U. S. NAVAL SUBMARINE MEDICAL CENTER

Submarine Base, Groton, Conn.

REPORT NUMBER 476

VISUAL RESOLUTION UNDERWATER

by

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Commander MSC USN

and

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Bureau of Medicine and Surgery, Navy Department
Research Work-Unit MF022 03 03-9019 09

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COMMANDING OFFICER
U S Naval Submarine Medical Center
5 May 1966

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SUMMARY PAGE

THE PROBLEM

To compare underwater visual resolution with that in air

FINDINGS

With divers wearing SCUBA masks, underwater visual resolution of a target at short range in clear water was found to be better than at the same physical distance in air, when the target luminances were equated under the two conditions The improvement, however, fell short of the theoretically predicted value This was attributed, principally, to fogging of the SCUBA mask

APPLICATIONS

The results would be useful where it is necessary to know the range of object sizes, or parts there of, that can be identified underwater The findings are also applicable to an evaluation of the visual standards for diving personnel

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work-Unit MF022 03 03-9019 09 — Visual Performance and Requirements in Submarine and Other Underwater Environments The present report is No 9 on this Work-Unit It was approved for publication on 5 May 1966 and designated as SMC, SubMedResLab Report No 476

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ABSTRACT

Visual resolution in air and underwater were compared using Landolt Ring targets and a self-luminous, water- and pressure-proof target mount SCUBA diving masks were worn during the tests, both in water and in air Comparisons were also made while viewing above and below surface targets through a periscope from a surface position

In both instances, visual resolution in clear water was better than in air at the same actual target distance, when apparent luminances were equated for the two conditions In most cases the improvement while wearing the SCUBA mask fell below predictions based on the magnification of the target image underwater The reasons for this were ascribed to fogging of the mask underwater, and the lack of sufficiently small targets for some observers The difference in resolution between air and underwater viewing through the periscope was nearer that predicted by theory

VISUAL RESOLUTION UNDERWATER

INTRODUCTION

As a preliminary phase of an investigation designed to determine how visual acuity underwater compares with that in man's normal environment in air, a questionnaire was developed and submitted to a group of Navy personnel trained in diving.* This was a group of 100 Navy officers and enlisted men, trained in either or both types of diving, SCUBA and 'hard-hat.'

Ninety-two responses were received to the questionnaire which contained basic questions regarding visual acuity and depth perception at shallow depths in clear water.

The question regarding visual acuity was as follows: Compare your ability to see underwater and on the surface. While underwater, do underwater objects within about 20 feet of you appear: (a) less clear than on the surface, (b) clearer than on the surface, or (c) no different? Of the SCUBA divers, 50% responded less clear, 11% clearer, and 39% no difference. For the hard-hat divers, it was 61% less clear, 7% clearer, and 32% no difference

The SCUBA divers were asked two questions related to depth perception: The first question was: Do you think that your depth perception (or ability to judge the distance of objects away from you) is different underwater than on the surface? There were 78% 'yes' answers, 18% 'no,' and 4% 'not sure.' The second question was: If your depth perception underwater seems different from that on the surface, do you think that objects underwater appear: (a) nearer to you, or (b) further away? Ninety-six percent responded 'closer,' and 6% 'further away.' There was overwhelming agreement that objects appeared closer in the underwater environment, but less of a consensus regarding underwater visual acuity

The next phase was an investigation of underwater visual resolution under controlled conditions

OBJECTIVE

The objective of this experiment was to compare visual resolution of a target, or set of targets, when viewed in air and underwater at the same physical distance.

