31. M. L. Hair (private communication) states that, at pressures of 16 torr and above, the very rapid increase in the amount of absorbed water makes it difficult to make precise measurements, and a fairly broad range of values for the number of molecules absorbed per hydrogen-bonded hydroxyl pair may be indicated. Hair's failure to produce anomalous water may have been due to the special nature of the surface treatment, which may prevent a clustering of hydroxyl pairs sufficient to form successive layers. Fortunately all that is needed for understanding the formation process is identification of hydrogen-bonded surface hydroxyl pairs with an increased absorption under the pressure condiitons favorable to the formation of anomalous water. Hair also proposed the anomalous water geometry given in Fig. 4h, but this has a higher energy than either squares or planar hexagons.
32. Even though the asymmetric cyclic hexamer has a per-bond binding energy comparable to, or slightly greater than, tetrahedral coordination, its geometry is not favorable for formation of the normal liquid because of its very low entropy relative to the tetrahedral arrangements.
33. There is a further decrease in the free energy, due to the lower vibration frequency, hence the higher entropy, of the symmetric hexamer over the asymmetric hexamer.
34. L. Pedersen and K. Morokuma, *J. Chem. Phys.* **46**, 3941 (1967).
35. When an anomalous-water bond is broken, the energy of the conformation immediately after breakage is close to that of a symmetric bonded chain. A concerted motion of each symmetric hydrogen to a corresponding asymmetric position is highly unlikely because of the between-layer interconnections.
36. W. W. Wright and W. A. Lee, *Progr. High Polymers* **2**, 193 (1968).
37. The question of the potential energy surfaces is more complicated, with a different H-F minimum for different F-F distances, but this does not change the conclusions drawn.
38. J. Jansen and L. Bartell, *J. Chem. Phys.* **50**, 3611 (1969).
39. A. L. Wells, *Structural Inorganic Chemistry* (Clarendon Press, Oxford, ed. 3, 1962).
40. The extra repulsion introduced by the two additional electrons of oxygen severely limits the number of possible analogous compounds.
41. E. G. Butcher, M. Alsop, J. A. Weston, H. A. Gebbie, *Nature* **199**, 756 (1963). The analogy with anomalous water was suggested to us by C. K. Jørgensen.
42. The existence of anomalous forms of some acids and alcohols has been reported in the Russian literature and also at several laboratories in this country.
43. This conclusion for alcohols and acids is in disagreement with the structure proposed by Lippincott *et al.* (*3*).
44. A. S. N. Murthy, R. E. David, C. N. R. Rao, *Theor. Chim. Acta* **13**, 81 (1969).
45. J. Sichel and M. A. Whitehead, *ibid.* **11**, 230 (1968).
46. W. Fink, thesis, Princeton University (1966); ——— and L. C. Allen, in preparation.
47. E. U. Frank and F. Meyer, *Z. Electrochem.* **63**, 571 (1959).
48. G. C. Pimentel and A. L. McClellan, *The Hydrogen Bond* (Freeman, San Francisco, 1960); W. C. Hamilton and J. A. Ibers, *Hydrogen Bonding in Solids* (Benjamin, New York, 1968).
49. H. A. Gebbie, W. J. Burroughs, J. Chamberlain, J. E. Harries, R. C. Jones, *Nature* **221**, 143 (1969).
50. R. M. Erdahl, thesis, Princeton University (1965).
51. M. De Pas, J. J. Leventhal, L. Friedman, *J. Chem. Phys.* **49**, 5543 (1969).
52. G. M. Barrow, *Introduction to Molecular Spectroscopy* (McGraw-Hill, New York, 1962), p. 218.
53. T. Carrington, *J. Chem. Phys.* **41**, 2012 (1964).
54. J. Horsley and W. Fink, *ibid.* **50**, 750 (1969).
55. We thank Michael Hair for several informative conversations on surface properties, and for preprints; Gregory Petsko for a preprint and for numerous talks about his various spectral and x-ray studies; Ellis Lippincott for general discussion of his research program; and Walter Kauzmann for vigorous and extended discussion on all aspects of anomalous water. The services of the Princeton University Computer Center (supported by NSF grants GU-34 and GU-3157) are acknowledged, and we appreciate the financial support of the Directorate of Chemical Sciences of the Air Force Office of Scientific Research, through grant AF49(638)-1625. This article is condensed from a manuscript originally submitted to *Science* on 30 September 1969.

Underwater Vision

The physical and psychological bases of the visual distortions that occur underwater are discussed.

S. M. Luria and Jo Ann S. Kinney

It is often said nowadays that man, after millennia of merely scratching the ocean's surface, stands on the threshold of returning to the sea. Many believe that the conquest of "inner space," as it is sometimes called, will prove to be far more important than the conquest of outer space. The oceans obviously contain incalculable treasures of food and minerals. A presidential commission has recently urged a vigorous and systematic investment in efforts to understand, exploit, and preserve the oceans (*1*). Nevertheless, the return is still more of a challenge than a temptation. Countless difficulties await man in the cold, bleak, and dangerous depths. Among them is simply seeing. In this article we review part of the research that we have recently been doing at the Naval Submarine Medical Center in Groton, Connecticut, on some of the problems of seeing underwater.

Alterations of the Physical Stimuli

Every aspect of vision appears to be altered underwater. These modifications in the appearance of the scene have a physical basis, for radiant energy is profoundly changed when it travels through water rather than air. First, water transmits far less total energy than air does. The fundamental equation describing the transmission of energy is the same for air and water:

$$P = P_0 e^{-\alpha d}$$

where P is the radiant power reaching a distance without loss, P_0 is the radiant power at the initial point, e is the base of the natural logarithmic system, α is the extinction or attenuation coefficient, and d is the distance (*2*, *3*). The numerical value of α, however, is generally larger by a factor of 1000 or more for water than for air. The relatively large size of α means a rapid attenuation of light with increasing depth. If 90 percent of the incident energy is transmitted through 1 meter of water, 81 percent will be transmitted through 2 meters and only 37 percent through 10 meters.

The magnitude of α depends on the size of two components, (i) loss due to scattering of the energy by minute particles suspended in the water, and (ii) absorption of the energy by the water. Each of these has important visual consequences.

Scattering causes a loss of energy from the line of sight between the object and the eye, blurring of the outline of the object, and a decrease in the natural contrast between the object and its environment (*3*). As a rough rule of thumb, we can say that the luminance contrast between an object and its background must be at least 2 percent in order for the object to be visible (*4*). While rarely a problem in air (except in fog or smog), the loss of contrast does become significant in water, because of this scattering.

