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Superior Underwater Vision in a Human Population of Sea Gypsies

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Summary

Humans are poorly adapted for underwater vision. In air, the curved corneal surface accounts for two-thirds of the eye's refractive power, and this is lost when air is replaced by water [1]. Despite this, some tribes of sea gypsies in Southeast Asia live off the sea, and the children collect food from the sea floor without the use of visual aids [2]. This is a remarkable feat when one considers that the human eye is not focused underwater and small objects should remain unresolved. We have measured the visual acuity of children in a sea gypsy population, the Moken, and found that the children see much better underwater than one might expect. Their underwater acuity (6.06 cycles/degree) is more than twice as good as that of European children (2.95 cycles/degree). Our investigations show that the Moken children achieve their superior underwater vision by maximally constricting the pupil (1.96 mm compared to 2.50 mm in European children) and by accommodating to the known limit of human performance (15–16 D) [3]. This extreme reaction—which is routine in Moken children—is completely absent in European children. Because they are completely dependent on the sea, the Moken are very likely to derive great benefit from this strategy.

Results and Discussion

Several animals, such as amphibious fishes, frogs, birds, and insects, are known to have evolved special adaptations—such as a flattened cornea or greater accommodative power—to be able to see well in both air and water [1, 4]. The human eye, however, is generally considered a typical example of a terrestrial eye because it uses both the curved outer cornea and an internal lens to refract the incoming light. If a human eye is immersed in water, which has about the same refractive index as the cornea and aqueous humor, the image becomes severely blurred because the eye loses about two-thirds of its refractive power. Thus, human eyes underwater produce a severely defocused image.

All over Southeast Asia live human populations called sea gypsies, a people known for their skills in swimming and diving [2]. The children do not use visual aids when diving for shells, clams, and sea cucumbers. For this, good underwater vision should be essential. A particular tribe of sea gypsies, the Moken, live in the archipelago of Burma and along the West Coast of Thailand [5]. Because these children clearly manage to see small objects underwater, we suspected that the Moken might be adapted for improved underwater vision.

We tested the visual acuity of six Moken children. We used 28 European children in the same age range, on holiday with their families in nearby areas, as a control group. We set up a head-stabilizing apparatus underwater with a fixed viewing distance. With this apparatus, we presented the children with achromatic sinusoidal gratings of different spatial frequencies. The results clearly show that the Moken children have significantly better underwater acuity (Mann-Whitney test: $p < 0.001$); they were able to resolve gratings (100% contrast) more than twice as fine as those resolved by the European children (Moken children: 6.06 ± 0.59 cycles/degree (mean ± SE), European children 2.95 ± 0.13 cycles/degree). When further tested with gratings having a range of different contrasts, the Moken children also had higher contrast sensitivities underwater at all spatial frequencies presented (Figure 1).

We next performed several experiments to explain this improved underwater vision. Some of the possible explanations require the eye to have undergone drastic changes in morphology. If, for instance, the Moken have evolved a flatter cornea and a stronger lens, they would achieve good resolution on land and improved resolution when diving. If, instead, they have become severely myopic, this would improve vision underwater but result in blurred vision when on land. And finally, if Moken children simply have the ability to accommodate more than normal, this too would improve underwater vision. All three of these strategies are known to exist in the animal kingdom. We thus examined (on land) the eye's corneal curvature (keratometry), refractive state, and accommodative power in both groups of children. These results show us that on land the Moken children do not differ from the European children in any of these respects. The keratometry values are well within the normal range [6] in both groups. The majority of the children are slightly hyperopic, with refractive errors ranging from +2 to −0.5 D, and there is no difference in accommodative range between the two groups of children. In conclusion, all results are well within the normal limits for children of that age range.

However, we did find one important difference concerning pupil size. On land, pupil size normally has little effect on resolution, and both groups of children were found to have the same pupil size (Moken children, 2.33 ± 0.06 mm, $n = 6$; European children, 2.30 ± 0.04 mm, $n = 15$; Mann-Whitney, $p = 0.48$). But underwater,

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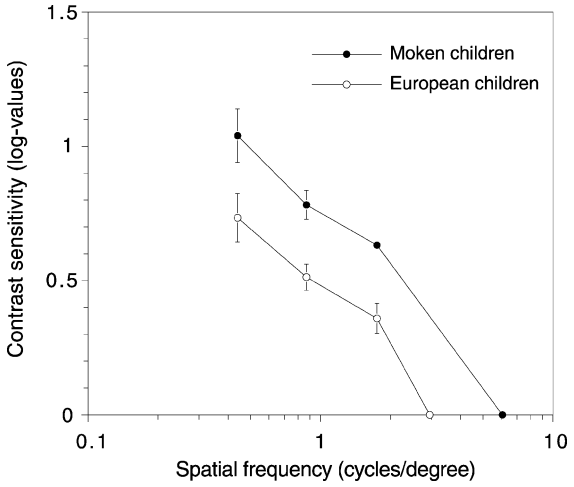

Figure 1. Contrast Sensitivity Underwater

Filled circles, Moken children; open circles, European children. The Moken children have greater sensitivity to contrast at all spatial frequencies tested ($p < 0.05$ at the lowest frequencies, down to $p < 0.0001$ at the highest frequencies).

when the image is severely blurred, a smaller pupil can significantly improve resolution. Our measurements clearly show that there is indeed a difference underwater; when diving, the Moken children constrict their pupils, whereas European children do not, and pupil size differs significantly (Figure 2, Moken children, 1.96 $\pm$ 0.05 mm, $n = 6$; European children, 2.50 $\pm$ 0.05 mm, $n = 15$; Mann-Whitney, $p < 0.001$).

