Effect of dysoxia and moderate air-hyperbarism on red-green color sensitivity

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Schellart NAM, Pollen M, van der Kley A. Effect of dysoxia and moderate air-hyperbarism on the red–green color sensitivity. Undersea Hyperbaric Med 1997; 24(1):7–13.—The effect of acute air-hyperbarism (maximal 520 kPa), normobaric low and high FI_{O_2} levels (minimal 0.1, maximal 1.0) and hyperbaric oxygen (HBO_2) on the red–green sensitivity ratio (rgSR) and on color discrimination for foveal vision were studied. Effects were quantified by measuring the red–green flicker (16 Hz) fusion point for normals with the Oscar tester (Am J Optom Physiol Opt 1983; 60:892–901). Color discrimination was examined with the Lanthony's Desaturated 15 Hue test. After 15–20 min of exposure rgSR is enhanced 4% (relatively increased red sensitivity) by normobaric acute hypoxia, and reduced 4% by normobaric hyperoxia ($FI_{O_2} = 1.0$), but HBO_2 gives a smaller reduction, and air-hyperbarism ($FI_{O_2} = 0.21$) has no effect. Hypercapnia (increased FI_{CO_2}), normobaric hypoxia (reduced FI_{O_2}), and HBO_2 increase the duration of the Lanthony's test about 20–40%, but the number of errors were practically unchanged. The reduced effect during HBO_2 upon rgSR is attributed to an opposing effect of hypercapnia. The absence of an effect during air-hyperbarism is probably due to a suppression by nitrogen of the effect of high P_{O_2}. In general, during moderate air-hyperbarism and HBO_2 color vision seems to be normal, but evaluation of the colored scene is probably less stable and slightly slower.

dysoxia, air-hyperbarism, red–green sensitivity, heterochromatic flicker, color discrimination

Spectral sensitivity in man, like other aspects of vision, shows small but significant dependencies on internal conditions, such as an acute change of blood ethanol level (1) and circadian rhythms (2.3). There is also a dependency on environmental, non-optical conditions, in particular the effect of a reduced P_{O_2} in the inspired gas, causing systemic hypoxia (2,4). However, the effects of a reduced P_{O_2} reported by various authors are inconsistent (2,4). In a recent study, hypobarism (altitude 4,350 m) was found to reduce the (relative) sensitivity to green with respect to red (2). After 3 days of exposure this effect was still present, although smaller.

In addition to an effect of hypobarism (aviation, mountaineering), an effect of air-hyperbarism (divers, caisson-workers) and hyperbaric oxygen (HBO_2) may be expected. We describe for the first time to what extent the relative sensitivity of the long (red) and middle (green) wavelength systems are affected a) by acute normobaric exposure to an increased FI_{O_2} (fraction of inspired O_2), b) by acute air-hyperbarism (maximal 520 kPa, normal FI_{O_2}), and c) by HBO_2, all resulting in systemic hyperoxia. We hypothesize that the effect of hyperoxia is opposite to that of hypoxia. We reexamined the effects of systemic hypoxia to test this hypothesis and to validate our methods with shorter exposures than those used in other studies (2,4,5).

To study the red–green sensitivity ratio (rgSR) we used the psychophysical method of heterochromatic flicker photometry. A change of this ratio implies a change of the photopic spectral sensitivity curve (V_λ curve). We measured the ratio of the sensitivity of the red and the green color channel. A few percent change of this ratio is expected to cause a mild, non-pathologic change of color discrimination. For systemic hypoxia, caused by a reduced FI_{O_2} and hypobarism, it has been found, with the FM (Farnsworth-Munsell) 100-Hue test, that color discrimination is impaired (5,6). With the Lanthony's Desaturated 15 Hue test we examined whether color discrimination was impaired during HBO_2 and reduced FI_{O_2}. Already at a diving depth of 20 meters of sea water (msw) ($P_{N_2} = 237$ kPa) nitrogen may cause mild N_2 narcosis. HBO_2 is known to cause hypercapnia. Therefore, it was examined whether enhanced FI_{CO_2} and high P_{N_2} influenced rgSR and color discrimination.

