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13. ABSTRACT (Maximum 200 words)

This grant: 1) tests alternative hypotheses about the mechanism that controls gaze-shifts when nearby objects are manipulated: Two quite different mechanisms have been proposed, namely, a) on-line feedback and b) learned, preplanned patterns of coordinated movements, and 2)studies the speed and accuracy of visually-guided hand movements and the correlation of these performance measures with binocular gaze-errors.The latter studies seek to determine how accurate binocular fixation must be to assure rapid and accurate manual performance in nearby 3-D space? The answer to this (and derivative questions) is not known because, until recently, binocular gaze-errors could not be measured accurately when nearby objects were handled by a subject free to move naturally.

During this past year, a unique movement monitoring instrument (the Maryland RFM) was used to make the first measurements that can be used to answer these questions. More than 200 Mb of eye and head movement data were recorded, and detailed analyses are underway. Arrangements have been made to disseminate the answers obtained widely at a number of international conferences during the remaining months of 1993. Manuscripts testing models of shape and size perception and reading of unspaced texts have been in preparation for submission publication soon.

14. SUBJECT TERMS

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Research Objectives: This grant has two thrusts. First, it tests alternative hypotheses about the mechanism that controls the gaze-shifts associated with arm motions, when an unrestrained, seated subject manipulates objects within arms's reach. Two quite different mechanisms have been proposed, namely, a) on-line feedback and b) learned, preplanned patterns of coordinated movements. These patterns might be learned during the course of practice in a novel manipulative task, or, might be brought to the task in the form of an already learned and calibrated eye-head-torso-arm map (or maps). Or, perhaps more plausibly, performance of novel manipulative tasks might reflect the action of both pre-existing and newly-acquired coordinated eye-head-torso-arm patterns. Patterning mechanisms are likely to assume that existing coordinated patterns can be modified rapidly (learned or adapted, depending upon one's linguistic preferences). If they can be adapted rapidly, they can provide an important role in adjusting visually-guided performance to changes in the environment. The likely importance of this kind of rapid learning, however, is likely to depend, at least in part, on the plausibility of the alternative hypothesis. If on-line feedback were to be very effective, the ability to modify preplanned patterns very rapidly becomes less important to the organism because on-line feedback could take care of any sudden unplanned demands made by perturbations in the environment. In other words, on-line feedback from the vestibular system can be used to make many if not all necessary corrections in ongoing patterns of visually-guided manipulative behavior required by perturbations of the subject's body.

The second thrust of the plan is to study the speed and accuracy of visually-guided hand movements and the correlation of these performance measures with binocular gaze-errors. In general terms, how well must you fixate a 3-D pattern of targets as you execute a visually-guided arm movement rapidly and accurately while moving naturally in 3-D space and performing a task that requires a sequence, rather than a single, visually-guided arm movement? A number of specific questions follow from this general problem: such as, how does binocular visual search proceed when a 3-D pattern is seen for the first time: How does this pattern change when the pattern of targets is seen again on the second and subsequent trials when the subject knows that the current, initially novel, pattern will be seen again: Does one eye fixate nearby 3-D targets more accurately than the other eye: If so, does this kind of eye superiority relate to eye or hand superiority in other tasks: Does the subject fixate accurately before reaching, or, does the subject look with only modest accuracy and reach for the target at the same time, or, does the subject look for the next target while reaching for the present target. Once again, how do these characteristics change as the task is repeated a number of times?

The answers to these and related questions are not known because, until recently, it had not been possible to measure binocular gaze-errors accurately as a subject manipulates nearby objects in 3-D space with the head and torso free to move naturally. We succeeded in making the first measurements of this kind during the second grant year (> 200 Mb of eye and head movement data). Currently, our ongoing analyses of these data are beginning to give answers to some of these questions and we have made arrangements to disseminate this information widely as it becomes available during this third year of the grant cycle (viz., The Marco Island Neural Control of Movement Meeting in April, The annual ARVO Meeting in Sarasota in May, The International Physiology Congress in Glasgow in August, The Wenner-Gren International Symposium in Stockholm in January 1994, see appended abstracts for all save Stockholm, which has not yet been prepared).