We assume that two opposing forces are at work here. One acts to open the pupil to increase the amount of light entering the eye as light levels decrease underwater. The other acts to constrict the pupil as the Moken children accommodate to see the spatial pattern—in bright light accommodation is normally coupled to a reduction in pupil size [7–9]. In the Moken children the force favoring accommodation is evidently the stronger one, but the European children seem not to accommodate at all. Unfortunately, available methods for measuring accommodation underwater require a pupil size of at least 3–4 mm, which is much larger than pupil sizes under our experimental conditions.

For optical reasons, human visual acuity underwater is severely limited, and the image on the retina will be out of focus. Because a severely blurred image usually triggers very little accommodation, or none at all [10, 11],

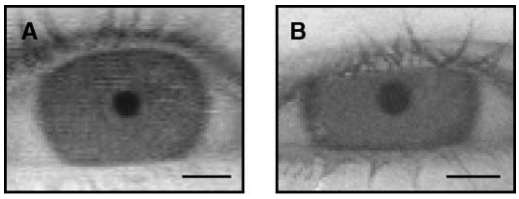

Figure 2. Images of Pupils Underwater

The pupil of a Moken child (A) is smaller than the pupil of a European child (B). Both images were taken with infrared light. Scale bars = 4 mm.

the response from the European children when diving is as one would expect. They open their pupil slightly, possibly in response to dimmer light, and show no evidence of accommodation. The Moken children, on the other hand, constrict their pupils when diving. Besides being an indicator of accommodation, this on its own improves spatial resolution because the diameter of the blur circle on the retina decreases with decreasing pupil size. In fact, the smaller pupil can explain a large part of the improvement in underwater vision (Figure 3), but the remaining part must be due to accommodation.

How much then do the Moken children accommodate? Knowing that the underwater acuity of Moken children is roughly twice as good as that of European children (Figure 1), we can calculate that the amount of accommodation necessary is about 15–16 D (Figure 3). This is actually the reported limit of accommodation for children of that age [3]. The pupil cannot constrict beyond 2 mm [7], so the Moken children both accommodate and constrict their pupil to the limit of human performance.

We can only speculate as to why the Moken children constrict their pupil and accommodate underwater and the European children do not. It has been shown that subjects can learn to accommodate voluntarily [12–14]. The Moken may learn to do this due to their extensive use of their eyes in water, where accommodation and concurrent pupil constriction is necessary for them to see the items they gather for food. It should then be possible for all humans to learn to see better underwater. But because sea gypsies have lived by and off the sea for thousands of years [5], evolution may also have favored those who had intrinsically better underwater accommodative powers. The ability to see well underwater could have become a genetic trait. Another possible explanation is that accommodation underwater is a side effect of the diving response; the parasympathetic nerves that control this reflex also control pupil constriction [7]. Other human populations that have a similar lifestyle to the Moken, for example the Bajau in the Philippines [15] or the Ama in Korea and Japan [16], are known to have an unusually strong diving reflex. Whatever its source, this behavior in Moken children is clearly an adaptive strategy.

Experimental Procedures

Underwater Acuity and Contrast Sensitivity

The Moken children (four females and two males, age = 8–13 years) were tested in the clear waters of Ko Surin National Park in Thailand. European children (17 females, 11 males, age = 7–14 years) were tested either on Ko Surin, Ko Poda, or Ko Phi-Phi, all in Thailand. In accordance with the Declaration of Helsinki, full consent was obtained from both children and parents before the experiments. All measurements were done outdoors during days with a clear sky between 10 a.m and 2 p.m. Achromatic sinusoidal gratings with spatial frequency 1.25, 1.45, 1.75, 2.18, 2.91, 4.36, 5.82, and 8.73 cycles/degree with 100% contrast were used as stimulus patterns. The pattern subtended 22.6° at the eye. The child dived down and rested his or her forehead against a stationary headrest placed 50 cm in front of the pattern. This apparatus was angled at 90° against the sun. The patterns were presented randomly, with an orientation that was either vertical or horizontal. When the child surfaced, he or she was asked to point to the correct pattern on a chart showing both possible orientations. Each grating was presented five times, and five correct answers were interpreted as evidence that the child

