Orientation, Movement and Motor Skills in Divers.

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Abstract.

The orientation of divers under water is disturbed by several factors. Visual factors include: optical disortion caused by refraction at the facemask in water; low visibility; water movement; absent or misleading visual landmarks; and loss of peripheral vision. Auditory factors include distortion of angular localisation and poor distance localisation. Vestibular factors include alternobaric vertigo, narcosis and High Pressure Nervous Syndrome. Tactile-kinaesthetic factors include: reduced tactile stimulation; reduced awareness of limb position; reduced knowledge of achieved locomotion; distorted sense of body and object weight; and a disruption of motor skills.

Introduction.

The diver operates in a hostile environment which deprives and distorts his senses in various ways. The physiological and technical factors affecting man's survival under water have been well described in many manuals. Much less attention has been paid to sensory and motor factors, though sections exist in some books (e.g. Woods and Lythgoe, 1971; Ross, 1974; Shilling et al., 1976; Drew et al., 1976), and a few are largely devoted to the topic (e.g. Adolfson and Berghage, 1974; Kinney, 1985). This review concentrates mainly on work since 1974, though earlier works are mentioned where they are of special relevance or are not well known.

The altered physical and sensory environment can give rise to misperceptions of bodily orientation and movement. There are many contributing factors, affecting the visual, auditory, vestibular and tactile-kinaesthetic systems - all of which interact in controlling posture and movement.

Visual factors.

Optical Distortion.

The unprotected human eye is extremely long-sighted in water. The refractive power of the cornea is lost, because the density of the cornea is similar to that of water. This results in a loss of focussing power of about 45 diopters (Kinney 1985). Normal focussing is restored if a facemask is worn, allowing the eye to operate in air. However, this introduces a distortion due to refraction of light at the air/glass/water interface: the rays are refracted away from the normal when passing from the denser water into the less dense air. This causes an angular enlargement of about 4/3, and a reduction in the image distance to about 3/4 of the physical distance. It also causes curvature distortion, the deviation increasing towards the periphery of a flat facemask in accordance with the sine law of refraction. These distortions affect the perceived size and distance of objects, and their perceived angular orientation when not in the centre of the field of view. Non-central objects appear more displaced towards the periphery than they really are. The result is that an inexperienced diver tends to misreach for objects - he underreaches for all objects, and reaches too far to the left for objects on the left and too far to the right for objects on the right. For the same reason he may perceive the orientation of his head with respect to a non-central object as having too large a deviation. This could affect the direction in which a diver swims, if he is attempting to navigate at an angle to a landmark.

Refraction also causes a distortion of slope. A diver swimming along the seabed will see a flat surface rising towards him in the distance. This should distort a diver's perception of the true horizontal - but there appear to be no experiments on this matter. Similarly a diver looking up will see the surface as tilting down in the distance.

Most divers show some degree of immediate adaptation to these distortions, followed by slower subsequent adaptation and by opposite aftereffects on return to land (see reviews by Welch, 1978; Kinney, 1985). Adaptation probably involves an appropriate change in the gain of the vestibulo-ocular reflex (VOR), as has been shown for magnifying lenses in air (Gauthier and Robinson, 1975).

Low Visibility and Distance Perception.

Visibility is much poorer in water than in air, even in the clearest water. The fine particles in the water scatter and absorb the light, the effect varying with the wavelength. Blue light is scattered and red absorbed, giving clear water a blue cast. Additionally there may be yellowish vegetable matter and other material in rivers and coastal water, producing a green appearance; or red material in a peat loch, giving a dark reddish brown appearance. These effects systematically alter the perceived colours of objects, depending on their depth and on their horizontal and vertical distance from the viewer. Changes in colour do not in themselves affect a diver's sense of orientation. However, the marked loss in colour and brightness contrast when viewing objects horizontally makes them appear too far away in the distance. This is similar to viewing objects in a fog on land - an effect known as aerial perspective (see Ross 1975). The increase in perceived distance is the opposite of the effect caused by the distortion of the facemask. The result of these combined distortions is that objects appear too near at short distances and too far at long distances, the changeover point increasing with the clarity of the water. It can vary from about one metre in murky water to about 20 m in the clearest water.

