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An underwater vision compendium for the optometrist

Abstract

A comprehensive compendium was assembled to aid the optometrist in understanding vision underwater and the unique visual needs of the SCUBA diver. Most every aspect of vision is altered underwater and a description of perceptual, optical, and physiological alterations is provided in the text. Partial adaptation to visual distortions gradually occurs as a function of time underwater, but adaptation can be accelerated with selected eye-hand activities. Methods of restoring the air-cornea interface are evaluated, and although the dive mask results in compromised visual function, it is still the most practical and cost effective means of restoring the refractive power of the eye. Based on personal experience and previous research, the authors suggest priorities for the novice diver selecting a dive mask. The ametropic diver is faced with choosing from four popularly available methods in selecting an underwater correction. Advantages and limitations of each method are cited. Lens bonded to the dive mask is the most versatile system but ultimate choice is dependent upon the diver's specific, individual needs. In an appendix the authors explore a theoretical lens system that compensates for magnification created by the air-water interface of the facemask.

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An Underwater Vision Compendium
for the Optometrist

Senior Research Project
Pacific University College of Optometry
March 1984

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TABLE OF CONTENTS

	Page
I. Introduction	1
II. Underwater Visual Perceptions.	2
A. Transmission	3
B. Magnification	6
C. Rippling, Shimmering, and Distortions	7
D. Visual Acuity	9
E. Visual Fields	9
F. Stereoacuity	10
G. Color.	12
H. Position Constancy	16
I. Size-Distance Estimation	16
J. Adaptation	19
III. Physiology	20
IV. Reestablishing the air-corneal interface	22
V. Facemasks	25
VI. Correction of Ametropia	33
A. Pre-Ground Faceplates	34
B. Suspended Specs	36
C. Bonded Lenses	38
D. Contact Lenses	40
Apendicies	
A. Distortions	
B. Color Discrimination Underwater	
C. Examples of Facemask and SCAWL lens	
D. Visual Fields through various facemasks	
E. Compensation Lens	
F. Available corrective eyewear for the diver	

ABSTRACT

A comprehensive compendium was assembled to aid the optometrist in understanding vision underwater and the unique visual needs of the SCUBA diver. Most every aspect of vision is altered underwater and a description of perceptual, optical, and physiological alterations is provided in the text. Partial adaptation to visual distortions gradually occurs as a function of time underwater, but adaptation can be accelerated with selected eye-hand activities. Methods of restoring the air-cornea interface are evaluated, and although the dive mask results in compromised visual function, it is still the most practical and cost effective means of restoring the refractive power of the eye. Based on personal experience and previous research, the authors suggest priorities for the novice diver selecting a dive mask.

The ametropic diver is faced with choosing from four popularly available methods in selecting an underwater correction. Advantages and limitations of each method are cited. Lens bonded to the dive mask is the most versatile system but ultimate choice is dependent upon the diver's specific, individual needs. In an appendix the authors explore a theoretical lens system that compensates for magnification created by the air-water interface of the facemask.

I. INTRODUCTION

A 1970 census found six million certified scuba divers in the United States. This represents nearly 3% of the population and does not include mask and snorkel skin divers, nor non-certified scuba divers.* The Northwest, with its abundance of good diving waters, has a large number of divers whose visual needs provide a challenge and opportunity for the local optometrist.

We obtain approximately 80% of our environmental information through vision, and the underwater environment profoundly alters most every aspect of vision.⁴² To the novice diver, the underwater world is a bewildering visual experience. Perceptual size, distance, color, position constancy, and visual field are uniquely different than in the normal air environment. To safely explore, enjoy, and work in the water world, the diver must see clearly and efficiently.

To best serve the diver, the optometrist must be aware of the unique demands of the underwater milieu and the individual's specific visual requirements. In addition, the optometrist must have available a complete catalog of underwater visual appliances and be knowledgeable of specific advantages and limitations of each device so that the diver will be best served.

An optometrist serving the diving population can reach out and provide a valuable educational link between the diver and his altered perceptual world. With his training in optics

* PADI (Professional Association of Diver Instructors, 1970.)

and human visual perception, the optometrist is the professional best suited for counseling the novice diver in adaptation to the perceptually distorted undersea world. The objective of this report is to serve as a compendium for the practicing optometrist. This report will summarize underwater changes of physical stimuli and alterations of visual perception; review appliances for the correction of ametropia and consider specific advantages and disadvantages of each. We will conclude with a special topic exploring the design of a theoretical lens for correcting induced magnification.

II. UNDERWATER VISUAL PERCEPTIONS

Under certain working conditions a professional or commercial diver must perform tasks in very turbid waters where visibility can be extremely limited. Experiments have been made to train blind or blindfolded divers in an attempt to avoid the feeling of disorientation and claustrophobia usually associated with the inability to see.²

Although such experiments have proved successful the majority of divers will not wish to function without vision, and in fact will depend on vision to obtain most of his/her information from the underwater environment. Any alteration in visual input, caused by the underwater environment will be of great interest to the diver.

Before analyzing individual aspects of visual alterations in the underwater environment, it is advantageous to examine visual perception as a whole. Internal assumptive world, probabilistic functionalism, and size-distance invariance, are terms which are used to explain visual perception. In essence, retinal image is not the sole input used in perception. Perception is a process by which the retinal image is compared with current sensory input and past experience. From this comparison, the most probable hypothesis is then selected to form the visual perception.

With this explanation of visual perception in mind, it becomes apparent how the underwater environment may drastically alter visual perception. When viewing an underwater environment, the past experiences of the air environment are no longer valid and this can lead to perceptual illusions or inappropriate judgments in the underwater environment.

Specific aspects of underwater vision can now be examined with respect to actual changes in physical stimuli and how these altered stimuli will, in turn, alter visual perception.

A. Transmission

Visual stimuli of the underwater environment are affected by transmission of light. Water transmits much less radiant energy than does air. The formula for transmission is the same for water and air:

$$P = P_0 e^{-\alpha d}$$

P represents radiant power reaching a point after extinction, P_0

is the power at the initial point, e is the natural log base, d is the distance, and α is the attenuation coefficient. For water, α is 1000 times or more greater than it is in air. The result of this formula applied to increasing water depth means exponential attenuation of light energy. If 90% of the incident energy is transmitted through the initial meter of water, only 81% remains after two meters, and by ten meters only 37% is left.³¹ The extinction of light energy as it passes downward is due to absorption of energy by water molecules and scattering by particles suspended in the water. In clear coastal ocean waters, photopic vision is limited to depths of approximately 150 feet, although the range may be greater in clear open ocean waters.³¹ In most rivers and harbors photopic vision is limited to depth of 10 feet or less.²

The practical implication for divers planning a deep dive during daylight is that dark adaptation should be carried out at least one hour before the dive with very dark sunglasses of transmission less than 5%* or spectral filtration lenses such as Dow Corning CPF 550's** which do not transmit wavelengths shorter than 550 nm.

Light transmission is dependent upon the individual characteristics of the water. Increased turbidity results in decreased

*Personal Communication with Dr. R. Yolton (Pacific University).

**Corning Medical Optics literature. Corning Glass Works, Corning, NY, 1983.

transmission and decreased contrast, resulting in objects having blurred outlines.³¹ Changes in tide increase bottom turbidity, whereas wind and rain increase turbidity near the surface. Diatoms and other marine life decrease visibility near the surface mostly during the spring season and are least abundant in the fall.¹⁵

The primary effect of decreased transmission is a decreased contrast between an object of regard and its environment. Although increasing illumination through the use of artificial lighting may seem to be an immediate solution to this decrease in contrast, one must recall that illuminating a turbid underwater environment will be similar to the well known back scattering effect experienced when turning on high beams when driving in a dense fog.

Polarizing filters have been used in the face plate to increase contrast ratios through reduction of polarized light scattered from particles in the water. A 15% increase in target detection was noted but polarizing filters are not currently available in diving masks.¹⁹

Secondary effects of decreased transmittance can also be noted with respect to visual perception. Contrast is used as a monocular cue in depth perception. The term for this is aerial perspective. Objects at greater distances have less contrast than objects at closer distances and this information is used in judging or perceiving distance. It follows that decreased contrast in the underwater environment should lead to over-estimation of object distance.²⁰ Actually, distance estimation underwater is affected by more profound changes in stimuli which

generally leads to an underestimation of distance. This will be discussed in conjunction with size-distance estimation.

B. Magnification

Since the refractive indices of water (1.333) and the cornea (1.376) are similar, much of the refracting power of the cornea is lost in the underwater environment. The discussions which follow refer to a system where the air-cornea interface has been restored by use of a face mask.

Magnification is a well known phenomenon with divers. Unfortunately the explanation for this magnification is not consistent in the current literature. Estimates for induced magnification vary from 25% to 33%.^{20,53,54,57} Factors cited which influence magnification always include refraction at the water-air boundary. Some sources also cite the glass plate and thickness of the glass plate.² Other sources cite decreased optical path length⁴² and others still, cite vertex distance as influencing factors.³¹

The most common error the authors have found in the literature consists of using optical path length as a method of calculating magnification. The equation for optical path length is $(f') = 1/n \times f$ where (f') equals the apparent distance of the object from the observer, f equals the actual distance of the object from the observer and n equals the index of refraction of the medium (water in this case, 1.33). The reduced optical path length, or reduced apparent distance, of an object in water

is thus three-fourths the distance in air. Actually this equation is correct and an object will appear 25% closer when viewed through the water but this does not equal a 25% magnification.

Magnification calculations should not be based on distance, but on angular subtense on the retina. The formula for this calculation is: $M = \tan \theta_1 / \tan \theta$ where M is the magnification, $\tan \theta_1$ is the tangent of the apparent angle, and $\tan \theta$ is the tangent of the true angle. For angles less than 20° the tangent function is considered linear and the equation can be reduced to $M = \theta_1 / \theta$. Use of this formula when calculating magnification for objects subtending more than 20° leads to calculated values of magnification which are lower than the true magnification. Use of the original formula yields a true value of 33% magnification.

Inclusion of the vertex distance in magnification calculations is valid and will change the magnification but the change is negligible for the diver.* For all practical purposes, the magnification created by the air-water interface will be 33%.

C. Rippling, Shimmering, and Distortions

Refraction of light causes obvious, as well as, unusual effects for the diver. When sunlight strikes a surface of water,

*The authors calculated less than 2% difference in magnification between reasonable extremes of vertex distance. Equation - magnification = $\frac{o + h}{i + h}$ where o is the distance from the object to the faceplate, i is the distance from the image to the faceplate and h is the vertex distance.

some light is reflected from the surface and the remaining light is transmitted into the water. The amount of light reflected depends on the angle of the sun and the condition of the water surface. Wave contours act as lenses and focus light, thus causing the well known rippling effect commonly seen on pool bottoms.⁵⁴

A less well known effect caused by the refraction of light at the air-water interface is the apparent shift in position of an object viewed across the air-water interface. For the diver, this shift can be seen with the sun which will appear to be higher in the sky than its true position.⁵⁴

The critical angle of refraction also produces a visual phenomenon unique to the diver. To the diver, the horizon appears at an angle of 48.6 degrees from vertical. Thus, the diver looks up at the surface of the water, this critical angle limitation causes the appearance of an illuminated circle.⁵⁴ (See Appendix A).

