On the optical theory of underwater vision in humans

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Defocus changes the visual contrast sensitivity function, thereby creating a complex curve with local dips and peaks. Since underwater vision in humans is severely defocused, we used optical theory and the phenomenon of spurious resolution to predict how well humans can see in this environment. The values obtained correspond well with experimental measurements of underwater human acuity from earlier studies and even point to an opportunity for humans with exceptional contrast sensitivity to see better underwater than the children in those studies. The same theory could be useful when discussing the visual acuity of amphibious animals, as they may use pupil constriction as a means of improving underwater vision. © 2004 Optical Society of America

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1. INTRODUCTION

Contrast sensitivity declines quite rapidly with even small amounts of defocus. Parameters such as pupil diameter and spatial frequency will affect the contrast sensitivity function during defocus in a way predicted by optical theory,[1] showing that the resulting complex curve is not smooth but contains several local dips and peaks. Some studies have theoretically and experimentally shown how contrast sensitivity can change in humans with only a few diopters of defocus.[2,3] However, there is one situation in which humans experience a considerable amount of defocus and that has never been considered, namely, unaided underwater vision. Without the help of goggles, our vision is severely blurred when we dive. Because of the similar refractive index of water and the aqueous humour behind the cornea, we lose ≈43 diopters (D) of refractive power when our eyes are immersed in water, and this loss generally makes vision underwater quite difficult.

However, in a recent study, Moken children from a tribe of sea nomads in Southeast Asia have been found to have an underwater visual acuity that is more than twice as high as that of European children.[4] It has been shown that this ability comes from a trained response to control accommodation that is followed by pupil constriction: After practice, European children learn to control their accommodation and show the same visual acuity underwater as the Moken children.[5] Pupil constriction and substantial accommodation (up to 16 D) endows these children with enhanced underwater acuity.

The main purpose of this study is to use optical theory to predict how well humans can see during conditions of extreme defocus such as those experienced underwater.

2. THEORY AND RESULTS

We first calculate the contrast sensitivity required for detecting the defocused image of a sinusoidal pattern on the retina. As we are studying cases with very large defocus (≈43 D), we can safely ignore diffraction effects. Light levels are high in tropical countries, and the light flux on the retina can be assumed to be constant, irrespective of small changes in pupil size.

The geometric modulation transfer function S of a sinusoidal wave modulation is given by[1]

$$S = \frac{2J_1(z)}{z}, \tag{1}$$

where J_1 is the first-order Bessel function and z the dimensionless parameter

$$z = \pi B f_S, \tag{2}$$

where B is the diameter of the blur circle produced by defocusing and f_S the spatial frequency of the sinusoidal wave pattern in cycles per meter. For our purpose it is more convenient to use the equivalent parameterization

$$z = 0.180 f_a P \Delta D, \tag{3}$$

where f_a is the angular spatial frequency of the wave pattern in cycles per degree, P the pupil diameter in millimeters, and ΔD the defocus in diopters. All these quantities can easily be measured. At the higher spatial frequencies that we consider in this paper, we can use the function

$$C = -\log(|S|) \tag{4}$$

as the contrast sensitivity necessary to detect a sinusoidal pattern. The z positions of the minima of the function C