The preliminary results of this study have been published as an abstract (7).

METHODS

Subjects

All subjects, four female (age 22–33 yr) and eight male (age 18–63 yr) volunteers, were lowland inhabitants in

good physical condition. Under the control condition, subjects had normal color vision with both eyes, as established by the Lanthony's Desaturated 15 Hue test for color discrimination and Oscar test (stable control values between +2 and −2 Oscar units, *see* Apparatus). Not all subjects were available to perform all types of experiments. The protocol used in this study was approved by our hospital human experimentation committee. Tenets of the Declaration of Helsinki were followed. Consent was obtained from all subjects after informing them about the aim of the study, the procedures of the various experiments, the symptoms of hypoxia and hypercapnia, and the prevention of hyperventilation.

Apparatus

Heterochromatic flicker photometry: The red–green flicker fusion point (FFP) was measured psychophysically with the portable Oscar tester (8), the Objective Screening of Colour Anomalies and Reductions (Medilog, The Netherlands). The tester is based on the method of heterochromatic flicker photometry, in which an observer watches an illuminated screen, with one color (a) abruptly alternating with another color (b). The sequence a-b is generally presented at frequencies between 5 and 20 Hz. Ideally, both colors have a spectral bandwidth of only a few nanometers and are denoted by their peak wavelength. The luminance of one of the wavelengths (colors) is adjusted such that the observer perceives no or minimal flicker (FFP). Now, both wavelengths have the same subjective brightness and consequently seem to differ only in hue. However, at FFP, the two wavelengths have (in general) a different intensity. The reciprocal of the intensity gives the spectral sensitivity to that particular wavelength.

The Oscar tester: The Oscar gives an accurate estimate of the (relative) deviation of the spectral sensitivity in the red–green wavelength region with respect to the standard observer as defined by the CIE (Commission International d' Eclaraige). It quantifies the change of spectral sensitivity of the long wavelength (red) channel and the middle wavelength (green) channel in the retina, whether sensitivity changed in both color channels or in only one color channel. The change is expressed as the ratio of the sensitivity of the two channels, here called the red–green sensitivity ratio (rgSR). Information about the absolute sensitivity is not obtained, but for the present investigation this is not relevant because rgSR measured during exposure is compared to rgSR of the control condition.

Basic design of the Oscar: The apparatus comprises a red (peak emission at about 620 nm) and green (peak emission at about 560 nm) LED in a single house, which illuminate a translucent white test panel with a diameter of 5.5 mm. The brightness of the test panel matches that obtained by an ambient luminance level of about 225 lux. The apparatus is designed in such a way that the two LEDs seem to flicker in counterphase with a repetition rate of 16 Hz. The strength of the perceived flicker can be adjusted with a thumbwheel knob. For the standard observer exclusively, the zero setting yields no (or minimal) flicker. Within a 16-Hz period, the mean luminance of both LEDs (and therefore also the hue) is independent of the setting. The 16-Hz luminance flicker itself, however, increases with increasing deviations from FFP. For the constancy of mean luminance and mean hue the Oscar is superior to other devices performing the method of heterochromatic flicker photometry. The scale of the thumbwheel knob is in arbitrary units (Oscar units, OUs) from −9 to +9. Positive deviations denote a relative increase of the red vs. green sensitivity. The reverse holds for negative deviations. Subjects without color anomalies have stable FFPs between −2 and +2 OUs. Deviations between ±2 and ±5 indicate color anomalies and deviations larger or smaller than ±5 indicate color deficiencies.

Calibration of the Oscar: We calibrated the arbitrary scale of the Oscar as an equivalent change of the luminance difference between the two half 16-Hz periods. One OU corresponds to an equivalent luminance difference of 8%. Thus, −1 OU is equivalent to an 8% decrease in the red sensitivity with respect to the green sensitivity. A 16-Hz luminance flicker with a 8% intensity difference between both half periods is perceived as a strong flicker, since the 16-Hz flicker fusion threshold for moderate intensities is about 10 times smaller. Although the full scale of the Oscar is not linearly related to equivalent luminance flicker, linearity holds well between +3 and −3 OUs.