Refraction at the faceplate causes pin-cushion distortion (see Appendix A). This is most noticeable with straight lines. The underwater environment does not usually contain straight lines and so this distortion does not present a problem to the diver. Experiments in adaptation (Ross 1969) show a 25% adaptation to this distortion.⁴¹

Shimmering is an unusual phenomenon which has been explored by Dill (1956). He has found that differential refraction due to temperature gradients of greater than 3° F. in less than 5

feet, can cause water masses with sharp thermal boundaries to exhibit a shimmering phenomenon similar to heat waves seen when hot air rises from heated pavement.⁹

D. Visual Acuity

Visual acuity is said to increase under water due to magnification. Actually, visual acuity does not improve, but the retinal image angular subtense of an object increases when viewed underwater through an air space.⁵³ When equal subtended angles are considered, visual acuity is actually decreased underwater.¹⁸ This can be attributed to attenuation of light. Since turbidity can greatly reduce light transmission, visual acuity can be greatly affected by local water conditions.

E. Visual Fields

The most important visual alteration imposed by diving is the reduction of the visual field. This annoying and troublesome problem associated with the use of the diving mask has not been solved. Terrestrially the normal visual field encompasses 200° in the horizontal meridian, and 130° in the vertical meridian.⁵³ In diving, the visual field is restricted by two components: the blinder effect of the mask housing, and the critical angle of reflection of light rays impinging upon the faceplate-water boundary. The blinder effect is dependent upon the individual design of mask housing, and varies greatly as there are a great number of mask designs and manufacturers.

The critical angle of reflection is dependent upon the change of index from water to glass, but practically speaking, all rays striking the faceplate at angles greater than 48.5° do not pass through, and are totally reflected. It follows that the maximum field possible is 97° in any meridian.⁵³ Attempts at utilizing curved faceplates or side ports have resulted in annoying peripheral aberrations or large image jumps in the periphery.³⁶

F. Stereoacuity

Stereoacuity is decreased underwater by a factor of two to three times.⁴⁰ This reduction in stereoacuity was found to be greater as clarity of the water decreased. Since loss of contrast occurs with decreased water clarity, decreased stereoacuity was attributed to loss of contrast.³² Measurements of stereoacuity in clear water, with little loss of contrast, showed stereoacuity to be about three times poorer than in air. This indication that loss of contrast could not completely account for the reduced stereoacuity, led to further theories and experiments.

One theory is that the underwater scene approaches a visual ganzfeld; an unstructured, homogeneous field of view. Since a ganzfeld is known to degrade visual processes, the reduction in stereoacuity is attributed to the effect of the ganzfeld type stimuli.^{30,50}

Based on the assumption that the ganzfeld effect is similar to loss of peripheral stimuli, stereoacuity was measured with various fields of view, and was found to decrease with decreased field of view.²⁵ Theoretically this supports the ganzfeld theory, but empirically the conclusion can only be that a reduction in visual fields leads to reduced stereoacuity. As stated previously, reduction in visual field is a problem inherent in diving.

In another theory for decreased stereoacuity, decreased duccion ranges were cited as the underlying mechanism by which decreased peripheral stimuli affected stereoacuity. Experiments showed that introduction of peripheral cues did restore duccion ranges, but did not restore stereoacuity.²⁶

The final theory cites increased accommodation as the cause of decreased stereoacuity. Experiments have supported this theory. Accommodation in the underwater environment is increased because objects appear to be 25% closer than their actual distance.³⁰ A face mask with a compensating lens which corrects for this apparent decreased object distance may, therefore, improve the diver's stereoacuity.

Accommodation is also increased due to decreased contrast with increased distance. Nearby objects will appear much clearer than distant objects, thus causing over-accommodation for the object of regard. The face mask itself, acting as an aperture, may cause over-accommodation as the eye tries to accommodate for both the object and the aperture.³⁰

G. Color

Underwater color alteration is a function of physical and perceptual components. Underwater colors vary with depth, illumination, specific transmission of the waterbody, and color of the object. Spectral absorption with increasing water depth varies with the type of water body and is not uniform with respect to wavelength.³¹ Luria found that extremely clear fresh water such as Morrison Springs, Florida, has a transmittance of up to 90% for 480 nanometer light (greenish-blue), whereas clear ocean waters of the Gulf of Mexico and Caribbean have less transmittance of blue and violet, possibly due to absorption by plankton. Coastal waters of Long Island Sound show overall spectral attenuation with the greatest losses occurring in blue-greens and blues. Highly turbid waters such as Connecticut's Thames River transmit very little light with the majority of that being in the longer wavelengths above green.³¹

As the sun angles lower in the horizon, more light is reflected instead of refracted and illumination levels decrease very rapidly underwater. As illumination levels approach mesopic levels, the spectral sensitivity of the diver shifts to the shorter wavelengths. This purkinje shift results in perceptual brightening of blues compared to the reds. The reverse phenomenon occurs when scotopic vision shifts to photopic.

Luria investigated the perceptual visibility of colors underwater in four different bodies of water, using fluorescent painted targets and nonfluorescent painted targets of the same color.³¹ In the murky waters of the Thames River, red, orange,

and yellow, respectively, were the most visible colors in natural light, with little difference between fluorescent and nonfluorescent targets. With increased water clarity in Long Island Sound and the Gulf of Mexico, green, yellow, and orange were most visible, with fluorescent targets clearly superior to nonfluorescent targets. In the crystal clear fresh waters of Morrison Springs green was the most visible color. Blue, which had been the least visible color in the other three waters, was the next most visible color after green. Red, which had been the most visible color in the Thames River, was invisible in Morrison Springs water.

The tests were repeated using artificial illumination provided by mercury (largely short wavelength), and tungsten (largely long wavelength) lights. With mercury lights, fluorescent yellow-green was most easily detected. Under tungsten lighting, yellows and oranges were best discerned with little difference between fluorescent and nonfluorescent targets.

Fluorescent paints introduce an interesting interaction: by converting short wavelength visible energy (to which the eye is relatively insensitive) into longer wavelength light, this quantity is added to the reflected light, thus increasing the brightness and contrast of the target. In clear water fluorescent paints can reflect over 100% of the incident visible light.⁵⁸ The short wavelength, exciting energy for fluorescent paints is well transmitted in clear water, rendering brilliant, longer wavelength fluorescent oranges that are poorly transmitted in clear water over distance. The result is fluorescent orange

targets are easily seen at short distance, but visibility rapidly decreases with increasing distance. In turbid waters there is practically no advantage in using fluorescent targets, as there is little available short wavelength energy, and it is poorly transmitted. Fluorescent paints also offer no real visibility improvement over nonfluorescent paints when used in clear water with artificial tungsten lighting because the illumination source lacks the proper amount of short wavelength, exciting energy.

From this research optometrists can offer valuable counseling to the diver concerned with maximum underwater visibility of diving tools, accessories, and paraphernalia. Fluorescent greens, and yellow-greens are the colors most visible in coastal ocean waters under natural lighting and with mercury-based diving lights. Ordinary yellow would be the recommended color for adequate target visibility in conditions of darkness with tungsten diving lights. The commercial diver whose activities involve a wide variety of turbidity conditions should paint his tools a combination of red and fluorescent yellows. (See Appendix B)

Yellow filters have been purported to improve the diver's visibility by enhancing contrast.²⁷ These facemask bondable yellow filters have been advertised in diving periodicals as being able to "cut through haze." Luria investigated underwater resolution thresholds of blue and yellow targets against blue, green, and yellow backgrounds through yellow and blue filters. He found lowered increment and resolution thresholds for long wavelength targets on short wavelength backgrounds.

The efficacy of yellow lenses was reduced when: background wavelength was increased, target size was decreased, with increased age (increased crystalline lens yellowing), and when overall luminance was reduced.

The practical recommendation for the diver is that yellow lenses will benefit the young diver in slightly turbid water who is working with yellow targets.

J.H. Sivak (1979) makes the observation that the axial chromatic aberration of the eye and the filter effect of water, should be considered when studying underwater vision.⁴⁵ (Water acts as a monochromator of blue light.) Sivak cites research indicating that chromatic aberration is used by the eye as a form of inactive accommodation; the red end of the spectrum is in focus when the eye is not accommodating and as the target distance is decreased the wavelength in focus shifts to the blue end of the spectrum.

In studies of fish eyes, 4 diopters of hyperopia was measured when using conventional retinoscopy, emmetropia was measured when using green light, and 2 diopters of myopia was measured when using blue light. Sivak concluded that in the human eye, a conventional refraction may yield a value which is up to 1 D less myopic than the refractive error present in the blue, underwater environment.

It can be noted that regardless of change in refractive error, disturbance of the accommodative system, due to the loss of the red focus, may alter the diver's perception of size or distance by altering accommodative feedback information.

Studies by Kinney et al (1967) showed an adaptation process associated with exposure to a monochromatic environment. Divers adapting to a blue-green environment experienced a shift in all colors perceived. Adapted divers saw yellow-reds when no such stimulus was actually present, and blue-green objects appeared whitish.²¹

H. Position Constancy

Ferris (1972) addressed the loss of position constancy which occurs underwater. Constancy of visual position refers to the fact that objects do not appear to move when the observer moves. When head movement and retinal image movement correspond, position constancy is maintained and the object of regard does not appear to move. The change in retinal image size which the diver experiences has been shown to upset the correspondence between head and retinal image movements. Thus, the visual and proprioceptive inputs underwater do not match, which results in loss of position constancy, creating a perception of object movement when the head is turned.¹³

I. Size-Distance Estimation

One of the most obvious changes in perception which the diver experiences is that of size and distance. Not only is visual information changed by such things as magnification and decreased transmission, but other sensory input usually used to judge distance and size is also altered.⁴⁰

Experiments in distance estimation error have found an underestimation of distance at near ranges, and an overestimation of distance at far ranges. The crossover point between underestimation and overestimation has been reported as 12 m (39 ft),² 1 m (3.28 ft),¹⁸ and 1.5 to 3.5 m (5 - 12 ft).²⁹

Kinney et. al. determined that the crossover point in estimation is effected by the turbidity of the water.⁵³ Turbidity decreases the contrast of an object. As Ross (1968) explains, decreased contrast makes an object appear further away due to aerial perspective effects.⁴⁰ In perception experiments (Ittelson & Kilpatrick, 1951) it was demonstrated that varying relative brightness or contrast of objects resulted in the perception of a change in physical distance. Decreasing brightness caused a perception of increased distance. Varying relative size of objects also resulted in the perception of a change in physical distance. Decreasing size led to the perception of increased distance.¹⁷

Luria and Kinney (1970) determined that the general lack of visual stimulation underwater, functions as does decreased contrast in causing an overestimation of distance.⁵³ In studying stereoacuity, Luria and Kinney found that increased stimulus to accommodation in the underwater environment affected stereoacuity. Proprioceptive feedback from the accommodative-convergence system may function in the underestimation of distance at close ranges. This feedback information would be less important or

exert less of an effect as object distance increased to ranges requiring little accommodation or convergence. This shift may also be a factor in the shift from over to under-estimation with increased distance.