Visual Resolution

Visual acuity, or resolution, is commonly denoted by the Snellen fraction. The numerator of the fraction stipulates the distance of observation and the denominator indicates the letter size, where size is related to distance in such a manner that for "normal" vision the ability to resolve letter detail subtending one minute of arc at the observing eye's nodal point is required. Visual acuity may also be expressed as the reciprocal of the Snellen fraction, i.e. $\frac{1}{20/20} = 1.00$, $\frac{1}{20/40} = 2.00$, etc. This decimal defines the letter detail in minutes of arc subtended at the observer's eye. In this experiment the testing distance was sixteen feet, therefore either 16/16 or 1.00 expresses normal acuity in air at this distance

APPARATUS AND METHOD

The investigation took place in the Escape Training Tank located at the United States Naval Submarine Base, New London/Groton, Connecticut. The tank is a large upright cylinder filled with water, 120 feet deep by 18 feet wide. The water is kept clear by constant recirculation through a filtering system and is held at a temperature of 92°F. During testing all outside windows were covered and the lights within the tank extinguished

*Navy divers may have no worse than 20/30 distance visual acuity in each eye, correctable to 20/20 Only three divers reported that they wore glasses for distance Two of these claimed to see poorer underwater, and one better

All acuity tests were performed at a distance of 16 feet, both in and out of water. Four pairs of target sets were used, consisting of Landolt Rings of various sizes and with gap orientation randomized in four positions. Each pair of target sets covered a different acuity range. Range 1 was from 16/64 to 16/178, Range 2 16/32 to 16/64, Range 3 16/16 to 16/32, and Range 4 16/9.6 to 16/19.2. The black Landolt Rings on a white matte finish had been reproduced photographically resulting in size accuracy and high contrast between target and background.

A water and pressure proof self-luminous target mount was used. It was equipped with a daylight type fluorescent lamp of 20 Watts power, whose length was a few centimeters longer than the mounted targets. The lamp had a highly reflective metal cover placed so that almost all of the illumination was directed towards the targets. This arrangement resulted in an average target luminance of 84 foot lamberts. The outer surface of the lamp cover and all other exterior parts facing towards the observer were painted black.

The target mount was equipped with a suspending line and support so that it could be lowered into the water after a target change. The targets were placed three feet beneath the surface when underwater tests were made.

Twenty subjects were used, with an age range of 20 to 43 years. It was first intended to use only qualified Navy divers but none was found with a monocular acuity poorer than 20/40 at twenty feet as measured with the Snellen Chart. Most had 20/20 or 20/15 visual acuity each eye. Since a spectrum of acuities seemed desirable, several non-diver subjects with distance acuity ranging to 20/200 were included.

SCUBA masks were worn during all visual acuity testing, both above and below the water surface. The face plate consisted of a single large plano lens. Care was taken to fit each subject with a mask that was comfortable and water tight. Some difficulty was experienced in keeping the lenses free of fog and tests were interrupted when necessary to clear them.

Prior to running tests a sensitive waterproofed light meter was used to take readings of the light reflected from the illuminated targets as measured from a distance of 16 feet, both above and below the surface. The percent attenuation along the water path was then computed and compensated for during the surface visual acuity tests by interposing neutral filters of the appropriate density. In this way luminance was equated above and below the surface.

Pupil size measurements were not made. It was assumed that the controls in effect for luminance at the entrance pupils would result in negligible pupil size variations.

Each subject's visual acuity was first determined with a Snellen Chart in order to select the correct target size range for the tests. A test consisted of presenting five different sized Landolt Rings, four times each, in random order of size and gap orientation. Targets were observed both monocularly (right and left eye) and binocularly.

Subjects were required to indicate the gap orientation of all rings that they could see well enough to make a judgment. During underwater testing a system of hand signals was used. The frequency of seeing for each target size was computed and the results were plotted on cumulative normal frequency of distribution graph paper. Acuity comparisons were made at the abscissa value (target size) of the 50% frequency of seeing intercept. This method results in a precise value for the denominator of the Snellen fraction (see Fig. 1). The advantages and rationale of this method have been pointed out by Prince and Fry (1).