The color discrimination test: To examine color discrimination, the Farnsworth-Munsell test method was used. The various tests of this method are ophthalmologic routine tests to distinguish color anomalies and deficiencies. In these tests a series of colored caps has to be positioned in the correct order, such that the hue difference between each two neighboring caps is minimal. For the standard observer the hue difference between any pair of neighboring caps is constant. When for some reason the sensitivity of one of the color channels is changed, this constancy no longer holds. Pairs of caps with a smaller hue difference than the average value will be evaluated more slowly, thus increasing test duration. Moreover, such pairs may result in a sequence error. A small change in the photopic ambient luminance does not affect the test results. A basic advantage of the Farnsworth-Munsell test-method is that, after having done the test a few times, learning and memory effect are absent. Another advantage is its short time of

performance. Furthermore, it can be used under abnormal environmental conditions, provided that the condition of lighting is standardized and that the motor abilities of the subject are constant.

The Lanthony's 15 Desaturated Hue test was chosen because it is very sensitive and can be performed within 1 min. Even marginal, non-pathologic impairments of color discrimination are detected. With this test, 15 caps have to be positioned in the correct sequence from pale blue to pale purple.

Procedure

Hyperbaric conditions were realized in an experimental monoplace chamber (only air-hyperbarism at 4 and 5.2 atm abs; latter pressure reached within 4 min) and a multiplace chamber (Academic Medical Center, Amsterdam; HBO_2 at 3 atm abs, air-hyperbarism at 3 and 4 atm abs, latter pressure reached within 15 min). Gas mixtures were made with flowmeters and a mixture chamber. The mixture was administered via a 2.3-liter balloon, 2.5-cm-diameter tubing and over-pressure release valve, and respirator mask with demand and release valve. The flow rate of the mixture was adjusted on demand of the subject. The mask was fitted gas-tight to the subject's face. Compositions of the mixtures were checked with an oximeter (Oxicom 800D, Dräger, Lubeck, Germany) and capnograph (Hewlett Packard 78345A, Santa Clara, CA). To monitor the general physiologic condition of the subject, heart rate (HR), minute respiratory volume (MRV), and the arterial oxygen saturation (Sa_{O_2}) (Nellcor N-180 pulse oximeter Hayward, CA) were determined. Occasionally, transcutaneous P_{O_2} and P_{CO_2} (TINA^{TCM3}, Radiometer, Copenhagen, Denmark) and expired P_{CO_2} were monitored.

The FFP, for binocular foveal vision, obtained with the Oscar depends slightly on viewing distance and angle. Therefore, viewing distance was standardized (30 cm). The viewing angle between the optical axis of the aperture (0.95° visual angle) and the common optical axis of both eyes was between 0° and 4°. The experimenter verified viewing distance and angle regularly. All experiments were performed under low photopic, constant ambient light intensity. Normobaric experiments and experiments in the hyperbaric monoplace chamber were performed with an ambient luminance of 13 lux. The multiplace hyperbaric chamber had an ambient luminance of 70 lux. Control experiments showed that an increase from 13 to 70 lux increases the Oscar setting by only 0.17 OU. Since all results of exposures are related to the control condition, measurements in the multiplace chamber could be compared directly with the other test results.

Each estimate of rgSR was the mean of 16 (control) or 8 (exposure) FFP settings. Also the SD of these 16 or 8 individual FFP settings was calculated (SD_{FFP}). rgSRs that were determined while breathing normobaric air (via the mask except for hyperbaric air experiments) just before exposure to gas mixtures were used as the control value ($rgSR_{con}$). The last 3 (or 4) rgSRs obtained at least 15 min after the start of exposure (lasting up to 33 min, occasionally longer) were averaged ($rgSR_{exp}$) to quantify the influence of exposure, i.e., $rgSR_{exp}$ - $rgSR_{con}$. Similarly SD_{FFPcon} and SD_{FFPexp} of the last 3 (or 4) SD_{FFP} values were calculated.

