IMPROVEMENT OF VISION UNDER WATER WITH CHROMATIC FILTERS

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SUMMARY PAGE

PROBLEM

To determine the effectiveness of colored goggles in improving visual performance under water.

FINDINGS

Yellow filters improve both detection and resolution thresholds for yellow targets on blue backgrounds. Their effectiveness decreases as the background becomes yellower, as the target gets smaller, and as the observer gets older. Blue filters have no effect.

APPLICATION

Yellow filters can be used to improve visibility for divers in certain underwater conditions; specifically, when looking for yellowish items in clear water.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work Unit M4306.03-2050DXC5 - Evaluation of Sensory Aids and Training Procedures on Navy Divers' Visual Efficiency. The present report is No. 6 on that work unit. It was approved for publication on 23 August 1971 and designated as Submarine Medical Research Laboratory Report No. 679.

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ABSTRACT

Detection and resolution thresholds for blue targets and yellow targets against blue, green, and yellow backgrounds were measured while subjects were wearing yellow and blue filters. Yellow filters improved thresholds for yellow targets against blue backgrounds. Their effectiveness decreased (1) as the wavelength of the background increased, (2) as the size of the target decreased, and (3) with the age of the observer. The blue filters were generally ineffective. The results are for the most part explained on the basis of changes in target contrast brought about by the filters. The effectiveness of yellow facemasks for divers under certain conditions is discussed.

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INTRODUCTION

Yellow sunglasses are currently enjoying great popularity. They are widely believed to improve visual acuity and thus to enhance performance in various tasks. Consequently, they can be found in countless numbers on the ski slopes and hunting grounds.

It is widely conceded that wearing yellow filters results in a strong impression of greater brightness of the visual scene. But the accompanying impression of increased ability to see has typically been dismissed as nothing more than a "psychological" phenomenon with no objective foundation. For example, W. D. Wright attributes the apparent increase in brightness to a tendency to associate yellow with sunlight and its high level of illumination.[1] And most of the scientific work, both experimental and theoretical, has concluded that they are of no value, if not actually detrimental.

The problem of the usefulness of yellow filters in enhancing vision has several facets. A basic question concerns acuity under different colors of illumination. LeGrand, in a brief summary of this work, has written that, "In spite of a subjective impression favorable to yellow light, the statistics give the same acuity if the luminances are equalized..." A little later, however, he writes, "The only point on which authors seem almost agreed is a slight superiority, at equal luminance, of yellow monochromatic light..." LeGrand concludes, "In short, the problem of acuity in colored light is extremely confused."[2] It seems safe to say, however, that the confusion centers around very small differences one way or the other. If acuity is not constant, it is improved only slightly at best by certain colors of illumination, and any improvement which may occur is probably of no practical significance. This is supported by Bierman's[3] and Ross's[4] studies of the performance of riflemen; they found that wearing yellow glasses generally lowered the scores.

Granted that yellow glasses may be ineffective under optimal viewing conditions, the question has also been raised, however, as to whether yellow lights or filters are beneficial under poor viewing conditions, such as reduced illumination. Luckiesh and Moss[5] studied the visibility of objects illuminated by sodium and tungsten lights. They, in fact, reported some advantage to sodium light for very small targets, but found that the advantage disappeared at low brightness levels due to the Purkinje effect. Richards has reviewed the evidence on the usefulness of yellow filters to improve night vision several times and always concluded that yellow glasses reduce vision.[6–8]

Fog and haze constitute another common type of visual obstruction. Luckiesh and Holladay[9] compared the visibility of tungsten and sodium lamps through fog. They found no difference and concluded that "the advantage of yellow light in foggy and misty atmospheres is greatly overrated and from a practical viewpoint is inappreciable, if not entirely non-existent."

Similarly, in a related study, Verplanck[10] tested the effectiveness of wearing yellow (and other) filters for extending the visual range at which targets could be discriminated through haze and found they did not work.

Finally, Wyszecki[11] subjected the problem of vision on a snowy surface to a theoretical analysis and concluded that no colored filter could be expected to improve visual performance compared to a neutral filter.

