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CONTRAST SENSITIVITY OF AIR-BREATHING NONPROFESSIONAL SCUBA DIVERS AT A DEPTH OF 40 METERS [1,2]

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Summary.—Photopic contrast sensitivity of air-breathing scuba divers was measured with a translucent test pattern at depths up to 40 m. The pattern was composed of sine wave gratings with spatial frequency and contrast changing logarithmically. The spatial transfer characteristics were measured at various depths under controlled optical conditions in seawater and in fresh water. Analysis indicates that the visual contrast sensitivity, and therefore probably also acuity, of sport divers is not affected up to depths of 40 m. This holds under ideal as well as poor diving conditions.

It is generally known that the performance of air-breathing scuba divers at moderate and great depths is reduced by physiological mechanisms and psychological factors (for reviews see Jennings, 1968; Fowler, Ackles, & Porlier, 1985). A reduction in sensitivity to sensory stimuli may (partly) be due to N_2 gas narcosis for depths greater than 30 m.

Baddeley (1968) found a twofold reduction of visual line acuity when the depth of open-sea scuba dives was increased from 10 to 30 m. This study was performed with natural spacelight. From the results it is not clear whether luminance, which can affect acuity substantially (Pirenne & Denton, 1952), or water turbidity, which influences contrast (Lythgoe, 1968), may have played a role. In addition to a possible N_2 narcosis effect, influence of temperature, which changes with depth, and psychological factors like anxiety (Davis, Osborne, Baddeley, & Graham, 1972) may have played a role. A low temperature and anxiety may impair visual abilities. These disturbing factors, hampering the interpretation of the data, do not play a role in a recompression chamber. In a dry recompression chamber visual acuity of air-breathing subjects, measured with a Landolt C test, generally did not decrease up to a pressure of 7.0 ATA (687 kPa) (Schellart, 1976). However, for free dives it cannot be ruled out that in addition to N_2 narcosis also anxiety will affect acuity. Therefore, spatial visual performance was reexamined with scuba divers. For the present experiments it is supposed that for experienced divers anxiety does not occur at 6 m depth, whereas a possible oc-

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currence of anxiety at 20 and 40 m is supposed to be roughly the same at both depths. In this way the effect of anxiety alone and a combined effect may be discerned. By choosing this approach the interpretation of the data is independent of the way anxiety influences contrast sensitivity, e.g., whether the effect is additive or multiplicative to the narcosis effect.

Contrast sensitivity to sinusoidal gratings, measured as a function of spatial frequency, was chosen as the test paradigm instead of acuity. Contrast sensitivity was preferred above acuity, since all frequencies are subsequently tested, whereas on an acuity test a combined sensitivity to many frequencies together is measured with the emphasis on the high frequencies. In natural waters, due to scatter and absorption, and optical imperfections of the glass in the face mask, the highest spatial frequencies are more strongly attenuated than intermediate and low spatial frequencies. Given these external factors, vision of very fine details is lost underwater.

Contrast sensitivity was estimated under ideal (Mediterranean) and comparatively difficult (Dutch lake) circumstances. The mental stress of divers was believed to differ substantially at the two locations, with anxiety, if any, being higher at the latter location. Measurements were made at 6, 20, and 40 m with constant, artificial illumination of the test object to eliminate any influence of turbidity and variable spacelight.

Method

Subjects

At Corse, six subjects (one female and five males) were tested up to 40 m, and in addition three divers (of whom two had less experience) were tested at 20 m. Two of the three subjects for the fresh water lake had done the experiments before at 40 m in Corse. During the test all used the same face mask and were wearing wet suits. The subjects, all sport divers, had normal vision, did not wear spectacles, and were 31 to 44 years old. The divers who did the test at 40 m were moderately to well experienced at depths up to 30 m, and had occasionally reached (2 to 7 times) depths between 40 and 50 m. All were diving monthly during the season. However, dives beyond 30 m had not been made a fortnight in advance of the experiment to prevent adaptation.

