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One fixates accurately *in order to* see clearly not *because* one sees clearly *

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Abstract—Binocular gaze was measured accurately under natural conditions with the Maryland Revolving Field Monitor to determine how visual-clarity affects gaze-accuracy. The gaze of 3 unrestrained, seated subjects (2 presbyopes and 1 myope) was recorded as they tapped 4 LEDs with a long, narrow rod cemented to a thimble worn on their index fingers. They wore positive contact lenses, permitting very clear vision only nearby, within 35 cm. This task was hard. It took more than 7 seconds to complete. Gaze-accuracy varied inversely with target-distance. Gaze was less accurate when targets were nearby, and seen clearly, than when targets were farther away and harder to see. This result was not anticipated. It implies that gaze is accurate *in order to* see clearly and not *because* targets can be seen clearly.

Keywords: Gaze-accuracy; gaze-error; cyclopean; microsaccade; steroacuity; visual-clarity.

INTRODUCTION

Epelboim *et al.* (1995) reported that their subjects controlled gaze in an efficient manner, that is, targets were fixated no more accurately than required to accomplish a specific task. Subjects instructed to fixate a series of targets accurately, fixated more accurately than when similar targets were fixated for the purpose of tapping them. In short, the oculomotor system does not, automatically, perform at, or even near, its capacity-limit. This dependence of gaze-accuracy on task-demands

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encouraged us to examine the relationship between the clarity of vision and gaze-accuracy.

We thought this relationship was intuitively obvious. Accurate fixation requires clear vision. You fixate accurately *because you can* see fine details. This proved not to be the case. We found that fixation is made accurate *in order* to see fine details, not *because* they can be seen. It seems that when you can see relevant objects clearly, gaze-errors are not obvious, and when they are not obvious, gaze-accuracy will be adjusted only to be sufficient for accomplishing the particular task at hand.

We studied the relationship between visual-clarity and gaze-accuracy under conditions that made very stringent demands on gaze-control. Subjects had to tap a small conical object with a thin rod attached to an index finger. Visual-clarity was also controlled. It could not be varied by the subject. This was accomplished by using emmetropic, geriatric, presbyopes as subjects. Their long-standing presbyopia left them virtually devoid of accommodative power. They wore positive contact lenses that allowed them to see nearby objects very well. Things looked clear only as long as they were very near, but only when they were very near. A third, much younger, mildly myopic, subject also participated. She also wore positive contact lenses. They guaranteed that she could only see nearby objects clearly. She could still accommodate, but relaxing accommodation completely, while wearing positive contact lenses, left her distance-vision blurred. She participated because we wanted to be sure our findings were not confined to geriatric presbyopes.

METHOD

Binocular eye movements of seated, unrestrained subjects were recorded with the Maryland Revolving Field Monitor (MRFM). Three subjects participated; two, RS (age 71) and YA (age 67) were very presbyopic emmetropes and one, JE (age 34), was mildly myopic (correction = 0.7 D). RS and JE were authors. RS had served in prior experiments on the gaze-control with nearby objects (Epelboim *et al.*, 1995, 1997; Epelboim, 1998). JE was also an experienced subject and knew the experiment's purpose. YA was much less experienced, and did not know its purpose when he participated. During half of the sessions, subjects wore hard contact lenses that gave them very clear vision at 20–35 cm. Powers were +5, +6.5 and +3.5 D for RS, YA and JE, respectively. When contact lenses were worn, visual-clarity was poor for distances > 35 cm. With natural, unaided vision, the two presbyopes could only see objects clearly when they were well-beyond arm's reach. The much younger, myopic subject could see everything within arm's reach clearly with unaided vision. She could see the most distant targets clearly when she did not wear positive contact lenses because all of the targets were located nearer than 1 m.

Arrangements to make tapping difficult

Tapping was done with a thin rod (1.5 cm $\times$ 2 mm diam.) cemented to a metal sewing-thimble worn on the index finger of the right hand. This made the task hard because: (i) the rod's tip had to press at the *exact center* of a 5 mm diam. conically-shaped LED, and (ii) the LED was mounted on a rod inserted into a closely-fitted tube with a microswitch at its bottom. There was little lateral play, so the force had to be directed *exactly downwards* to close the switch, causing a sound which signified a successful tap.

Instructions

Subjects were asked to complete each trial, as fast as possible, without making tapping-order errors.

Figure 1 shows the arrangements used in this difficult tapping task.

DATA COLLECTION

Apparatus

The Maryland Revolving Field Monitor (MRFM) is a unique eye movement recording instrument capable of absolute calibration. It records binocular gaze accurately with the head free to move naturally. It is described in detail in Edwards *et al.* (1994) and in Epelboim *et al.* (1995). Its main features were summarized in Epelboim *et al.* (1997); Epelboim (1998); Malinov *et al.* (2000) and again in Herst *et al.* (2001), so only specifications will be provided here. The MRFM consists of 3 subsystems: (1) The Revolving-Field Monitor/Sensor Coil subsystem (RFM) uses phase-detection to measure angular positions of the eyes and head (angle measurement accuracy = 1 min arc, linearity = 0.01%). Data are acquired at 976 Hz, successive sample-pairs are averaged, and stored at 488 Hz, so effective bandwidth was 244 Hz. Cube-surface field coils (2.1 m on a side), produce a spatially homogeneous magnetic field throughout a large fraction ($\sim$1 m^3) of the cube's volume. Skalar-Delft sensor coils measure horizontal and vertical eye-angles. Recording sessions are limited to 20 minutes in conformance with the recommended wearing-time for the Skalar-Delft sensor coils. Head roll-, pitch- and yaw-angles are measured with two orthogonal coils mounted on a tightly-fitting cap. (2) The Sparker Tracking System (STS) measures 3-D translations of the head by detecting the arrival time of acoustic signals generated by a 'sparker' mounted firmly on a cap. The head translation measurement precision was 0.2 mm with accuracy $\sim$ 1 mm. (3) A worktable serves as a platform for the targets. Its surface contains a grid of 154 wells, each with a microswitch at its bottom. Rods topped with LEDs of different colors served as targets. A target without an LED, located near the subject, defined the 'home' position.