During the experiments, subjects were not informed about their test results and during the normobaric experiments they were not informed about the composition of the breathing mixture.

During the gas mixture experiments, Oscar tests were (mostly) alternated with Lanthony's D 15 Hue tests to study the effects on color discrimination. The duration of performance of both types of tests was left to the subject.

Six to nine Lanthony's tests were performed before exposure. The last three tests were used as control set. One set of three tests was performed after 15–20 min of exposure. The duration of each Lanthony's test, performed as fast as possible, and the number and type of errors were recorded. The number of errors were scored in accordance with the method of Farnsworth for the FM 100-Hue test (9). The mean duration and mean number of errors were calculated for each set of three tests, and the differences between control and exposure condition were determined.

RESULTS

General: The rgSR ranged from +3 to −3 OUs for all subjects under all conditions. Significant age-dependent effects were not observed. All conditions tend to have slightly prolonged test durations. Figure 1 presents the data for various normobaric $F_{I_{O_2}}$ levels (O_2–N_2 gas mixtures) as a function of exposure time, measured for one subject. The maximum effect seemed to occur after 15–20 min of exposure and remained constant up to at least 45 min of exposure. Also, after 15–20 min of exposure, Sa_{O_2} and transcutaneous P_{O_2} stabilized. A similar time course was observed for other subjects and for other conditions. A slow change of the effect after many hours of exposure cannot be excluded, but this is hard to establish due to the diurnal rhythm of rgSR. Such a rhythm has been observed during altitude exposure (2) and under normobaric conditions (3). Figure 2 gives the data for the subject of Fig. 1, obtained as a function of P_{O_2} in the inspired gas from 10 to 300 kPa.

Effects of normobaric hypoxia: During normobaric respiration of O_2/N_2 mixtures with $F_{I_{O_2}} = 0.13$ and espe-

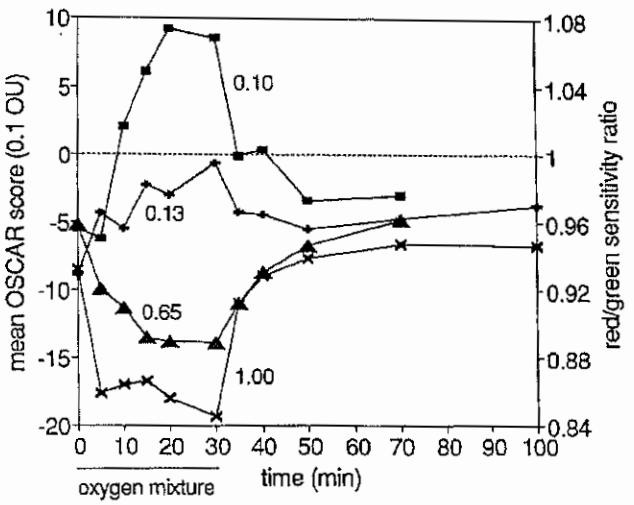

FIG. 1—Influence of normobaric O_2–N_2 mixtures on rgSR expressed in Oscar units (*vertical axis*) as a function of exposure time. (One subject, each curve mean of three sessions.) O_2–N_2 mixtures with a FI_{O_2} of 0.13 and 0.10 are equivalent to altitudes of 3,900 and 5,900 m, respectively. Figures marking the curves denote FI_{O_2}.