Conditions

At Corse the experiments were done at the east coast in the late midsummer mornings with quiet sea (sea state mostly 3 or less), unclouded air, and water visibilities from 20 to 35 m (measured in horizontal direction with a white diving bottle). At 40 m depth, ambient light was still photopic and temperature 14° to 16° C. At 20 m and 6 m temperature was 16½° to 18½° C and 20½° to 22° C, respectively. The divers did not feel impaired in any way by these temperatures.

In the Dutch "Oostvoornse Meer," temperature was 6° C at 40 m, 6° to 9° C at 20 m, and 13° to 15° C at 6 m, depending on the season (autumn and late spring). Temperatures of 6° to 9° were judged as unpleasant. At 40 m depth, ambient light levels were scotopic and at 20 m scotopic to low twilight. Visibility was 4 m to 8 m.

The small temperature difference between 20 m and 40 m, about 2° C, makes it unlikely that this temperature difference causes a difference in sensitivity between the two depths. All divers claimed that they were not anxious and did not feel N_2 narcosis symptoms during the test. However, for all subjects mental stress was probably higher than before a normal dive. In fresh water the test was considered as fairly difficult, especially at 20 and 40 m (darkness, low temperatures). The task was to do the test as accurately as possible at a speed left to the subject.

Apparatus

The main components of the apparatus were an underwater torch, a grating holder with the grating illuminated by the torch, and a face mask holder, to ensure that the distance from grating to eye was always the same. These three parts were mounted on an optical bench.

Contrast sensitivity was measured with a translucent photograph of a sine wave grating of variable spatial frequency and contrast. Along the horizontal axis the spatial frequency increases nearly logarithmically from 1.5 periods/cm at the left to 67 periods/cm at the right, or 1.0 to 45 cycles/degree. From bottom to top contrast modulation depth decreases (practically) logarithmically from ca. 45% to 0.40%. [For a photograph of such a grating see, e.g., Ratliff (1974).] Average background grey was constant all over the sheet, measuring 147 × 118 mm. The distance between grating and eye was 50 cm. The quality of such gratings is insufficient to perform precise, absolute measurements, but certainly good enough to do comparative measurements like the present ones. Although the reproducibility of this method is not as good as for other tests, it is the only appropriate and fast test (ca. 1.5 min. at every depth) to measure contrast sensitivity in open sea underwater experiments. (For comparison, measurement of acuity underwater by a Landolt test with 100 Cs while using an underwater telephone will last at least 5 minutes.)

The grating sheet was mounted in a waterproof holder and was illuminated indirectly by a 50-W, 12-V iodide lamp, mounted in a torch-house and driven by rechargeable batteries. At the side of the torch, directly behind the grating, a milky Perspex panel was inserted to obtain a homogeneous illumination of the test grating. The mean photopic luminance level of the grating, as seen by the subject, was 216 cd/m^2, a level that occurs under good diving conditions (unclouded air, clear water, and shallow depths). It is nearly the level of maximal contrast sensitivity.

At the subject's side of the test plate a thin Lexane sheet could be tightened in the grating holder. On this sheet, the subject had to draw the spatial transfer characteristic, i.e., the line indicating the border between visibility and invisibility of the grating. The light path from torch to grating holder within sea or lake water itself was restricted to 3 cm by fitting a nontranslucent tube (of 45 cm in length) filled with tap water and closed at each end by a Perspex window. A similar tube (33 cm in length) was inserted between the grating holder and the face mask. The optic pathway from grating to mask through natural water was restricted to 14 cm. Nearly this whole distance was in front of the grating to enable inserting the Lexane sheets and drawing. The tubes prevented any significant influence of turbidity of the diving water. The apparatus was suspended on a rope and was 1.5 to 4 m above the bottom at the greatest test depth.

Procedure

At each depth a set of four curves were drawn on a single Lexane sheet (by turning the sheet 180° and using both sides). The curves were drawn from left to right. For statistical analysis the curves were sampled at 5-mm and 10-mm intervals.