This weight of scientific evidence has even found its way into the popular press. A recent article aimed at sportsmen cautioned, "Never wear sunglasses at night--and this includes yellow lenses....There is even some question as to the value of the yellow shooting lenses under any conditions."[12]

Despite such gratifying unanimity, there is still some basis for refusing to completely discount yellow glasses. Richards has explained their failure to improve vision at night on the grounds that "Contrast is not increased by a yellow lens at night because there is too little blue color to be affected selectively," and he quotes Frey as similarly saying, "Yellow glasses are scarcely useful for motorists because of the small amount of blue and blue-gray contrasts on roads."[13] That is, the yellow filters can be expected to be effective only in the presence of the conjunction of short and long wavelength stimuli, one as target and the other as background.

Such conditions have not been set up in attempts to evaluate yellow glasses. Rather, the studies have generally been carried out under "natural" conditions which may afford little color contrast, or black and white acuity charts have been used. Yet, the possibility of enhancing visual performance by color contrast seems completely reasonable. It might be noted that Jameson and Hurvich have theorized that contrast phenomena result not from depressed sensitivity but rather in the neural tissue associated with the test area.[14] It might be supposed, then, that conditions producing a large additional induced neural response might enhance vision, and, indeed, Burkhardt and Riggs[15] have reported enhancement of cortical evoked potentials during chromatic adaptation. Kinney and Cooper,[16] on the other hand, did not find improved reaction time to long wavelength stimuli after adaptation to short wavelengths fields, but more relevant to the present problem is Martin's[17] report that yellow lenses did significantly enhance both the ability to perceive certain colored targets (but not gray targets) and the response time to these targets.

There are, thus, reasons to believe that yellow filters may improve vision when the target is of long wavelength and the background is of short wavelength. These conditions are quite typical of the underwater environment and thus make such a study eminently appropriate in connection with the visual problems of divers. This paper examines the effectiveness of blue and yellow filters in improving the visibility and resolution of blue and yellow targets against three chromatic backgrounds.

APPARATUS

The apparatus is diagrammed in Fig. 1. The observer's head was positioned in a chin-rest at the center of a white hemisphere 90 cm in diameter. He looked toward a circular hole 12.7 cm in diameter which was covered from the back with milk-glass. Behind the glass was a camera-shutter set to open for 40 msec. This was built into a box which excluded light from the glass except through the shutter. The shutter was close enough to the glass to produce a just noticeable shadow, providing S with a fixation guide. Farther back, stood a baffle in front of which was mounted a series of neutral density filters. For the increment threshold measurements, there was a small light source mounted in a flashlight reflector and powered through a voltage regulator. For the acuity measurements, a slide-projector was substituted for the light.

The interior of the hemisphere was evenly illuminated from above with either yellow, green, or blue light through Corning glass filters (Figs. 2A), equated to illuminate the sphere to 0.1 foot-lamberts. (A low photopic luminosity level probably exists under poor viewing conditions in the water.) The test stimuli were either yellow or blue, also obtained through Corning glass filters (Fig. 2B). The observer viewed the display binocularly through filters mounted on two sets of goggles. The first set consisted of yellow or

