The purpose of this study is to determine visual performance in water, including the influence of pupil size. The water environment was simulated by placing goggles filled with saline in front of the eyes with apertures placed at the front of the goggles. Correction factors were determined for the different magnification under this condition in order to estimate vision in water. Experiments were conducted on letter visual acuity (seven participants), grating resolution (eight participants), and grating contrast sensitivity (one participant). For letter acuity, mean loss of vision in water, compared to corrected vision in air, varied between 1.1 log min of arc resolution (logMAR) for a 1 mm aperture to 2.2 logMAR for a 7 mm aperture. The vision in min of arc was described well by a linear relationship with pupil size. For grating acuity, mean loss varied between 1.1 logMAR for a 2 mm aperture to 1.2 logMAR for a 6 mm aperture. Contrast sensitivity for a 2 mm aperture deteriorated as spatial frequency increased with a 2 log unit loss by 3 c/°. Superimposed on this deterioration were depressions (notches) in sensitivity with the first three notches occurring at 0.45, 0.8, and 1.3 c/° with estimates for water of 0.39, 0.70, and 1.13 c/°. In conclusion, vision in water is poor. It becomes worse
as pupil size increases, but the effects are much more marked for letter targets than for grating targets.

## Introduction

The human eye is poorly adapted to an aquatic environment. Some vertebrates have good vision both in air and in water due to features such as a combination of a flat cornea and a highly powered lens so that the majority of refraction occurs always in the lens, part of the eye being adapted to air and part to water by having two optical axes coinciding with the principal meridians of highly elliptical lenses, powerful intraocular muscles to make considerable changes in the shape of the cornea and/or the lens, and reduction or change in pupil shape above water compared with in water (Herman, Peacock, Yunker, & Madsen, 1975; Katzir & Howland, 2003; Levy & Sivak, 1980; Mass & Supin, 2007; Murphy et al., 1990; Schaeffel & de Queiroz, 1990; Schusterman & Balliet, 1970; Sivak, 1976, 1978; Sivak & Vrablic, 1979). When the human eye is immersed in water, the anterior cornea power, responsible for two thirds of the eye’s power in the unaccommodated state, is largely neutralized, leaving the eye with severe hyperopic defocus of about 43 D. This can be overcome by goggles or masks that restore the air-anterior corneal boundary and have a flat boundary of zero power between the water and the goggles/mask.

The few studies of human uncorrected vision in water involved people being placed underwater and either holding their breath, breathing through a snorkel, or using underwater breathing apparatus. Luria and Kinney (1969) found grating resolution loss for 15 emmetropes of 1.33 ± 0.15 log min of arc resolution (logMAR) at 3.0 m and 1.02 ± 0.04 logMAR at 0.81 m in water compared with in air with the difference at the two distances being attributed to water clarity. Across the emmetropes, six myopes, and two hyperopes, resolution in water was 1.07 ± 0.13 logMAR. Cramer (1971) determined mean vision underwater for a group of subjects for a Landolt C target to be 2.3 logMAR with significant but small effects of refraction group (myopes 0.04 less logMAR). Participants in the study wore masks containing one of three levels of tonicity of water, but this did not affect results.

There were large differences between the visual acuities obtained in the above studies of about 1.0 logMAR. The nature of the tasks would be important to this, including that Luria and Kinney’s (1969) study was conducted in daylight, which provided the target illumination, and Cramer’s (1971) study was conducted at night with lamps illuminating the target. The likely lower ambient lighting levels for the second study and the consequent larger pupils should have contributed to poorer vision. In the presence of even small levels of blur, vision is highly dependent on pupil size (Atchison, Smith, & Efron, 1979; Kamiya, Kobashi, Shimizu, Kawamorita, & Uozato, 2012; Tucker & Charman, 1975). For example, Atchison et al. found that a 1.0 mm diameter pupil gave better vision than larger pupils for myopia >1.5 D. For typical pupil diameters and for refractive errors greater than about 1 D, Smith (1991) predicted that spherical refractive error and visual acuity should be related by

$$A = k\phi\Delta L$$  \hspace{1cm} (1)

where A is uncorrected visual acuity in min of arc, \(\Delta L\) is absolute refractive error, \(\phi\) is pupil diameter, and \(k\) is a constant depending upon the test. Smith’s subsequent work supported this relationship (Smith, 1996).