Measurements were subsequently made by a buddy pair at 6, 40, 20, and again at 6 m (all depths, except 6 m ± 2 m). A depth of 40 m was chosen since this is below the transition zone around 30 m where effects of nitrogen narcosis start to occur. The first test, at 6 m during the descent, was used as practice. The second test at 6 m during the ascent was used as reference.

Results and Discussion

Fig. 1a presents the contrast sensitivity recorded in air with the complete apparatus, but without a face mask and with high ambient light levels. Measurements in air under the same conditions (no direct sunlight) but with the lamp switched off yielded a decrease in sensitivity of 0.15 log unit (LU) for frequencies up to 15 c/d (cycles/degree) and a shift of the cut-off frequency from 24 to 18 c/d (Subject NS). Both effects are caused by the lower luminance of the grating (Van Nes & Bouman, 1967). In water the cut-off frequency shows a shift to higher frequencies by a factor of about 1.2, which is caused by the enlargement of the visual angle according to Snell's law, when wearing the face mask underwater. However, the theoretical factor of 1.33 is not reached, which may be due to optical imperfections of the face mask. From the control experiments in air it is concluded that ambient light levels in the water, irrespective of depth and cloudiness, did not influence the measures.

In air the variability among the four curves is smaller than underwater for all depths, a difference which is mainly caused by suboptimal motor control of the floating diver during drawing in the water.

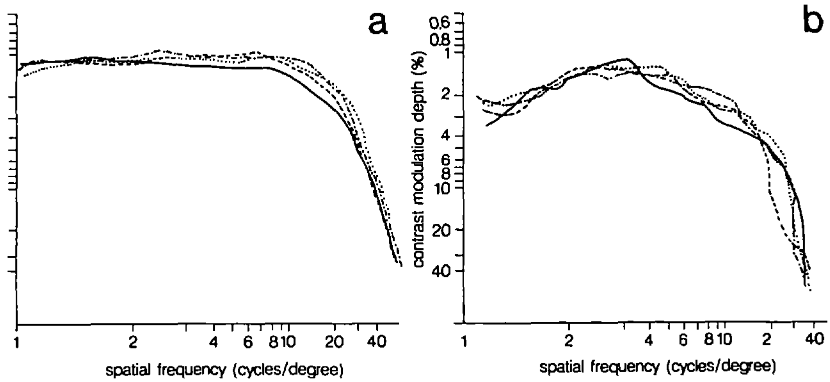

FIG. 1A AND 1B. Contrast sensitivity curves in air (a: Subject NS) and at 40 m depth (b: Subject WS). The curves display the actual recordings.

Fig. 1b gives the four contrast curves at 40 m for one of the subjects. The vertical scatter of this set amounted to 0.06 ± 0.05 log unit ($N = 52$, 13 samples at 1-cm intervals, Subject WS), expressed with respect to the normalized mean of the four curves. The spatial transfer characteristic typically has a steep high frequency cut-off (about 36 dB/octave) and a weak low frequency attenuation (intra-individual range ½ to 5 dB/octave).

The four curves estimated at each of the three depths were averaged for each subject. Next, for each subject, the mean curve obtained at 6 m was subtracted from that at 40 m and from that obtained at 20 m. The 40 m versus 6 m (40/6) and 20 m versus 6 m (20/6) difference curves, obtained in sea, are depicted in Figs. 2a and b. Both panels also give the interindividual mean (dots).

To know whether the interindividual difference is significant, the difference curves must be analysed using statistical methods. Since contrast sensitivity values at the various frequencies are not independent of each other, the values along the frequency axis of the difference curve are correlated. Therefore, from a statistical point of view the difference curve should be considered as a single value. The mean values of each 40/6 curve and 20/6 curve of all tests were calculated (Table 1). Both the 40/6 and 20/6 data do not deviate significantly from 0 LU (*t* test). Also the 40/6 and 20/6 data do not deviate significantly from each other (paired *t* test). Comparing the data of Corse and the lake show that, despite the poor diving conditions in the lake (lower temperature, lower visibility, lower ambient light levels, especially at 20 and 40 m), contrast sensitivity in the lake at 40 m was not diminished.