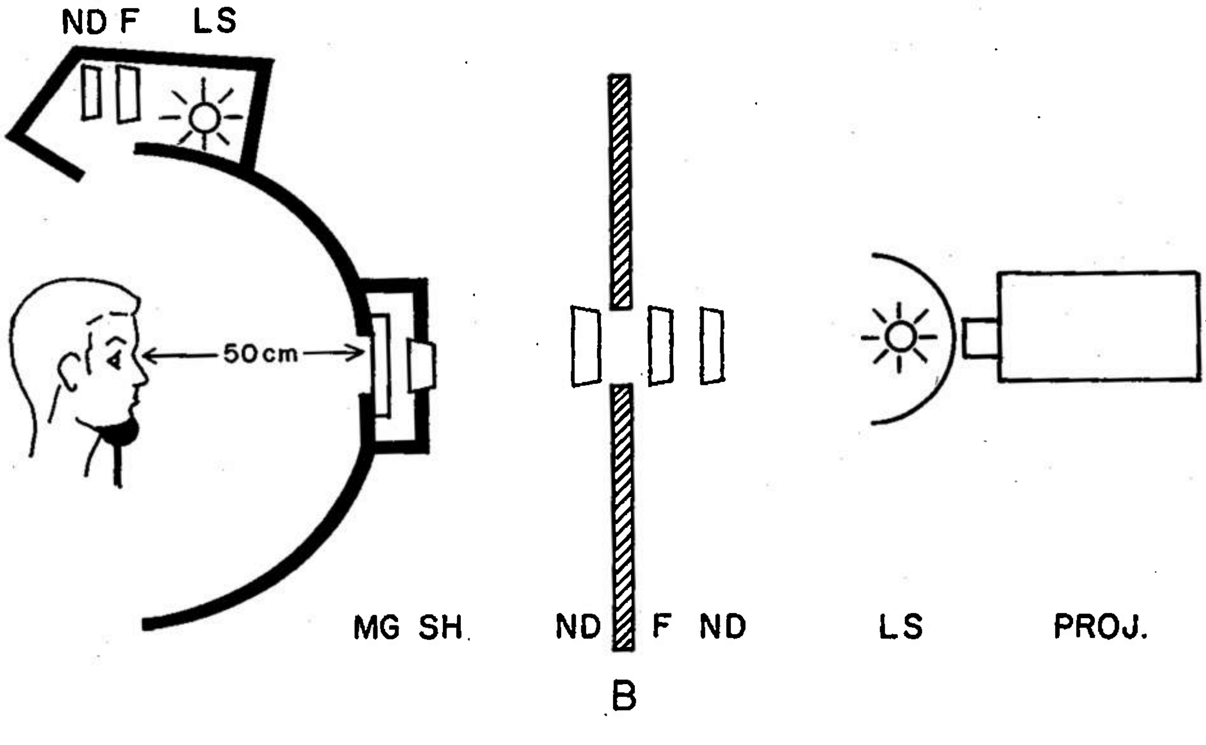

Fig. 1. Schematic diagram of the apparatus, showing the slide projector or the light source (LS) in its parabolic reflector. The light passes through neutral density filters (ND) and selective filters (F) and then a set of neutral density filters (ND) in 0.1 log unit steps all mounted on a baffle (B); then through a camera-shutter (SH) and onto a sheet of milk-glass (MG). The observer views the target on the inside of a white hemisphere from a distance of 50 cm. The interior of the hemisphere is illuminated by light from a source (LS) on top of the hemisphere which also passes through neutral density and selective filters before being reflected into the sphere by a flat white surface.

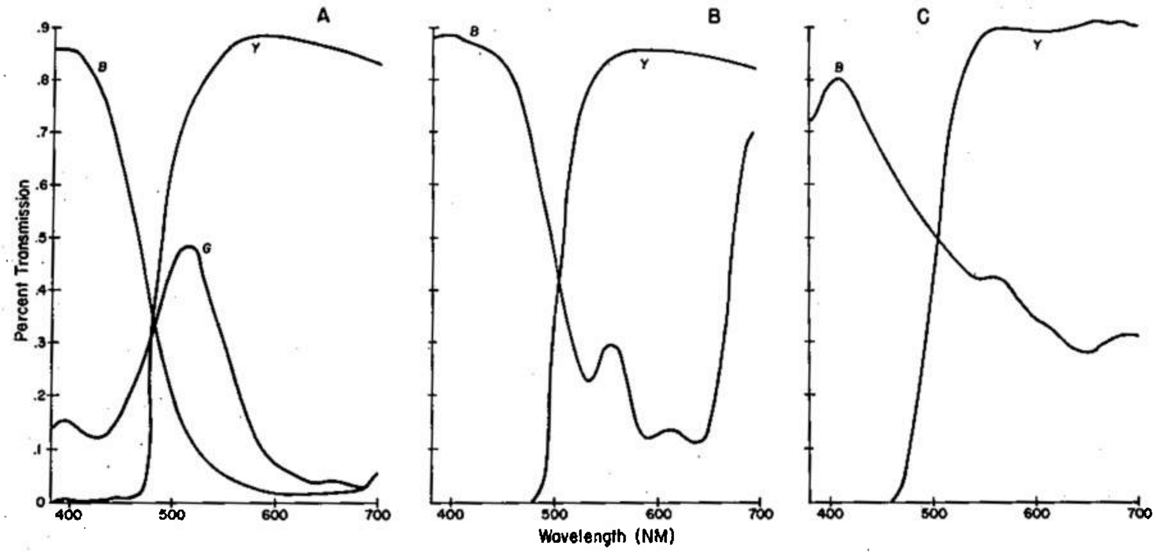

Fig. 2. Spectral transmission curves of the selective filters used (A) to produce the yellow, green, and blue background, (B) to produce the yellow and blue stimuli, and (C) in the yellow and blue goggles.

neutral density filters equated for brightness; the second set consisted of blue or neutral density filters, also equated for brightness (Fig. 2C).