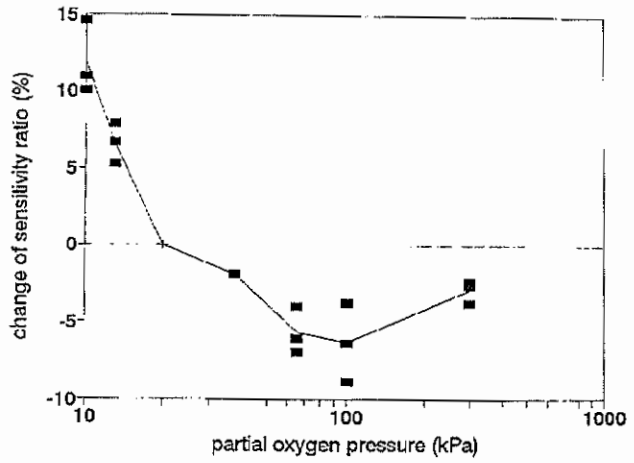

FIG. 2—Influence of oxygen on rgSR expressed in percent (*vertical axis*) as function of PO_2 (*horizontal axis*) under normobaric (10–100 kPa) and hyperbaric conditions (HBO_2 at 300 kPa). Each square denotes one session, depicting $rgSR_{exp} - rgSR_{con}$ (*see* Methods). The subject, same as in Fig. 1, showed the largest effects to a change of PO_2. Since the temperature in the hyperbaric chambers varied about 4°C during a session, the rgSRs obtained under pressure were corrected for the temperature coefficient of the Oscar (0.07 OU/°C) + control value.

cially with $FI_{O_2} = 0.10$, alertness was clearly impaired and often drowsiness, sometimes with short absences, was observed. Moreover, Sa_{O_2} decreased, and HR and MRV increased substantially (Δsa_{O_2}, ΔHR and ΔMRV in Table 1). During low FI_{O_2} levels, the variability of the Oscar settings increased. With an FI_{O_2} of 0.10, $rgSR_{exp}$ seemed to be enhanced with 4.2% by normobaric acute hypoxia as shown in Fig. 3, which gives the pooled data of all subjects. With $FI_{O_2} = 0.10$, the variability of the individual settings of FFP increased substantially. SD_{FFPexp}, obtained after averaging over the experiments, increased 84% (ΔSD in Table 1) with respect to SD_{FFPcon}. The test duration to determine $rgSR_{exp}$ was about 25% prolonged, which is more than during other conditions. The duration of the Lanthony's test was also substantially and (highly) signifi cantly increased, and the test resulted in just significantly ($P \approx 0.05$, one-tailed t test) more errors (Δt and Δerrors, respectively, in Table 1).

Effects of normobaric hyperoxia: With normobaric hyperoxia (FI_{O_2} generally 0.65 or 1.0) the basic physiologic parameters hardly changed. HR changed most with a decrease of $9 \pm 4\%$ ($P \approx 0.05$, one-tailed t test). However, $FI_{O_2} > 0.21$ clearly causes the opposite effect of $FI_{CO_2} < 0.21$. At $FI_{O_2} = 1.0$ a reduction of rgSR by 4% was found (Fig. 3).

Effect of HBO_2: With HBO_2 the duration of the Lanthony's test was significantly increased (20%), but the test did not result in more errors (Table 1). HBO_2, as normobaric $FI_{O_2} > 0.21$ reduces rgSR. However, for $PO_2 >$ 100 kPa (multiplace chamber) a further reduction of rgSR was not found (Fig. 3). The decrease of rgSR during HBO_2 at 300 kPa is only 1.2%, which is 2.8% less ($P < 0.001$, one-tailed t test; pooled data of all subjects) than with pure O_2 at 100 kPa. HBO_2 at 300 kPa gives symptoms of hypercapnia (e.g., MRV increased, Table 1). A hypotheti-

