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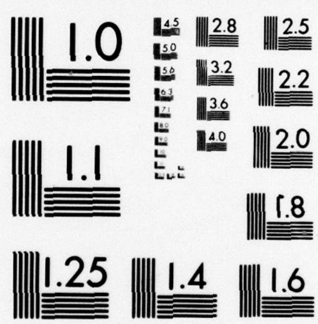

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IS THE EYE SMART OR THE BRAIN FORGIVING ?

Stanley N. Roscoe
Russell A. Benel

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Somehow we see things clearly, or at least are unaware that they are unclear, when in fact the images on our retinas are badly out of focus as determined by an infrared optometer. Although the average accommodation distance may be far from the distance of the viewed object, the more or less rhythmic fluctuations in accommodation distance are sufficiently large to bring an out-of-focus object into focus momentarily every so often, at which times it may be sampled by the brain. Furthermore, if objects are brought →

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into focus regardless of accommodation distance by the use of a small artificial pupil, the accommodative mechanism will quickly lapse toward its intermediate resting position and then, after a minute or two for many subjects, will embark upon a series of extreme fluctuations, as if searching for an out-of-focus image to back away from. These and other incidental experimental observations are now subjects of an ongoing systematic investigation.

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IS THE EYE SMART OR THE BRAIN FORGIVING?

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University of Illinois at Urbana-Champaign

Somehow we see things clearly, or at least are unaware that they are unclear, when in fact the images on our retinas are badly out of focus as determined by an infrared optometer. Although the average accommodation distance may be far from the distance of the viewed object, the more or less rhythmic fluctuations in accommodation distance are sufficiently large to bring an out-of-focus object into focus momentarily every so often, at which times it may be sampled by the brain. Furthermore, if objects are brought into focus regardless of accommodation distance by the use of a small artificial pupil, the accommodative mechanism will quickly lapse toward its intermediate resting position and then, after a minute or two for many subjects, will embark upon a series of extreme fluctuations, as if searching for an out-of-focus image to back away from. These and other incidental experimental observations are now subjects of an ongoing systematic investigation.

BACKGROUND

During the second half of the last century, students of visual sensation and perception were starting to call themselves psychologists. Many of these psychologists, particularly the Germans, had taken their formal training in physics or physiology. Quite naturally they devoted much of their early attention to physical adjustments that could be observed and measured, either directly by inspection or indirectly by introspection. Unfortunately, in their compulsion to make things tidy, they bequeathed us a legacy including some untested assumptions and a few downright misunderstandings that they had brought along from physics and physiology.

The Misunderstandings

One assumption that has misdirected psychologists for more than a century is the misbelief that the dark focus of the eye -- its relaxed accommodation distance -- is at the far point, normally taken to be "optical infinity." This long-accepted "fact" was brought into question with the discovery of the phenomenon of "empty-field myopia" experienced by pilots of high-flying airplanes (Whiteside, 1957). However, it was not until the present decade that the "intermediate distance of dark focus" was firmly established by Hershel Leibowitz and his students at Pennsylvania State University (e.g., Leibowitz & Owens, 1975) and by Robert Randle and his associates at NASA's Ames Research Center (e.g., Roscoe, Olzak & Randle, 1976). Although individual resting accommodation distances vary widely, the typical distance is at arm's length.

A closely related misconception, often an implicit assumption in experiments, is the belief that the eye reflexively accommodates reasonably accurately to the distance of an object being attended to in central vision. In fact, Hennessy and Leibowitz (1971) have shown that accommodation depends upon the distance to the peripheral surroundings as well as to the foveal target; Roscoe, Randle, and their associates (Roscoe, et al., 1976; Roscoe, 1977; Randle, Roscoe, & Petitt, in press) have shown that accommodation outward or inward is a compromise between the "pull" of the stimulus and the tendency of the eye to lapse toward its resting position; and Randle (1971) has shown that, through biofeedback conditioning, accommodation can be brought under voluntary control independent of the visual stimulus.

For accurate accommodation, two conditions are necessary: (1) adequate textural and/or perspective cues to distance and (2) the requirement to make a fine discrimination. Lacking either, the lazy eye simply doesn't bother to focus, and the forgiving brain pretends not to notice. Thus, the validity of countless experiments done in darkened rooms is limited to those conditions, and the generality of the findings to the everyday visual world is suspect. Indulging the naive "scientific" compulsion to study the "pure" effect of one variable at a time, and to hold constant or eliminate the presence of all other variables, is to deny the undeniably interactive complexity of visual processes.