Emmert's Law states that with a given constant retinal image, apparent size is proportional to perceived object distance. The perceiver takes both retinal image size and distance into account when determining the size of an object. Thus a small retinal image from an object located at a great distance will be perceived as large where as a large retinal image from an object located close to the eye will be perceived as small. In this way, objects subtending varying angles of subtense on the retina, can be judged as constant in size based on the perceived distance. Because of this size constancy, objects should appear the correct size if the diver perceives them to be at their optical distance, or objects should appear enlarged if the diver perceives them at further distances.³⁹

As previously stated, at short distances, both an over-estimation of size and under-estimation of distance is made. It should follow that as the crossover point in distance estimation is reached, size estimation should approach true size. This theory is not supported by psychophysical tests done by Luria et. al., where over-estimation of size was found to be about 18% with slightly less over-estimation at 3 meters than at 0.3 meters.²⁸ Although the perceived magnification did statistically decrease at the greater distance, the perceived size did not approach the true size. In fact, the data was skewed

by one set of estimations without which an increased magnification was perceived at distance.

J. Adaptation

Adaptation to underwater distortions has been studied by many researchers. Adaptation does occur and the process has been shown to be enhanced when tasks requiring hand-eye coordination and attention, are performed.²⁰

Experienced divers show greater adaptation than novice divers. As Ross (1969) explains, the diver learns a new set of perceptual responses or develops a new assumptive world which is referred to only when underwater.⁴¹

Luria (1970) states that both short-term and long-term adaptation occurs. An adaptation of 18% was found when the diver merely entered the water and took tests.²² This is more accurately explained by perception. Actually, this so called short-term adaptation can be more simply explained as the initial perceptual interpretation of underwater distortions.

Long-term adaptation actually does occur after the diver has spent much time underwater. Using educational and developmental theories, Luria tested the effectiveness of various activities on long-term adaptation. Although size estimation does not seem to be affected by adaptation, visual-motor skills can be improved with adaptation. The most effective method of increasing adaptation was the use of games (crossword puzzles and checkers) played for five minute intervals spaced by out-of-water activities.²²

Decreasing adaptation time was also attempted by exposing the diver to magnifying lenses prior to their entering the water. No improvement in the amount of adaptation was found.³⁵

III. PHYSIOLOGY

Physiological effects of diving are primarily due to the fact that barometric pressures vary greatly with the depth of water. Thirty-three feet of fresh water exerts the same pressure as all the atmosphere above the earth's surface (760 mm Hg).¹⁶ Thus, relatively short descents or ascents can cause gaseous volume changes which can be fatal to the diver. As an example of the drastic volume change, one liter of gas at a depth of 300 feet would expand to 10 liters at sea level.

Serious complications of increased partial pressures occur upon ascent. When a diver remains at a particular depth for an extended period, nitrogen diffuses throughout the intra- and extracellular tissues and equilibrates at a higher pressure. When the diver ascends, the pressure on the outside of the body will lessen and the dissolved gases can escape from the solution and form bubbles inside the tissues.¹⁶ Several terms are used for the resulting condition; decompression sickness, compressed air sickness, bends, Caisson Disease, diver's paralysis, and dysbarism are all terms for the same condition. Although no specific visual conditions are associated with decompression sickness, it must be included in any discussion of diving because of its severity and relevance to the diver.

When breathing compressed air, the nitrogen produces an intoxicating effect similar to that of alcohol, anesthetic gases, or narcotic drugs. This effect increases rapidly beyond 100 feet making 300 feet the limit for breathing standard compressed air.⁵⁵

Although the intoxicating mechanism of nitrogen is not known, it is known that the effect of intoxicating gases is increased with increased partial pressure and increased solubility in lipids. Helium is relatively insoluble in lipids and produces little narcotic effect in the compressed air environment. Helium-oxygen mixtures can be used which increases useful diving limit to 600 feet.^{16,55}

Bennet (1969) believes that nitrogen and inert gas narcosis are due to the absorption of the narcotic agent on cell membranes which in turn effects their permeability to cations and produces a reversible ion imbalance. Bennet also suggests that oxygen may act in a similar manner until enzyme functions are inhibited, resulting in convulsions.⁵

When breathing compressed oxygen at 3 atm for 4 hours, progressive contraction of the visual fields occurs with dilation of the pupils and some impairment in central vision.⁴

Oxygen toxicity caused by breathing oxygen at high partial pressures can lead to convulsive seizures and coma. Six percent of divers experiencing oxygen toxicity have disturbances of vision.⁵⁵ Such oxygen poisoning is not a threat when breathing compressed air because nitrogen narcosis and decompression become limiting factors. Oxygen poisoning can be a problem when nitrogen-

oxygen or helium-oxygen mixtures are used.⁵⁵

In studies on the effects of breathing compressed air, manual dexterity was found to be affected at 4 atm and arithmetic calculation ability was affected at 7 atm. At 13 atm changes in mood, impairment of consciousness, disturbance of perception and deterioration of motor functions were found to occur.¹

IV. REESTABLISHING THE AIR-CORNEA INTERFACE

In air approximately 75% of the eye's refractive power is due to the air-cornea interface. In water the difference in index of refraction at the water-cornea interface becomes negligible (1.333 vs 1.376), and thus much of the cornea's refracting power is lost, creating a hyperopic system. Cramer measured the naked eye underwater as 42 diopters hyperopic yielding an acuity of 20/4000.⁸

Duane found that placement of a +64.5 diopter lens in front of the submerged eye restored visual acuity to 20/20.⁵³ Use of such a lens underwater is not practical for the diver because it does not protect the eye in the water environment and it reduces the visual field to 20° binocularly. A better solution for restoring vision underwater is to place an air space between the cornea and the water. This can be accomplished in several ways.

Swim type goggles can be used to restore the air space in front of the cornea. Their use was documented as early as 1331, where transparent turtle shells were used by Arab divers

in the Persian Gulf.⁵⁷ While modern swim goggles are currently popular for swimming and water skiing,³ their use in diving is limited due to their restricted fields (60°) and the inability to equalize pressure under the goggles to prevent "squeeze".

Helmets are also used to create an air-cornea interface for the diver. Helmets are attached to water-tight dry suits, and thus the entire body is surrounded by air and the diver views his environment through portholes in his helmet.

The most interesting method of restoring normal refraction underwater is with the air-cell contact lens. This swimmer's contact air-water lens (SCAWL or SCAL), consists of a haptic lens with an air-separated double wall in front of the cornea. Thus the SCAWL functions like a tiny facemask before the eye. Objects appear at three-quarters their real distance and are similarly magnified as through a conventional facemask. SCAWL's were developed in the 1950's and have been extensively tested and modified by the British, American and French navies for use by military divers. SCAWL's are easily modified to correct ametropia, provide good acuity both in air and underwater, and are not easily dislodged from the eye. They provide an extensive underwater binocular lateral field of about 157°,¹² and problems with fogging and pressure equilization are eliminated. (See Appendix C).

Although the French version was reported to be successful,¹⁰ the SCAWL has not gained widespread acceptance due to its many disadvantages. The enclosed air chamber buoyancy creates problems

of centration and rotation because the lenses tend to ride high on the eye. The large outward protrusion of the air-cell lens creates problems of comfort and restricts upper lid movement. Peripheral distortions have been reduced in some designs by opaque side supports but this reduces peripheral fields. As with any scleral lens, wearing time is limited due to cornea edema and halation which can appear within 15 minutes after insertion.¹² The scleral portions of the French design are vented and longer wearing times are possible.¹⁰ The most serious limitation is the marked conjunctival irritation that occurs in sea water. Use of high viscosity lens solutions have delayed the onset but not the severity of the irritation.¹² Because SCAWL's must be custom manufactured and individual measurement and adjustment are necessary the cost is high. The 1980 cost was between \$500 and \$1000 per pair.²³

Douthwaite attempted to overcome these difficulties by designing a non air-cell lens which incorporated a flint glass button fused to a plastic haptic lens.¹⁰ This lens was reported to provide a wider view, greater comfort and did not give rise to magnification and distortion encountered with the SCAWL. Slight displacement of this lens caused a loss of vision underwater and the out-of-focus image formed by the peripheral portion in air, resulted in haze, reduced contrast, and decreased visual acuity.

V. FACEMASKS

For the SCUBA diver the facemask is the most practical and cost effective method of restoring the air-cornea refractive interface. Although facemasks have many limitations and are a compromise to peripheral vision, binocular vision, distortion, buoyancy, comfort etc., they will continue to be the optical appliance of choice with SCUBA divers in the foreseeable future.

To a diver, the most personal piece of equipment is the scuba mask. The diver has the bewildering task of choosing among the myriad of commercially available dive masks. Contributing to the wide variety of masks is the almost unlimited variety of facial geometry. No one design is superior for every circumstance. Although most divers and shop owners are aware that proper fit is the single most important consideration in mask selection, few are knowledgeable in comparative optical performance between the designs. In fact, these authors found only two studies in the literature comparing visual performance through different mask designs.

Scuba mask features such as size, weight, viewing area, number of windows, vertex distance, pantoscopic tilt, construction, material used, and design, all combine to yield a wide variety of masks. For comparison it is useful to group popularly available masks into six categories on the basis of design, albeit some masks can not neatly be categorized. The basic categories are: oval or standard, kidney, recessed kidney, bioptic recessed

kidney*, wide field, and goggle type masks (See Appendix C.)

Luria evaluated four of these designs** by testing both optical quality in air, and underwater human visual performance with them.²⁸ In addition, Luria included a unique compensation mask*** in the comparison. This was an ovular mask possessing a special optical system to compensate for underwater size and distance distortion.

In testing optical quality, visible transmittance was greatest through the oval and kidney masks, slightly less through the widefield and goggle, and substantially reduced through the compensating mask. Color transmittance was compared to three CIE illuminance C coordinates and all faceplates were judged neutral in color transmittance. Prismatic deviations were judged negligible as were spherical and cylindrical power errors in all the plano faceplates. On the AAO 60-line grating Optical Tester all faceplates were judged as having "satisfactory" distortion levels, although the oval and goggle facemasks were reported as having "moderate" distortion. All masks were found to have tempered faceplates based on colmascope and Polariscope results.