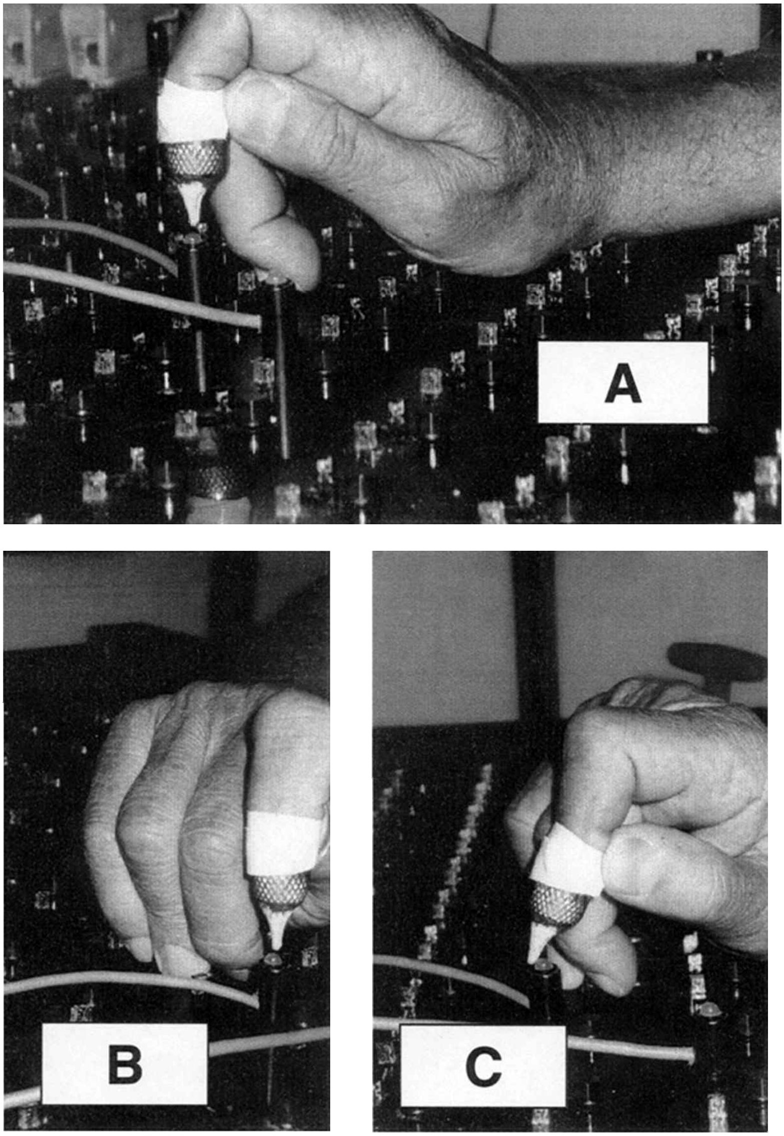

Figure 1. Subject RS engaged in 'Hard Tapping'. (A) Shows the position of the hand on the Worktable. (B) Shows the index finger almost aligned in a position that will be effective, and (C) Shows the narrow rod after it has slipped off the conical top of the LED. See text for other details.

DATA ANALYSES

General procedures for handling MRFM are in print (see above), so only a brief summary will be given.

Calibrations

Three calibrations were performed: (i) sparkers of different heights were placed in 18 locations on the worktable to calibrate 'sparker-space', (ii) sighting-centers of each subject's eyes were measured psychophysically with the head on a bite-board, and (iii) sensor-coils orientations, relative to its line-of-sight, were recorded at the start of experimental sessions by having the subject fixate each eye's pupil seen in a mirror orthogonal to the axis of the coordinate system of the worktable, whose direction corresponds to the straight-ahead direction when the subject is on a bite-board.

Definition of cyclopean gaze

Cyclopean gaze was defined as the line that passes through the midpoint of the subject's baseline (a line connecting sighting-centers of each eye, 'midpoint' henceforth) and the binocular fixation point. The familiar concept of the binocular fixation point, however, is almost always a simplification of the actual situation. If the right and left lines-of-sight intersected in 3-dimensional space, as visionists tend to assume for convenience, one can easily find this point. But in reality the two lines-of-sight seldom actually intersect, so it becomes necessary to define the binocular fixation point more elaborately. We define it as the midpoint of the line that is simultaneously perpendicular to both lines-of-sight. It can be shown that such a line is unique (unless the two lines-of-sight are parallel) and that the length of this line represents the smallest distance between the two lines-of-sight. Once the binocular fixation point is defined, the cyclopean gaze vector is defined as the vector from the midpoint to the binocular gaze point.