For example, many investigators have used ophthalmic lenses of varying dioptric power to "induce" accommodation to different distances, not bothering to measure the actual resulting accommodation levels. Randle, et al. (in press) recently attempted such a manipulation and did measure accommodation. The investigators were surprised by the extent of the eye's disobedience and the brain's indifference. Over a stimulus range of three diopters, the eyes of 20 pilots shifted their accommodation to real images by 1.46 D, on average, and to virtual images by only 1.27 D.

The Reduced Schematic Eye

One legacy from physiological optics that remains suspect is the central assumption upon which currently accepted models of the reduced schematic eye are based, namely: that the angle subtended by the projected retinal image of an object is proportional to the visual angle subtended by the object, regardless of the distance to which the eye is accommodated (Davson, 1972; Duke-Elder, 1940). Both the Law of Size Constancy and Emmert's Law regarding the projection of afterimages depend upon this assumption, and both laws break down when the eye accommodates to different distances (Holway & Boring, 1941; Young, 1948; 1952).

The proportional retinal angle assumption and an alternative hypothesis are illustrated in Figure 1. The testing of the assumption is the subject of an ongoing investigation by the authors for the Air Force Office of Scientific Research. If the assumption proves false, the way will be cleared for the explanation of unexplained findings throughout the literature of visual perception of size and distance and various bias errors in vehicle control. Available evidence from experiments by Young among others supports the rejection of the proportional-angle hypothesis and acceptance of the alternative.

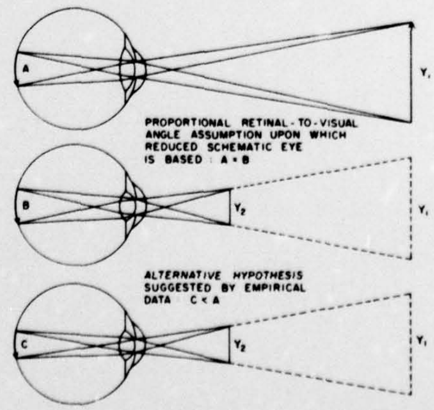

Figure 1. Illustration of the proportional retinal-to-visual angle assumption and the alternative hypothesis that the retinal angular projection is attenuated with increasing lens convexity.

THE MEASUREMENT OF ACCOMMODATION

Much of the misunderstanding and dependency upon untested assumptions concerning visual perception has resulted from the difficulty of measuring accommodation, either overtly or covertly, while subjects are making perceptual judgments. What has changed recently is the ready availability and widespread use of devices capable of relatively accurate covert measurement of accommodation without affecting it or seriously restricting the subject's performance of perceptual tasks (Crane & Steele, 1978; Crane & Clark, 1978). Measurement techniques have been available for a much longer time, but they have not been widely used -- some not at all since their original development (e.g., Wulfeck, 1952).

Overt Measurement

Leibowitz and his students and many others have made frequent and effective use of a simple and inexpensive laser optometer that requires an overt vocal or manual response by the subject (Leibowitz & Hennesy, 1975). The device has the advantage of absolute, as opposed to relative, measurement. While it does not affect the subject's accommodation, it does distract attention from a primary perceptual task. Furthermore, it does not yield continuous measurement as required for the study of the speed of accommodation or its microfluctuations.

Covert Measurement

Oculomotor adjustments that constitute part but not all of the accommodation process are changes in the curvature of the front and back surfaces of the lens. These are visibly revealed by changes in the size and position of reflections from these surfaces known, respectively, as the 3rd and 4th Purkinje images. Although the 3rd image is difficult to produce in a measurable form (and to find even then), these reflections have been observed by many investigators and measured by a few including Wulfeck (1952) who took motion pictures of the reflections from two infrared point sources.

The recent explosion in accommodation research, however, has been made possible (and greatly stimulated) by the development of the Crane-Cornsweet three-dimensional eye tracker, an infrared oculometer/optometer combination available from SRI International (Cornsweet & Crane, 1970; Crane & Steele, 1978). Briefly, the device provides a continuous, high-bandwidth output of changes in optical refraction required to keep an infrared image in focus on the retina as the eye accommodates. Its major limitation is that its measurements are relative to an approximation of zero diopter and therefore not absolute.

FUNNY THINGS THE EYE DOES

Since the original Crane-Cornsweet optometer was developed for NASA's Ames Research Center, the recordings of its outputs from many experiments have been full of surprises. The eye does some strange things; it is not only lazy and disobedient but also stubborn, emotional, and occasionally a practical joker. Several of these curious things can be seen in Figures 2, 3, and 4 which are based on representative stripchart recordings taken by Lynn Olzak and Donna Miller in an experiment conducted at Ames Research Center (Roscoe, et al., 1976; Roscoe, 1977).