The test stimuli for the increment threshold study were circular spots of light whose diameters were altered by changing the shutter diaphragm. For the acuity study, the test-stimulus was a transparent Landolt C which was also illuminated from behind. Its body subtended 1.15° visual angle, the stroke width subtended 7.0' visual angle, and the gap subtended 3.5 min. visual angle.

PROCEDURES

The increment thresholds were measured with the method of constant stimuli. The approximate range was determined with the method of limits after which five intensity levels were chosen in 0.1 log steps and presented eight times in random order. The resulting frequency of seeing curve was plotted on cumulative probability paper and the 50 per cent point taken as threshold. Standard deviations were read directly from the graph.

The acuity thresholds were measured by varying the luminance of only one Landolt C using an increasing method of limits. Each run began at a luminance level too low for resolution. The light was progressively increased in 0.1 log steps until the observer judged the position of the gap. Each of the four positions (up, down, right, left) was presented twice in random order for each goggle. Observers were discouraged from guessing; when an incorrect judgment was made, the run was simply terminated without informing the observer of his error.

Four thresholds were obtained during each session, two for the neutral and two for the colored goggle, in ABBA order, with the first goggle chosen randomly. Each session began with a four minute adaptation period. Observations were binocular and fixation was always foveal.

RESULTS

I. Increment Thresholds

A. Effect of Size

The yellow goggle was first compared with the neutral goggle using yellow stimuli of various sizes on a blue surround. Five staff members of the laboratory were subjects. Their thresholds for the yellow spot are given in Table I. For the smallest target, for example, AM's threshold while wearing the neutral goggle was .054 ft-L, whereas with the yellow goggle it was .044 ft-L. An indication of the advantage of wearing the yellow goggle is given by the ratio of the neutral to the yellow thresholds. In this case, R = 1.23.

Table I. Relative effectiveness of yellow goggles for yellow stimuli on a blue background

Obs (age)	Goggle	Stimulus Size: 0.33° Threshold (ft-L)	0.33° Ratio (N/Y)	1.4° Threshold (ft-L)	1.4° Ratio (N/Y)	2.3° Threshold (ft-L)	2.3° Ratio (N/Y)
AM (21)	Neutral Yellow	.054 .044	1.23	.0115 .0076	1.51	.0088 .0049	1.80
MK (23)	N Y	.055 .048	1.14	.0103 .0085	1.21	.0069 .0051	1.35
BK (24)	N Y	.060 .052	1.15	.0123 .0120	1.02	.0100 .0066	1.52
CM (26)	N Y	.037 .030	1.23	.0103 .0076	1.36	.0050 .0035	1.43
SF (27)	N Y	.082 .088	0.93	.0120 .0107	1.12	.0072 .0050	1.44
Mean Ratio			1.13		1.24		1.50

Table I shows that thresholds were lower with the yellow goggle in every case except one. Further, the advantage for the yellow goggle increased as the size of the test-spot increased, from a mean ratio of 1.13 for the smallest target to a ratio of 1.50 for the largest.

These results are somewhat artificial from a practical point of view, of course, since the basic question involved is whether the yellow filters are preferable to no filter at all. Such a comparison should yield a somewhat smaller advantage for yellow since the neutral filter undoubtedly decreases the visibility of the test spot. To test whether the yellow filter is superior to no filter at all, the procedure was repeated for the largest test-spot with the neutral filters removed from the goggle for three of these subjects. The results are given in Table II. Although the advantage for the yellow was reduced, it did not disappear.

Table II. Effectiveness of yellow goggles compared with no goggles for 2.3° yellow stimuli on a blue background

Obs.	Goggles	Threshold (ft-L)	Ratio (N/Y)
AM	None Yellow	.0082 .0062	1.33
CM	None Yellow	.00315 .00255	1.24
AF	None Yellow	.0058 .0048	1.21
Mean Ratio			1.26

B. Effect of Age

Tables I and II suggest something else: the subjects are arranged in order of increasing age in both tables. Although all are in their twenties, there appears to be a decreasing advantage to the yellow goggle with age. To test this, 20 additional subjects were tested with the largest yellow test-stimulus on a blue surround. Most of the subjects were inexperienced observers who were given only a few practice trials and no explanation of the experiment. Their results are given in Table III and plotted in Fig. 3. It is quite clear that there is, indeed, a decreasing advantage to wearing the yellow filters with age.*

C. Effect of Retinal Position

These findings lead, of course, to the conclusion that the reduced effectiveness of the yellow filters results from increased yellowing of the ocular media with age.[20] Whether the basis of the phenomenon has to do with the lens or with the macular lutea can be determined by comparing the ratios in the fovea with those in the periphery. This was done for five subjects with high foveal ratios and five subjects with low ratios. These ten subjects were tested again while fixating 10° above the center of the test spot. Their thresholds are presented in Table IV, together with their previous foveal ratios in parentheses. There is virtually no difference in the mean ratios for the

It is interesting to note that whereas it is well known that absolute threshold worsens with age [18,19] there appears to be no degradation of photopic increment threshold with age in Table III.