One purpose of these studies was to relate underwater acuity to operational situations where SCUBA or hard hat gear is worn. A certain amount of lens fogging must be accepted under these circumstances. In an attempt to compare surface and underwater acuities under more nearly optimum conditions, a waterproofed periscope was designed for below the surface viewing The two subjects used in this experiment observed the targets monocularly through the periscope from a surface position The targets were set at a distance of 16 feet from the observer, both above and 3 feet below the water surface During underwater testing the objective of the periscope was placed at the same depth as the targets The periscope is shown in Fig 2

The right and left eye acuities of both subjects was correctable to 20/20 Various amounts of myopia were simulated by adding plus spheres to the distance lens prescription

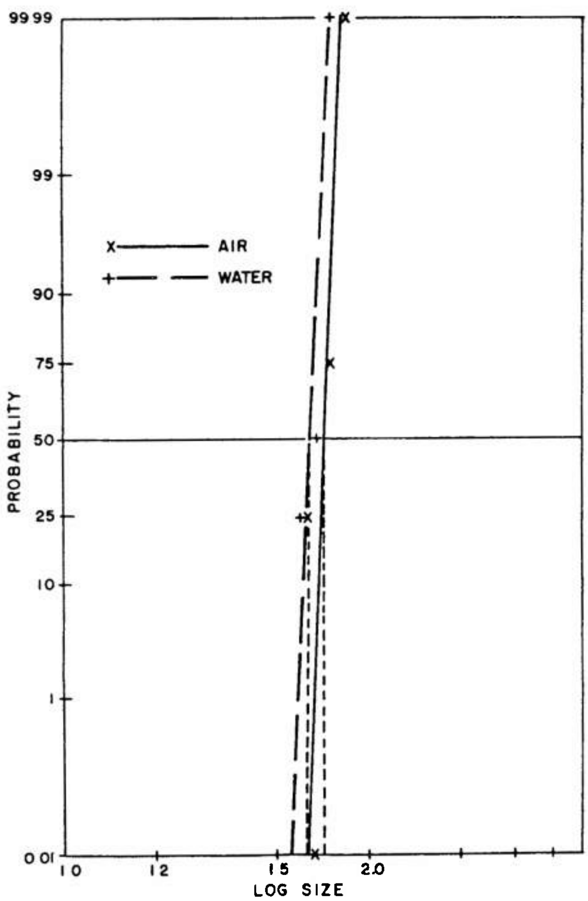

Figure 1 Plot of the air and underwater visual resolution of Landolt Ring targets for one subject. The abscissa unit is the logarithm of the Snellen fraction denominator

RESULTS

Comparative visibility of the Landolt Ring targets in air and underwater at the same physical distance using the SCUBA mask, are shown in Table 1 and Figure 3

The means and medians indicate that smaller size test targets were seen underwater, both binocularly and monocularly Binocularly, eleven of twenty subjects saw smaller sized targets underwater than in air at the same physical distance Of the remainder, seven tested the same above and below the water surface, and two saw better in air Twenty-four of forty monocular determinations showed increased visibility underwater There were twelve equalities and four reversals, two each for right and left eyes.

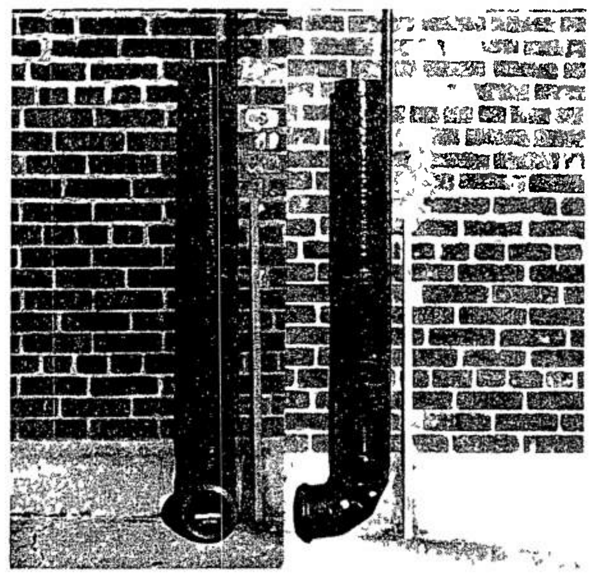

Figure 2 Side and front views of periscope. A 45 degree mirror was situated at the bend