*Author's description

**Commercially available masks, manufacturer(s) and model not specified

***Design characteristics of the compensating lenses were not provided

Using a perimeter underwater, Luria measured the combined monocular visual fields of eight subjects in eight meridians. Each subject was tested with all five masks and the results were averaged for each mask in the horizontal and vertical meridians. The mean field in degrees is listed in Table 1.**

Table 1	<u>Mask</u>	<u>Vertical</u>	<u>Horizontal</u>
	Oval	86	86
	Kidney	70	90
	Widefield	84	87*
	Goggles	63	72
	Compensating	70	75

*plus two approximately 20 x 50° islands in the horizontal periphery, the result of the two widefield mask side windows

Using a different type of perimeter apparatus and testing method, Weltman, et. al. measured the separate monocular fields in twelve meridians of six subjects wearing oval, kidney, and recessed kidney masks.***⁵⁶ Table 2 lists the approximate means of the horizontal and vertical meridians for the three commercial mask designs.**** Also listed below are the visual fields of two subjects wearing two uncommon and non-commercially available masks, the full face and the wrap around.

Table 2	<u>Mask</u>	<u>Vertical</u>	<u>Horizontal</u>
	Oval	70	90
	Kidney	65	90
	Recessed kidney	80	90
	Full face	80	75
	Wrap around	70	180

**A diagram of the fields presented in Appendix D

***Commercially available masks 1965, manufacturer(s) and model not specified

****Measured and approximated from Weltmans diagrams by the authors

Of the commercially available mask designs tested by Luria and Weltman, nearly all had identical lateral fields of view. Exceptions to this were the goggles, which had more constricted lateral fields, and the Widefield mask, whose wide lateral fields were supplemented by additional seeing islands in the periphery. Much greater variation was measured in the vertical fields between the competing mask designs. Luria's oval mask gave the widest vertical view, followed by the widefield and Weltman's recessed kidney. The goggles again produced the narrowest view. Weltman's field maps differ from Luria's in that not only are more meridians charted, but all the fields are displaced upwards compared to Luria's measurements through the same mask designs. This may be an artifact of measurement procedure or apparatus, as the overall fields are similar in shape.

Interesting to note are the binocular fields in the oval, kidney, and recessed kidney masks measured by Weltman. The oval design produced the largest overlap of monocular fields. The crossover of the monocular fields occurred near the periphery resulting in a very high proportion of binocular field to total field with the oval mask. Although the recessed kidney mask had a larger total field than either the oval or kidney, its binocular field was the smallest.

The full facemask had a much larger window area than any other mask but the horizontal and vertical fields were not appreciably larger than other masks. The wrap around mask had, by a large margin, the widest lateral fields, approximating those measured in air without a mask in place. It was reported

that only 50 percent of the lateral vision in the wrap around mask was free of gross optical distortion. Diplopia and visual discomfort were reported very common with this mask.

In measuring visual acuity through the facemasks, Luria found no statistically significant differences in resolution between the widefield, kidney, oval or goggle masks. The mean visual acuity was significantly less with the compensating mask, presumably due to reduced transmittance through the lens system.

In the same study, median stereoacuity threshold, (as measured with a three rod Howard Dolman apparatus at 3 meters) was best with the widefield mask (5.6 arc. sec), and poorest with the goggle mask (9.9 arc. sec). These results were reported to have been "just short" of statistical significance.

Luria tested hand-eye coordination underwater with these same masks. While wearing a mask both underwater and in air the subject marked the perceived location of the underside of a target without visual feedback of hand location. With the exception of the compensating mask, every mask produced a shift of the perceived target location towards the subject when tested underwater. The oval, widefield, kidney and goggle masks produced displacements of the mark at 3.86 cm, 3.61 cm, 2.36 cm and 1.02 cm respectively. An analysis of variance revealed that the goggle mask yielded significantly less distortion than either the widefield or oval masks. The compensating mask was roughly equal in distortion to the goggles but the displacement was away from the subject.

In estimating distances from six-tenths of a meter to six meters, under-estimation was significantly greater with the kidney mask than with the others. Estimations were most accurate with the compensating mask followed by the goggles.

Size estimation was tested with the five masks at 30 cm and three meters both underwater and in air. Subjects selected disks corresponding to four coin sizes at the near distance and four balls at the far distance. At the near distance all four commercial masks yielded nearly identical over-estimation of size but at three meters, the goggles exhibited significantly less over-estimation than the widefield mask. At both distances the compensating mask produced the most accurate estimation of size. Additionally over-estimation was slightly greater with the commercial mask at 30 cm.

Luria's last test in this series measured the susceptibility of each mask to fogging underwater. Resistance to fogging was measured as the length of time a subject could resolve both a high and low contrast Landolt C. The widefield and oval masks were significantly superior in resistance to fogging with respective mean times of 74 and 57.6 seconds for the high contrast target and 51 and 50 seconds for the low contrast annulus. The goggle mask fogged to resolution threshold in approximately 40 seconds with both targets, and the kidney mask fogged to sub-threshold in 31 seconds with both targets.

Based on optical and visual performance findings, which type of mask should the diver choose? Based on Luria's work there is no overall superior all-purpose mask. Although there

were significant differences among the masks tested in various visual processes, good performance in one area was offset by poorer performance in another.

On the practical level, the diver must prioritize his needs in choosing a facemask. For example, proper fit may be more important than extensive lateral fields, or resistance to fogging may be more important than more accurate distance estimation. The diver should be cautioned against drawing hard-and-fast rules of visual performance between different mask designs based on Luria's previous research study. With the proliferation of many new hybrid mask designs and evolution in construction materials, these new masks may not have directly comparable performance to the masks Luria evaluated over 10 years ago. As an illustration, a contemporary mask of the same design as Luria tested may have a much different pantoscopic angle with respect to the diver's face. It may also have a different vertex distance and as a result might yield different distortion in hand-eye perceptual tasks, or it may have a changed susceptibility to fogging. The recent substitution of translucent silicone for black neoprene housings may yield a mask with more extensive fields and better stereoacuity.

Based on this author's more than 10 years of extensive scuba diving experience, a priority hierarchy will be suggested for mask selection. After rejecting masks that do not fit properly, the diver should choose the mask with the most extensive fields, especially the lateral. The diver's enjoyment and safety are

dependent upon his/her visual data gathering skills. Novice divers often complain of clausterphobia associated with their newly acquired "tunnel vision" underwater. For these reasons a clear silicone widefield mask would be the first choice. Although Weltman did not include a widefield mask in his binocular field measurements, the binocular fields of the widefield could be predicted to be as extensive as those of the oval mask due to the broad faceplate and absence of nasal obstructions. Inferior fields are important in mask selection. Most masks severely limit the inferior view. Loss of this visual field deprives the diver of visual feedback about his body position in the nearly weightless world. Lacking visual information from this natural gaze position, the diver must nod his/her head far forward to read the guages or see the sea bottom below.

After these criteria are considered, potential fogging should be evaluated. Luria postulated that the rate of fogging was dependent upon "(1) the volume of air space between the mask and the face, and (2) the distance of the faceplate from the eyes."²⁸ Neither variable could explain why the kidney mask fogged the most, even though both vertex distance and volume were next to best. It is this author's opinion that the first variable is not an adequate measure in predicting fogging. It is this author's experience that a mask with a desirable vertex distance may have such a pantoscopic tilt of the faceplate as to almost contact the cheeks and as a result, fog frequently. With the advent of new effective and non-toxic antifog substances this problem has been somewhat attenuated.

Choosing a mask with minimal size and distance distortions is not of great importance to the average diver. The compensating mask had the least distortion of size and distance information but this was traded for decreased transmittance, resolution, and stereoacuity. Furthermore the visual fields were constricted and gross peripheral distortions were present.* If the prospective diver wanted a mask that would minimally distort size and distance initially, the goggle mask should be chosen. Our visual perception of size and distance is altogether altered underwater. However, as was stated earlier in this report, perceptual adaptation to distortion occurs over time reducing their effect. The greater the diver's underwater experience the more he/she has developed "situation contingent responses" to the distortions underwater, and the less significant they become in time.⁴²

VI. CORRECTION OF AMETROPIA

Recreational diving is in large part a visual experience. Good underwater vision is important for the full enjoyment of aquatic exploration. The safety of the diver can also be dependent on how well he can see. Keen eyesight is essential in recognizing a buddy in trouble, identifying a shark at distance, or in distinguishing poisonous sealife from other non-toxic forms.

*Specific design features of the lens system were unavailable but a theoretical size compensating lens has been proposed by the authors in Appendix .

It has been estimated that seven out of ten persons have refractive error.⁴² Far fewer ametropic divers utilize correction when diving than when not diving. In a 1980 survey of 56 dive shops, Leech and Arnquist found that only 30 percent of the dive shops responding felt an underwater optical correction would benefit the diver who wore glasses on land.²³ Many divers feel that the underwater magnification compensates for their refractive error. The underwater environment lacks familiar angular contours and normal contrast and, as a result, the diver may attribute the decreased acuity in the unfamiliar environment solely to water conditions, rather than to uncorrected ametropia.

Clear vision is essential to the full enjoyment of diving. Thus the optometrist should encourage those individuals who depend upon full time correction to utilize correction underwater as well. The diver has many available options for refractive correction underwater, and the consulting optometrist should be familiar with the benefits and limitations of hydrogel contact lenses, pre-ground faceplates, mask bonded, and suspended corrections.

A. Pre-Ground Faceplates

Ready made masks with pre-ground faceplates are available from many different companies. These pre-ground faceplates are manufactured with an equal refractive correction ground into a single piece of glass or as separate lenses for two-window masks. Leech and Arnquist reported that 85 percent of dive

shops responding to their questionnaire sold pre-ground faceplate masks, and that 45 percent of the shops judged ready made masks to be the most popular type of diver correction.²³ The most important advantage of the ready made mask is that it is available immediately to the diver. The dive shop merchant can quickly insert the spherical corrective faceplate(s) chosen by the diver into the specific housing. The total cost of ready made mask and corrective lens(es) is less than purchasing a mask and having corrective lenses bonded to it.