The interesting aspect of the loss of energy due to absorption is that it varies with wavelength and with the particular type of water involved. Figure 1 shows transmission curves measured through a distance of 1 meter of water for some of the different bodies of water in which

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we have worked. At the top is the transmission curve for water from Morrison Springs, Florida, a body of fresh water famous for its clarity. The curve is essentially the same as that for distilled water and has a maximum transmittance of over 90 percent at a wavelength of 480 nanometers. Water from the Gulf of Mexico (and the Caribbean) has a lower transmittance in the violet and blue, presumably because of absorption of these wavelengths by plankton. The water from Long Island Sound is typical of coastal water; it shows less transmittance throughout the spectrum, with the greatest loss in the blues and blue-greens. Finally, the Thames River in Connecticut is a fine example of a highly turbid, polluted body of water; it transmits very little light, and the shape of the curve is completely transformed, the greatest transmittance being at the long wavelengths. As a result of these variations, both the absolute and the relative visibility of colors underwater vary greatly at different distances and in different bodies of water.

Finally, light rays are refracted as they pass from water to air (*5*). This refraction displaces the optical image and causes distortions in the apparent size, distance, and direction of the object.

Thus, an underwater object is usually viewed by light that is insufficient and that has been scattered and drastically changed in wavelength, and the optical image has been modified in size and position. The object is, in short, less visible than it is in air, its size and color seem different, and it is not located where it appears to be. We turn next to an examination of some of the perceptual consequences of these physical distortions.

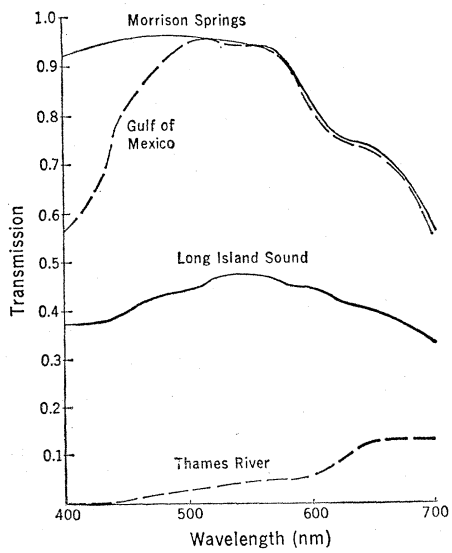

Fig. 1. Transmission of various wavelengths through a distance of 1 meter of various bodies of water. The water varies from exceptionally clear in Morrison Springs, Florida, to very turbid in the Thames River at New London, Connecticut. The peak transmission shifts toward the long wavelengths as turbidity increases.

Visual Acuity

There are several different kinds of visual acuity—a term which refers to the fineness of detail that can be perceived. We can distinguish, for example, between resolution acuity and stereoscopic acuity ("stereoacuity"). The former is the ability to resolve small details; the latter is the ability, based specifically on binocular disparity, to perceive differences in the relative distance of different objects.

As a result of refraction of the light rays at the water-air interface, a virtual image of an underwater object is created at three-quarters of the distance from the interface to the object. The retinal image of the object is thus larger than the image from the same object in air (*6*).

As a result of this magnification, we would expect maximum resolution acuity and stereoacuity to be better underwater than in air. Indeed, Kent and Weissman (*7*) have found this to be true for resolution acuity under ideal conditions. By "ideal conditions" we mean very clear water, a clean face mask, and short viewing distances. Since these conditions are rare, it is more common to find that acuity is poorer underwater than in air.

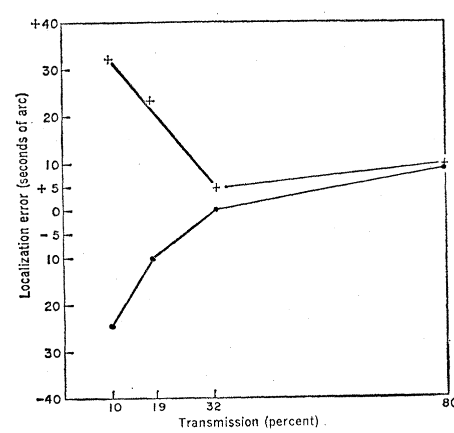

Fig. 2. Stereoacuity in water of various clarities. Typically in such an experiment, half the subjects, in attempting to set a movable rod at the same distance as a stationary rod, consistently set it too near, and half consistently set it too far. For both groups of subjects the magnitude of the localization error increases as the clarity of the water decreases.

Quite different results, on the other hand, have been found for stereoacuity. This is somewhat surprising, since most changes in physical conditions affect this form of acuity in much the same way that they affect resolution acuity (*8*). Yet we, working at short distances in an experimental pool (*9*), and Ross (*10*), working at much greater distances (up to 18 meters) in the Mediterranean, found stereoacuity very much worse underwater than in air. Furthermore, both the size of the error made by a subject attempting to set an object at the same distance from him as a test object and the variability of his settings increased as the clarity of the water decreased (Fig. 2). Since this drop in stereoacuity with decreasing clarity of water closely resembled the drop in stereoacuity with decreasing target contrast found by Lit (*11*), we have concluded that a major cause is the loss of contrast produced by the increasing turbidity.

However, this does not explain why stereoacuity is about three times poorer in the clearest water, where there appears to be no loss of contrast or of target visibility (*9*), than it is in air.

One aspect of the underwater scene that is distinct from the scene in air seems pertinent: the fact that there are few clearly visible objects; the world appears hazy, lacks definition, and approaches what is known in psychology as a *Ganzfeld*, an unstructured, homogeneous field of view. It is well known that a *Ganzfeld* distorts many visual functions (*12*), impairs target detection (*13*), and degrades other processes which are considered to be basically foveal, such as reading (*14*). We therefore tested the hypothesis that loss in the water of much of the usual peripheral stimulation is the cause of the drop in stereoacuity. We determined the effect of reducing the extent of the field of view on both resolution and stereoacuity. Grating targets or a Howard-Dolman three-rod apparatus were presented to subjects through binocular viewing ports which afforded fields ranging from 45 degrees to only 3.8 degrees. The visibility of the test apparatus was, of course, always unobstructed for both eyes.