It might be thought that stereoscopic information would override aerial perspective and ensure that objects are seen at their optical distance. However, stereopsis is frequently overridden by conflicting information. Stereopsis is particularly poor in water, being reduced by a factor of three or more compared to air. While facemask magnification should improve stereoacuity, in practice it is degraded by such factors as low luminance contrast, the impoverished visual scene, loss of peripheral vision, and perhaps inappropriate accommodation (see Kinney, 1985). Other cues that normally assist distance perception in air are texture gradients and motion parallax. Texture gradients are absent or much reduced in most underwater scenes. It is claimed that motion parallax contributes little under water, perhaps because refraction distorts the normal relation between head or eye movements and movement of the retinal image (Ferris, 1974).

Speed Perception.

Distortions of perceived size and distance contribute to distortions of the perceived speed of objects. Perceived velocity is partly determined by the perceived distance travelled over perceived time. Given consistent time estimates, objects travelling across the line of sight should appear to travel further in the same time, and thus faster than in air. Objects travelling at close distances along the line of sight, towards or away from the diver, should appear to travel a shorter distance and thus more slowly than in air. Speed distortions in the predicted directions were found by Ross and Rejman (1972). At greater distances, where perceived distances increase due to aerial perspective, an increase in perceived speed would be predicted. However, this has not been tested. Subjects partially adapt to these distortions after several minutes of wearing a facemask in water, and show negative aftereffects (reversed errors) in air.

Factors Affecting Ambient Vision.

When the diver descends sufficiently deep his visual acuity suffers due to the reduction in the light level through absorption by the particles in the water. In clear ocean water in good daylight, photopic vision (illumination greater than about 3cd/m^2) may continue to depths of about 100-300 m; mesopic and then scotopic conditions (illumination less than 10-3 cd/m^2) hold at greater depths, some useful vision continuing to about 500-1000m. The theoretical depth limit is hard to calculate, as it depends on the attenuating properties of the water at different wavelengths and on the critical wavelengths for the scotopic eye (Kinney, 1985). In turbid water or overcast conditions the change to scotopic vision is of course reached at much shallower depths. Low illumination affects visual acuity, the luminance contrast needed for object detection rising from about 2% in photopic conditions to 10% in mesopic conditions and 30% in scotopic conditions. However, the reduced illumination has less effect on diver orientation, since the ambient orienting system operates satisfactorily at mesopic levels.

Peripheral vision contributes to ambient orientation, but the field of view is seriously reduced by the diver's facemask. It is possible to use a large wrap-around mask, but these are not popular due to the difficulty of clearing the large air space and to the increased optical distortion in the periphery. For most facemasks in water the useful horizontal field of view is reduced to about 80-85 degrees, compared to 180-190 degrees in air without a mask (Kinney, 1985). This leads to a reduction in sensitivity to peripheral movement, and a deterioration in stereoacuity and depth perception.

The ambient orienting system is particularly sensitive to optic flow and to vertical and horizontal lines, all of which may be misleading under water. Waves and currents may produce streaming of particles and plants past a diver, inducing the sensation that he is moving in the opposite direction (vection). The underwater topography is usually lacking in good visual indicators of the vertical and horizontal. The seabed may slope, plants may grow out of cliffs at an angle to the vertical, and man-made objects such as shipwrecks tend to lie at an angle. The visual information available for orientation is thus much impaired under water.

Auditory factors.

Auditory Loss and Directional Sensitivity.

Auditory information normally contributes to spatial orientation. However, the density of water causes losses and distortions for the auditory system, just as it does for the visual system. The human ear functions poorly in water, probably operating by bone conduction rather than by the middle ear: there is a loss of sensitivity of about 30-60 decibels compared to air, the difference increasing with the frequency (Hollien and Feinstein, 1976). There is also a loss of directional sensitivity, the minimum discriminable angle being much greater than in air at all angles. Discrimination is best for broad-band noise and for low frequencies, and improves with head movements and with training (Goeters, 1972; Hollien and Feinstein, 1976). Man can localize pulsed white noise under water to an accuracy of about 9-10 degrees under the best conditions. Though this performance is poorer than in air (which has a maximum accuracy of about 1 degree), it is comparable to that of marine mammals.