Ready made mask correction is ideally suited only for a limited number of ametropic divers due to its limitations. It is not practical for astigmatism, hyperopia, presbyopia or in most cases, anisometropia. Only spherical minus corrections in one-half diopter increments are available. The maximum correction is either seven or ten diopters and the minimum is either one or two diopters depending upon the manufacturer. With a single faceplate identical powers for each eye are ground. With a two window mask, separate minus lenses can be used if the diver is willing to purchase two separate pairs of correcting faceplates. Interpupillary distance is fixed with either the single or double faceplate mask. These investigators measured a 62 mm separation from one manufacturer and 67 mm was reported by another. In choosing a ready made correcting mask the diver is limited to only a few different mask styles and types which may not be ideally suited to his individual needs or facial geometry. Of greatest concern is the method by which

a final correction is chosen. Most of the dive shops visited by these authors hand the diver a box of lenses with the instructions: "choose the one you see best with". The diver who is unfamiliar with optics has no way of knowing that he may be over-minusing himself by choosing a lens that yields a smaller, blacker, and more distinct image. Nor will it be apparent that prolonged use of this mask may result in eye strain from over-accommodation, diplopia from overtaxed fusional vergence, or in prismatic deviation if the interpupillary distance does not match the fixed separation of optical centers in the mask. In summary, the ready made correcting mask is suitable only for the pre-presbyopic relatively low spherical myope, with no anisometropia and whose PD and facial geometry matches those of the specific mask.

B. Suspended Specs

Many different methods have been devised to incorporate a spectacle correction within the dive mask. Standard spectacles cannot be used for two reasons. Most masks are not large enough to accommodate the standard frame and even if a proper sized frame and mask were used, the temples would not allow the mask to seal properly. Small frame fronts that clamped onto the nose, (oxford or pince-nez) were tried but proved unsatisfactory due to frequent dislodgement. Suction cups, adjustable stays, metal clips, and clear, pliable, silicone adhesives have all been used to mount corrective lenses and plastic frame fronts

to the inside of the faceplate. To date the most practical mounting system is the "scuba-spec".

With the "scuba-spec", a mount is glued to the center of a one window mask and a special nylon spectacle front (containing the habitual prescription) can be snapped in and out of the mount.²³ This method of correction has numerous benefits for the diver. The diver's habitual lens type is used so that bifocal or even trifocals can be used by the presbyopic diver. Because habitual corrected curve lens design is utilized along with proper pantoscopic angle, distortions and aberrations (especially peripheral) are much less than with plano front surface corrections.⁴² As a consequence, this system and hydrogel contact lens are the only alternatives for the hyperopic diver not wishing to deal with gross optical distortion.

In the past, fogging has been a troublesome problem with this design as there are three surfaces inside the mask to fog. To clear the fog from all three surfaces requires that nearly the entire mask volume must be flooded. Shedrow maintains that fogging is not a problem with the "scuba-spec" as long as an antifog cleaner developed by NASA* is used. The "scuba-spec" can only be used with one window masks and reportedly will not fit all one window masks.⁴²

*Reported to prevent fogging from +215° to -25° F. Available to the public but brand name not specified

C. Bonded Lenses

Perhaps the most versatile method of correcting refractive error is by bonding plano front surface lenses to the inside of the divemask faceplate. Myopia, astigmatism, presbyopia, anisometropia, and hyperopia can all be corrected. Edged and decentered lenses can be bonded to any facemask and can include all the parameters of the patient's habitual prescription with the exception of habitual base curve and pantoscopic angle.

Three main types of bonding agents: Canadian balsam, General Electric Sealent, and optically clear epoxy, have been used to fuse lenses to the faceplate. The latter is reported to bond and remain colorless indefinitely. Williamson disclosed that lenses bonded to tempered faceplates with clear epoxy can be removed for rebonding by heating them to 550° F.⁵⁷

For the presbyopic ametropes requiring clear vision to resolve gauges and near objects, blanks can be bonded which contain a high index bifocal fused to the front surface. For the emmetropic presbyope, plano plus blanks in the desired shape are bonded so that habitual bifocal height remains unchanged. A single button add is often sufficient for the presbyope who does not want bifocals. It is routinely bonded to the left inferior portion of the mask because the diver's gauge console is on the left hand side.

The main disadvantage with bonded lenses is increased optical aberration and visual distortion. Proper pantoscopic angle is not replicated, plus the entire lens power is derived

from single surface refraction at the rear of the lens. Gillilan* has stated that distortion is the reason why lenses greater than plus three are not customarily bonded. Very few divers have reported distortions with bonded lenses as troubling underwater.¹¹ It is possible that visual distortions are not as readily apparent when surrounded by an unfamiliar environment lacking straight lines and familiar contours.

Another disadvantage with bonded lenses is that it requires one to four weeks before the mask is bonded and returned. Cost of the bonded system is greater than the ready made if a new mask is purchased, and slightly less if the diver already owns a mask. Divers opting for the bonded lenses should provide a current prescription with PD, so that vertex distance and decentration can be incorporated by the bonding firm.

Although many practitioners specializing in the field feel the bonded lens system is the most practical for the majority of divers,^{3,11,38,57} a 1980 poll of dive shop owners revealed that only 25% of them thought bonded lenses were the most popular method of correction with divers.²³ Few if any of these shops bonded lenses themselves so it might be reasonable to assume that they might stress the type of correction (ready made) that yields them a greater profit margin. Here again, the optometrist can provide useful information to his diving patients.

*Personal communication with Dr. R. Gillilan (private practitioner Eugene, OR.)

D. Contact Lenses

The consulting eye care professional must deal with the question of whether or not to recommend the use of contact lenses for the ametropic diver. There is no unqualified answer for soft lenses but hard lenses should be avoided.

Bradley and Simon⁴³ investigated corneal physiological response to contact lenses in hyperbaric environments. Two subjects were examined while monocularly wearing (1) a rigid PMMA lens (2) a rigid PMMA lens with a 0.4 mm central fenestration and (3) B & L "Soflens". During decompression at 70 feet, (following 30 minutes at a simulated depth of 150 feet) bubbles formed underneath the non-fenestrated rigid lens. These nitrogen bubbles increased in number and later coalesced at subsequent decompression stops. After 30 minutes at sea level the out-gassing had ceased leaving central corneal nummular areas of epithelial edema. This phenomena was associated with subjective reports of corneal discomfort, halos, specular highlights and decreased visual acuity. The Soflens and the fenestrated lens did not produce this effect.

Interpalpebral hard lenses are held in place by the capillary dynamics of the pre-corneal tear film acting between the hard lens and the cornea. If the eye is opened underwater in a face-mask flooded with either freshwater or seawater, the hard lens can easily float off the cornea.⁴⁸

Lens displacement is much less a problem with hydrogel contact lenses.²⁴ An interesting interaction occurs with hydrogel lenses in a fresh water environment. When the eye is opened

in fresh water the lenses become hypotonic and increase their adherence to the cornea,²⁴ becoming more difficult to dislodge.⁴⁹ Many recent studies have noted the low rate of lens loss underwater when the eyes are open.^{48,24,47,50,14} Even lower rates of lens displacement occur if the lenses are primed with fresh-water by splashing^{49,50} or insertion of drops⁴⁸ for approximately one minute before entering the water. Stein⁴⁹ reported zero lens loss in 102 test periods where subjects swam laps and turned somersaults underwater with their eyes open. In a stimulated underwater environment each of five subjects submerged and performed vigorous eye movements and frequent blinking for 15 minutes. Not a single soft contact was lost when properly fitted lenses were worn.²⁴

Stein states that increased adherence is presumably due to osmotic bonding whereby the hypotonic lens forms a tight adhesion with the cornea by pulling fluid out of the epithelial cells.⁴⁹ This statement is not consistent with contemporary understanding of osmotic pressure dynamics. Solvent will move across a semi-permeable membrane to a region of lower solvent concentration.³⁴ In this case, water should move from the hypotonic lens to the cornea if all other factors are ignored. Clearly more research is needed to settle this issue. Solomon⁴⁷ feels the "sticking" may also be influenced by changes in lens parameter as well as tear film thickness changes and surface change. Maximal corneal adherence of the hypotonic lens is reached at 0.3% tonicity. Although OAD of HEMA changes little

over a wide tonicity range,³⁴ Roggenkamp & Peterson believe the increased adherence of the hypotonic lens is due to a steepened base curve.* Investigators suggest not removing the lenses until 30 minutes have elapsed since last exposure to freshwater, in order to prevent epithelial denuding. Lens equilibration can be hastened by installation of saline drops.⁴⁸

Ocean water has greater osmolarity than freshwater, therefore the lenses will not adhere as tightly and the probability of lens loss is greater.**⁴⁹ In contrast, Lovsund,²⁴ et. al. measured virtually identical adhesion between hydrogel lenses in freshwater and in saltwater. He instructed his subjects to immerse their heads underwater in various salt concentrations for 15 minutes while blinking and performing vigorous eye movements with the eye wide open. Out of five trials per lens with four different hydrogels, not a single lens was lost.

In a broader sense what are the limitations of soft contacts in scuba diving? Very few investigations have examined physiological response to contact lenses, and visual performance with them, in the actual underwater environment. Cotter examined the visual acuity, eye comfort, and anterior segment changes of 23 volunteer divers in order to define safe parameters of soft contact lens use in diving.⁶ Experimental group A consisted of five divers with no more than four hours previous experience

*Personal communication with Dr. J.R. Roggenkamp and J.E. Peterson (Pacific University)

**Water temperature may also be a factor by altering lens parameters

wearing soft contact lenses. After having a B & L polymacon lens inserted monocularly, subjects dove to 10 feet in the 2½° C. waters of Lake Superior for 40 minutes, and while at that depth the subjects removed their masks for 60 to 90 seconds while blinking. Group B was made up of 15 divers (3 to 5 weeks previous contact lens experience) wearing bilateral polymacon lenses, and three controls who wore no lenses. Subjects first dove to 90 feet and then to 30 feet, where they removed their masks and blinked for 60 to 90 seconds. The cumulative dive time was 35 to 40 minutes per subject. Three subjects from group B were further examined in a hyperbaric chamber while wearing a facemask and contact lens monocularly. The three were subjected to 145 feet of simulated depth for 25 minutes followed by standard decompression.

In group A, pre, post, and underwater acuity was unaffected by the contact lens. Group B experienced a post-dive mean acuity decrement of nearly one Snellen line whereas two of the three controls also suffered a decrease of one line. Later all subjects had normal acuity when tested one hour post-dive.

Post-dive slitlamp evaluation revealed no serious corneal changes in either test group A or B. One group A volunteer who lost her lens demonstrated minimal superficial punctate keratopathy in the eye from which the lens was lost. Ten percent of the eyes in the post-dive examination had slight limbal conjunctival injection. One hyperbaric chamber subject developed monocular scleral hyperemia and vessel dilation with mild limbal injection in the eye without the soft contact lens. Two of

the test group subjects had scars from previous traumatic injuries. Neither demonstrated any corneal changes as a result of testing. Follow-up examination three to five days after the experiment yielded 100% normal slit lamp results for all subjects. Subjectively 93% of the volunteers thought diving with the hydrogel lenses was better than without, including the subjects who experienced lens loss. The sole diver rating diving with the lens as worse, suffered decreased acuity throughout the dive from a superiorly dislocated lens. The most serious complication in the study was lens loss. Two of the five contact lenses in group A were lost when the masks were removed at 10 feet. Both subjects had only four hours of contact lens wearing experience and one was a newly qualified diver. Both group B subjects who lost a lens were experiencing difficulty with the diving protocol. One subject lost her lens because her mask was flooded and would not seal during the entire test, the other was hit in the face by a wave on the surface while not wearing a mask.