Reduction in the size of the field of view did not systematically affect resolution acuity but it had a clearly delete-

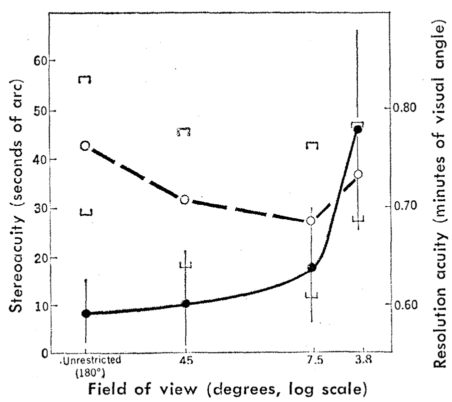

Fig. 3. Resolution acuity (dashed line) and stereoacuity (solid line) with various fields of view. The vertical lines give the average variability for the subjects with respect to the stereoacuity thresholds, and the horizontal brackets give the average variability with respect to the resolution acuity thresholds.

rious effect on stereoacuity (*15*). Under every condition of restricted view, there was an increase in both the error and the variability of the equidistance setting as compared to performance when the field of view was unrestricted (Fig. 3). The maximum reduction in stereoacuity was reduction to about one-fifth that of normal values, quite comparable to the reduction found in water. It appears likely, then, that it is the typical lack of peripheral stimulation in the underwater environment that causes the decrease in stereoacuity. This conforms to findings by Goldstein *et al.* (*16*) that individuals suffering from retinitis pigmentosa and a consequent loss of field down to a 10-degree visual angle also show a marked loss of stereopsis. It remains to be seen if underwater stereoacuity can be significantly improved by introducing clearly visible peripheral stimuli.

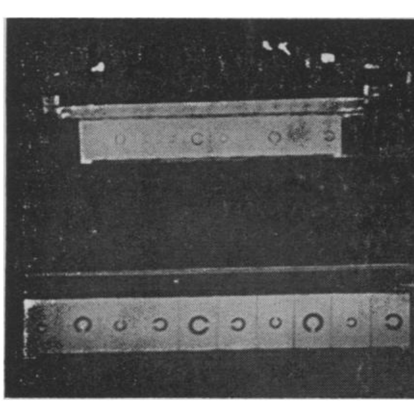

Fig. 4. Two photographs of the same target, both taken from a distance of 4.88 meters (top) in the air and (bottom) underwater.

Perception of Size and Distance

The magnification of the target image should also affect the perception of size and distance. Indeed, it is a common observation that underwater objects appear to be enlarged and closer than they really are, as shown in Fig. 4. This distortion is clearly seen when one stands with his head erect and looks at a partially submerged object with one's face mask half out of the water. Special techniques are needed to eliminate distortion in a photograph of an object half in and half out of the water (*17*). Divers report that it is a common occurrence to underestimate the distance of an object they are reaching for underwater.

We have made several studies on the perception of size and of distance underwater. Generally speaking, the perception of size can be predicted accurately from the magnification of the optical image. For example, subjects who were asked to judge underwater which disks were the same size as certain coins made selections that were much too small relative to the actual size of the coins. The size of the magnified retinal image of the selections did, however, correspond to the actual coin sizes (*18*).

On the other hand, the perception of distance is predictable from refraction data only within certain limited ranges. At very short distances and in clear water, distances are *under*estimated, as one would expect from the magnified retinal image. Figure 5 shows data obtained at short distances under two conditions of water clarity. In one, labeled "clear," transmittances ranged from 0.5 to 0.85 per meter of water; in the other, called "turbid," transmittances varied from 0.3 to 0.38 per meter. Target distances were underestimated when the target was closer than 1.2 meters; beyond that the median estimates were always too great. Moreover, the median estimates of distance were invariably greater under the more turbid condition (*19*).

Figure 6 is another example of the overestimation which occurred at all distances between 1.2 and 4.2 meters—virtually the limit of visibility in the lake in which the study was conducted (*20*). These results agree with those of Ross (*21*), who found similar overestimations in the Mediterranean at much greater distances.

In the study depicted in Fig. 6, judgments of size and of distance were made by the same subjects. In air, both judgments were accurate, as is typically found when subjects have a full field of view and utilize binocular vision.

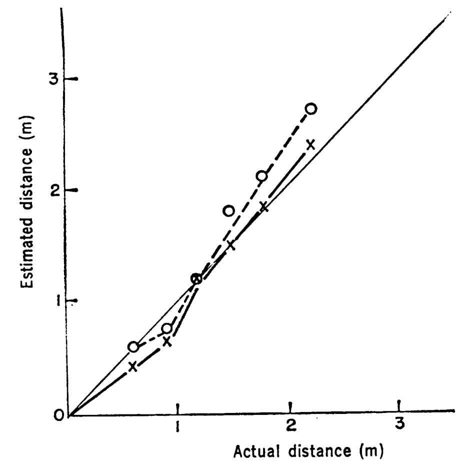

Fig. 5. Distance judgments made in water of different clarities and at relatively close distances. (Dashed line) Turbid water; (solid line) clear water. "Turbid" here means a transmission of 0.30 to 0.38 through 1 meter of water; "clear" signifies a transmission of 0.50 to 0.85 through 1 meter of water. The solid line indicates the locus of accurate judgments.

The overestimation stems in part from the loss of contrast underwater, due to the scattering of light by particles. Fry *et al.* and Ross have reported similar effects of reduced contrast in air (*22*), and the fact that the overestimations increase as turbidity increases lends further support. Overestimations are, however, more severe than would be expected solely on the basis of loss of contrast, for they do occur under conditions of fairly high contrast.