Table III. Effectiveness of Yellow Goggles for 2.3° Yellow Stimuli on a Blue Background as a Function of Age of Observer

Obs.	Age	Threshold (ft-L) for Neutral Goggles	Threshold (ft-L) for Yellow Goggles	Ratio (N/Y)
PE	15	.0074	.0054	1.37
NV	16	.0106	.0081	1.31
AM[a]	21	.0088	.0049	1.80
CS	21	.0223	.0143	1.56
LaC	22	.0051	.0036	1.42
ST	22	.0047	.0029	1.62
SM	22	.0096	.0064	1.50
MK	23	.0069	.0051	1.35
BK	23	.0100	.0066	1.52
TK[a]	24	.0142	.0078	1.82
CM[a]	26	.0050	.0035	1.43
SF[a]	27	.0072	.0050	1.44
LG	34	.0127	.0090	1.41
JD	36	.0048	.0036	1.33
SL[a]	40	.0104	.0081	1.28
JK[a]	42	.0119	.0086	1.38
GM[a]	46	.0105	.0101	1.04
AR[a]	48	.0058	.0045	1.29
BM	53	.0153	.0113	1.35
CK	61	.0068	.0057	1.19
CG	61	.0093	.0076	1.09
ED	64	.0088	.0069	1.28
FS	65	.0087	.0086	1.01
WS	67	.0095	.0088	1.08
JV[a]	69	.0062	.0058	1.07

[a] Previous experience in psychophysical experiments.

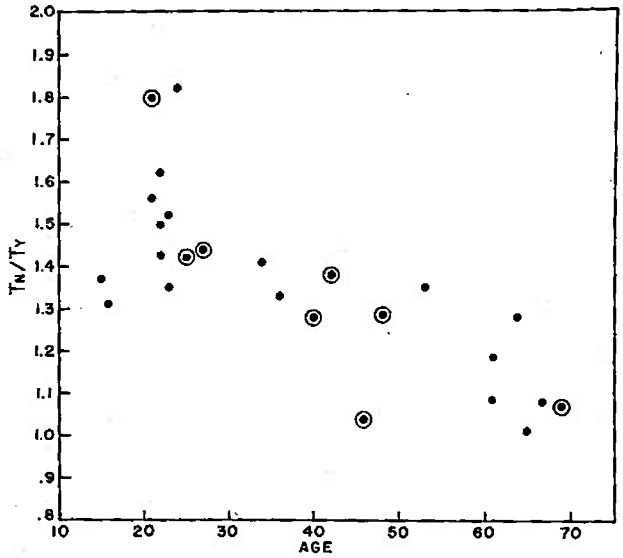

Fig. 3. Effectiveness of the yellow goggles, expressed as the ratio of the thresholds in foot-lamberts of the target seen through the neutral goggles to their thresholds seen through the yellow goggles, as a function of the age of the observer. The circled points represent the ratios for those observers who had had previous experience in psychophysical experiments.

two retinal positions, indicating that it is the change in the lens which is producing the changes with age.

D. Effect of color of background, test-stimulus, and goggles.

The yellow filters clearly improve increment thresholds for yellow stimuli on a blue background, particularly for younger observers. The question next arises as to how effective the yellow filters would be against other surrounds and with other test stimuli. Presumably, their effectiveness would decrease as the color of the surround approached that of the yellow stimulus, or conversely, as the color of the test-stimulus approached that of the surround. On the other hand, we may ask whether the effectiveness of the yellow filters would be as great for a blue stimulus on a yellow surround as for the converse. To answer such questions, three staff members experienced in psychophysical observations, were tested extensively. Foveal increment thresholds for both yellow and blue stimuli of 2.3° vis. angle were measured on blue, green, and yellow backgrounds of 0.1 ft-L with the observers wearing yellow and blue goggles. The respective thresholds in foot-lamberts with the yellow goggles are given in Table V and those obtained with the blue goggles are given in Table VI. The left half of these tables gives the thresholds for yellow stimuli on blue, green and yellow backgrounds, and the right half gives the thresholds for blue stimuli on these backgrounds.