In a study that considered indirectly the effect of pupil size on vision in water, Gislén and colleagues (Gislén et al., 2003; Gislén & Gislén, 2004; Gislén, Warrant, Dacke, & Kröger, 2006) compared the underwater vision of Moken (“sea gypsy”) children in Southeast Asia with that of European children. Grating target resolution was much better (6.1 ± 0.6 as compared with 3.0 ± 0.1 c/°), and contrast sensitivity between 0.4 and 1.8 c/° was 0.3 log unit better for Moken than for European children. The improvement was determined to be due to an ability to accommodate and reduce pupil diameter in water (2.0 ± 0.1 mm compared with 2.5 ± 0.1 mm). With training and appropriate adaptation, the European children’s vision improved to match that of the Moken children (Gislén et al., 2006).

Following Gislén et al., we investigated the effect of pupil size on vision in water. We did this by the simple method of filling goggles with water, placing them on the eye, and controlling effective pupil size by apertures placed over the front of the goggles.

## Methods

### Participants

Participants were recruited from staff and students of the Queensland University of Technology. The study complied with the tenets of the Declaration of Helsinki and was approved by the University Human Research Ethics Committee. Informed consent was obtained after explaining the nature and possible consequences of the study. Right eyes were tested with the pupil dilated with single drops of 1%...
tropicamide. Participants had best corrected visual acuities of 6/6 or better and were screened for ocular pathology. Relevant participant details are in Table 1. Experiment 1, testing letter acuity, was conducted with seven subjects. Participants 5 and 6 were not available for Experiment 2, testing grating acuity, and were replaced by participants 8 through 10. Participant 7 alone was used for Experiment 3, testing contrast sensitivity.

### Conditions

Experiment 1 was conducted under three conditions. In the baseline condition “no goggles–air,” visual acuity was determined in air with appropriate correction placed in a trial frame. In the test condition “goggles-saline,” a pair of swimming goggles was placed on the head and visual acuity was determined with saline (AMO Lens Plus, AMO Inc., Santa Ana, CA) placed between the right side of the goggles and the right eye. A control condition, “goggles-air,” was used to investigate any effect of the goggles by measuring visual acuity when the goggles were worn without containing saline. As the results with this condition were not significantly different from those for the no goggles–air condition (see Results), it was not used in Experiments 2 and 3.

Artificial apertures were placed at the front of trial frames or goggles with diameters between 1.0 and 7.0 mm with accuracy of stated values within ±0.05 mm.

### Experiment 1: Letter visual acuity

The Freiburg Visual Acuity Test (Bach, 1996, 2007) with an adaptive staircase procedure called best PEST (parameter estimation by sequential testing) was used to determine size threshold. The participant’s task at each trial was to determine in which of four orientations a Landolt-C was presented. High-contrast letters on a white background were projected from an Epson EMP 1810 multimedia projector onto a high-resolution rear projection screen (Novix Systems, Praxino rear projection screen). Screen luminance was 2750 cd/m². The screen was viewed from 6 m for the no goggles–air and goggles-air conditions and from 1 m for the goggles-saline condition. Testing was done in the order no goggles–air, goggles-air, and goggles-saline. Aperture diameters were 1.0 to 7.0 mm in 1.0 mm steps with the largest aperture tested first and then progressing to the smallest aperture. Acuities were specified in logMAR. Three measurements were averaged across each goggles condition and aperture combination.

### Experiment 2: Grating acuity

Targets were 100% contrast, vertical sinusoidal gratings presented on a Sony Triniton Multiscan G520 monitor and under the control of a computer program with a Visual Stimulus Generator VSG 2/5 system (Cambridge Research Instruments). The dimensions of the screen were 40 cm horizontal × 30 cm vertical. The green gun of the monitor was used to display the stimuli (mean wavelength: 545 nm; full width at half maximum luminance height: 62 nm; CIE chromaticity coordinates: x, y = 0.32, 0.57). Mean luminance was 49 cd/m². Room lights were turned off to make it easy for participants to align the visual field through the apertures with the center of the monitor. Apertures were 2.0, 4.0, and 6.0 mm diameters with testing in this order and with three or four runs at each aperture. The participant’s task was to distinguish between two stimuli presented in 0.5 s intervals, one with the sinusoidal grating and one with an empty field; a control box with two buttons was used for this. A staircase procedure determined the 79% threshold (three consecutive correct re-