These particular recordings were taken to determine the resting, or "open loop," accommodation level of each subject prior to his participation in the main experiment. Following a brief interval of preaccommodation to either a 0 D or 4 D stimulus target, a 1-mm diameter artificial pupil was positioned 8 cm in front of the subject's left eye while the subject continued to fixate the target. The artificial pupil serves to maintain a focused image as accommodation drifts "open loop" toward its resting level.

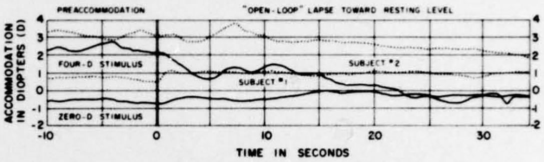

Figure 2. Preaccommodation to zero-diopter and four-diopter stimulus targets by two pilots, followed by their "open-loop" responses subsequent to the insertion of an artificial pupil in front of the left eye at time-zero.

Preaccommodation

In Figure 2, the recordings for two subjects have been smoothed to illustrate more clearly a number of typical findings: (1) Individuals accommodate differently to the same stimuli, particularly as their distance increases; to the 0-D target, Subject 2 preaccommodated to a dioptric level that corresponds to a distance of 1-1/2 meters, whereas Subject 1 preaccommodated to a distance beyond minus 1/2 D (a response analagous to that of a zoom lens). (2) Subjects preaccommodated more steadily to more distant targets. (3) Despite the large displacement of preaccommodation levels for the two subjects, the differences in responses to 0-D and 4-D stimuli by each subject were of a similar magnitude.

Open-Loop Responses

Upon insertion of the artificial pupil, Subject 1's eye took off in a hurry, wandered a bit, and then proceeded to its resting level just beyond optical infinity (<0 D); Subject 2's eye went immediately to 1 D from its preaccommodation to the 0-D target and hugged the 1-D line thereafter; but, from its 4-D target, it initially wandered around as if confused, actually rising to almost 4 D at the 7-sec point, and then slowly lapsed toward a resting level of 2 D, showing a hysteresis of 1 D relative to its resting level from preaccommodation to the 0-D stimulus.

These responses are typical of two types of subjects between and beyond which there is continuous variation within the normal population. Individuals (e.g. Subject 1) with distant resting accommodation tend to underaccommodate to either near or far targets and to lapse quickly to their resting level from either direction. Individuals (e.g. Subject 2) with near resting accommodation tend to overaccommodate to far targets and to lapse slowly and uncertainly from their near preaccommodation level toward a resting level that is much nearer than their resting level following preaccommodation to a far target. These are the individuals who contribute to the typically observed group hysteresis in resting accommodation levels.

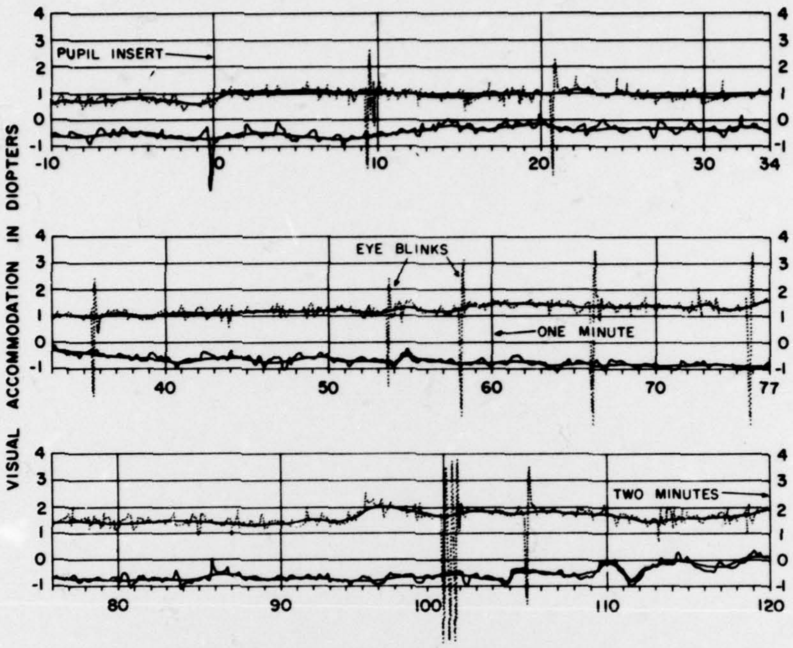

Figure 3. Continuous records of "open-loop" accommodative responses of two subjects, with smoothed curves superposed, for two minutes following preaccommodation to a zero-diopter stimulus.

