function of filter orientation irrespective of the position of the sun.

Despite these positive findings, the comparison of target visibility with and without the polarizing filter does not suggest that the polarization phenomenon has much practical utility. In the sunlight, target visibility without the filter was, if anything, slightly better than with the filter in its optimal orientation. When an attempt was made to maximize the polarization phenomenon by polarizing an artificial light-source, there was a great decline in both acuity and detection when the diver looked through a polarizing filter. The reason must be that the filter reduces the amount of light reaching the eyes. In bright sunlight (where visual acuity has reached the plateau of the acuity-luminance function [Geldard 1953]) this reduction has only small, if any, effects on acuity. Under the much dimmer artificial illumination, these reductions in luminance lead to appreciable decreases in acuity.

These results do not, of course, conform with the studies cited above which reported positive findings with polarizing filters. The paucity of reports of positive findings suggests a difficulty in obtaining such improvements and perhaps the existence of a greater number of negative, unpublished reports. However, there may be other reasons for the discrepancy. It should be noted that Briggs and Hatchett (1965) were concerned primarily with the improvement of photographic and television images. They pointed out that techniques which are effective with such equipment need not be effective in improving unaided vision. They noted that their results were achieved by matching the elements of the video system to the problems peculiar to the underwater environment, and the human eye is not subject to such modification. Further, their report of improved visibility with polarizing filters was made very briefly in passing, and they stated that their results were "not conclusive, since there were some basic faults in the experimental setup" (p. 1304).

Lythgoe and Hemmings (1967) studied both visual perception and photographic effects. Although their photographs show a clear effect, their data for a human observer seem to show that the polarizing filters were useful for targets only of intermediate (15-30%) reflectance. Their data for targets of smaller and greater reflectance show little, if any, difference between distance thresholds with and without the filter.

The greatest improvements in visibility were reported by Gilbert and Pernicke (1966). They believe that the reason for their success is that they are apparently the only experimenters to use circular rather than linear polarizing filters. They state that the improvement in visibility with linear polarizers is based on the operation of different physical principles than that resulting from circular polarizers: linear polarizers depend on depolarization, whereas circular polarizers depend on the number of random multiple reflections of photons; theoretically, there will be only one reflection from smooth scattering particles in the water, but many reflections from a rough target surface. Thus, more light coming from the surround will be rejected by the analyzing filters of the camera or diver than light from the target.

It is not clear why this distinction should produce a difference in effectiveness. Although the method of producing the differential reduction in luminance from target and surround is different, the net result is presumably the same: more light is filtered out from the surround than from the target by both linear and circular polarizers.

Scanned for the Undersea and Hyperbaric Medical Society by The Rubicon Foundation
in cooperation with Global Underwater Explorers. (http://rubicon-foundation.org)

Circular polarizers would seem to have only one advantage of a practical nature. They need not be kept in perfect alignment. Linear polarizing filters, on the other hand, require a constant relative orientation, which might not always be maintained by a free-swimming diver. This presumably would not happen with circular polarizers.

This study was supported by the Bureau of Medicine and Surgery, U.S. Navy Department, Research Work Unit M4306.03-2050DXC5. The opinions and assertions contained herein are the private ones of the authors and are not to be construed as official or reflecting the views of the Navy Department, the Naval Submarine Medical Research Laboratory, or the naval service at large.

Received for publication June 1974.

REFERENCES

Briggs, R. O., and G. L. Hatchett. 1965. Techniques for improving underwater visibility with video equipment. Ocean Sci. Eng. 2:1284-1308.

Geldard, F. A. 1953. The human senses. Wiley, New York.

Gilbert, G. D., and J. C. Pernicke. 1966. Improvement of underwater visibility by reduction of backscatter with a circular polarization technique. *In* Underwater photo-optics seminar proceedings, Society of Photo-optical Instrumentation Engineers, Santa Barbara, CA.

Kent, P. R. 1966. Vision underwater. Am. J. Optom. 43:553-565.

Luria, S. M., S. H. Ferris, C. L. McKay, J. A. S. Kinney, and H. M. Paulson. 1972. Vision through various SCUBA facemasks. Report 734, U.S. Naval Submarine Medical Center, Groton, Conn.

Lythgoe, J. N., and C. C. Hemmings. 1967. Polarized light and underwater vision. Nature 213:893-894.

Mertens, L. E. 1970. In-water photometry. Wiley-Interscience, New York.

Waterman, T. H. 1955. Polarized light and animal navigation. Sci. Am. 193:88-94.