In order to determine whether or not the *Ganzfeld* characteristics of under-

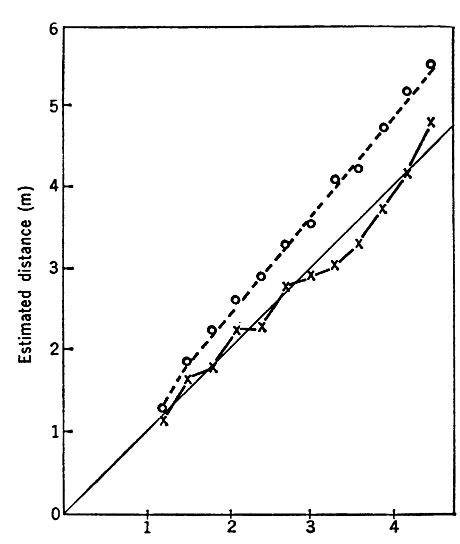

Fig. 6. Distance judgments made in air (X's) and underwater (circles).

water viewing were influential in depth perception, as they were in stereoacuity, the following control experiment was performed in air (*23*). Using the same targets and procedure as before, subjects estimated the distance to the target in three different environments. The first was an ordinary, well-lighted room about 6 meters square with all the usual apparatus and furniture in full view. Under this condition, the median estimates of distance were quite accurate (Fig. 7). When the experiment was repeated in the center of a large, empty, well-lighted gymnasium, the median estimate at every target distance was higher than in the first room; moreover, every estimate, except in the case of the shortest distance, was greater than the actual distance. Finally, the same procedure was carried out in a completely dark room with nothing visible except the target, at a constant, dim illumination. The distance of the target was now even more markedly overestimated, increasingly so as the actual distance increased. Thus, as fewer of the usual cues to distance were available, observers tended more and more to overestimate distance.

In short, both relative and absolute depth perception are less acute underwater. Various changes in the physical characteristics of the light underwater are responsible. Loss of contrast, which increases with increasing turbidity, and the typical lack of stimulation underwater cause increasingly larger errors in stereoacuity and increasingly larger overestimations of distances. Refraction results in underestimation at very short distances.

Perception of Color

The perception of color is another aspect of underwater viewing which is of considerable importance. Since the use of color is the most generally employed means of either enhancing or camouflaging an object, it is important to know which colors are most and least visible. We have already pointed out that water selectively absorbs electromagnetic energy, and that the degree of this absorption varies with the body of water (Fig. 1). Since a long column of water is one of the best monochromators that can be devised (*24*), the relative visibility of different colors can be expected to vary greatly with the body of water in which the colors are immersed.

Table 1. Amounts of underwater experience and original distortion.

Subjects	*N*	Amount of distortion* (cm)
Never used snorkel, mask	42	5.59
Occasionally used snorkel, mask	69	5.00
Frequently used snorkel, mask	20	3.30
Scuba class		
No scuba experience	14	3.23
Some scuba experience	12	2.64
Navy divers	8	2.03

* Group average.

Using scuba divers as subjects, we have investigated the relative visibility of colors underwater, in a number of different bodies of water which were selected for sampling a continuum from clear to murky. Natural illumination (*25*) and two of the most common underwater lights, a tungsten and a mercury light, were used (*26*). Spherical targets were painted black, gray, white, blue, green, yellow, orange, and red, with both regular and fluorescent paints. The latter have been widely used to increase visibility in air. They convert short wavelength energy, to which the eye is relatively insensitive, into longer wavelength energy, to which the eye is more sensitive. The converted energy is added to the reflected light, thus increasing the brightness and contrast of the painted object. In this way, reflectances in excess of 100 percent of the incident visible energy are often possible.

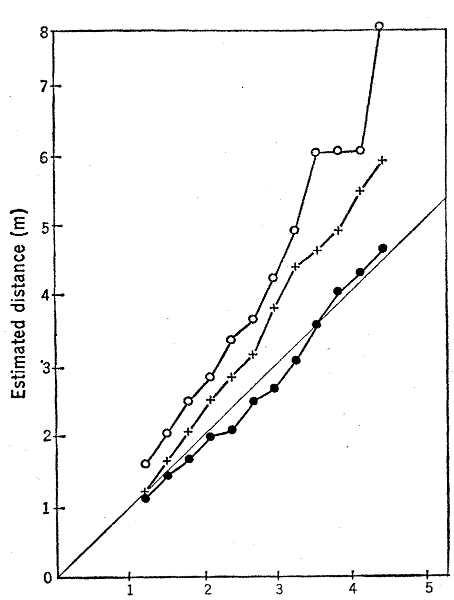

Fig. 7. Distance judgments made under normal conditions (solid circles), in the center of a well-lighted but empty gymnasium (X's), and in a dark room with nothing visible but the target (open circles).

The fluorescent paints were much more visible than nonfluorescent paints of the same color, and the visibility of the various colors was quite different in different bodies of water. In turbid water under natural light, red, orange, and yellow were the most visible colors (Fig. 8). With increasing clarity of the water, there was a shift in visibility toward the blue end of the spectrum. In water from Long Island Sound and the Gulf of Mexico, green, yellow, and orange were most visible. In Morrison Springs water, green was the easiest to see; red, which was the most visible in Thames River (Connecticut) water, was invisible, and blue, which heretofore had been the least visible, was now second only to green.

The fluorescent paints introduce an interesting interaction. The exciting energy for fluorescence is in the shorter wavelengths of visible energy. These wavelengths are well transmitted in clear water and produce good fluorescent oranges. The longer wavelengths that are thus produced, however, are relatively poorly transmitted. The result is that, in clear water, the oranges are brilliant at short distances but decrease rapidly in visibility as distance is increased.

Artificial lights introduce additional variables. For a given color to be visible, the wavelengths reflected by the paint must, of course, be present in the light source. Moreover, to activate the fluorescent paint, there must be short wavelengths present in the source, and they must be transmitted through the water to the target. Thus we found that with a mercury light, which is rich in short wavelength energy, the fluorescent paints are far superior to the nonfluorescent paints in every kind of water tested; with a tungsten light, the advantage of the fluorescent paints is lost in turbid water—there is too little short wavelength energy, and what little is available is poorly transmitted (Fig. 9). While the yellows and oranges were most visible with the tungsten light, yellow-green was most visible with the mercury light.

Thus, visibility can be predicted from a knowledge of the spectral sensitivity of the eye and the spectral distribution of energy reaching it. To specify the latter, we must know four spectral distributions: (i) the energy reaching the target, (ii) the reflectance of the target, (iii) the absorption of the water from the target to the eye, and (iv) the background. From these values, both the brightness and the color contrast can be calculated.

Color Coding

It is important to distinguish between the visibility of colors and their absolute identification. The question of which colors to use for color coding is an equally important problem, but quite different from the question of visibility. White, for example, while always highly visible, tends to take on the color of the water; for this reason, it is the easiest to confuse and should not be used for color coding.

In general, it is hard to distinguish a given color from the colors closest to it on either side of the spectrum. Where correct discrimination is important, it is best to use only two colors—one from each end of the spectrum—with black as a possible third choice. The choice of colors depends on the body of water and the type of illumination. We have found that use of green, orange, and black leads to the least confusion under most conditions. If four colors are needed, red and yellow may be substituted for orange in murky water in daylight or in any water with a tungsten light; blue may be used in clear water in daylight. However, with a mercury light—a commonly used underwater light source—we found no fourth color that was not confused with one of the other three.