Calculation of gaze-errors

All gaze-shifts were performed naturally and, as such, very few were purely horizontal, or purely vertical. Furthermore, designating arbitrary space-fixed planes such as horizontal and vertical was not practical because the head was free to move, which caused the relationship between head and worktable coordinates to vary during trials. For this reason, gaze-errors will be reported as absolute angular errors without reference to their directions. Angular gaze-error is defined as the angle between the gaze vector for a given eye and the vector from the sighting-center of the eye to the target (see Fig. 2).

Cyclopean gaze-error is defined in the same way as the gaze-errors for each eye. Another way to assess cyclopean gaze-error is to compute the distance between the binocular fixation point and target (see Fig. 2). The distance method incorporates vergence error as well as directional error. We preferred to use angular errors instead of the distances because we found that subjects under-verge significantly under natural conditions (Malinov *et al.*, 2000), and wanted to avoid a possible confounding of vergence strategies with gaze-direction strategies.

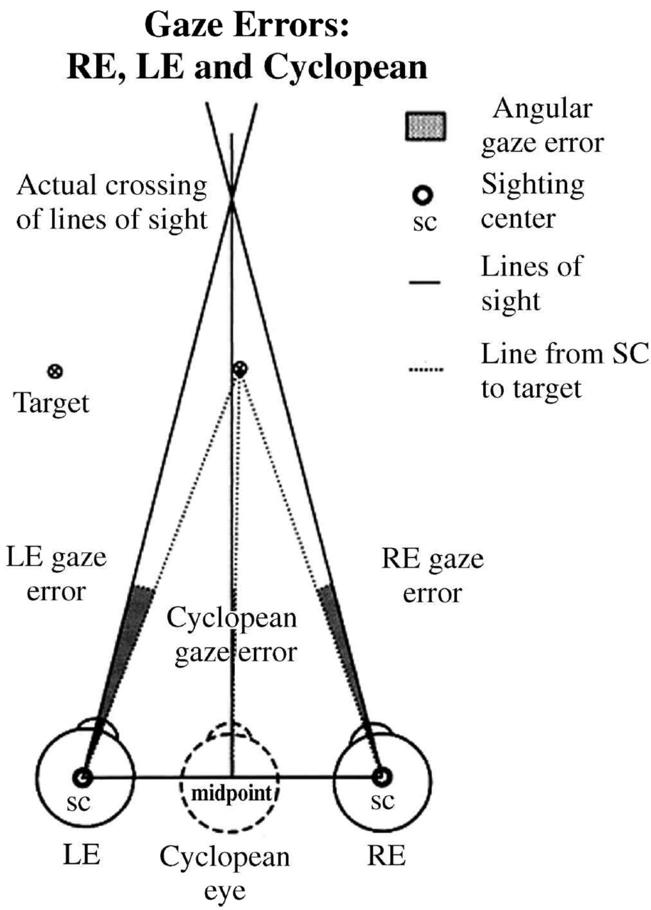

Figure 2. Definition of gaze errors (see text for details).

Three 100 ms *minimum* gaze-errors will be reported, the gaze-error of the left eye, right eye and cyclopean ‘eye’. These 100 ms *minimum* gaze-errors were the smallest gaze-error, averaged over 100 ms, observed in the interval between the end of a successful tap of the previous target and the beginning of the tap of the current target. A tap ‘ended’ when the microswitch closed.

Procedure

Trials contained 4 targets whose order was indicated by the colors of their LEDs; namely, gold, green, red, and flashing-gold. Each randomly-generated target configuration was tested in a block of 5 trials (replications). The subject kept eyes closed before each block, while the targets were placed in random locations. Eyes were also kept closed between trials within each block of replications. When the configuration was prepared, the subject began the trial by pressing a button. Trials lasted 12 s. Experiments took place in a well-lit room with a clear view of objects on the worktable.

RESULTS

Gaze-errors

The scatterplots in Figs 3–5 show the gaze errors of the left eye (LE), the cyclopean eye (CYC) and the right eye (RE) as a function of viewing distance for each of the three subjects. Subjects' cyclopean gaze-errors tended to be as small as, or smaller than, the gaze-errors of either eye in both conditions. In other words, there is no 'dominant eye' when it comes to the binocular control of gaze. The superior accuracy of cyclopean gaze-control confirms a prior finding (Epelboim *et al.*, 1995) and extends it to a quite different task, one that requires exceedingly fine visuomotor coordination of the hand and eyes. The top panels show results when viewing was done with contact lenses. The bottom panels show results when contact lenses were not worn. The bar-graphs shown in Fig. 6 summarize these results. They show the mean gaze errors (with error bars) of each subject under both viewing conditions. Viewing distances in this figure have been grouped into near (less than 35 cm) and far (greater than 35 cm) viewing distances. Recall that at near distances, the presbyopic subjects required contact lenses to see the targets clearly. The young myope, however, could see them clearly without contacts. She wore positive contact lenses to limit her accommodative range, leaving near targets clear, but far targets relatively blurry. So, in the case of the two presbyopes at our near distances (<35 cm), the difference in the clarity of vision, when contacts were worn compared to when they were not worn, was large. They had almost no accommodative power left in their crystalline lenses. Without positive contact lenses, they could only see objects clearly at distances very much farther than any used in this experiment. Their 'near points' were several meters away. At our far distances (>35 cm), the two presbyopes (RS, YA) saw the targets more clearly when they wore contact lenses, but the young myope (JE) saw all but the closest targets more clearly when she did not wear contact lenses.