The loss of sensitivity is partly due to the loss of one of the main binaural cues - the intensity difference between the two ears. This occurs because the head in water is acoustically transparent, the density of the head and water being similar. The head no longer casts a sound shadow, so that the intensity of sound at the two ears remains similar regardless of the angle of incidence. The other main binaural cue, the temporal difference between the two ears, is also affected. The speed of transmission of sound in air is 335 m/s, but this increases to 1437 m/s in fresh water and about 1500 in sea water - an increase by a factor of 4.0-4.5. This reduces the interaural temporal difference to about a quarter of the air value, effectively shrinking the diver's head to about the size of a golf ball in air. It is perhaps remarkable that humans retain any localization ability in water.

Distortion of Auditory Localization.

Auditory localization is distorted as well as reduced. The reduction in the interaural temporal difference causes sounds to be distorted towards the median plane. A sound source at 90 degrees to the right or left in water should be equivalent to one at 17 degrees to the front or back in air. This theoretically leaves a large auditory lacuna (equivalent to a 'blind spot') to each side of the head, compressing the apparent auditory field to a cone of 34 degrees to the front and back. Because of the distortion, a diver in darkness or zero visibility pointing towards a sound source points too close to the median plane (Wells and Ross, 1980). (This is the opposite of the effect of the optical distortion, so such experiments must be performed blindfold). A diver homing in on an invisible sound source located to one side usually swims in a wide loop before reaching the source. Leggiere et al (1970) attributed this effect to a 'random walk', while Wells and Ross (1980) claimed it was due to medial bias. There is some evidence that divers may partially adapt to the medial distortion, showing an aftereffect away from the median plane immediately on returning to air (Wells and Ross, 1980).

There is also poor distance localization, due to a reduction or distortion of most of the auditory distance cues. There is a tendency to localization within the head, making it very difficult to locate the source of a noise such as an explosion or a boat's engine.

Vestibular factors.

A diver's vestibular system can, in principle, function normally as in air. Neutral buoyancy does not simulate zero gravity: the otoliths continue to respond to gravity even when the diver's body is floating. However, the vestibular system is susceptible to alternobaric vertigo (pressure vertigo), and to several other effects related to breathing gases at pressure (see reviews by Kennedy, 1974; Farmer, 1982).

Alternobaric Vertigo.

Vertigo can be brought on by a failure to equalise the pressure between the middle ear and the outer environment. Overpressure of the middle ear is probably more important than underpressure. High pressure air trapped in the middle ear somehow stimulates the vestibular system, causing sensations of rotation, tumbling or tilting. Such incidents occur more frequently on the ascent nearer the surface, where pressure changes are more rapid and high pressure air is more likely to become trapped in the middle ear. Ingelstedt et al (1974) conducted pressure chamber studies which showed a connection between vestibular nystagmus and asymmetrical equilibration of middle ear pressures during ascents from shallow depths.

Ross (1976) noted that the most common reports from divers were of incidents in a head-upright position, involving the sensation of self-rotation towards the overpressured ear, accompanied by fast rotation of the visual world in the same direction. This is consistent with the fast phase of nystagmus being towards the overpressured ear, and the slow phase (tracking component) in the opposite direction. It is not known whether the direction reverses when the head is inverted, as might be predicted by analogy with other types of vertigo. The effects are similar to that of caloric nystagmus, which could be implicated if an outer ear blocked with wax or covered by a hood suddenly clears, allowing access of cold water to the ear drum. Rupture of the ear drum (caused by failure to equalise the pressure on descent) has similar effects. However, these latter two categories are rare, and most incidents appear to be cases of alternobaric vertigo. The sensation of bodily rotation is usually strong under water, probably because of a lack of any tactile contradiction. The sensation can be inhibited or reduced by clinging to a rock or other fixed object. This observation is analagous to zero-gravity experiments which show that the sensation of bodily rotation caused by a "rotating dome" (rotation of the whole visual field) can be reduced by providing tactile cues to the astronaut's feet (Young et al, 1986).

Effects of Gases at Pressure.
Vestibular decompression sickness, or "vestibular bends", may occur on ascending from relatively deep dives (deeper than about 100 m) - with symptoms of unsteadiness, dizziness, nausea and vomiting. "Isobaric vertigo" may also occur when there is no change in total atmospheric pressure, but the subject breathes a different gas or gas mixture from the surrounding atmosphere. In neither case is the mechanism clearly understood (Shilling et al, 1976).