Adaptation to Visual Distortion

It is clear that the visual distortion which afflicts the diver is extensive. Fortunately, there is a saving factor: human beings have a remarkable ability to adapt to changes in all kinds of stimulus conditions, such as illumination, color, and a wide variety of optical distortions.

Responses to distorted stimulation have been widely investigated in air (*27*), and our ability to adapt to even the most distorted situations has been recognized since Stratton wore inverting lenses, around the turn of the century (*28*). Recently there has been a great resurgence of interest in this type of adaptation (*29*). There have been some dramatic demonstrations, such as those of Kohler (*30*), whose subjects were able to ski, fence, and ride a motorcycle while wearing inverting lenses.

In all the studies of adaptation, the distortions have been produced artificially—by lenses, prisms, pseudophones, and the like. By "artificially" we mean that the subjects are fully aware that their perceptions are being manipulated by the experimenter and that distortions are being introduced. The underwater environment, on the other hand, provides a unique opportunity to study adaptation to perceptual distortions under natural conditions. That is, the subjects are not asked to wear unexpected and irrelevant equipment for the purposes of the experimenter, and the experimenter is clearly doing nothing to produce any distortions. Many subjects, in fact, are completely unaware that the distortions exist. Yet the distortions of size and depth are fundamentally the same as those produced in the laboratory; a diver's responses to the visual distortions underwater are at first the same as the responses of a subject wearing distorting lenses. When asked to pick up an object, both subjects will fail on the first attempt. Their errors in reaching are gradually reduced on successive attempts until both can make motor responses which are appropriate to the distorted display. When the distortion is removed, both will make errors in the opposite direction.

Using the apparatus shown in Fig. 10 (*31*), we have made extensive measures of hand-eye coordination of subjects with various amounts of underwater experience. If the subject has not adapted, his responses to the test objects underwater should reflect the fact that (i) they appear closer to him than they actually are, and (ii) they also appear displaced toward the edges. If the subject has adapted, his responses should agree more closely with the actual location of the targets than with the optical appearance.

The amount of theoretical optical

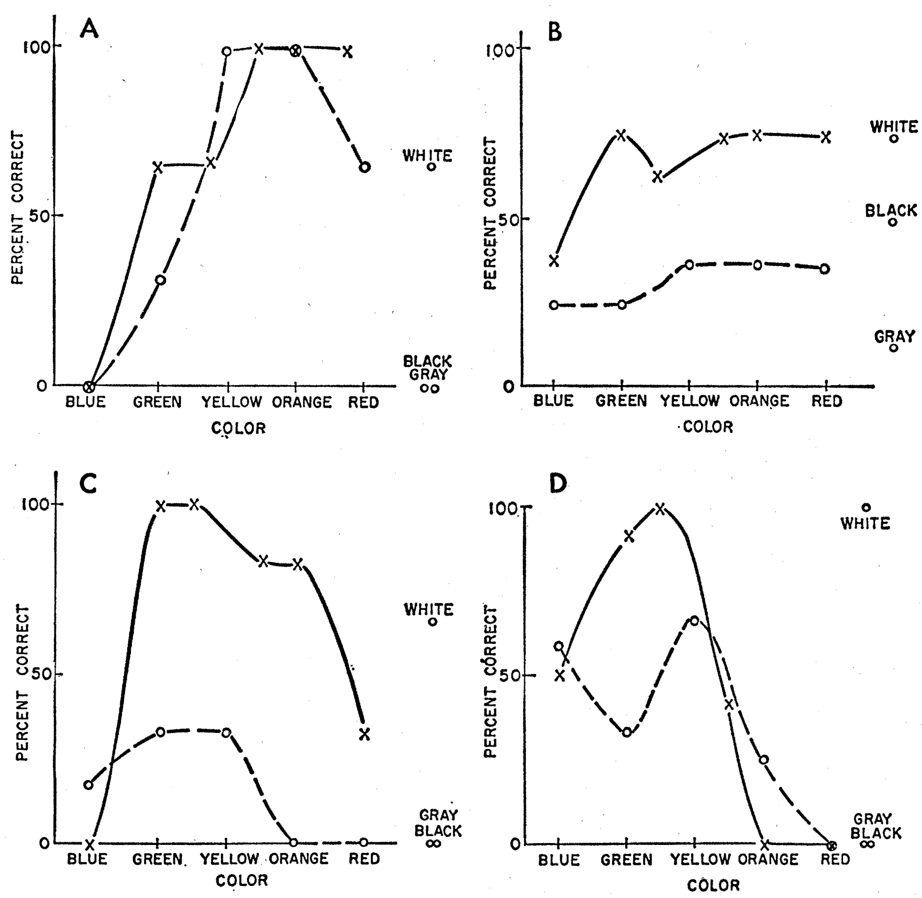

Fig. 8. The visability of various colors in (A) the Thames River, New London, Connecticut, (B) Long Island Sound, (C) Gulf of Mexico, and (D) Morrison Springs, Florida, for (solid line) fluorescent paint and (dashed line) nonfluorescent paint. Scuba divers viewed the colored targets one at a time at distances near the limits of visibility; these ranged from 1.8 meters in the Thames River to nearly 30 meters in Morrison Springs. The divers reported whether or not the target was visible, and if so, they attempted to identify its color. The two open circles shown on the abscissas of A, C, and D under "gray" and "black" indicate that these two colors were never visible.

displacement on this particular test averages 5.6 centimeters toward the subject. The amount of apparent displacement is measured empirically by relating the marks made on the underside of the table in the water to those made in air. A value of zero indicates perfect correspondence between the two sets of marks; that is, the water produced no difference in the apparent location of the test objects. A positive value indicates a shift in the apparent position toward the subject; a negative value, a shift away from the subject, relative to the apparent position on the preliminary test in air.

Table 1 is a compilation of the data from many subjects tested over the past 2 years. There is excellent agreement between the amount of prior underwater experience and the amount of compensation for distortion. Only inexperienced subjects show complete reliance on the optical image; the average amount of displacement for them is the theoretical maximum of 5.6 centimeters toward the subject. For the others, there is increasing correspondence between their determination of the apparent location of the test object and its actual location. Those entering a Navy scuba class did well on the hand-eye coordination test even without prior scuba experience, presumably because of the extensive experience in the water required to qualify for the class.