Consider first the comparison between viewing with and without contact lenses. In the case of the two presbyopes (Figs 3 and 4), all three gaze-errors (LE, CYC, RE) tended to be larger when they wore contact lenses, especially at near distances. This can be confirmed easily by looking at Fig. 6, which plots their mean gaze-errors. In the case of the naive subject (YA), the differences in all three gaze errors between contacts and no contacts were statistically significant for both near and far viewing distances (note the small standard errors). In the case of RS, two of his gaze-errors (LE, CYC) were significantly larger with contacts than without contacts. His remaining gaze-error (RE) was about the same in both viewing conditions for both near and far viewing distances. JE's results for near distances are similar to those of YA and RS (Fig. 6). Specifically, two gaze-errors (CYC, RE) were significantly

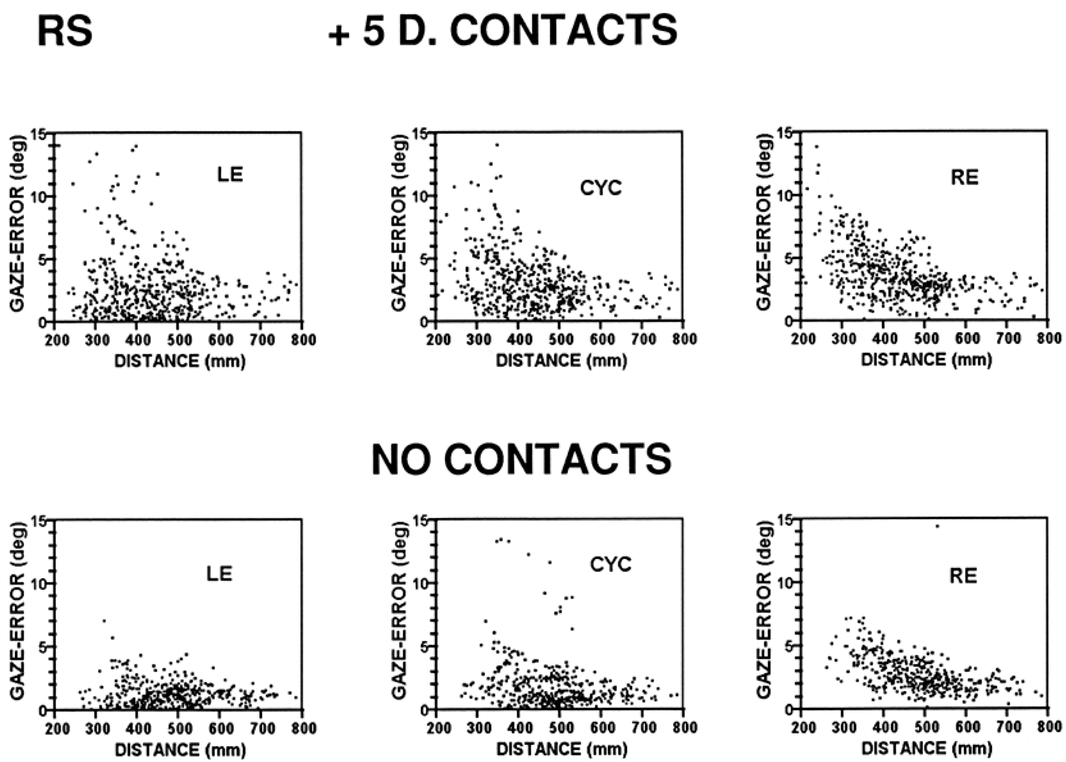

Figure 3. Subject RS's minimum 100 ms absolute GAZE-ERROR in degrees of visual angle of the left and right eyes (LE and RE) and the cyclopean eye (CYC) plotted as a function of the DISTANCE in mm from the origins of the lines-of-sight at each eye's sighting-center or from the mid-point of the line connecting them, which is the origin of the cyclopean line-of-sight (see the METHODS section). Graphs on top show these gaze-errors when positive contact lenses were worn ($N = 568$). These contacts permitted clear vision of nearby objects. The graphs on bottom show gaze-errors when contact lenses were not worn ($N = 520$).

larger with contacts than without contacts, and the remaining gaze error (LE) was about the same in both conditions (Fig. 6). For far distances, all of JE's gaze-errors were about the same in both viewing conditions.

Clearly, these results show that gaze-errors tend to be smaller when targets are harder to see. The most likely, and intuitively obvious reason (albeit overlooked by us and by all others known to us), is that when targets are hard to see, the subject must fixate more accurately to accomplish a visuomotor task that requires making-out fine details. Another way of thinking about this is to say that the observer, rather than the environment, controls the accuracy of the observer's eye movements.