The High Pressure Nervous Syndrome (HPNS) has been studied in more detail. It may affect subjects breathing oxyhelium gas mixtures at depths below about 200 m. They may suffer nausea and vertigo, together with disturbances of balance and the oculomotor system (Török, 1982). An increase in slow phase velocity of the VOR has been observed at very high pressure under mixed gases, though the cause is unclear (Hempleman et al, 1984).
Braithwaite et al (1974) claimed that the dizziness of HPNS was not accompanied by sustained nystagmus, and did not originate from the vestibular end organ. Farmer (see Farmer, 1982) suggested that it was due to a decrease in the normal cerebellar inhibitory modulation of the vestibular nuclei, leading to equal increases in the left and right vestibular pathways. Gauthier (1976) noted symmetrical increases in the left and right VOR during HPNS.
Nitrogen narcosis may also play a part in disorientation. This may be through general depression of the central nervous system, or through more specific effects on the vestibular system. Increases in body sway have been found in pressure chamber studies by Adolfson et al (1972), Adolfson et al (1974) and Jones et al (1979). Adolfson et al (1974) found that subjects breathing compressed air at pressures up to 10 ATA showed increased body sway on a Romberg rails balance test, particularly with their eyes closed. The authors found no evidence of vestibular changes, and assumed the CNS was involved. However, Hamilton et al (1986) did find vestibular changes in subjects who breathed a mixture of 25% nitrous oxide - a situation normally equivalent to nitrogen narcosis when breathing air under pressure. The subjects showed an increase of about 50% in the velocity of the slow phase of the

VOR. This suggests that the vestibular end organs, or the central pathways controlling nystagmus, or both, are affected by nitrous oxide. The difference between this and earlier studies may lie in the fact that Adolfson et al (1970) measured the number of beats and the phase difference between stimulus and response, while Hamilton et al (1986) measured the velocity of the slow phase component relative to the stimulus velocity. Perhaps the latter measure is more sensitive to narcosis.

While the current evidence suggests that gases at pressure may affect some aspects of vestibular control, it does not suggest that they cause a true rotary vertigo simular to that of alternobaric vertigo.

Tactile-Kinaesthetic Factors and Combined Senses.

Buoyancy and Motor Skills.

The upthrust of the water counteracts the force of gravity, making objects lighter or more buoyant by an amount that varies with their volume (1 g per cm^3). The human body is positively buoyant in sea water, and normally neutral or slight buoyant in fresh water. A Scuba diver adjusts his weight to be as near neutrally buoyant as possible, though his buoyancy inevitably varies with depth and the amount of air left in his cylinder. Neutral buoyancy simulates zero gravity to some extent, though gravity continues to act on the components of the equilibrium system. However, the viscosity of the water means that extra effort is required to move the water aside. Movement in water thus entails different forces from movement in air, but whether the force is greater or less varies with the direction of movement.

There is reduced tactile stimulation due to the numbing of the skin through cold, or to its protection with a thick rubber suit. This, and other factors such as lack of anchorage, lead to reduced manipulatory ability. A deterioration has been shown in many miscellaneous 'standard tests' of skills (Adolfson and Berghage, 1974; Shilling et al, 1976). A greater understanding of the components of skills has been gained through studies with a more theoretical basis. One such component is the effective reduction in weight of the diver's arm and other objects, which leads to systematic misperceptions of weight and mass (see Ross, 1981; Gassman, 1986). There is some degree of initial mass constancy, followed by subsequent adaptation and by an aftereffect in air when objects feel too heavy. The ability to distinguish between the weights of objects also deteriorates, partly due to maladaptation and partly to cold and other factors. Position and force estimates are also affected (see Adolfson and Berghage, 1974); submerged subjects tend to aim too high, take longer to locate and press push-button switches, and make incorrect force estimates. Other motor skills deteriorate, such as the ability to tap accurately between target areas (Kerr, 1973, 1978; Hancock and Milner, 1982). Errors in such tasks may be due partly to the increased force required to move the arm against viscous drag, partly to maladaptation to the altered force and buoyancy effects, and partly to visual distortion of the target areas when looking into water. A systematic series of experiments is needed to distinguish between these variables.

Posture and Knowledge of the Vertical.

The free swimming diver has little stimulation on the soles of his feet, and a reduced loading on the gravity-resisting joints. This loss of information should lead to a reduction of awareness of limb position, as it does under zero gravity (Watt et al, 1985). However, the question does not appear to have been investigated.