Since sample data did not suggest that a normal parent distribution would be assumed, a non-parametric statistic (Wilcoxon signed rank test) (2) was used to test the null hypothesis that Landolt Ring size discrimination is no different in water than in air, when targets are at the same physical distance This probability was found to be less than 005 binocularly, 03 right eye, and 006 left eye There is sufficient reason, therefore, for rejecting this hypothesis under all three viewing conditions

Table 1 — Comparison of Landolt Ring target sizes resolved in air and underwater at the 50% frequency of seeing intercept Sizes are noted as the angular subtense of the gaps in the rings in minutes of arc at the nodal point Test distance was 16 feet A SCUBA mask was worn for both underwater and surface testing Twenty subjects

O	Binocular		Right		Left	
	Air	Water	Air	Water	Air	Water
1	0 62	0 62	1 00	1 02	1 07	1 00
2	0 60	0 56	0 61	0 60	0 87	0 56
3	0 60	0 60	0 68	0 68	0 60	0 60
4	1 37	1 90	1 63	2 04	2 50	2 29
5	1 00	0 74	1 58	0 93	0 75	0 70
6	1 40	1 10	1 02	1 00	1 25	1 08
7	0 60	0 60	0 60	0 60	0 60	0 60
8	1 25	1 00	1 63	1 29	1 33	1 00
9	3 08	1 90	3 80	2 04	2 88	2 23
10	4 56	6 65	6 91	4 77	3 80	5 00
11	2 56	2 12	3 46	2 24	3 21	2 19
12	0 83	0 75	0 97	0 60	0 87	0 83
13	0 56	0 56	0 59	0 59	0 59	0 60
14	1 35	1 00	1 20	1 20	1 00	1 00
15	7 50	6 50	9 55	8 30	11 15	10 45
16	4 00	2 65	5 25	5 20	4 00	2 34
17	0 60	0 60	0 60	0 60	0 60	0 60
18	2 24	2 00	3 08	2 35	2 75	2 40
19	0 56	0 56	0 56	0 56	0 56	0 56
20	0 56	0 56	0 56	0 56	0 91	0 62
Σ	35 84	32 98	45 29	37 17	41 30	36 65
$\bar{x}$	1 79	1 65	2 26	1 86	2 07	1 83
Mdn	1 12	0 87	1 11	1.01	1 04	1 00

Figure 4 was taken with a water-proof camera in an attempt to show the appearance of the target above and below water with the focal plane of the camera set at the image distance in water

Target discrimination through the periscope was better underwater for all degrees of induced blur tested, as shown in Table 2 and Fig 5 There were no reversals or equalities Mean and median target sizes were both smaller underwater

DISCUSSION

The apparent displacement x, along the line of sight, of an object located in a homogeneous optical medium of refractive index n, when viewed normally to the plane of the interface from a second homogeneous optical medium of refractive index n', is, for paraxial rays: $\frac{n - n'}{n} d$ (3), where d is the distance from object to interface For an object in water, with the eye in air, the displacement varies slightly with water temperature For water at 92° Fahrenheit, and d = 16 feet, $x = \frac{1\,331 \;-1\,00}{1\,331} 16 = 3\,98$ feet An object at 16 feet would appear to be at 12 02 feet (16 — 3 98), if the observing eye is at, or very near, the interface

Table 2 — Comparison of Landolt Ring target sizes resolved in air and underwater, at the 50% frequency of seeing intercept, as seen through a periscope fitted with plano lenses and mirrors Plus additions were made to the distance lens correction in order to simulate various degrees of myopia Test distance was 16 feet Sizes are noted as the angular subtense of the gaps in the rings, in minutes of arc, at the nodal point Combined data for two subjects