Cotter concluded that: "Ametroptic divers report better vision and normal eye comfort when diving with soft contacts in freshwater. Lens loss remained the most serious complication. Loss occurred only at or very near the surface with the face mask removed. Divers with the least diving or lens wearing experience proved most liable to lose a lens." He further speculated that minimal conjunctival injection noted on some divers may have been a pressure effect and was not due to temperature, water, or lens irritation.⁶

It has been suggested by many investigators that exposure of hydrogel lenses to underwater contaminants may result in the binding of the contaminants to the lens polymers triggering an allergic response.⁴⁷ For this reason many experts recommend that soft lenses not be worn in chlorinated pools.^{37,46} Chemical analysis of polymacon lenses has been carried by Basch & Lomb following several investigations in chlorinated pools.^{47,48,49} Although the chemical analysis was not carried out by an independent uninterested laboratory, no contamination, harmful substances or lens damage were reported. Swimmers have been reported to wear soft lenses for the singular purpose of preventing "chlorine burn". Less keratopathy, microcystic edema, and staining have been reported in the eyes covered by soft lenses.⁴⁸

Does hydrogel lens wear while diving increase the possibility of conjunctivitis? Warm water and even chlorinated pools periodically show low bacterial counts of fecal coli, staph, strep and pseudomonas.^{49,50} Presumably a small abrasion from a foreign body behind a contact lens might become infected. Not a single case of ocular infection was reported in the literature from contact lens use in the water, albeit the potential may be marginally greater. More research is needed.

Soft contact lenses offer many advantages in correcting the ametropia of the scuba diver. Manufacturers of the lenses recommend against swimming with the lens¹⁴ and one must infer this also applies to scuba diving. Contact lenses offer the diver the widest and most natural corrected field of view --

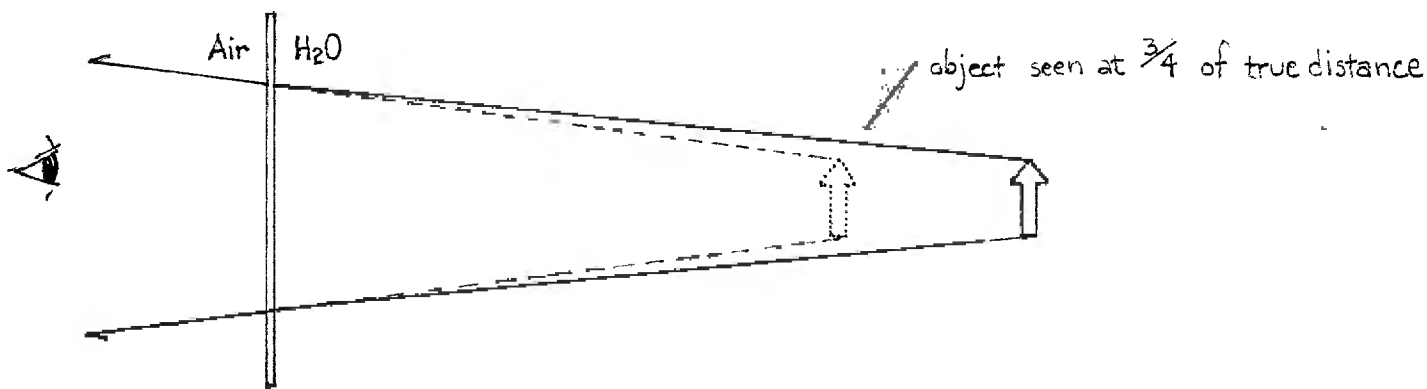
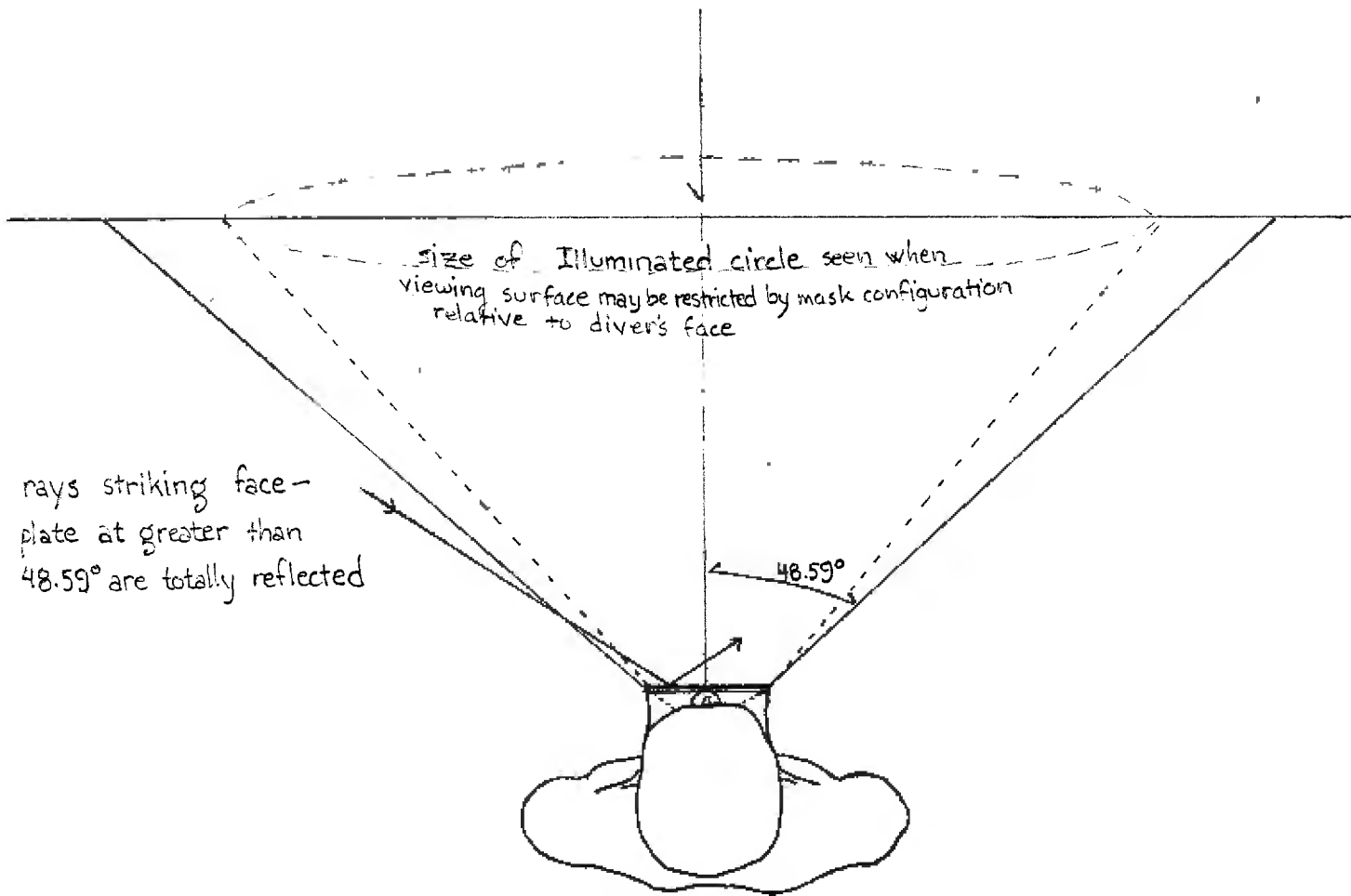
especially with high corrections. This is the only device that allows the diver a clear view through the side plates of a wrap around mask. Contact lenses also provide correction when the mask is removed in air, and underwater they will not fog. For the hyperopic diver with a correction greater than three diopters, contact lenses or suspended spectacles offer greater correction with less aberration.

A pragmatic approach should be adopted in recommending contact lens correction for the scuba diver. Hard lenses are contra-indicated for diving. Hydrogel lenses can enhance the visual diving experience but they should not be used by the novice diver until he/she acquires a fundamental competence and confidence in the undersea world. Before adopting contacts the diver should possess the skill to calmly empty a flooded mask while the eyes are closed. The diver should be instructed to immediately close the eyes in case of mask flooding, and to open them only after purging the mask.

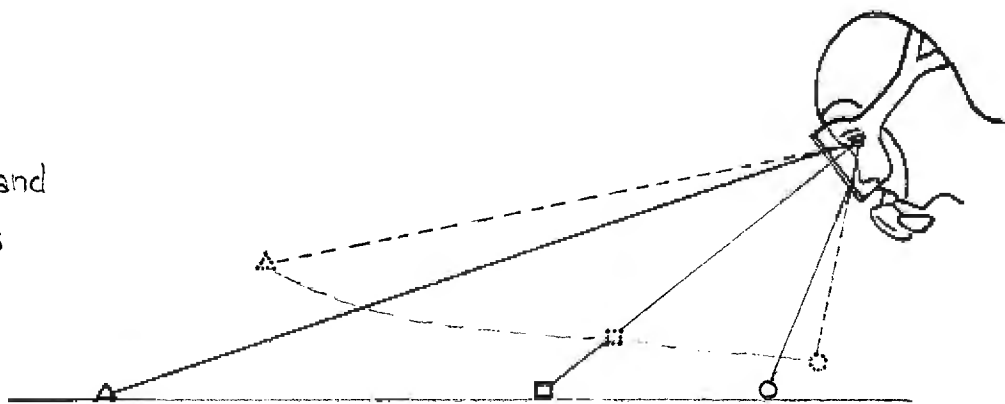
The diver should be told that a few investigators feel that risk of lens loss is greater in seawater and thus greater caution should be exercised when diving with hydrogel lenses in that environment. The diver should be counseled to keep a spare pair of hydrogel lenses on hand when going out on a dive to avert the possibility of having to call a dive short due to lens loss, or alternatively, a spare pair spectacles should also be kept on hand to avoid having to drive uncorrected. From a potential cost standpoint, the diver should realize that

loss of a pair of spherical soft lenses, or single toric lens, is approximately that of services and materials for two lenses bonded to one's facemask. The presbyopic diver may still require a bonded near add in addition to his contact lenses. In summary, if the experienced diver is an experienced and properly fit hydrogel lens wearer, and he or she understands the risk of lens loss, soft contact lenses can then safely be recommended. For the high hyperopic diver, hydrogel lens or spectacles suspended in the mask are the first choice in correction.