Next, consider the effect of viewing distance. The scatterplots in Figs 3–5 show that gaze-errors tended to be smaller at larger distances. This was especially true when contact lenses were worn. Why should viewing distance affect the magnitude of gaze-errors? There are three possible factors. The first is related to the fact that far away targets are seen less clearly because their retinal images are smaller and their images are blurred more when contact lenses are worn than when contact lenses are not worn. As a result, the subject *must* fixate more accurately to perform the difficult task employed in our experiment (this reason was suggested above). The second factor is related to the error inherent in our measurement of eye position. Let the magnitude of this error be x, the viewing distance d, and let the gaze error produced by x be α. For small α, $\alpha \approx x/d$. Thus, the relation between α and d is hyperbolic. Note that, although some scatterplots in Figs 3–5 represent a hyperbolic relation, others do not. More importantly, however, the errors x predicted from the gaze-errors that we measured are, on average, 2 cm. This is an order of magnitude greater than our measurement error. Clearly, measurement errors cannot account for the effect of distance on the gaze-errors shown in Figs 3–5. A third factor, which might explain why gaze is more accurate at larger distances, is that for a given physical target, the size of the target's retinal image is a hyperbolic function of the viewing distance. If dispersion of fixation were proportional to the retinal size of the image of the target, the dispersion of gaze would be a hyperbolic function of the viewing distance, the type of function seen in some scatterplots in Figs 3–5. It is known, however, that the gaze-stability does not vary systematically with the retinal size (diameter) of a fixation target disc, at least when target size is varied between 1.9 and 87.2 min arc (Steinman, 1965). The retinal image size of the LED targets used in the present experiment varied as the subject moved back and forth to see, reach for, and tap the targets with the narrow rod. Such movements caused the target's retinal image size to vary between 86 min arc (when the distance to a target was 20 cm) and 21 min arc (when the target was far away, but still within arm's reach, i.e. 80 cm). Such retinal image target sizes are well within the range where fixation stability does *not* depend on the fixation target's size. It follows that the subjects' ability to maintain gaze (fixation stability) was not likely to be responsible for the smaller gaze-errors at the larger distances observed in the present experiment.

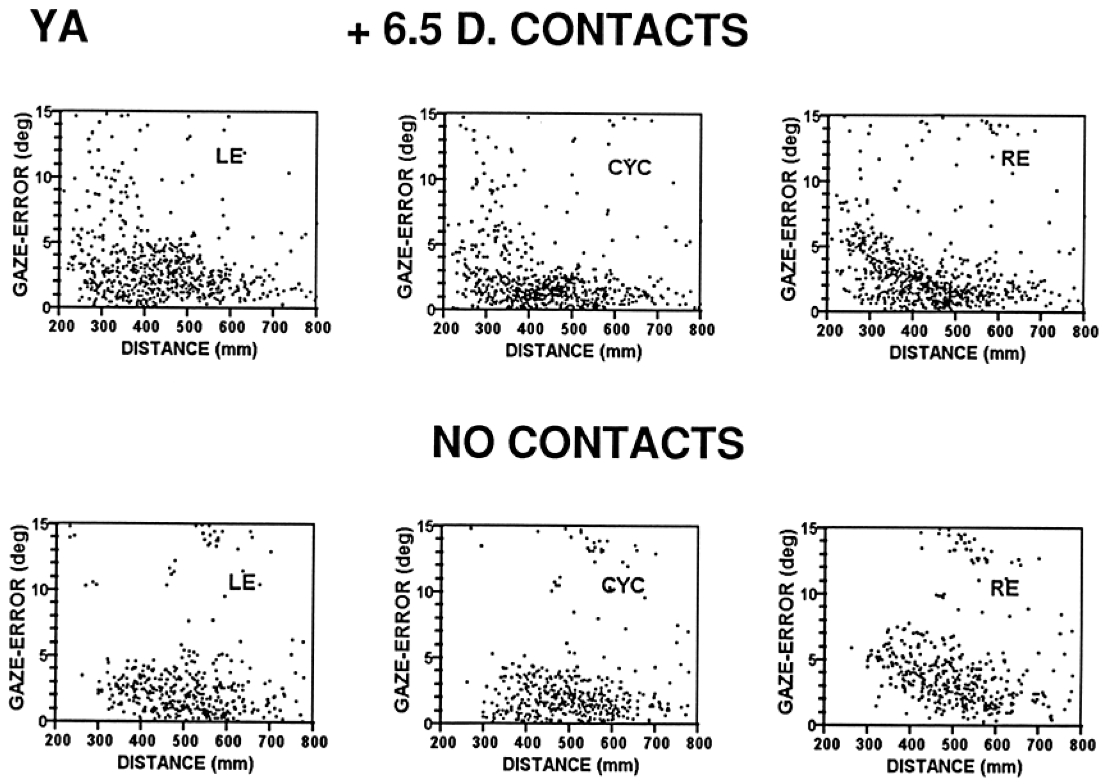

Figure 4. Subject YA's minimum 100 ms absolute GAZE-ERROR in degrees of visual angle of the left and right eyes (LE and RE) and the cyclopean eye (CYC) plotted as a function of the DISTANCE in mm from the origins of the lines-of-sight at each eye's sighting-center or from the mid-point of the line connecting them, which is the origin of the cyclopean line-of-sight (see the METHODS section for details). Graphs on top show these gaze-errors when positive contact lenses were worn ($N = 776$). These contacts permitted clear vision of nearby objects. The graphs on bottom show gaze-errors when contact lenses were not worn ($N = 735$).