Navy divers, while clearly showing the greatest amount of adaptation to the visual distortion, did not achieve zero distortion for a group average. There were, however, sizable individual differences, and it is noteworthy that the rank order correlation between the proficiency scores for the individual divers by their commanding officer and their results on this test was .85.

These differences in the test results for experienced and for inexperienced subjects suggest that considerable adaptation occurs naturally as a consequence of underwater experience. In an effort to measure this adaptation and its time course, a battery of underwater visual tests was given every week for 4 weeks to the men of a scuba class undergoing daily scuba training. During these 4 weeks the men adapted to the visual distortion to some extent, but the amount of adaptation was surprisingly small. At the end of 4 weeks of intensive work underwater, the divers exhibited an amount of adaptation sufficient to compensate for only 20 percent of their original visual distortion.

The failure to find sizable amounts of adaptation after a 4-week training period is in sharp contrast to the results obtained with prisms in air and undoubtedly resulted, at least in large measure, from two things: (i) visual stimulation underwater is minimal, and (ii) the distortion in water is symmetrical, rather than all in one direction. Furthermore, this failure suggests that specific activities should be provided for inexperienced scuba divers, to facilitate their adaptation.

Facilitating the Adaptation Process

We have carried out several experiments to determine the most effective way of training inexperienced subjects. Different groups of subjects were assigned different activities underwater and were tested for hand-eye coordination before and after these activities, both in air and in water. The difference between the two sets of underwater measures gives the measure of compensation; the difference between the measures in air gives the size of the aftereffect.

Some of the underwater activities were chosen on the basis of predictions from several theories that have resulted from extensive work on adaptation to distortion in air (*32–35*). For example, one activity involved repeatedly placing a small weight on different locations on a checkerboard grid. Some subjects moved their own hand, while, in the case of others, their hand was moved for them by the experimenter (*33*); other subjects were allowed to see the results of their movements only after the movement had been completed (*34*); another group consisted of pairs of subjects (Fig. 11) one of whom was blindfolded and directed in his movements by his partner (*35*).

Other activities were based on more practical considerations or on well-used educational techniques: some subjects

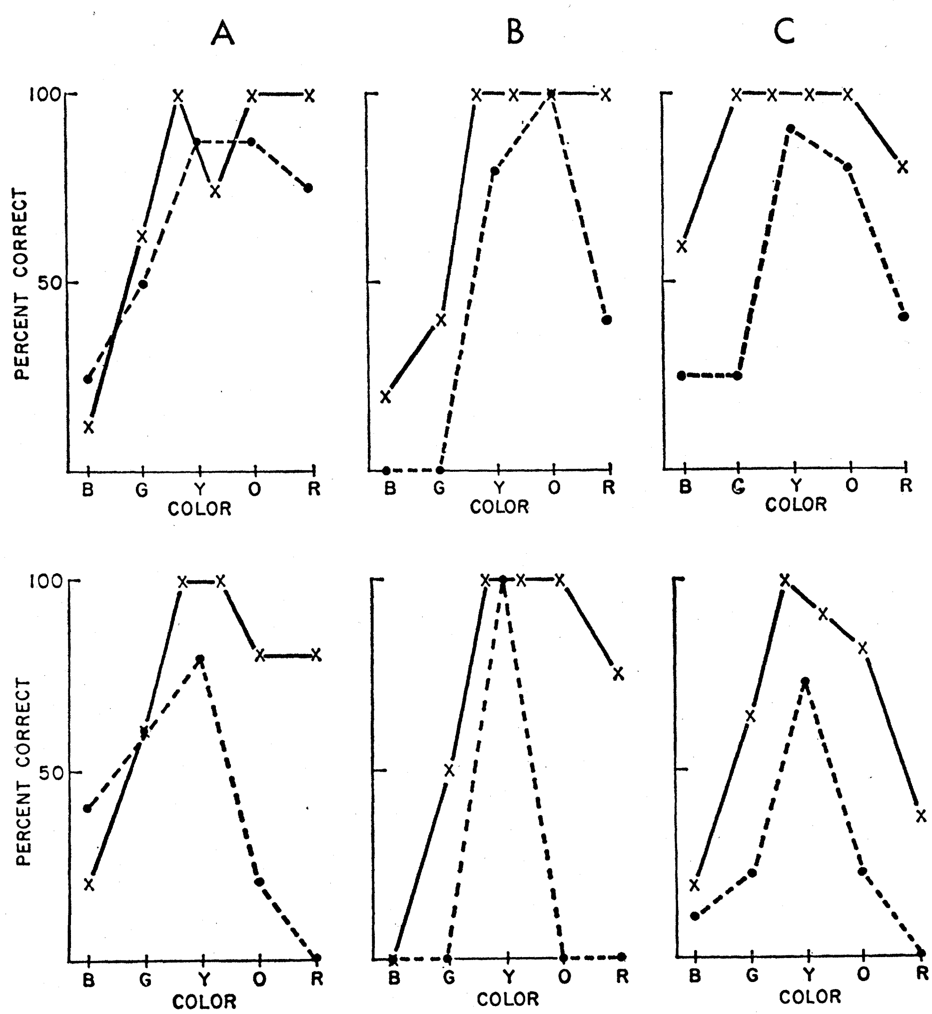

Fig. 9. The visibility of various colors in (A) the Thames River, (B) Long Island Sound, and (C) the Caribbean Sea, under illumination by (top row) a tungsten and (bottom row) a mercury light source. (Solid lines) Fluorescent paints; (dashed lines) nonfluorescent paints.

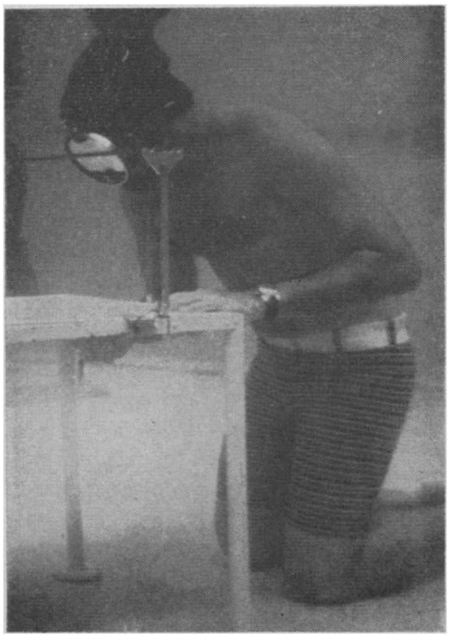

Fig. 10. Testing for hand-eye coordination underwater. The subject is directed to make a mark on the underside of the table directly under a given point on the top.

were given a lecture on distortion and then allowed to practice placing the test object; other subjects played games which involved the same type of placing response.