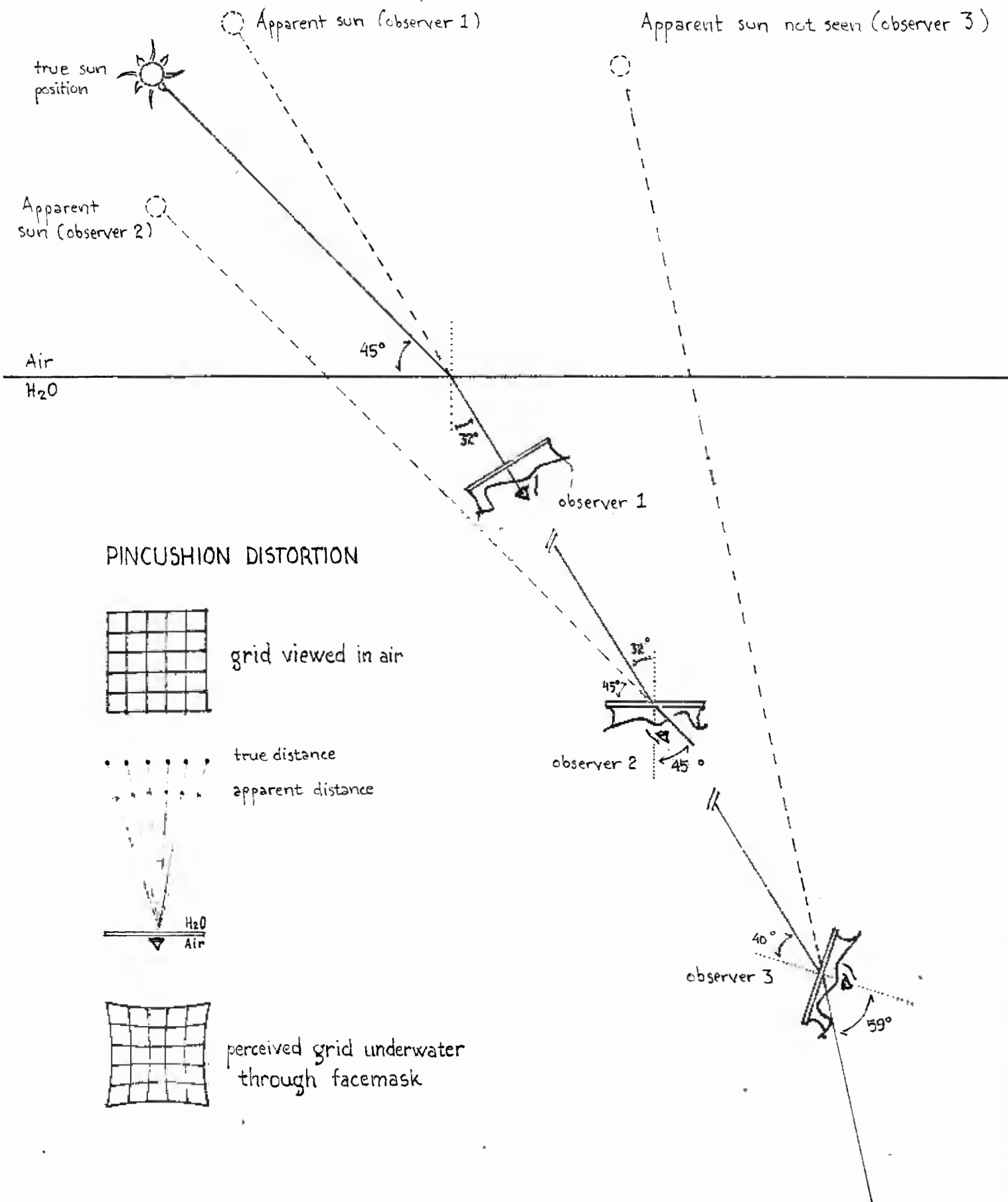
Appendix A



bottom appears raised and curves upward towards the diver



Appendix A' cont.



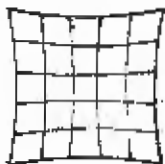
PINCUSHION DISTORTION



grid viewed in air



true distance
 apparent distance



perceived grid underwater through facemask

Appendix B

Color Discrimination Underwater

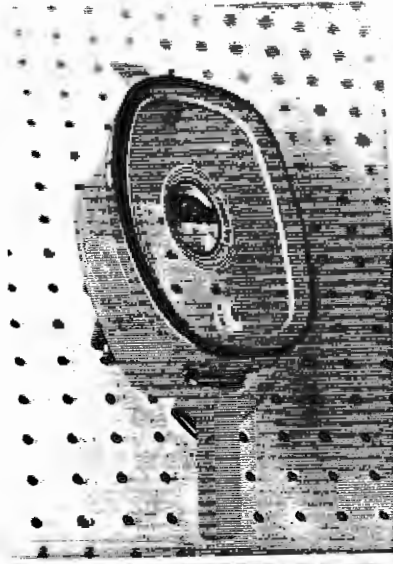
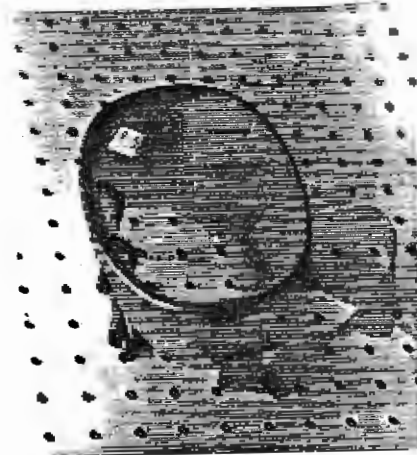
- A. For clear water (southern water, deep water off shore, clear lakes, etc).
 - 1. With any type of illumination fluorescent paints are superior.
 - a. With long viewing distances, fluorescent green and yellow-green.
 - b. With short viewing distances, fluorescent orange is best.
 - 2. With natural illumination:
 - a. Fluorescent paints.
 - b. Regular yellow, green, white.
 - 3. With incandescent light source:
 - a. Fluorescent paints.
 - b. Regular yellow, orange, white.
 - 4. With mercury light source:
 - a. Fluorescent paints.
 - b. Regular yellow, white.
- B. For moderately turbid water (sound, bays, coastal water).
 - 1. With natural illumination or incandescent light source:
 - a. Any fluorescent in the yellow, oranges, or reds.
 - b. Regular yellow, orange, and white.
 - 2. With a mercury light source:
 - a. Fluorescent yellow-green or yellow-orange.
 - b. Regular yellow and white.
- C. For murky, turbid water of low visibility (rivers, harbors, etc.).
 - 1. With natural illumination:
 - a. Fluorescent yellow, orange, and red.
 - b. Regular yellow, orange, and white.
 - 2. With incandescent illumination:
 - a. Fluorescent and regular yellow, orange, red, and white.
 - 3. With a mercury light source.
 - a. Fluorescent yellow-green and yellow-orange.
 - b. Regular yellow and white.

Nonfluorescent colors that result in poorest visibility against a water background:

- A. Orange and red in clear water
- B. Blue and green in turbid water
- C. Blue and green with incandescent light
- D. Orange and red with mercury light

Adapted from Adolphson: Perception and performance underwater.

OVAL or STANDARD

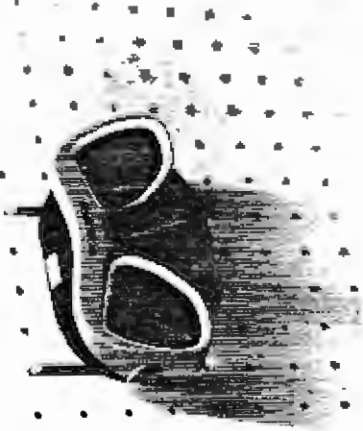


WIDEFIELD



GOGGLE MASKS

Appendix C'



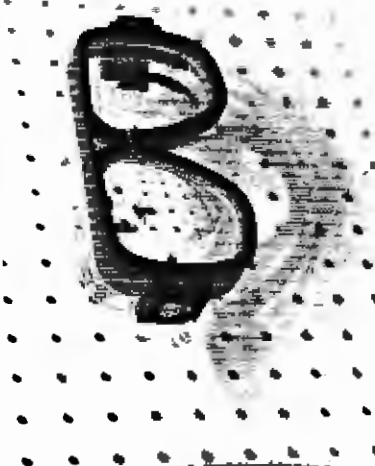
RECESSED KIDNEY MASKS



BIOPTIC RECESSED KIDNEY MASKS



BIOPTIC MASKS WITH PRE-GROUND FACEPLATES



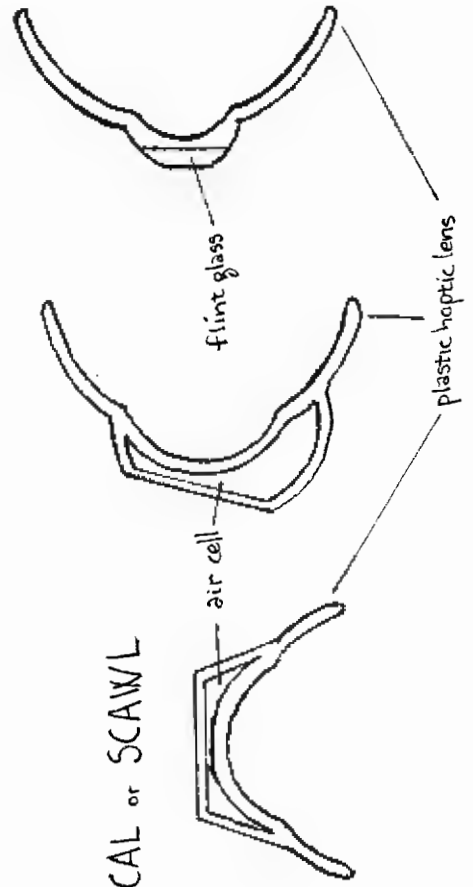
RECESSED KIDNEY MASK WITH BONDED LENSES



DOUTHWAITE'S BIFOCAL FLINT GLASS
BUTTON LENS

LOWER LID SUPPORTED SCAL

SCAL or SCAWL



Adapted from Stone & Phillips

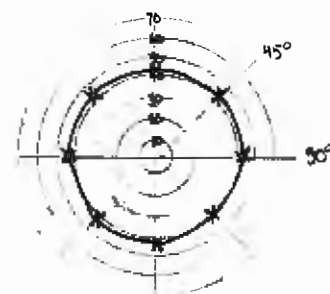
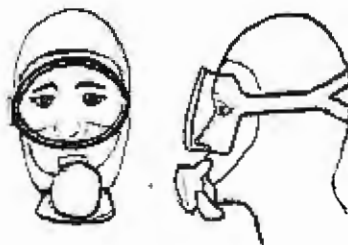
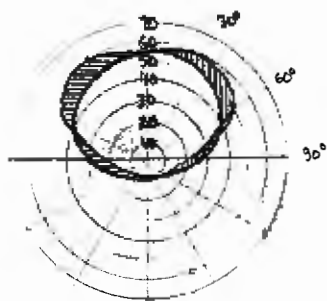
Appendix D