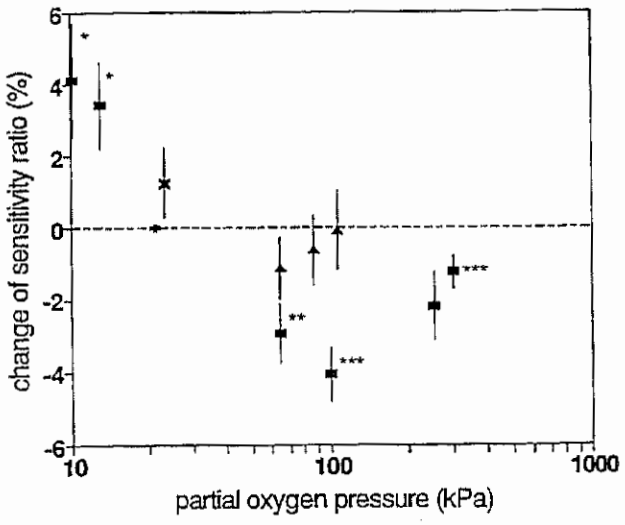

FIG. 3—Influence of PO_2 in the inspired gas under normobaric and hyperbaric conditions. *Bars* are 2 × SE. ■ Normobaric abnormal FI_{O_2} (PO_2 = 10 kPa with 5 subjects (Ss) and 11 sessions in total; PO_2 = 13 kPa, 5 Ss, 8 sessions; PO_2 = 65 kPa, 5 Ss, 9 sessions; PO_2 = 100 kPa, 7 Ss, 9 sessions), and HBO_2 (250 kPa, 2 Ss, 2 sessions; 300 kPa, 6 Ss, 10 sessions). ▲ Hyperbarism with $FI_{O_2} = 0.21$ (all pressures 4 Ss, 7, 8, and 5 sessions from low to high pressure). × Enriched, hyperbaric N_2 mixture (4 Ss, 8 sessions) + control value. $^*P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$) (one-tailed t test). The data obtained with 10 and 13 kPa taken together yield a very significant increase of rgSR ($P < 0.001$, one-tailed t test).

Table 1: Basic Physiology and Test Results Under the Most Extreme Conditions

	Physiologic Parameters			rgSR		Lanthony's Test		
Condition	ΔSa_{O_2} m±SE, %	ΔHR m±SE, %	ΔMRV m±SE, %	ΔSD_{FFP} m±SE, %	Session No.	Δt m±SE, %	Δerrors m±SE, %	Session No.
$FI_{O_2} = 0.10$	−39±2[a]	28±6[a]	37±5[a]	84±19[a]	11	39±8[a]	7.9±4.3[b]	11
HBO_2 (300 kPa O_2)	1.5	−11±2[a]	59±6[a]	90±46[b]	10	20 ±1.5[a]	−0.9±0.7	10
$FI_{CO_2} = 0.04$	0.3	10±5[b]	56±2[a]	71±25[b]	6	34±15[b]	1.6±3.7	5
Enriched N_2	0.5±0.4	−0.2±1.2	44±4[a]	48±18[b]	8	15±9	14.4±5.4[b]	5

$\Delta SD = 100\% \times (SD_{FFPexp} - SD_{FFPcon})/(SD_{FFPcon})$. Similarly, Δsa_{O_2}, ΔHR, ΔMRV, and Δt were calculated but now for arterial oxygen saturation, heart rate, minute respiratory volume, and test duration, respectively. Δerrors = (number errors exposure − number of errors during control) of the Lanthony's test. m = mean of parameter indicated averaged over number of sessions indicated; SE = standard error.

[a] $P < 0.001$ (one-tailed t test); [b] $P < 0.05$.

cal explanation is that systemic hypercapnia, mainly caused by the strong hyperoxia, reduces the effect of O_2. To test this hypothesis, systemic hypercapnia was induced by exposure to normobaric CO_2 mixtures with a FI_{CO_2} of 0.02 and 0.04 (with $FI_{O_2} = 0.21$).

Effect of normobaric hypercapnia: An FI_{CO_2} of 0.02 had almost no effect, but with 0.04 clear symptoms of hypercapnia were observed, like a significant increase of MRV (Table 1). Moreover, an FI_{CO_2} of 0.04 resulted in an increased variability of FFPs and a 34% ($P < 0.05$, one-tailed t test) increase in duration of the Lanthony's test (Table 1), but not in significantly more errors. The CO_2 mixtures increased red sensitivity by 1.4% ($FI_{O_2} = 0.02$) and 3.1% ($FI_{CO_2} = 0.04$; $P < 0.05$, one-tailed t test) (two subjects, three sessions per subject per condition).