O	Eye	+ add	Target size			
				Surface (x_a)		Underwater (x_w)
1	R	1 50		10 25		6 65
"	R	1 00		4 40		4 00
"	R	0 75		2 70		2 35
"	R	0 25		1 35		1 10
"	R	0 00		1 10		0 95
2	L	1 50		6 30		5 65
"	R	1 50		8 00		4 65
"	R	0 50		2 45		2 18
			Σx_a	36 55	Σx_w	27 53
			$\bar{x}_a$	4 57	$\bar{x}_w$	3 44
		median	$(\bar{x}_a)$	3 55	$(\bar{x}_w)$	3 17

Since the image of an underwater target is displaced towards the observer, it will also appear larger than if in air and the amount will be in proportion to the displacement, if the line of sight is normal to the interface This is represented schematically in Figure 6, where AD is the positive displacement of the target ABE, whose underwater image is DCF Figure 6a is schematically similar to the case where the targets were viewed underwater through a SCUBA mask, with the air/glass/water interface (s) very near the observers eye

How much smaller can the target in water be whose image will subtend the same visual angle as another target observed in air at the same physical distance? Referring to Fig 6a the problem consists of determining the size of the target whose image, CD, subtends the same visual angle as target ABE It can be computed as follows

Let y = AB + BE, x = CF, AB = DC and CF = BE, then DC = y — x and $\frac{y}{AN} = \frac{y - x}{DN}$ If AN = 16 feet and DN = 12 02 ft, then, by substitution

$$\frac{y}{16} = \frac{y - x}{12\ 02}, 16x = 3\ 98y, x = 25y$$

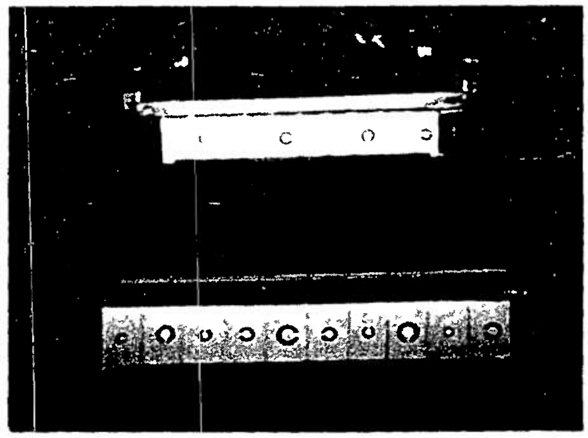

Figure 4 Photographs of one of the test targets taken from a distance of 16 feet in air (above) and underwater (below) The camera was focussed for 12 feet in both cases

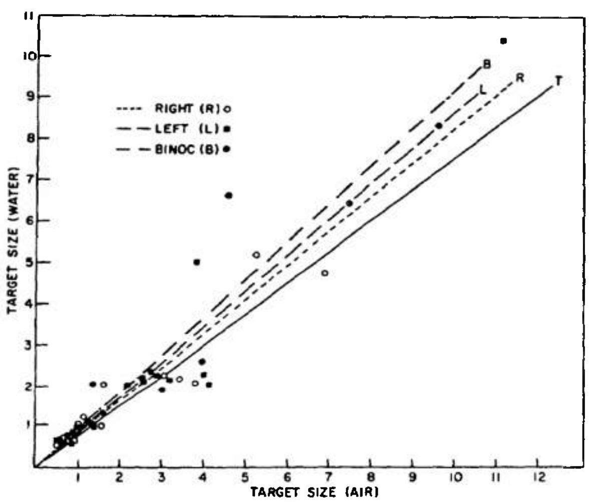

Figure 3 Scattergram, with fitted least squares lines, of the coordinates for air and water viewing of Landolt Ring targets through a SCUBA mask. Data for right (R), left (L) and binocular (B) vision of twenty subjects Line T conforms to the theoretically expected relationship Criterion was 50% frequency of resolution of the gaps in the rings Target size is noted as the angular subtense of the ring gaps, in minutes of arc, at the nodal point