Table V shows that the improvement in the thresholds for yellow stimuli on a blue background produced by the yellow goggles was reduced when the background was changed to green and still further reduced when the background was yellow.

With a blue stimulus it would be expected that there would be no advantage to wearing yellow goggles with a blue background. Table V shows that the yellow goggles did produce an improvement for the blue stimulus on a blue background for all three subjects. The reason undoubtedly must be that, as shown in Fig. 2, the blue stimulus is not identical to the blue background; the test-stimulus has more transmittance in the green and red than does the background, and the yellow goggles transmit this.

Table VI shows the results for the various stimuli and backgrounds when wearing the blue goggles. The thresholds for the yellow stimulus on a blue

Table IV. Effectiveness of Yellow Goggles for 2.3° Yellow Stimuli on a Blue Background Presented 10° Below the Fixation Point. Previous Foveal Ratios are Given in Parentheses.

Obs. With High Foveal Ratios in Table III	Goggles	Threshold (ft-L)	Ratio (N/Y)	Obs. With Low Foveal Ratios in Table III	Goggles	Threshold (ft-L)	Ratio (N/Y)
AM	Neutral	.0158	1.58	GM	Neutral	.0125	0.86
	Yellow	.0092	(1.80)		Yellow	.0145	(1.04)
LaC	N	.0110	1.45	AR	N	.0052	1.30
	Y	.0076	(1.42)		Y	.0040	(1.19)
TK	N	.0140	1.61	CG	N	.0078	1.07
	Y	.0087	(1.82)		Y	.0073	(1.09)
CM	N	.0133	1.49	CK	N	.0150	1.27
	Y	.0089	(1.43)		Y	.0118	(1.19)
SF	N	.0180	1.38	JV	N	.0085	1.06
	Y	.0130	(1.44)		Y	.0080	(1.07)
Mean			1.50 (1.58)				1.11 (1.14)

Table V. Foveal Increment Thresholds and Standard Deviations in foot-Lamberts Through Yellow Goggles and Equated Neutral Goggles

Back-ground	Obs.	Yellow Stimulus			Blue Stimulus		
		Neutral Goggles	Yellow Goggles	Ratio (N/Y)	Neutral Goggles	Yellow Goggles	Ratio (N/Y)
Blue	AM	.0088 ±.0009	.0049 ±.0017	1.80	.0053 ±.0035	.0039 ±.0025	1.35
	CM	.0050 ±.0015	.0035 ±.0015	1.43	.0037 ±.0040	.0028 ±.0025	1.33
	SF	.0072 ±.0005	.0050 +.0004	1.44	.0075 ±.0030	.0055 ±.0025	1.36
	Mean			1.55			1.35
Green	AM	.0067 ±.0009	.0056 ±.0004	1.20	.0033 ±.0006	.0037 ±.0006	0.89
	CM	.0031 ±.0015	.0030 ±.0014	1.04	.0031 ±.0004	.0031 ±.0003	1.00
	SF	.0078 ±.0016	.0048 ±.0004	1.62	.0068 ±.0016	.0063 ±.0015	1.08
	Mean			1.29			0.99
Yellow	AM	.0054 ±.012	.0052 ±.0008	1.04	.0044 ±.0004	.0051 ±.0005	0.86
	CM	.0034 ±.0095	.0035 ±.0005	0.98	.0034 ±.0004	.0034 ±.0004	1.00
	SF	.0070 ±.006	.0055 ±.0015	1.28	.0070 ±.0006	.0055 ±.00045	1.27
	Mean			1.10			1.04

Table VI. Foveal Increment Thresholds and Standard Deviations in foot-lamberts Through Blue Goggles and Equated Neutral Goggles