<table>
<thead>
<tr>
<th>Participant number</th>
<th>Age (years)</th>
<th>Right eye refraction (diopters) for distance</th>
<th>Right eye anterior corneal radii of curvature (mm) and principal meridians (degrees)</th>
<th>Vertex distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>21</td>
<td>−1.00</td>
<td>7.60; 5; 7.48; 95</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>Plano</td>
<td>7.27; 170; 7.14; 80</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>Plano</td>
<td>7.76; 150; 7.64; 60</td>
<td>10</td>
</tr>
<tr>
<td>4*</td>
<td>30</td>
<td>−1.00</td>
<td>7.63; 15; 7.45; 105</td>
<td>14.5</td>
</tr>
<tr>
<td>5*</td>
<td>21</td>
<td>−1.50</td>
<td>8.13; 13; 7.80; 103</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>+0.25</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>7*</td>
<td>59</td>
<td>−2.25/−0.50 × 90</td>
<td>7.82; 25; 7.75; 115</td>
<td>16</td>
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<tr>
<td>8</td>
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<td>+1.00/−0.50 × 85</td>
<td>7.38; 155; 7.39; 65</td>
<td>12</td>
</tr>
<tr>
<td>9</td>
<td>21</td>
<td>−0.25</td>
<td>7.70; 80; 7.67; 170</td>
<td>15</td>
</tr>
<tr>
<td>10*</td>
<td>22</td>
<td>−2.75</td>
<td>7.86; 35; 7.78; 145</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 1. Participant details. Notes: Asterisks indicate that trial lens correction was used for distance tasks, and the dash indicates that measurements were not taken.
sponses before increase in spatial frequency; one incorrect response to decrease spatial frequency) with a step size of 0.1 log spatial frequency. The mean of the last six of nine reversals was taken as threshold. The relationship between acuity in logMAR and as spatial frequency $SF$ in $c/\circ$ is

$$\text{logMAR} = \text{log}(30/SF)$$  \hspace{1cm} (2)

Measurements were done for the no goggles–air condition at 18 m and for the goggles-saline condition at 2 m. Aperture diameters were 6, 4, and 2 mm and were used in this order.

**Experiment 3: Contrast sensitivity function (CSF)**

Most conditions were similar to those given in Experiment 2. Contrast sensitivity to vertical sinusoidal gratings was determined at a range of spatial frequencies between 0.175 $c/\circ$ and 3.2 $c/\circ$ at 2 m distance. Each stimulus was presented for 0.5 s. We used a visible/not visible choice staircase algorithm to determine the threshold. The subject’s task was to press one of two buttons depending upon whether or not the grating was visible. Step size was 0.1 log unit. The first two reversals for a spatial frequency were ignored, and the mean was taken as the average of six subsequent reversals. For each spatial frequency, results of three or four runs were averaged. For the majority of goggles condition and spatial frequency combinations, standard deviations were <0.1 log unit.

**Theory**

Atchison and Charman (accepted for publication) determined spectacle magnification under various conditions. In water, spectacle magnification $SM$ is given by

$$SM = \frac{1.333 - dL_1}{1 - d(L_1 + F_v)}$$  \hspace{1cm} (3)

where 1.333 is the refractive index of water, $L_1$ is the object vergence relative to the front of the eye, $d$ is the distance from the anterior cornea to the eye entrance pupil, $F_v$ is the power of the water-air boundary having the radius of curvature matching that of the anterior cornea. In the goggles-saline simulation, spectacle magnification is given by

$$SM = \frac{(1.333 - tF_v)(1 - t) + dL_1}{1.333}$$  \hspace{1cm} (4)

where $t$ is the thickness of water inside the goggle, and $L_1$ is now the object vergence relative to the front of the goggle. The ratio of spectacle magnification in water to that with goggles-saline is given by dividing the right hand side of Equation 3 by that of Equation 4:

$$SM_{ratio} = \frac{1.333(1.333 - dL_1)}{(1.333 - tF_v)(1 - d[L_1 + F_v])} (1 - t + d[L_1])$$  \hspace{1cm} (5)

This is the factor by which visual acuity (in inverse min arc) or resolution (in $c/\circ$) with the simulation should be multiplied to estimate visual acuity or resolution in water. In Experiment 1, using a mean saline thickness of 12 mm, $d$ of 3.047 mm from the Gullstrand number one eye (Atchison & Smith, 2000; Gullstrand, 1909), and $F_v$ of −43.2 diopters derived from the Gullstrand number one eye, the correction factor is 0.84. In Experiment 2, with a mean saline thickness of 13 mm the correction factor is 0.82. In Experiment 3 involving one subject, individual data were used. These included a saline thickness of 16 mm and anterior eye data from measurements with an Oculus Pentacam instrument: anterior corneal radius of curvature component along the horizontal meridian: 7.81 mm; posterior corneal radius of curvature component along the horizontal meridian: 6.56 mm; corneal thickness: 0.511 mm; and anterior chamber depth: 2.74 mm. Based on these values, the back surface of the saline goggles had a power of −42.6 diopters, and the entrance pupil was 2.71 mm inside the eye. The correction factor is 0.78.