Finally, some subjects obtained all their underwater experience in one underwater session; for others, the same total training time underwater was divided into three periods separated by activity out of the water. Adaptation periods of two different lengths were tried, 3 to 4 minutes and 15 minutes. The former is very brief, of course, but is comparable to adaptation periods used by many investigators in air.

The results of these experiments were quite clear. Three to 4 minutes of underwater activity yielded about 20 percent compensation—a small but significant amount. The type of activity, however, made no difference; all subjects achieved the same compensation as long as they were in the water for that length of time with their eyes open.

Fifteen minutes in the water, however, produced not only greater amounts of compensation but distinct differences among the groups of subjects as well. Subjects who played various games underwater for three 5-minute intervals did significantly better than subjects in any of the other groups; they achieved 60 percent compensation on one test and 100 percent on another. Explaining the distortions to subjects and then allowing them to practice placing the test object did not help; in fact, this group did considerably less well than the group that played games. The control subjects, who simply swam around, showed the least compensation.

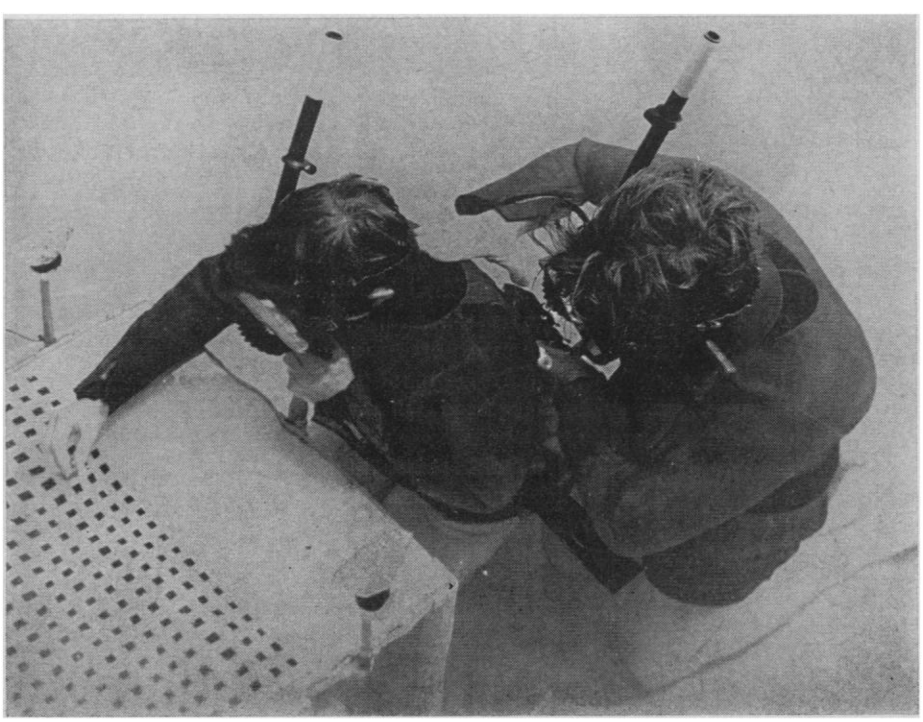

Fig. 11. Team practice in the placement task. The subject actually placing the weight is blindfolded. His teammate is signaling where to put the weight by tapping him on the shoulder.

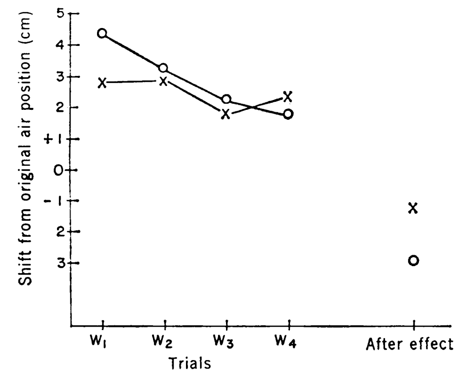

Fig. 12. Changes in the apparent position of targets with repeated testing underwater (tests W_1 to W_4) and on final testing in air (*after effect*). Positive values indicate a shift in apparent position toward the subject; negative values, a shift away from the subject relative to the apparent position of the object in air on the preliminary test. The total time in the water during the course of the experiment (W_1 to W_4) was 3 weeks for the scuba class (X's); for the inexperienced subjects (open circles) the total time in the water was 30 minutes. which included three 5-minute periods of practice and four test periods of about 4 minutes each.

Figure 12 illustrates our results. It shows four consecutive measures of compensation for the scuba class and for our most successful group. This group initially exhibited greater visual distortion than the scuba class and at the end of the test exhibited less. Moreover, it should be remembered that between the "Water$_1$" and "Water$_4$" tests. the scuba class had had 3 weeks of underwater activity, while our group had had only 30 minutes—including four testing periods of about 4 minutes each.

The factors underlying the success of this underwater activity in promoting adaptation in our subjects are not all known, but they undoubtedly include the active placing of the test object, the use of spaced rather than massed trials, and the fact that the activity held the interest and attention of the subjects. Further refinements and more time in the water should result in complete compensation for all subjects.

Summary

Both physical and psychological factors act to produce a wide variety of perceptual distortions underwater. The image of an underwater object is altered in apparent size and distance; the color and brightness of the object are changed, and its outline becomes less

distinct. Decrements in a scuba diver's performance which result from these distortions, however, may be considerably lessened by adaptation to the underwater environment. Our involvement stems from a need to improve the visual performance of divers. But in the course of this work we have become increasingly aware of another great opportunity that the underwater world provides: It is a unique laboratory for the investigation of countless perceptual problems which bear on the most fundamental theories of perception.