Effect of air-hyperbarism: The variability of the performance of the Oscar test seems to be increased at all tested pressures. ΔSD of the FFP values increased 30 ± 5% (m ± SD, $n = 25$, $P << 0.001$, one-tailed t test), indicating that performance of the test is less easy than under the control condition. Figure 3 suggests that hyperbaric air gives a smaller effect on rgSR with increasing pressure. At 520 kPa there is no effect. However, it was shown that normobaric O_2–N_2 gas mixtures with the same P_{O_2}, have significant effects on rgSR. This discrepancy may be due to mild hypercapnia caused by a higher resistance of ventilation or to an opposite effect of N_2 narcosis.

Effect of high P_{N_2}: To test these possibilities, four subjects were exposed twice to a hyperbaric-enriched N_2 mixture with a normal P_{O_2} (22 kPa) and $P_{N_2} = 378$ kPa ($FI_{N_2} = 0.95$). This resulted in no change of Sa_{O_2}, an inconsistent small increase of transcutaneous P_{CO_2}, about a 60% increase of P_{CO_2} in expired gas (assumed to be due to a higher ventilation resistance), and a significant increase in MRV, associated with symptoms of mild hypercapnia. Although this gas mixture is equivalent to 38 msw, the subjects denied the feelings of N_2 narcosis. The small increase in rgSR seems to be insignificant.

DISCUSSION

The spectral sensitivity test results: The data indicate that acute systemic dysoxia, caused by abnormal FI_{O_2} levels and HBO_2, and acute systemic hypercapnia, caused by high FI_{CO_2}, affect spectral sensitivity. Paradoxically, however, air-hyperbarism has no significant effect. The red–green sensitivity ratio measured with the hyperbaric-enriched N_2 mixture seems to be increased, but the effect is not significant and too small to explain the discrepancy between the results of hyperbarism with air (no effect) and normobaric high FI_{CO_2} (strong effect). The absence of an effect during the hyperbaric enriched N_2 normal P_{O_2} mixture indicates that N_2 alone does not have an effect. Therefore, the simplest explanation of the absence of an effect during air-hyperbarism (high P_{O_2} and high P_{N_2} together) is inhibition of the effect of O_2 by N_2.

Hypoxia and hypercapnia increase red sensitivity, and hyperoxia increases green sensitivity. Since the effect of HBO_2 is much smaller than the effect of hyperoxia caused by normobaric pure O_2, we conclude that the reduction of the effect on rgSR may be attributed to hypercapnia accompanying HBO_2. This explanation is strengthened by the results of Lanthony's test. During HBO_2 this test is performed better than during application of normobaric pure O_2.

The results obtained under hypoxia confirm the results of recent field experiments at 4,350-m altitude (2) and validates our method of short exposures obtained during normobarism. The altitude experiments, performed with the Oscar and other devices to measure rgSR, showed large and significant effects, measured after 3 h of acute exposure. The effect of hypoxia in our study is smaller than in the field study. This discrepancy in size of the effect is

probably due to a developing acute mountain sickness in the field study. From a perimetry study, performed during acute normobaric exposure to low FI_{O_2} levels, Kobrick (4) concluded that the sensitivity for red is more strongly reduced than for green, which contrasts with the results of the altitude study (2) and our study. However, this conclusion cannot hold for foveal vision. A physiologic explanation for these effects of hypoxia is not known.