The entrance pupil of the eye in water is smaller than in air. For the Gullstrand number one eye, the factor involved is 1.132, and for the participant in Experiment 3 it is 1.115. Assuming that threshold sizes for letter vision and grating vision are proportional to pupil size in the presence of defocus (Smith, 1991, 1996), the correction factors were changed to 0.95, 0.93, and 0.87 in Experiments 1, 2, and 3, respectively.

We note that the saline solution we used has refractive indices of 1.335–1.336 at wavelengths in the middle of the visible spectrum (Pearson, 2013), but changing the refractive index in Equation 5 from 1.333 to 1.335 or to 1.336 has negligible effects on the correction factors.

For Experiment 3, a theoretical CSF was obtained as a comparison with the experimental CSF. The optical design program Zemax EE (Zemax Corporation) was used to determine the geometric modulation transfer functions (MTF) in the no goggles–air and goggles-saline conditions with the Gullstrand number one eye altered to match the participant’s anterior eye parameters and the vitreous length altered to match his refraction. The MTFs were given in c/mm on the retina and converted to $c/\circ$ in object space. Interpolation between CSF values was made.
as necessary. The CSF in the goggles-saline condition was estimated as

$$CSF_{\text{goggles-saline}} = CSF_{\text{no goggles-air}} \times \text{MTF}_{\text{goggles-saline}} / \text{MTF}_{\text{air}}.$$  \hspace{1cm} (6)

For the low spatial frequencies investigated, $\text{MTF}_{\text{air}} \approx 1$, which reduces Equation 6 to

$$CSF_{\text{goggles-saline}} = CSF_{\text{no goggles-air}} \times \text{MTF}_{\text{goggles-saline}}.$$  \hspace{1cm} (7)

**Statistical analysis**

Data were analysed by analyses of variance with participants as repeated measures. As applicable, within-participants variables were goggles condition and aperture diameter. If Mauchly’s test for sphericity gave a significant finding for a variable, degrees of freedom were adjusted according to the Greenhouse-Geisser correction. Post-hoc tests were applied using the Bonferroni correction ($p$ value was multiplied by the number of pairwise comparisons). The criterion for significance was $p < 0.05$.

**Results**

**Experiment 1: Letter visual acuity**

Figure 1 shows visual acuity as a function of aperture diameter for no goggles–air, goggles-air, and goggles-saline conditions. For corrected vision, aperture diameter affected visual acuity, $F(2.02, 12.11) = 5.9$, $p = 0.01$, but the goggles did not, $F(1, 6) = 3.4$, $p = 0.11$. Best corrected visual acuity occurred for 4–6 mm apertures although there were few significant differences for post-hoc comparisons between apertures. There was no significant interaction of goggles and aperture for corrected vision.

Vision for the goggles-saline condition was much poorer than for the corrected conditions with the mean loss of vision increasing monotonically from 1.1 logMAR (13 times) for the 1 mm aperture to 2.2 logMAR (160 times) for the 7 mm aperture. Estimated vision in water (dashed line in Figure 1) was only slightly worse (0.02 logMAR or 1.05 times). Variation between participants was considerable for this condition.

Figure 2 shows the results for goggles-saline after visual acuity was converted to min arc. Based on Equation 1, a linear equation to the data that goes through the origin is visual acuity $= 22.6\phi$, where $\phi$ is aperture diameter in millimeters with $R^2 = 0.96$ and 0.48 based on mean data and all individual data, respectively. Correcting for the water environment (dashed line) gives the relationship visual acuity (min arc) $= 23.7\phi$. Using Equation 1, Smith (1996) obtained a constant $k = 650$ min arc in his study. Its use with a defocus $D_L$ of 43 D gives the relationship visual acuity (min arc) $= 28.0\phi$, similar to that found here despite our use of much greater defocus and of different experimental conditions than those of Smith.
Figure 2 shows considerable variation between participants. We think that this is due to very different abilities to interpret a highly blurred target.