Back ground	Obs.	Yellow Stimulus: Neutral Goggles	Yellow Stimulus: Blue Goggles	Ratio (N/Y)	Blue Stimulus: Neutral Goggles	Blue Stimulus: Blue Goggles	Ratio (N/Y)
Blue	AM	.0060 ±.0010	.0081 ±.0017	0.74	.0063 ±.0007	.0064 ±.0007	0.98
	CM	.0062 ±.0007	.0082 ±.0008	0.76	.0078 ±.0003	.0078 ±.0009	1.00
	SF	.0092 ±.0003	.0096 ±.0007	0.96	.0084 ±.0010	.0076 ±.0007	1.11
	Mean			0.81			1.04
Green	AM	.0041 ±.0008	.0044 ±.0005	0.93	.0046 ±.0006	.0046 ±.0009	1.00
	CM	.0050 ±.0006	.0046 ±.0005	1.08	.0050 ±.0008	.0044 ±.0006	1.13
	SF	.0078 ±.0006	.0083 ±.0009	0.94	.0075 ±.0012	.0080 ±.0008	0.94
	Mean			0.98			1.00
Yellow	AM	.0058 ±.0006	.0054 ±.0006	1.07	.0044 ±.0006	.0042 ±.0007	1.05
	CM	.0037 ±.0006	.0042 ±.0008	0.88	.0037 ±.0007	.0035 ±.0004	1.05
	SF	.0082 ±.0006	.0076 ±.0008	1.08	.0058 ±.0007	.0051 ±.0012	1.14
	Mean			1.00			1.11

background were worse with the blue goggles. This is understandable, since the goggles let through the background but screen out the test stimulus. This was less true with the green background, and the yellow background resulted in no mean change.

With the blue stimulus, there were no mean changes with the blue goggles for both the blue and green backgrounds, but some slight improvement with the yellow background.

II. Acuity

Table VII gives the luminance thresholds in foot-lamberts of the Landolt C under the various conditions with the yellow goggles and its neutral equivalent. Compared to the increment threshold data, the yellow goggles were less effective in lowering the threshold for a yellow target on a blue background, and had little effect on a green or yellow background. With the blue target, there was again little change in the mean ratios whatever the background.

These measurements were repeated with blue goggles (and equated neutral goggles). There was virtually no change in the mean ratios from one condition to another, and at the same time considerable variability in the results when attempts were made to replicate them than was the case with the yellow goggles. For these reasons, these data are not presented.

DISCUSSION

These experiments show that yellow filters result in lower increment and resolution thresholds for long wavelength targets on short wavelength backgrounds. The effectiveness of the yellow filters decreases (1) as the wavelength of the background increases, (2) as the size of the target decreases, (3) with the age of the observers, and perhaps (4) as the luminance decreases. Conversely, with a blue target on a yellow background, the yellow filters interfere with visibility. No difference in the effect was found between foveal fixation and fixation 10° above the fovea.

The obvious explanation for the basic results is that the yellow filter increases the contrast of the yellow target by filtering out the short wavelength background. The effectiveness of the filter decreases with age because of the natural yellowing of the lens.[20] As this increases, an external yellow filter can, of course, add less and less to the total effect.

The extent to which the goggle-filters alter the contrast of the test stimulus is easily quantified. Using Illuminant A as the source, the luminances of the test stimuli and the backgrounds were calculated from the spectral transmittances of all components. The contrast of a test stimulus against a given background is then given by the expression $(L_t - L_b)/L_b$ where L_t is the luminance of the test stimulus and L_b is the luminance of the background.

Table VIII gives the results of these calculations. It shows, for example, that contrast of the yellow test stimulus against the blue background when viewed through the yellow goggles is 18.1, but it is only 13.6 when seen through the equated neutral goggles. On the other hand, the contrast of the

Table VII. Luminance Thresholds in foot-Lamberts of Landolt "C" Through Yellow Goggles and Equated Neutral Goggles

Background	Obs.	Yellow Target			Blue Target		
		Neutral Goggles	Yellow Goggles	Ratio (N/Y)	Neutral Goggles	Yellow Goggles	Ratio (N/Y)
Blue	AM	0.110	0.075	1.47	0.125	0.119	1.07
	CM	0.078	0.049	1.59	0.081	0.069	1.17
	SF	0.200	0.165	1.21	0.110	0.150	0.73
	M			1.42			0.99
Green	AM	0.300	0.280	1.07	0.255	0.244	1.04
	CM	0.099	0.088	1.12	0.070	0.067	1.04
	SF	0.200	0.210	0.95	0.290	0.240	1.22
	M			1.05			1.10
Yellow	AM	0.099	0.110	0.90	0.118	0.111	1.06
	CM	0.058	0.046	1.26	0.069	0.068	1.01
	SF	0.170	0.160	1.06	0.184	0.171	1.08
	M			1.07			1.05

Table VIII. Contrast Values of The Test Stimulus Against The Background When Viewed Through The Goggles

Background	Yellow Goggles		Neutral Goggles		Blue Goggles		Neutral Goggles	
	Yellow Test	Blue Test	Yellow Test	Blue Test	Yellow Test	Blue Test	Yellow Test	Blue Test
Blue	18.1	4.0	13.6	3.3	11.3	3.0	13.7	3.4
Green	19.2	4.3	16.8	4.3	14.9	4.2	16.9	4.3
Yellow	18.1	4.0	16.2	4.1	14.6	4.0	16.3	4.1

yellow test stimulus against the blue background is 11.3 when viewed through the blue goggles and 13.7 when viewed through the neutral goggles.