So, the second year of the grant was, as anticipated, very busy, very demanding technically and very exciting. It was also somewhat stressful because of the need to meet a firm deadline for gathering together our group of collaborators (Collewijn, Erkelens, Kowler and Pizlo) in College Park where they would work with Epelboim and Steinman to use the Maryland RFM to collect novel data with this unique instrument. We met the deadline, ran the planned experiments and succeeded in collecting all of the data required to deal with many of the questions mentioned above. This means that our research plan is proceeding pretty much on schedule and work during the current year is proceeding in a somewhat less stressful laboratory atmosphere. Whew!

<u>Summary of Activities:</u>

<u>**Overview:**</u> The year began with the completion of a prototype of the Sparker worktable. The plastic worktable for use inside the magnetic fields while recording eye and head position was finished only 2 weeks ahead of the visitor's arrival. The prototype table with its PC interface provided the means for developing the protocols for the experiments that were completed during May-June when the visitors were in residence in College Park. We (primarily Kowler and Epelboim) used the prototype table to explore conditions and parameters for the eye-head-arm recording experiments to be run when the visitors arrived (<u>e.g.</u>, size of the set of patterns, trial length, number of replications/block with the same pattern, necessary controls, etc.). Epelboim implemented the experimental designs worked out in these pilot experiments in C-language programs for generating target patterns and collecting subject's responses (button presses) while head and eye position data were collected. Fritz did the C programs for both the prototype and plastic worktables as well as for the RFM and Grafpen interfaces.

Kowler and several paid hourly undergraduates served as subjects in the pilot research because Steinman and Epelboim wanted to remain unpracticed, thereby keeping themselves available for the eye movement recording sessions in which only informed scientists can serve as subjects (see human subject welfare protocol). Kowler met this criterion but she requires an 8 diopter correction for myopia and also has an appreciable phoria, following strabismus surgery in childhood. This made her unsuitable for our initial experiments because general oculomotor populational characteristics were sought. Kowler's performance in the tasks, however, was as good and in some cases better than the performance of our subjects with "normal" oculomotor characteristics. This means that she will be an interesting subject for future research, as will Dell'Osso, a biomedical engineer/neurologist who has CN. Dell'Osso has worked with us in the past (see appended "CN Trilogy") and will be particularly interesting in the future because he has only very brief periods of "normal" fixation stability and has little, if any, difficulty in executing difficult visually-guide manipulative tasks rapidly and accurately. Epelboim, who also met the informed-scientist-criterion for serving as an eye movement recording subject, became pregnant in March, which meant that she could not spend time near or in our magnetic fields and could not be a recording subject (see human subject welfare protocol). Epelboim, however, was invaluable for her programming skills both on our data acquisition PC and on the SUN we use to analyze our data.

<u>**Experiments:**</u> We collected and have begun to analyze data from two series of experiments. The first to be described dealt with the learning of patterned responses, henceforth called the "tap" experiments. (These experiments bear on the second thrust described above.) We also completed an experiment bearing on the first thrust, on-line feedback, henceforth called "push" experiments. A summary of the tap experiments follows (this summary is based on our appended ARVO abstract):

<u>Tap:</u> We used the Maryland RFM to study the coordinated behavior of 4 free-headed subjects searching for and tapping small objects within arm's reach (Collewijn, Erkelens, Pizlo and Steinman). These objects were placed on the plastic worktable, which contained a grid of 154 equally-spaced wells into which rods topped with colored LEDs (the targets) were inserted. The bottoms of the wells contained switches, which signalled that the rod had been tapped. We recorded 3-D head orientations, 3-D head translations, and H and V orientations of both eyes (orientation accuracy = 1 minarc, precision < 1 minarc and effective bandwidth = 244 Hz; translation accuracy = 1 mm, precision 0.2 mm and effective bandwidth = 30 Hz). These measured quantities permitted computation of binocular gaze directions in worktable coordinates.