There is no doubt that knowledge of the gravitational vertical is reduced under water, due to impoverished visual and somesthetic information. Investigators have used many different methods and have come up with widely varied estimates of angular errors, ranging from 4-180 degrees (See Ross, 1971; Adolfson and Berghage, 1974; Shilling et al, 1976). Many investigators strapped their blindfold subjects to chairs or tilt tables in a pool, tilted them, and then required them to point to the vertical or readjust their body to the vertical. The mean error estimates were about 7 degrees in the upright position and about 30 degrees when inverted; and the errors increased with the length of exposure to a given tilt angle. Such errors are considerably larger than for the equivalent tests in air.

Ross et al (1969) appear to have been the only investigators to test free swimming Scuba divers in the sea. They asked their subjects to disorient themselves by turning sumersaults, and then to align their trunk, extend their arm and point with their finger to the gravitational vertical. They did this either upright or inverted, and either with vision or blindfold. The divers were photographed beside a plumb line by two photographers at 90 degrees to each other. The angular deviations were measured from the photographs, and the maximum deviation calculated. The mean errors for pointing with the finger when fully sighted were 8.1 degrees upright and 24.1 degrees inverted; and when blindfold they were 16.8 and 29.6 degrees respectively.

The typical direction of error in the upright position was pitch forward, but the direction was more variable when inverted. A well-balanced inverted diver has the head slightly dorsiflexed, in a similar position to an inverted acrobat on land (Clément and Rezette, 1985), but few divers achieved this. The errors in aligning the trunk were sometimes greater and sometimes less than that for the finger. When upright, both trunk and finger normally show a pitch forward error, but when inverted they may show different errors. Pointing errors could be due to uncertainty over arm and finger position in relation to the trunk, in addition to uncertainty of head-/trunk orientation.

The divers' accuracy was, as expected, greater with normal vision than when blindfold; but it was poorer with 'whiteout' vision than when blindfold. The latter effect was shown in a second experiment in which the diver wore a scratched perspex plate over the facemask, to imitate 'whiteout' or low-visibility conditions: the whiteout mask gave greater errors than a blackout mask, particularly when the diver was upright. The effect may occur because attention to a valueless source of information interferes with the ability to use other more reliable sources. Alternatively, it may be that the subject uses the nil visual input as evidence that he has not moved. An upright diver attempting to settle in a slight pitch forward position may thus overshoot in the absence of visual feedback, resulting in an exaggerated error. This interpretation is consistent with findings that stabilized vision leads to greater pitch forward error both on land (Vidal et al, 1982) and in zero gravity (Clément et al, 1985).

As in previous studies, errors were always greater in the inverted position than upright. This may be due to inexperience of the inverted position, or to difficulties in balancing in that posture; or it may be because the vestibular system is less efficient in that range (the vestibular 'blind spot'). The contribution of the otoliths to orientation is known to be greatest in the head-upright position on land (e.g. Schöne, 1975; Young et al, 1975), and the contribution of the visual and somesthetic systems is probably greatest when inverted. Since the somesthetic input is reduced under water, the diver's sense of orientation is particularly impaired when inverted. Indeed, some authors have found an underwater impairment for the subjective vertical only in the 'head down' position (Schöne, 1964; Wade, 1973). Prior adaptation to an off-vertical tilt affects the subjective vertical, but Lechner-Steinleitner and Schöne (1980) found no obvious difference between wet and dry conditions in this respect.

Locomotion and Geographical Orientation.

There is inadequate feedback under water about the effects of one's own locomotion. The diver has difficulty in knowing how far he has swum, what depth he is at, and whether he has maintained a straight line or not. Errors can occur even when using navigational aids. Andersen (1968) studied course and depth keeping. He investigated navigation accuracy by the extent to which divers using magnetic compasses deviated from a course over a range of 235 m at a depth of 10-12 m. He found an average deviation of about 22 m, or 5.2 degrees, in compass heading. With practice this was reduced to about 16 m or 3.9 degrees. Errors were commonly due to an error of arm position - the failure to hold the compass parallel to the longitudinal axis (direction of motion) of the body. Another common mistake was to look down instead of sighting ahead over the compass, causing a temporary loss of orientation.

Andersen also studied depth-keeping in divers using depth gauges. Subjects who were neutrally buoyant or 1 kg negative tended to swim about 0.5 m too high at first, and then to sink to about 1 m too low. Subjects 3-4 kg negative swam slightly too low at first, the error then increasing to about 1.5 m too low.