Although the number of subjects is certainly limited, it is doubted whether an increase in number will change the results substantially due to

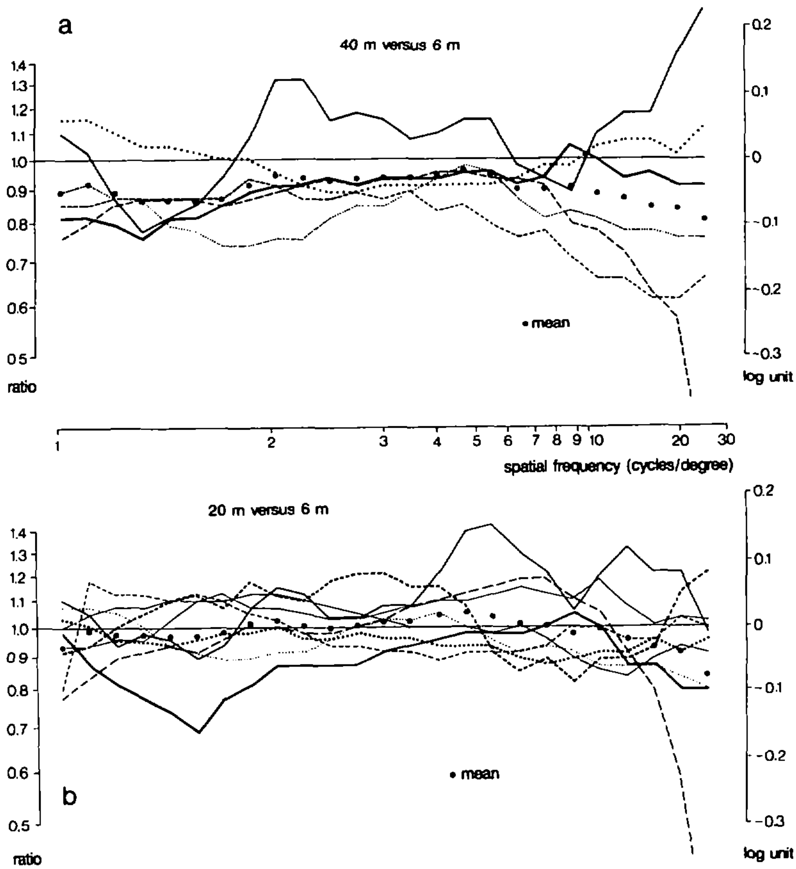

FIG. 2. Differences in contrast sensitivity at 40 m (a) and 20 m (b) with respect to 6 m. For clarity, only the data of the experiments done in the Mediterranean are shown. In Figure (a) the results of the six subjects are indicated by six different types of curves. These curves correspond with those in Figure (b). The thick solid dots are the averaged values of the subjects.

the large interindividual scatter. Only a very large sample could show any significant decrease, but it will be so small that it has no practical meaning. Nevertheless, for an individual, also dependent on his condition, a slight impairment can occur. For three of the six divers tested at Corse, the contrast sensitivity curve at 40 m showed for all frequencies (up to 25 periods/degree) a threshold decrease with respect to 6 m. For one of them (Subject NS), with low scatter among the individual recordings, it was examined whether the four 40-m curves did deviate significantly from the four 6-m curves. To this end, the mean contrast sensitivity curve, based on the 12 (3 × 4) curves, was calculated. This mean curve was subtracted from the 12 individual curves yielding 12 difference curves. The appropriate fit of the curves appeared to be a horizontal line, i.e., the difference averaged over frequency. With a statistical test applied to these differences (*t* test and a Lord-test for small numbers) for this subject the sensitivity was slightly smaller at 40 m than at 6 m ($p < 0.05$). However, the subject with the largest deviation at 40 m (Subject RR, Table 1) did not show a significant decrease in sensitivity at 40 m, due to the large variation among the curves at a specific depth. The same holds for Subject GB, the third subject with a lower sensitivity at all frequencies. Surprisingly Subject NS did not show a decrease at 40 m in the lake. Apparently, changes of contrast sensitivity at 40 m compared to 6 m show small daily variations.