The ratio of the contrast through the chromatic goggles to the contrast through the neutral goggles should predict the relative effectiveness of the chromatic filter in improving the visibility of the test stimulus. These ratios are given in Table IX for both stimuli against the various backgrounds.

Table IX. Ratio of Test Stimulus Contrast through Chromatic Goggles to that through Neutral Goggles

	Yellow/Neutral Goggles	
Background	Stimulus Yellow	Stimulus Blue
Blue	1.33	1.21
Green	1.14	1.00
Yellow	1.11	0.98
	Blue/Neutral Goggles	
Blue	0.82	0.88
Green	0.88	0.98
Yellow	0.90	0.98

Table IX shows that the yellow goggles should improve the contrast of the yellow stimulus against the blue background by a factor of 1.3, while the contrast of the blue stimulus against the blue background should be improved by about 1.2. Conversely, the blue goggles should decrease the contrast of the yellow stimulus against the blue background by about one-fifth.

A comparison of Tables V and VI with Table IX shows that there is indeed a satisfactory correspondence between the calculated effectiveness of the goggles and the experimental results. It is clear, therefore, that this simple enhancement of contrast is the essential explanation of the effectiveness of the colored filters.

It is not clear why the effectiveness of the yellow filter decreases with target size. It is well known however that the center of the fovea suffers to some degree from depressed sensitivity of the blue receptor mechanisms.[21,22] Perhaps there is reduced sensitivity to the blue background along the contours of a small foveal target. The yellow filter would then be relatively less likely to further reduce sensitivity to blue and thereby increase the contrast to a yellow target. Such a mechanism would also account for the somewhat reduced effectiveness of the yellow filter for the acuity data, since in this case we are always dealing with a small target--the gap in the ring.

In conclusion, the yellow filter has been shown by these experiments to be effective in improving the visibility of yellow targets against short wavelength backgrounds. Except in the most turbid conditions, the dominant wavelength of water will be in the shorter wavelengths.[23] And if the target of interest is in the longer wavelengths, the essential conditions for effective utilization of the yellow filters exist. Thus, the underwater environment would appear to be an excellent situation for the use of the filters to improve the visibility of divers. One other point is of interest in this regard. Martin, in his study cited above,[17] reported that in his experiment the yellow lenses were effective only under conditions of simulated haze. It is well known, of course, that pictorial demonstrations of color contrast are appreciably enhanced by a sheet of tissue paper over the picture,[24] although the reason for this is not clear. In any event, some turbidity of the water is typical and thus may serve to enhance color contrast.

In short, the fortuitous combination of virtually optimal pairs of contrasting colors for use with the yellow filters as well as what may be a beneficial presence of haze in the water would appear to lead to the recommendation for the use of yellow filters by divers. The analogous use of spectral filters in photography to increase contrast is well known and has recently been discussed in connection with photography in the water.[25]

On the other hand, the effectiveness of the yellow filters will be decreased with increasing depth of water. There is, first of all, a considerable reduction in light level, and Luckiesh and Moss[5] concluded that any advantage of yellow decreases with decreasing luminance because of the Purkinje effect. Second, little long-wavelength light penetrates to the deeper depths, and so there would be no long-wavelength targets visible. The use of artificial illumination, particularly tungsten lights, should prove effective with yellow filters.

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13. ABSTRACT

Detection and resolution thresholds for blue and yellow targets against blue, green, and yellow backgrounds were measured while wearing yellow and blue filters. Yellow filters improved thresholds for yellow targets against blue backgrounds. Their effectiveness decreased (i) as the wavelength of the background increased, (ii) as the size of the target decreased, and (iii) with the age of the observer. The blue filters were generally ineffective. The results are for the most part explained on the basis of changes in target contrast brought about by the filters. The effectiveness of yellow facemasks for divers under certain conditions is discussed.

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