Without vision or navigational aids the difficulties are much greater. Ross, Dickinson and Jupp (1970) investigated this with a 'triangle completion' task, in which the subject swam blindfold round two sides of a triangle, holding a rope as a guideline, and then attempted to swim unguided back to the starting post. The divers tended to swim too far, and to turn through too small and angle compared with walking on land. Both these tendencies were confirmed in further experiments by these authors.

Blindfold divers generally swim in curved paths rather than straight, a tendency also found in people walking in a fog on land. Luria (1979a) had blindfold divers attempt to swim a straight line, make 90 degree turns to the left and right, and a 180 degree turn. The median error was 12 degrees. Errors to the left and right were about equal, and individual subjects were fairly consistent in their direction of error whether they were wearing Scuba tanks or not, and whether they were swimming blindfold or sighted in low visibility water (about 2 m). Errors were not correlated with hand or foot preference, or with the relative strength of the legs. Luria (1979b) also found that errors were not corrected by using swimfins of unequal length, or attaching a rudder to the Scuba tank. The bias is probably of central origin, perhaps due to an asymmetry of vestibular functioning or to an imbalance in the kinaesthetic senses.

We normally see stationary objects as stationary, despite movement of the retinal image caused by our own eye, head or body movements. It is sometimes argued that visual stability occurs because the brain compensates for the effects of such movements. Others argue that correction is unnecessary, since object motion is seen only when objects move in relation to other objects. The contribution of active and passive body movements to visual stability were investigated by Ross and Lennie (1969), by observing the apparent movement of afterimages and of fixed lights when swimming. A betalight (a small glowing light) was fixed in a blacked-out face mask, to provide a stimulus that was fixed in relation to the diver's head movements. In addition, an afterimage was obtained from a flashgun, to provide a stimulus that was fixed in relation to eye movements. When wearing the mask the outside world cannot be seen, so any apparent movement of the betalight or afterimage must be due to correction for eye movements or self motion. When a diver moves actively (e.g. turns a forward somersault), he initially sees the betalight and afterimage jerk back in the opposite direction to himself (upwards in this case), the afterimage moving a lot further than the betalight. As he continues to move in the same direction the afterimage and betalight gradually return to centre, and both appear to move with him. The initial displacement of the betalight may be due to an uncompensated reflex eye movement, but this is unlikely since the afterimage moves in the same direction, and may appear to move right outside the visual field. While the initial effect is hard to explain, the subsequent steady movement of the light and afterimage show that the visual stability system corrects adequately for active bodily movement.The apparent movement is seen only during active or intended movement. Slow passive movement - sinking, rising and drifting - has no effect. A diver may attempt to swim upwards, but actually sink: he then sees the betalight as rising up with him, even though he may know from pressure changes in his ears that he is sinking. This observation demonstrates that 'cognitive' information about depth and movement does not feed into the visual stability system. It seems that the diver corrects for his intended rather than his actual bodily movement.

Given the reduction in sensory feedback under water, one might expect divers to underestimate the distance they have travelled. Ross, Dickinson and Jupp (1970) found that when swimming horizontally along a rope on the seabed (depth about 15m), inexperienced divers tended to swim too far when asked to reproduce distances of about 5-25 m. This was true both without vision, and with vision in water of low visibility (about 5 m). Ross and Franklin (1976) asked sighted divers to descend to a specified depth (without looking up). At shallow depths (less than about 11 m) they swam too deep, thus underestimating their true depth; but at greater depths they did not descend deep enough, thus overestimating their depth. Ross, King and Snowden (1970) led divers to various depths between 3 and 20 m and then asked them to look up to the surface and make a verbal judgement of its distance: divers initially underestimated their depth, but their judgements improved with practice. Gassman (1985) found that when sighted divers followed a rope down the sloping bed of a quarry, they tended to estimate their depth as shallower than it was. The underestimation increased over the depth 3-15 m, and was greater for experienced than novice divers. The conflict between these findings is probably due to the nature of the test (whether a numerical estimate from a given position, or a requirement to swim to a stated depth or distance), and to the experience of the subjects. Novices are particularly prone to anxiety, and most subjects prefer to err on the side of safety when asked to swim deep. Anxiety may have little effect on numerical estimates, or on horizontal swimming at shallow depths. It is clear that more systematic studies are needed to uncover the variables affecting the estimation of distance travelled.

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