TABLE 1
MEAN DIFFERENCE IN CONTRAST SENSITIVITY IN LOG UNITS

Subject	40 m vs 6 m	20 m vs 6 m
Corse		
GJB	-0.079	0.015
GK	-0.045	-0.052
R	-0.092	-0.034
NS	-0.083	-0.025
GS	-0.002	-0.027
WS	0.030	0.039
JB		0.003
ERP		-0.006
NS		-0.006
Dutch lake		
GK	0.028	-0.024
NS	0.017	-0.021
NSN	-0.007	-0.021
Total Mean	-0.026 ± 0.049	-0.014 ± 0.024

Note.—0.026 LU is 1.3 mm on the grating sheet.

It would be interesting to know the impact of occasional reductions in contrast sensitivity. For a diver, a decrease in contrast sensitivity is perceived as a reduction in viewing distance, due to the much shorter viewing distance underwater than in air. For a horizontal path of sight, contrast diminishes exponentially with distance, according to $C_r = C_0 e^{-r/\tau}$ with C_r contrast of a target at a distance of r meter, C_0 contrast at 0 meter and τ the space constant (Lythgoe, 1968). Consequently, the viewing distance D_{40} at 40 m depth is given by: $D_{40} = D_6 - 2.3\tau d$ with D_6 viewing distance at 6 m depth and d the sensitivity decrease in LU (under the assumption of optical conditions being invariant with depth). Since $D = c\tau$, with c a constant, the relative reduction in viewing distance is 230 d/c%. The constant c decreases from nearly 4 at low frequencies to 3 at 20 c/d (calculated from Fig. 1 with 100% initial contrast). A 0.08 LU reduction in contrast sensitivity yields a decrease of viewing distance with 5%, a value too small to impair the visual performance when actually diving.

The present findings are in general agreement with the invariance of visual acuity at 7 ATA (Schellart, 1976) and of other simple visual tests during N_2O breathing (see Fowler, *et al.*, 1985, for references). However, other variables of visually induced performance, like the reaction time to a reading recognition task at 6.5 ATA (Fowler, Pogue, & Porlier, 1990), were affected.

It is well known that the effect of high nitrogen pressure may be drastic, like memory failures and inadequate behavior (Jennings, 1968; Fowler, 1972; Fowler, *et al.*, 1985). However, the effect of high nitrogen pressure on vision appears to be moderate. The critical flicker fusion frequency only decreases slightly (Bennett & Cross, 1960) and acuity is not affected (Schellart, 1976). It is known that complex recognition tasks and complex psychomotor performance are seriously impaired under high nitrogen pressure, whereas simple tasks were less or not affected (Kiessling & Maag, 1962; Biersner, Hall, Linaweaver, & Neuman, 1978; but see Fowler, 1972).

Contrast discrimination is thought to be a simple visual task, in which the performance of the eye and lower-order visual brain centers play a dominant role. Drawing the contrast threshold curve is also thought to be a relatively simple visually controlled motor task in which higher brain centers are assumed not to play a prominent role. Another fairly simple task, oral specification of the opening of a Landolt C in an acuity test, also did not show a decreased acuity at 7 ATA (Schellart, 1976). Therefore, it is concluded that spatial vision and simple, visually guided, motor control performance are not impaired at 40 m. Due to the found invariance the question, which model explaining the influence of inert gas narcosis (Fowler, *et al.*, 1985) holds, is not under discussion.

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