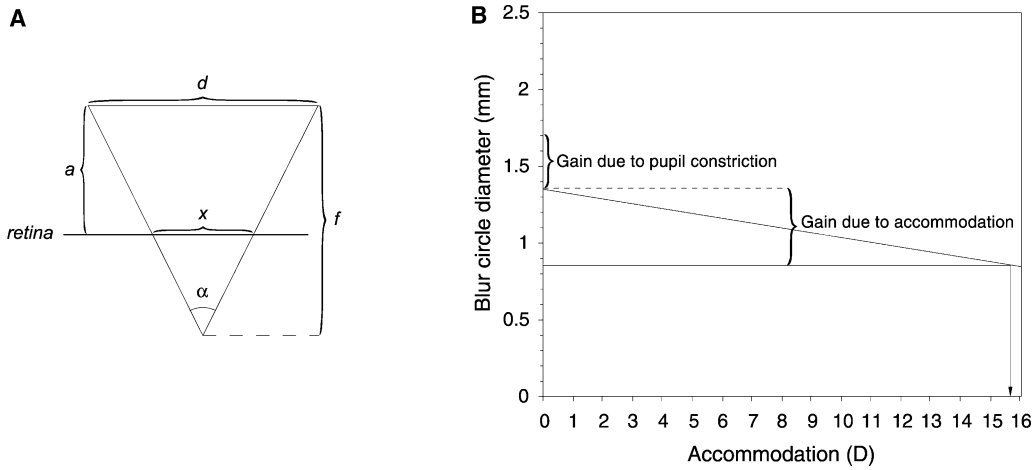

Figure 3. Amount of Defocusing Underwater

(A) According to simple geometry, the diameter of the blur circle (x) on the retina is $d(f\text{-}a)/f$, where d is the diameter of the pupil, f the focal length, and a the distance to the retina from the lens. (B) The solid line shows how the size of the blur circle on the retinas of Moken children changes with their accommodative response, if one assumes that pupil size stays constant. If we assume that the European children do not accommodate underwater, their blur circle diameter is 1.71 mm. The Moken children need to accommodate 15.7 D (arrow) to reduce the diameter of the blur circle to half this value (0.85 mm). When the Moken children dive, their pupil size decreases from 2.33 mm on land to 1.96 mm underwater.

could resolve the grating (the probability of the child by chance guessing correctly five times is then less than 0.05). Any other result was interpreted as an inability to see the pattern. Finer gratings were then presented until the child could no longer correctly determine which way the gratings were oriented. The finest grating the child could resolve was taken as the resolution limit. For contrast sensitivity measurements, gratings of 0.44, 0.87, and 1.75 cycles/degree with various contrasts (log values 1.6, 1.4, 1.1, 0.95, 0.87, 0.65, 0.56, 0.40, and 0.30) were used. The contrast was lowered until the child could no longer correctly determine the orientation of the gratings. Contrast sensitivity was then defined as the reciprocal of the lowest (threshold) contrast at which the child correctly judged the orientation.

Accommodation and Refractive Error

Seventeen Moken children (ten girls, seven boys, age = 7–13 years) and 18 European children (14 girls, four boys, age = 7–13 years) were tested. The Moken children were examined in a rural area where no electricity was available. Because they are illiterate and have a strong tendency to agree with the examiner, a dioptric method, together with a preferential-looking technique at a distance of 1 m, was developed to evaluate accommodative ability and refractive error [17]. In brief, this method consists of a card with a peeping hole in the center, through which the examiner can observe whether the subject preferentially looks at the stimulus on one end of the card, or a "blank" consisting of a gray patch on the other end of the card. A Teller acuity card equivalent to Snellen acuity 0.8 (20/25) [18] was used in combination with lenses varying from +5 D to −10 D. Accommodative range was calculated as the difference between the most positive (least negative) and the most negative lens that gave a positive result in the preferential-looking test. When estimating the accommodative range, we accounted for the testing distance. Reducing the measured refractive errors by one diopter compensated for the fact that no cycloplegia was used to paralyze the ciliary body.

Keratometry

Seventeen Moken children (ten girls, seven boys, age = 7–13 years) and 18 European children (14 girls, four boys, age = 7–13 years) were tested. In order to determine the curvature of the cornea, we constructed a simple keratometer by using a 35 mm camera and a disk of Placido, a circular plate with concentric rings in black-and-white. Via a small hole in the center of this disk, an image of the reflected rings on the cornea can be obtained. The shapes of these rings are then used for calculating corneal curvature [19]. Both eyes of each examined child were photographed several times. Pictures were transferred to a computer, and keratometry values were calculated with Matlab software [19].

Pupil Measurements

The children were filmed with an infrared-sensitive video camera (Sony) in a watertight shell. For pupil illumination, an infrared light source consisting of 48 light-emitting diodes was positioned in a ring around the camera lens. The lens was covered with an infrared-transmissive filter (RG9). Extracted images were digitally filtered, and the mean pupil size was calculated.

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