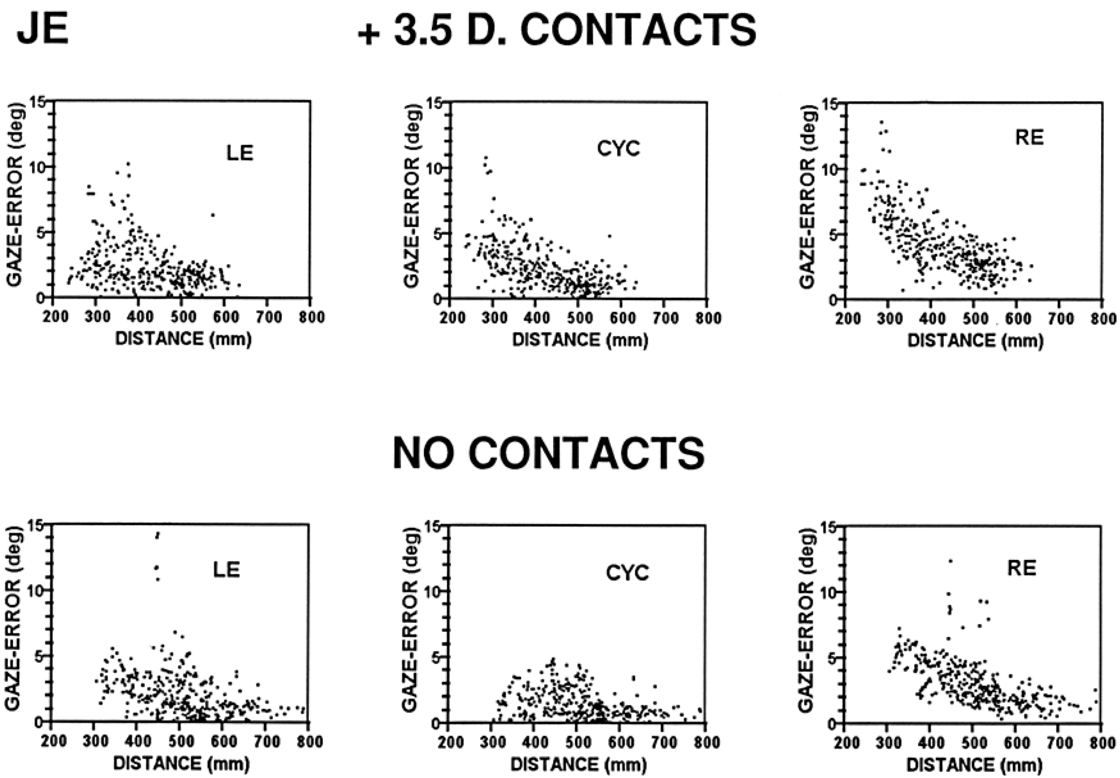

Figure 5. Subject JE's minimum 100 ms absolute GAZE-ERROR in degrees of visual angle of the left and right eyes (LE and RE) and the cyclopean eye (CYC) plotted as a function of the DISTANCE in mm from the origins of the lines-of-sight at each eye's sighting-center or from the mid-point of the line connecting them, which is the origin of the cyclopean line-of-sight (see the METHODS section). Graphs on top show these gaze-errors when positive contact lenses were worn ($N = 376$). These contacts permitted clear vision only of nearby objects. The graphs on bottom show gaze-errors when contact lenses were not worn ($N = 371$).

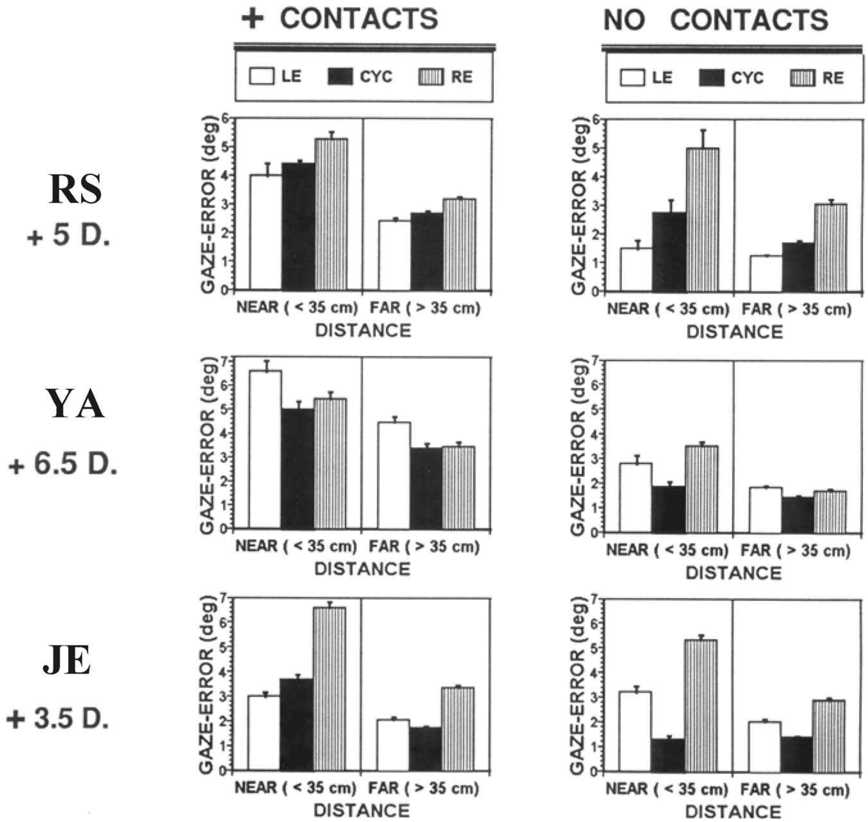

Figure 6. Mean gaze errors (with standard errors) computed from the results shown in Figs 2–4.