FIELD OF VIEW THROUGH FACEMASKS OF VARIOUS DESIGN

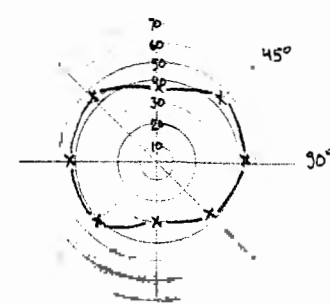
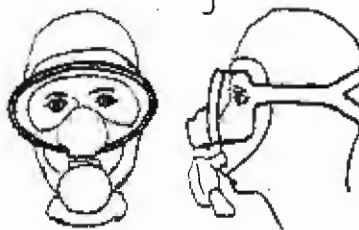
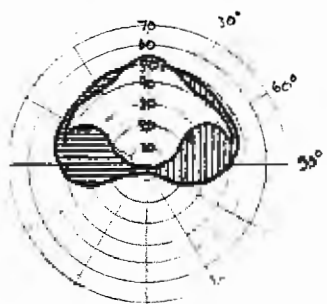
Weltman, et al

Luria, et al

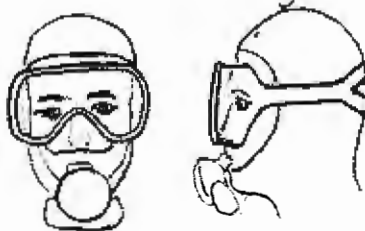
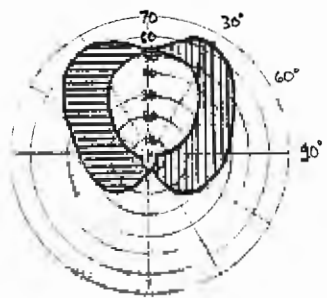
oval or standard






kidney

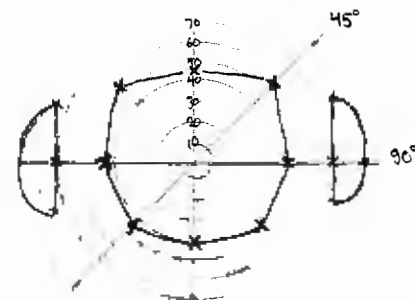
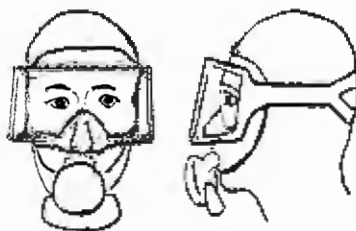


recessed kidney

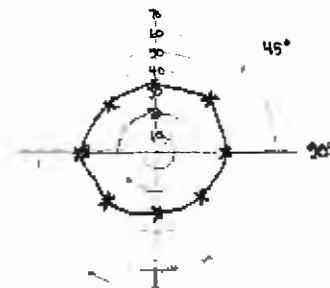
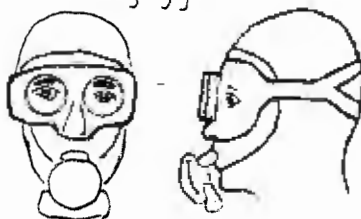


widefield

-  left eye
-  right eye
-  binocular



goggle



Appendix E

Compensation Lens

Problem:

To design a lens system that could be incorporated into a dive mask that would optically minify the underwater environment by 33% (underwater environment magnified 33% by air-water interface as cited earlier in this report).

Constraints:

40 mm maximum allowable vertex distance in commercially available divemasks prevents lens system thickness from exceeding approximately 30 mm (leaving 10 mm for eyelash clearance). Back vertex power must approximate zero. Aberration and distortion precludes use of steep lens curvatures.

Formulas:

(1) spectacle magnification,

$$sm = \left(\frac{\text{shape } 1}{1 - t/n P_1} \right) \times \left(\frac{\text{power } 1}{1 - h P_{BV}} \right)$$

t = lens thickness in m
n = lens index
P₁ = front surface power
h = vertex dist.
P_{BV} = back vertex power
P₂ = rear surface power
"t" = lens thickness mm

(2) % increase in mag
(Jalie formula)*

$$= - \frac{"t" P_2}{10 n}$$

From formula (2) it can be seen that using crown (1.523) or high index glass eg. High-Lite (1.701) will not greatly alter the amount of magnification, so we will assume crown for our calculations.

From the same formula it follows that use of a lens thinner than 20 mm would result in a P₂ of greater than 20 D. Alternatively we can not have P₂ be less than 10 D as this would mean the lens would have to be greater than 50 mm thick.

Assume t to be the maximum 30 mm thickness:

$$33.0 = - \left(\frac{30(P_2)}{10(1.523)} \right) \quad P_2 = \frac{-10(33)(1.523)}{30} = -16.75$$

Assuming P_{BV} ≈ 0 and using the spectacle Mag formula (1) to solve for P₁:

$$1.33 = \left(\frac{1}{1 - .03/1.523 P_1} \right) \times 1 \quad \text{therefore } P_1 = + 12.60$$

*Teshima, R. The Optics of Ophthalmic Lenses Illinois College of Optometry, Chicago, Ill. 1981, p. 162.

Appendix E'

Thus a lens of the parameters $P_1 = +12.60$, $P_2 = -16.75$ $N = 1.523$, and $t = 30$ mm would result in a 33% change in mag when mounted in a facemask.

To achieve minification this afocal lens would be mounted inside the divemask so that minus side would be bonded to the faceplate and the plus side would serve as the ocular.

Limitations:

Although this lens system could theoretically neutralize 33% magnification it would suffer from a number of optical and practical limitations.

- Transmittance of light would be greatly reduced to 83% in passage through this thick lens, resulting in decreased contrast and resolution acuity. (Most of this loss is due to reflection at the four surfaces.)
- A mask of large volume and vertex distance would be required to accommodate the size lens. Such large volume and vertex distance masks are more easily dislodged and flooded in current.
- The weight of the size lens would conceivably decrease the buoyancy as to make the mask less likely to maintain a water-tight seal on the active diver.
- To minimize weight a smaller diameter lens would need to be used resulting in decreased visual fields and stereoacuity.
- With surfaces curvatures of -16.75 and $+12.60$ optical aberrations and distortions would be increased significantly.
- The lens would require difficult-to-obtain custom lens blanks and non-readily available manufacturing techniques resulting in high fabrication costs.

Suggestion for Further Research:

Although the induced underwater magnification is mathematically predicted as being 33%, Luria's psychophysical experiment resulted in a perceived mean magnification of only 18%. The reasons for this discrepancy are not well understood. The authors have speculated that a portion of the discrepancy may be due to a reverse Galilean minification effect. The water-glass-air interface acts as a diverging or minus lens requiring increased accommodation by the diver looking through it. This in-effect would constitute a reverse Galilean telescope slightly reducing the magnified underwater view. Further research is needed to quantify the amount of magnification that is perceived by the diver underwater.

The authors* suggest a simple experiment for quantifying the amount of optical magnification underwater. An opaque object of known dimension could be suspended in an aquarium full of water. At the opposite end of the aquarium a pinhole camera

*In consultation with Dr. Meyer-Arendt

Appendix E²

with a ground glass screen would be positioned so that with proper illumination the object would form an image on the ground glass screen of the camera. The dimension of the image would be measured and the experiment would again be repeated with the water drained from the tank. In this way the image sizes of the two conditions could objectively be compared. Their ratio would represent an objective measure of magnification. The effect of vertex distance upon magnification could easily be investigated by varying the distance from the water-glass-air interface to the front of the pinhole camera.

To quantify the perceived magnification underwater additional psychophysical experiments of the type carried out by Luria would be needed. Additional variables such as distance, object size, illumination, water clarity and experience underwater, could then be included.

Appendix F

Available Corrective eyewear for the diver

A. Supplied by manufacturer

Manufacturer	Mask	Powers	Increments	Price*
AMF Mares 2151 Las Palmas or Suite F Carlsbad, CA 92008	Prima/optical Santiago/optical	-1.5 to -10.00	.5 D	\$82-\$97
Tabata V.B.H. Inc. 20818 Higgin Ct. Terrance, CA 90501 (213) 320-6483	splendive	-2.0 to -7.0	.5 D	\$78-\$92
Scuba-Pro 3105 E. Harcourt Rancho Dominguez, CA 90221	Futura A Futura B Optical C Optical D	-1 to -6.0 -1 to -6.0 -1 to -10 -1 to -16	.5 D .5 D .5 D .5 D	\$74 \$99 \$95 \$130
Dacor 161 Northfield Rd. Northfield, Ill 60093 (312) 446-9555	DM45K, DM456 DM455, DM456#	-1.0 to -6.0	1.00 D	\$100
Ocean Dynamics 336 W. Victoria St. Gardinia, CA 90248	Superview B Superview T	-2.0 to 7.5	.5 D	\$96 \$173

* Price will vary according to dive shop.

Dacor lenses are bonded.

Appendix F'

B. Bonding services

1. Aquatic Optics
121 S. Central Exp
Richardson, Texas 75080

Aquatic Optics has not found any spherical or cylindrical power that could not be made. Flat-top bifocals are available.
2. Harbor Aquatics
Michael J.J. O'Brien, Jr., O.D. Inc.
575 W. 6th Street
San Pedro, CA 90731

Harbor Aquatics can incorporate plus power, minus power, cylinder, bifocals and prism correction in the lenses. Fabrication time is one week.
3. Leonard Maggiore
69-03 Fresh Pond Rd.
Ridgewood, Queens, NY 11385
(212) 386-5339

Mr. Maggiore has found no prescription too strong or too complex for a prescription face plate. Fabrication time is one week. Cost - Single Vision \$69.50, Bifocal \$99.50.
4. Opti-Sport Co.
2460 Willamette St.
Eugene, Oregon 97405

Dr. Gillilan offers corrective sports eyewear for the swimmer, water and snow skier, and diver. Cost - Single vision \$62.50, Bifocals \$86.50.
5. Scuba Center of Spokane
3607 N. Division
Spokane, Wa. 99207
(509) 326-4653

Mr. Moss can grind bifocals into pre-ground lenses as well as bond custom-ground lenses (minus powers only) to face plates.

C. Miscellaneous

1. Libra Optics
P.O. Box 6342
Huntington Beach, CA 92648

Libra Optics supplies a kit containing a small +2.50 D lens, cement, and instructions for placement of the add in the lower temporal portion of the faceplate. This location is advantageous to the presbyopic diver who must see gauges when using this portion of the mask. Cost - \$16.95.
2. Scuba-Spec Inc.
P.O. Box 22356
Savannah, Ga. 31403

A device can be attached to the mask which can hold prescription lenses. Cost - about \$15.00.

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