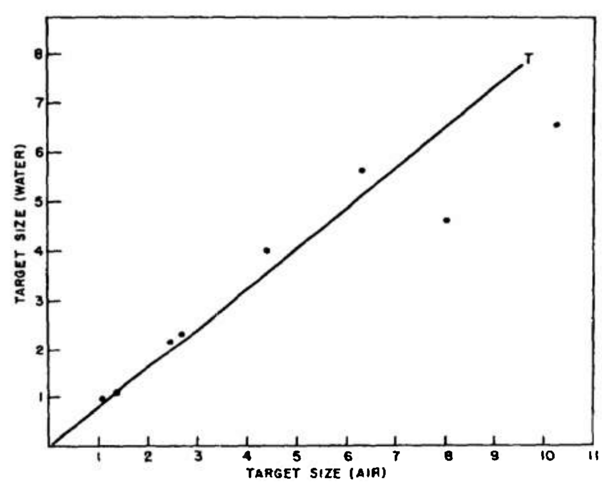

Figure 5 Scattergram of the coordinates for air and water resolution, at the 50% frequency of seeing intercept, of Landolt Ring targets when viewed through a non-magnifying (1·1) periscope, combined data of right and left eyes of two subjects Line T represents the predicted relationship Myopia, of various degrees, was simulated by interposing plus spheres Target size is noted as the angular subtense of the ring gaps, in minutes of arc, at the nodal point

The linear dimension of the target ABE, as seen in air, may be reduced by an amount equal to the segment BE, or 25%, when viewed underwater, and the subtended visual angles under the two conditions will be equal A reduction of this order was reached, and even exceeded with some subjects but in most cases the minimum target size resolved underwater was larger than theory would predict This is illustrated in Fig 3 The slopes of the lines fitted to the data for binocular, right, and left eyes by the least squares method are all less than that of the line corresponding to theory, although a few paired air and water tests yielded coordinates below this line, indicating an improvement in resolution underwater exceeding the predicted

The results were affected by (1) Lens fogging, which no doubt led to some of the reversals and (2) lack of sufficiently small targets for some observers who were able to discriminate the smallest targets presented, both in and out of water It is reasonable to expect that if fogging had been better controlled and smaller target sizes provided, the results would have more nearly approached the predicted

Since the retinal image size difference for the two conditions is determined by the tangents of the angles subtended at the eye by the target in air and its positively shifted image in water, the difference will decrease with increasing distance from the air/water boundary (observer in air), when line of sight is normal to the interface This was the case with the periscope, where 54 6 inches of the 16 foot light path from the target was through air within the instrument Referring to Figure 6b, the increase in retinal image size, ef, is proportional to AD as before, but AD is now a smaller fraction of the dimension AN and, therefore, ef will be smaller also