To summarize, it seems clear that the effects of visual clarity and viewing distance on the magnitude of gaze-error must be attributed to the difficulty of the task: larger and clearer nearby targets demand less of both the visual and oculomotor systems. We already knew from prior work (Epelboim *et al.*, 1995) that the oculomotor system prefers to work no harder than required for the successful completion of a particular task. Once the contact lenses allowed the observer to see the spatial relationship between the tip of the narrow rod and the exact center of the conical LED clearly, the oculomotor system did not have to perform at anywhere near its capacity limit. This meant that the task could be completed successfully despite the presence of relatively large gaze-errors. When the target and rod were far away, however, this relationship could *not* be seen clearly, and the control of gaze became more important. The task could not be accomplished without accurate fixation. This led to smaller gaze-errors. After the fact, this inverse relationship between the clarity of vision and the accuracy of gaze seems sensible, even intuitively obvious. Before this experiment had been performed, however, we, and we suspect that most vision scientists, would not have anticipated this result.

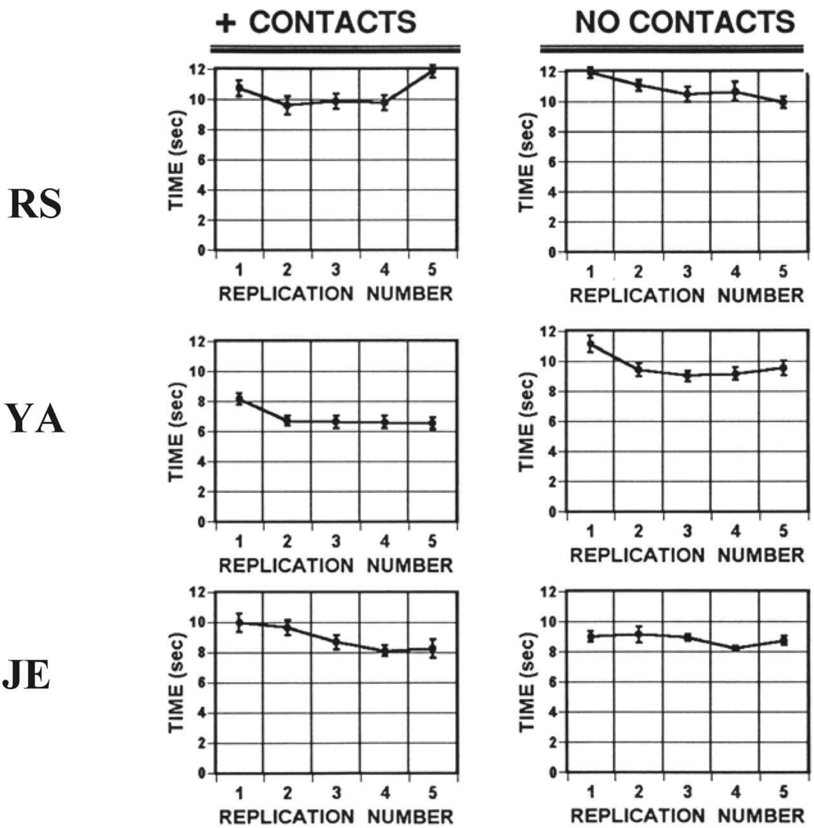

Figure 7. Time to complete a trial as a function of its position in the sequence of replications.

Learning

Figure 7 shows the subjects' learning curves (time to complete a trial as a function of its position in the sequence of replications of each target configuration). The task was difficult. On average, it took RS and JE about more than 8 seconds to complete the 4-target sequences in both conditions. YA also took more than 8 seconds when he did not wear contacts but he was able to complete the task in about 7 seconds when he could see better. The task remained difficult for all subjects under both conditions, i.e. practice helped speed little. There were only small improvements in the time it took to complete the series over the replications.

Microsaccades

Common sense, unlike the oculomotor literature, suggests that microsaccades might be common during a difficult visually-controlled motor task. They were not. Only 4 of the 3258 saccade vectors sampled (0.12%) were $<$ 17 minutes of arc. Our motivation for estimating the likelihood of a microsaccade and the significance of finding that they were unlikely is explained in the Appendix, where the history of microsaccades in visual science is reviewed. This appendix was provided because there has been, what we believe to be, a misguided resurgence of interest in these laboratory curiosities recently.

IMPLICATIONS

These results have three implications. Namely: (i) Do not assume that an individual is looking directly at something because s/he says that it can be seen clearly. (ii) Humans look only as accurately as needed to get a job done. (iii) If one wishes to use the direction of gaze to guide the direction of an action in the outside world, it would be best to make the target of the action hard, rather than easy, to see. In practical terms, degrading, rather than enhancing, the quality of a visual display might be the best way of using a human being's gaze to control events taking place within the visual field.