**Experiment 2: Grating acuity**

Figure 3 shows log grating detection acuity as a function of aperture diameter for no goggles–air and goggles-saline conditions. For the no goggles–air condition, acuity became slightly poorer with an increase in aperture diameter, $F(2, 14) = 8.0, p = 0.005$, with the 6.0 mm aperture giving significantly poorer acuity than the 2.0 mm aperture ($p = 0.024$). Acuity for goggles-saline was much poorer than for no goggles–air with a mean loss of 1.1 logMAR. Acuity for goggles-saline was significantly affected by pupil size, $F(2, 14) = 24.4, p < 0.001$, with the 4.0 mm and 6.0 mm apertures having significantly poorer acuity than the 2 mm aperture ($p < 0.010$) but not being significantly different from each other. The mean loss from the 2.0 mm to the 6.0 mm aperture was 0.17 logMAR (from 3.7 to 2.5 c/° or 1.5 times). Estimated vision in water was only slightly worse than the simulation (+0.03 logMAR or 1.07 times).

**Experiment 3: Contrast sensitivity function**

Figure 4 shows CSFs of a participant for the no goggles–air and goggles-saline conditions together with the CSF for the goggles-saline condition as predicted from the no goggles–air condition and the goggles-saline MTF (Equation 7). Loss of contrast sensitivity in water was profound, going through a series of undulations. The experimental CSF skims across the top of the predicted CSF with a steady increase to 2.0 log units by 3 c/°. The first three depressions or “notches” in the experimental function are distinct, occurring at 0.45, 0.8, and 1.3 c/°, slightly above those of the predicted function of 0.39, 0.71, and 1.03 c/°. From the explanation in Methods, the estimated notches in water would occur at a factor of 0.87 of the experimental notches, that is, at 0.39, 0.70, and 1.13 c/°.

**Discussion**

Vision in the water simulation was poor. For letter acuity, mean loss, compared to corrected vision in air, varied between 1.1 logMAR for a 1 mm aperture to 2.2 logMAR for a 7 mm aperture, and vision in min of arc was described well by a linear relationship with pupil size. Mean grating acuity loss varied between 1.1 logMAR for a 2 mm aperture to 1.2 logMAR for a 6 mm aperture. Contrast sensitivity for a 2 mm aperture deteriorated as spatial frequency increased with 2 log unit loss by 3 c/°. Superimposed on this deterioration were depressions (notches) in sensitivity.

Vision in the water simulation became worse as pupil size increased, but the effects were much more marked for letter targets than for grating targets with change of 1.1 logMAR between 1 and 7 mm apertures for the 2 mm aperture. Contrast sensitivity for a 2 mm aperture deteriorated as spatial frequency increased with 2 log unit loss by 3 c/°. Superimposed on this deterioration were depressions (notches) in sensitivity.
former and only 0.2 logMAR between 2 and 6 mm apertures for the latter. The contrast sensitivity results in Figure 4 help to make it clear why this should happen. The function passes through a series of notches while the grating remains visible beyond 3 c/°.

Corresponding to each notch is an approximately 180° change of phase. While changes of phase do not affect the visibility of isolated gratings, they influence the resolution of more complex targets, such as Landolt Cs, having a range of spatial frequency content. As pupil size increases, the notches occur at smaller intervals, and so Landolt Cs should become unresolvable at much larger sizes.

Our findings explain the discrepancies in acuities between two previous studies in terms of the different tasks and likely differences in pupil sizes. Luria and Kinney (1969) found mean grating resolution loss for 15 emmetropes of 1.0 logMAR at 0.81 m water thickness, similar to that found here. Cramer (1971) determined mean vision acuity underwater for a Landolt C target of 2.3 logMAR, similar to what we found for the large pupil sizes likely to occur under the low lighting conditions of Cramer’s study.

Gislén et al. (2003) attributed the two times better water vision of Moken children than of European children at a grating task (6.1 compared with 3.0 c/°) to the ability of the former to accommodate and reduce pupil size. In our Experiment 2, we found only a 1.5 times improvement in vision (from 2.5 to 3.7 c/°) when stop diameter decreased from 6 to 2 mm. While acknowledging that the two studies were conducted under very different experimental conditions, our results indicate that the small pupil size differences between the two groups in Gislen et al.’s study should have played only a small part in the better performance of the Moken children.

Our study used a small thickness of saline provided by the goggles. For vision in water compared with in air, the level of turbidity would be expected to reduce visual performance further than found here.

Keywords: contrast sensitivity, goggles, grating acuity, visual acuity, vision in water

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