References and Notes

1. *New York Times* **1969**, 1 (12 Jan. 1969).
2. W. E. K. Middleton, *Vision through the Atmosphere* (Univ. of Toronto Press, Toronto, 1952), p. 12.
3. S. Q. Duntley, *J. Opt. Soc. Amer.* **53**, 246 (1963).
4. H. R. Blackwell, *ibid.* **36**, 624 (1946).
5. L. E. Kinsler, *Amer. J. Phys.* **13**, 255 (1945).
6. The maximum amount of magnification is 1.33. The exact amount obtained depends on the distance of the eye from the interface; with a typical face mask, the magnification is approximately 27 percent.
7. P. R. Kent and S. Weissman, *Nav. Submarine Med. Center Rep. No. 476* (May 1966); P. R. Kent, *Amer. J. Optom.* **43**, 553 (1966).
8. C. H. Graham, in *Handbook of Experimental Psychology*, S. S. Stevens, Ed. (Wiley, New York, 1952), p. 885.

S. M. Luria and J. A. S. Kinney, *Amer. J. Psychol.* **81**, 359 (1968).

10. H. Ross, in *Underwater Association Report 1966–67*, J. N. Lythgoe and J. D. Woods, Eds. (T. G. Williams Industrial and Research Promotions Ltd., London, 1967), p. 61.
11. A. Lit, *Optom. Weekly* **59**, 42 (14 Nov. 1968).
12. L. L. Avant, *Psychol. Bull.* **64**, 246 (1965).
13. T. C. D. Whiteside, *Roy. Air Force Inst. Aviat. Med. Flying Personnel Res. Comm. Rep. No. 910* (Nov. 1954).
14. T. Eames, *Amer. J. Ophthalmol.* **43**, 279 (1957); *J. Educ. Res.* **19**, 469 (1936).
15. S. M. Luria, *Science* **164**, 452 (1969).
16. J. Goldstein, A. Clahane, S. Sanfilippo, *Amer. J. Ophthalmol.* **62**, 702 (1966).
17. C. Phinizy, *Skin Diver* **18**, No. 5, 41 (1969).
18. J. A. S. Kinney and S. M. Luria, paper presented at a meeting of the Eastern Psychological Association, April 1969.
19. ———, D. O. Weitzman, *Percept. Mot. Skills* **28**, 331 (1969).

S. M. Luria, J. A. S. Kinney, S. Weissman, *Amer. J. Psychol.* **80**, 282 (1967).

21. H. E. Ross, *Quart. J. Exp. Psychol.* **17**, 329 (1965).
22. G. Fry, C. Bridgman, V. Ellerbrock, *Amer. J. Optom.* **26**, 9 (1949); H. E. Ross, *Brit. J. Psychol.* **58**, 301 (1967).
23. S. M. Luria and J. A. S. Kinney, *Percept. Mot. Skills* **26**, 1019 (1968).
24. J. E. Tyler, *Limnol. Oceanogr.* **60**, 102 (1959).
25. J. A. S. Kinney, S. M. Luria, D. O. Weitzman, *J. Opt. Soc. Amer.* **57**, 802 (1967).
26. ———, *ibid.* **59**, 640 (1969).
27. W. Epstein, *Varieties of Perceptual Learning* (McGraw-Hill, New York, 1967); J. F. Wohlwill, *Annu. Rev. Psychol.* **17**, 201 (1966).

G. Stratton, *Psychol. Rev.* **4**, 341 (1897); *ibid.*, p. 463.

29. See, for example, S. J. Freedman, *The Neuropsychology of Spatially Oriented Behavior* (Dorsey, Homewood, Ill., 1968).
30. I. Kohler, *Acta Psychol.* **11**, 176 (1955); *Psychol. Issues* **3**, No. 4 (1964).
31. J. A. S. Kinney, S. M. Luria, D. O. Weitzman, *Nav. Submarine Med. Center Rep. No. 541* (July 1968).
32. I. Rock, *The Nature of Perceptual Adaptation* (Basic Books, New York, 19[illegible] C. S. Harris, *Psychol. Rev.* **72**, 419 (1965); J. G. Taylor, *The Behavioral Basis of Perception* (Yale Univ. Press, New Haven, 1962); K. U. Smith and W. K. Smith, *Perception and Motion* (Saunders, Philadelphia, 1962).
33. R. Held and S. J. Freedman, *Science* **142**, 455 (1963); R. Held, *Sci. Amer.* **213**, 84 (Nov. 1965).
34. I. P. Howard and W. B. Templeton, *Human Spatial Orientation* (Wiley, New York, 1966), chap. 15.
35. S. Weinstein, E. A. Sersen, L. Fisher, M. Weisinger, *Percept. Mot. Skills* **18**, 641 (1964).

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The Experience of Living in Cities

Adaptations to urban overload create characteristic qualities of city life that can be measured.

Stanley Milgram

"When I first came to New York it seemed like a nightmare. As soon as I got off the train at Grand Central I was caught up in pushing, shoving crowds on 42nd Street. Sometimes people bumped into me without apology; what really frightened me was to see two people literally engaged in combat for possession of a cab. Why were they so rushed? Even drunks on the street were bypassed without a glance. People didn't seem to care about each other at all."

This statement represents a common reaction to a great city, but it does not tell the whole story. Obviously cities have great appeal because of their variety, eventfulness, possibility of choice, and the stimulation of an intense atmosphere that many individuals find a desirable background to their lives. Where face-to-face contacts are important, the city offers unparalleled possibilities. It has been calculated by the Regional Plan Association (*1*) that in Nassau County, a suburb of New York City, an individual can meet 11,000 others within a 10-minute radius of his office by foot or car. In Newark, a moderate-sized city, he can meet more than 20,000 persons within this radius. But in midtown Manhattan he can meet fully 220,000. So there is an order-of-magnitude increment in the communication possibilities offered by a great city. That is one of the bases of its appeal and, indeed, of its functional necessity. The city provides options that no other social arrangement permits. But there is a negative side also, as we shall see.

Granted that cities are indispensable in complex society, we may still ask what contribution psychology can make to understanding the experience of living in them. What theories are relevant? How can we extend our knowledge of the psychological aspects of life in cities through empirical inquiry? If empirical inquiry is possible, along what lines should it proceed? In short, where do we start in constructing urban theory and in laying out lines of research?

Observation is the indispensable starting point. Any observer in the streets of midtown Manhattan will see (i) large numbers of people, (ii) a high population density, and (iii) heterogeneity of population. These three factors need to be at the root of any sociopsychological theory of city life, for they condition all aspects of our experience in the metropolis. Louis Wirth (*2*), if not the first to point to these factors, is nonetheless the sociologist who relied most heavily on them in his analysis of the city. Yet, for a psychologist, there

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