The color discrimination test results: On the basis of the effects on rgSR, effects on color discrimination may also be expected. Measurements were performed during systemic hypoxia and hypercapnia, HBO_2, and the hyperbaric-enriched N_2 mixture. Although variability among sessions and subjects was large, hypoxia, HBO_2 and hypercapnia resulted in substantially longer durations of the Lanthony's test (Table 1). From observations of the subjects it was concluded that the lengthening was mainly due to hesitations about the right sequence of the caps, indicating a slight impairment of color discrimination, not of motor performance. During HBO_2, motor performance was tested by putting the Lanthony's caps in a random sequence. The change of duration of the motor test (control duration 15.2 ± 1.4 s (m ± SD, n = 9) expressed as percentage of the duration of the control Lanthony's test (about 35 s) is only 3.0 ± 6.1% . Consequently, the longer duration of the Lanthony's test is completely attributed to a visual-cognitive effect. Hypoxia and hyperbaric P_{N_2} with normoxia resulted in significantly more errors (Table 1). In an earlier study under similar lighting conditions, it has been found that acute hypoxia results in more errors on the blue-yellow (tritan) axis of the FM 100-Hue test (6). Our type of errors (mostly cap transpositions in the range 11 to 14, infrequently in the range 1 to 4) suggests a small change of red–green color vision. A similar impairment has been found in another hypoxia study performed with the FM 100-Hue test (5). However, differences in the results obtained with both types of color discrimination tests are hard to evaluate for theoretical reasons and because conditions were different.

Predictions and practical impact of the observed effects: Although with respect to clinical anomalies all effects are small, they may have practical relevance, especially because the variability among and within subjects is large. The absence of an effect on rgSR during air-hyperbarism at 40 msw does not imply that for other gas mixtures no effect may be expected. Supposing that the inhibitory effect of N_2 is proportional with P_{N_2}-79 (79 kPa is P_{N_2} normobaric air) and that at 40 msw N_2 inhibits the O_2 effect completely (Fig. 3), then at 15 msw, for nitrox (FI_{O_2} = 0.4, then P_{O_2} = 100 kPa, P_{N_2} = 150 kPa) a decrease of rgSR of about 2.5% may be expected. This change in spectral sensitivity is large enough to cause a slight impairment of color discrimination abilities (slowing down and more errors) of nitrox divers (or caisson workers) at such moderate depths. With poor spatial color contrast (high water turbidity, foggy caissons) relevant objects may become invisible. The same holds for all types of recreational aviation at extreme altitudes (fog, cloudy weather), where the hypobaric systemic hypoxia can be very acute and the effects possibly stronger by the fast decompression. Awareness of impairments under such visual conditions and dangerous environmental circumstances may be worthwhile because invisibility of objects relevant to orientation and navigation can be fatal.

Other aspects of vision, such as acuity (10) and contrast vision (11), have been reported to be not (or hardly) affected by air-hyperbarism. However, it cannot be ruled out that opposing effects of N_2 and O_2 cancel each other. In contrast, visual reaction times (12) and reaction times to visual recognition are prolonged during air-hyperbarism (13), which confirms the general finding that central visual processing is slowed.

Retinal or central origin of the effects and the underlying mechanism: The change of rgSR, a change of spectral sensitivity, is thought to occur mainly in the retina. From animal research it is known that retinal neurons (especially distal ones) respond well to flicker, but for central visual neurons, flicker is generally an inadequate stimulus. Moreover, the spectral sensitivity of cells in the distal retina matches a linear combination of the (three) photopigment absorption curves. Also the (human) psychophysical spectral sensitivity curve matches such a combination. Therefore we think that changes of rgSR probably occur already in the outer retina. In contrast, neurons in the inner retina and central visual neurons show spatial color opponency, which is the neural basis for color discrimination. Since color discrimination is preceded by processing wavelength information, it is likely that the observed changes in color discrimination occur more proximally than the changes in red–green spectral sensitivity. This would imply a location in the proximal retina and central visual pathway. A similar hypothesis has been proposed by other authors (5,6).

Both systemic dysoxia and changes of systemic P_{CO_2} affect retinal vessel diameters and circulation (14) and thus indirectly, pH. However, P_{O_2} and P_{CO_2} may also directly affect rgSR. Future physiologic experiments may unravel the underlying mechanisms of the effect of systemic dysoxia on the red–green sensitivity ratio.

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