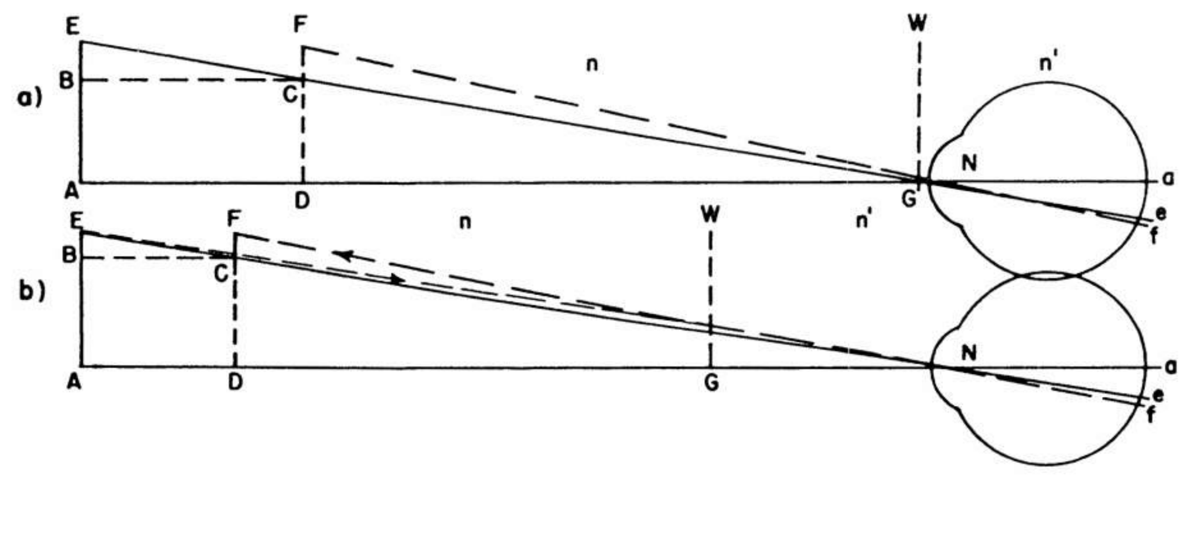

Figure 6 (a), (b). Reduced eye schematic of object/retinal image relationship when the target ABE is viewed in the air, and in the water, when it's positively displaced image is shown as DCF The retinal images are, respectively, ae and af N is the nodal point WG represents the air/glass/water interface (s) in two positions Very close to the observing eye (a), and significantly distant from it (b).

The target displacement in water at 92° would be

$$AD = \frac{n - n'}{n} d, \text{ where } d = AG = 137\ 4$$

inches, n = 1 331, and n' = 1 00

Substituting, $AD = \frac{1\ 331 - 1\ 00}{1\ 331} 137\ 4 =$ 34 2 inches Since GN = 54 6 inches, the target distance in air is 137 4 + 54 6 = 192 inches, or 16 feet, and its image would be 137 4 — 34 2 + 54 6 = 157 8 inches, or 13 15 feet distant in water

The theoretically expected reduction in target size underwater can be computed as before Let CF = x, AB + BE = y and DC = y — x, then $\frac{y}{AN} = \frac{y - x}{DN}$.

Since AN = 16 ft and DN = 13 15 ft, then by substitution, $\frac{y}{16} = \frac{y - x}{13\ 15}$, 16 x = 2 85y, x = 0 18y The linear dimension of the target ABE, as seen in air, may be reduced by an amount equal to the segment BE, or 18%, for equal angular subtense in water The scatter-plot (fig 5) shows that most experimental values were reasonably close to those theoretically predicted, except for two tests, when resolution underwater substantially exceeded the predicted

CONCLUSIONS: Given clear water and good illumination, visual resolution of the image of an underwater object, as seen through a SCUBA mask, is better than if the object was observed in air at the same physical distance and with the same apparent illumination However, the improvement is, on average, less than would be predicted on the basis of image magnification

Underwater vision would be significantly improved if fogging of the SCUBA mask face plate could be eliminated

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13 ABSTRACT

Visual resolution in air and underwater were compared using Landolt Ring targets and a self-luminous, water- and pressure-proof target mount. SCUBA diving masks were worn during the tests, both in water and in air. Comparisons were also made while viewing above and below surface targets through a periscope from a surface position. In both instances, visual resolution in clear water was better than in air at the same actual target distance, when apparent luminances were equated for the two conditions. In most cases, the improvement while wearing the SCUBA mask fell below predictions based on the magnification of the target image underwater. The reasons for this were ascribed to fogging of the mask underwater, and the lack of sufficiently small targets for some observers. The difference in resolution between air and underwater viewing through the periscope was nearer to that predicted by theoretical computations.

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Underwater vision in divers						
Visual resolution of targets in air and underwater						

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