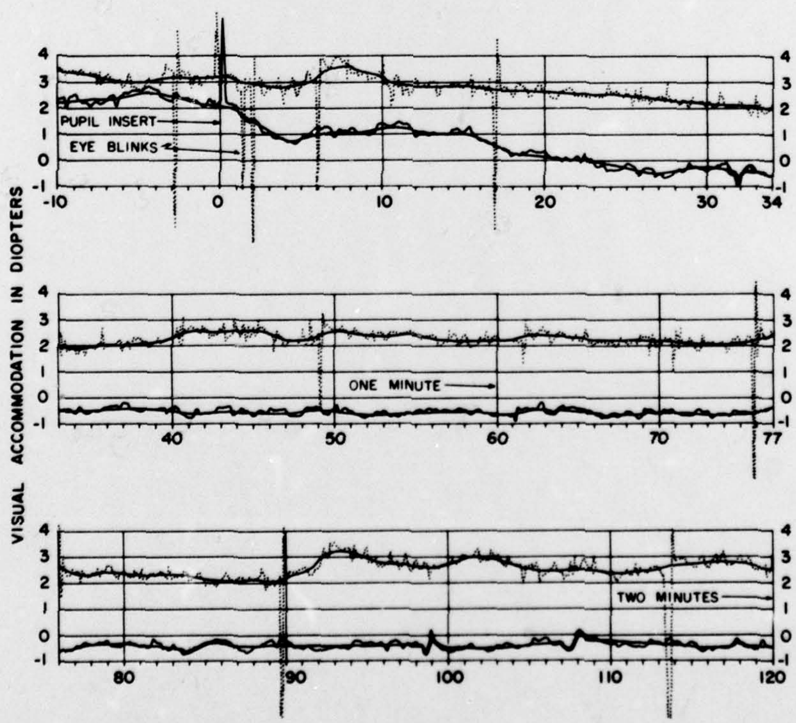

Figure 4. Continuous records of "open-loop" accommodative responses of two subjects, with smoothed curves superposed, for two minutes following preaccommodation to a four-diopter stimulus.

Hyperopic individuals (like Subject 1) are readily trained to accommodate voluntarily, and when so trained, their relatively smooth spontaneous fluctuations in accommodation, to be seen in Figures 3 and 4, become even smoother, particularly at their resting distance. In contrast, myopic individuals (like Subject 2) are resistant to conditioning of accommodation control, and their "noisy" spontaneous fluctuations and frequent blinks persist. People like Subject 1 are referred to by Randle (personal communication) as "sympathetic" types: outgoing, flexible, attentive to their environment; those like Subject 2 as "parasympathetic" types: inward-looking, defensive, perseverative. So much for Randle as a clinical psychologist.

And so much for typical findings; now for the surprises. Figures 3 and 4 follow the open-loop responses of the same two subjects for another minute and a half beyond the limit of Figure 2. These figures include the actual unsmoothed output of the optometer, as well as the smoothed curves, and show the spontaneous fluctuations in accommodation that range over about ± 1/2 diopter for Subject 2. These fluctuations are not unlike the spontaneous fluctuations in the line of sight that are essential to normal vision (Pritchard, 1961), and they suggest a mechanism that allows us to see clearly though not accurately accommodated by recourse to a scanning process.

But the big surprise is yet to come. In most tests of resting accommodation, responses have been recorded for only one minute. When Lynn Olzak asked the senior author how long to record the subjects' open-loop responses, he said, "Let's let it run for two minutes. Maybe the hysteresis will wash out." The hysteresis did not wash out, but something else happened. At varying times during the second minute of open-loop response, the eyes of several of the subjects entered a hunting mode of one type or another -- as if they were looking for an out-of-focus image to back away from.

In the case of Subject 1, the hunt did not start until the fourth half-minute and the searching strategy was oscillatory. For Subject 2, the strategy was different: after preaccommodation to a 0-D target, this subject maintained a steady 1-D resting level for almost a minute, then shifted inward about 1/2 D for about 40 sec, and then abruptly inward to the 2-D level, which he tended to maintain for the rest of the second minute. After preaccommodating to the 4-D target, this subject's eye drifted to a resting level of about 2 D within half a minute, wandered around between 2 D and almost 3 D for the next minute, and then abruptly jumped to 3-1/2 D and wandered near that level for the next half minute.

The responses just described are not unusual; in fact, they have been selected as typical of two different types, tending toward but not reaching the extremes. What they illustrate in common is that, while different eyes employ different strategies, eyes in general seek an out-of-focus image to back away from, thereby maintaining a sufficiently clear image for the perceptual task at hand. What else these recordings indicate is that the literature of visual perception of size and distance is replete with data that do not mean what the investigators thought they meant and a host of conclusions that can be dead wrong.

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