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APPENDIX

Microsaccades are very small (<12 min arc on a single meridian) high velocity shifts of the line-of-sight that have figured prominently in oculomotor and visual science for almost 50 years, beginning about 70 years ago (Adler and Fliegelman, 1934). The functional significance of microsaccades, observed frequently when many adult human subjects maintain fixation on a stationary target with their heads immobilized, came into question when Steinman *et al.* (1967) reported that simple instructions reduced their frequency in the fixational oculomotor pattern by 50% or more. Many subjects could even inhibit them completely for many seconds. Changes like these in microsaccade rates had no effects, whatsoever, on the subject's vision. Steinman *et al.*'s (1967) initial observations were followed by a series of publications, which showed that these small saccades were in the voluntary behavioral repertoire. In less than a decade, Steinman *et al.* (1973), and many other oculomotorists, accepted the fact that microsaccades were a laboratory curiosity. They were not an important oculomotor behavior. Furthermore, they had no significance for vision. Ditchburn (1980) disagreed, and published a comment on one of the papers in this series that led to an exchange of letters (Kowler and Steinman, 1979, 1980). This exchange should be read by anyone interested in the significance of fixational microsaccades. Their role in processing visual contrast and spatial detail was summarized and discussed in great detail a decade later (Steinman and Levinson, 1990). Furthermore, it became clear that microsaccades were probably not present in the oculomotor pattern when it first became possible to study gaze-control accurately under relatively natural conditions (Steinman and Collewijn, 1980). Proving this, and disseminating this information widely, became important recently because oculomotor researchers, using monkeys as subjects, seemed to be unfamiliar with the voluminous 'old' (pre-1991) literature on human microsaccades. They were actually taking them seriously despite all that was known from prior work (e.g. Bair and O'Keefe, 1998; Martinez-Conde *et al.*, 2000; Rucci *et al.*, 2000). This led Malinov *et al.* (2000) to examine the likelihood of observing a microsaccade when human subjects performed two sequential looking tasks under relatively natural conditions, i.e. when viewing was binocular and heads were free to move naturally. Malinov *et al.* (2000) found that only 0.06% of the saccades (2 of the 3375) sampled could be classified as 'microsaccades', i.e. they were less than 12 min arc on a single meridian. These authors concluded that: "We have another reportable, but expected result. Namely, microsaccades were extremely unlikely. Those, who have studied human eye movements under natural conditions with instrumentation sufficiently sensitive (noise $< 2'$) to measure microsaccades, have rarely seen microsaccades (Steinman and Collewijn, 1980, were probably the first). But as far as we know, the actual likelihood of finding a microsaccade under natural conditions has never been reported, in part because: (i) other issues were under study; and microsaccades had lost their significance by 1980. They were laboratory curiosities, confined to human adults, whose head were supported artificially" (p. 2089).

Concern with this issue encouraged us to examine the likelihood of finding such small saccades in our dataset. Their frequency had never been determined in an experiment that made as extreme demands on finely-guided hand-eye coordination as the task we employed. We did not expect to find many, however, because Winterson and Collewijn (1976) had already shown that microsaccades become infrequent, even dropping out completely, when subjects threaded a needle and aimed and shot a rifle in an experiment in which their subjects' heads were immobilized by means of a chinrest.

We did our microsaccade analysis in the following way. Saccades were measured with respect to the head. The eye-in-head angles (orientation of the eye with respect to the head) were defined by the Helmholtz coordinate system. The coordinate axes of the Helmholtz system, defined during the mirror trials, were fixed to the head as it moved. Saccade size (offset−onset) was analyzed separately for horizontal and vertical meridians and the 2D saccade vector was calculated. We adopted the conventional definition for the size of a 'microsaccade'; namely, 12 min arc on a single meridian. This meant that a saccade would be dubbed a 'micro' when its vector was less than 17 min arc.

Saccades were detected and marked manually with a mouse on a graphic display of the data. Why? When eye movements are measured under natural conditions with the head free, saccade amplitudes can range from less than 5 min arc to more than 100°. We had saccade-detecting algorithms, but they could not cover the entire range efficiently. With parameters set to detect microsaccades, fast drifts would be flagged. Set for large saccades, microsaccades would be missed. Once the range of saccade sizes and peak velocities is large, visual inspection of all of the algorithm's detections becomes necessary

We chose to sample representative trials, rather than to use the algorithm on all records, and then be forced to separate wheat from chaff by visual inspection (see Fig. 1 in Malinov *et al.* for examples of micro- and large-saccades as they appear in recordings made with the MRFM). Saccades made in a random sample of 100 trials were examined (50 from the 'contact lens' and 50 from the 'no contact lens' conditions). The mean number of saccades/12 s trial each subject made in the 'contact' and 'no contact' conditions did not differ significantly and they were combined. RS's mean number of saccades/12s trial = 12.3 (SD = 2.85); JE's = 10.9 (SD = 2.85) and YA's = 9.39 (SD = 2.88). The total number of saccades made by the three subjects was 3258. Of these, one of RS's and three of JE's were small enough to meet our conventional 'microsaccade' criterion. Only 4 of the 3258 saccades sampled fell into this category, only 0.12%. We conclude that microsaccades were sufficiently infrequent in our 'difficult' tapping task to suggest that their significance, if any, can be ignored when human vision and oculomotor performance are studied under conditions that approximate those present in everyday life.