The subject's task was to find and tap sets of 2, 4 or 6 targets in the order indicated by their colors. New, randomly chosen, target configurations were presented in blocks of 10 trials. After only 3 repetitions of a target sequence, the eye, head and hand established a highly stereotypical pattern. Average saccadic landing positions were 2-3° from the target. These were not "errors": corrective saccades were rare and the variability of landing positions was remarkably small, showing that the eye had reached the chosen goal, compensating for the retinal perturbations created during gaze-shifts by head movements. Gaze-shifts to a target preceded the tap by about 500 msec, putting the eye at least one target ahead of the hand. This pattern was established at trial onset, when the eye (but not the arm) skipped the first target. The eye-hand lead decreased during the course of the trial, as arm movements began to rely less on memory and more on newly-acquired visual information. The highly stereotypical temporal relationship of eye, head and arm movements suggests precise coordination of the 3 systems. However, since individual movements of eye and arm towards a given target were not initiated concurrently, the coordination must have been established at a high level (pattern generation) rather than at the level of the programming of individual motor commands.

Data from this experiment and essential control experiments are being analyzed and should be ready to present at ARVO, perhaps even with a video tape based on animated graphics software developed for the SUN by Epelboim. Her software provides quite clear and vivid views of the subject's head and lines of sight moving in slow motion as the tapping tasks are performed in 3-D worktable space. Epelboim has also developed software that shows gaze-angles and target-angles as a function of time with the time of each tap superimposed on the plots. A comparison of gaze-angles and target angles can provide a measure of gaze-accuracy or gaze-error, a measure very useful for evaluating the on-line feedback hypothesis. A video tape of these graphical representations will be a useful tool for communicating our findings at conferences, but its development is of secondary importance; publishable quantitative summaries of our results come first and it is these that we must have ready by May 8.

The controls we ran for these tap experiments, which must be analyzed along with the basic tap experiment (outlined above), are as follows: a) the subject tapped the targets in a self-selected order, or b) the subject looked at, but did not tap the targets, in the order specified by the experimenter (in other words, the initial experiment without the arm movements), or, c) the subject only looked at the targets, but he looked in a self-selected order.

<u>Push:</u> Eye and head positions were recorded while the subject executed gaze-shifts among 3 targets while sitting naturally. He merely looked from target to target and did nothing with his arms. Trials lasted 6 seconds and a metronome beat continuously at 1 beat/sec to pace the gaze-shifts. The targets formed a triangle with its base near the subject. Shifting gaze between the targets required rather large saccades, <u>viz.</u>, between 30 and 50 deg on the shorter sides of the triangle and about twice as large when gaze shifted across the nearby base. The saccades made by each subject (Erkelens and Pizlo) were rather different because they their stature differed, requiring them to sit at different distances from the targets. Collewijn sat on the floor behind the subject wearing a pair of gloves, each containing a switch in the palm, which closed on contact with the subject's body when Collewijn pushed him from behind. Pushes, which were made with one or with both hands, moved the subject's torso to the right or to the left with varying amounts of force.

Collewijn's task was to synchronize his pushes with the subject's gaze-shifts in such a way that relatively high rotational velocities of the head would be produced while the subject shifted gaze from one target to another. The large saccades used to shift gaze in our experiment have durations of at most about 150 msec, so, getting useful data required that the subject and experimenter got their acts together very well. This need dictated our choice of experimenter and subjects. Collewijn, who was the experimenter, had considerable musical training, as did Pizlo, who served as the main subject. This training allowed them to follow the metronome beat pretty well. Subjects were not pushed on every trial and the force and direction of pushes were varied haphazardly so as to discourage the subject from hunkering down to be ready for the worst whenever it was about time to shift gaze. Our protocol is surely the most difficult and least certain way of testing the on-line feedback hypothesis, but it allows unambiguous conclusions, providing a sufficient number of relevant observations can be made, the kind of observations one might call "golden", i.e., a fast passive head rotation during the brief window during which gaze shifts.

Our trained musicians' ensemble was good and we were lucky. We found 54 golden observations in Pizlo's data set (400, 6 sec trials) and 34 in Erkelen's somewhat smaller set (300, 6 sec trials). Now that we know precisely where the gold is buried we will begin an exhaustive study of the characteristics of these observations as soon our final calibrations of "worktable space" are completed (see appended Theory Of RFM "book"). Our timetable will allow Collewijn to describe the outcome of the push experiment in his tutorial lecture scheduled for the International Physiology Congress in Glasgow in August (see Collewijn's appended abstract, which leaves out discussion of the results of our push experiment, but promises to reveal all in the lecture!). We, in College Park, anticipate no difficulty in providing the information he will need in time for his presentation.

This finishes a summary of this year's work on the main thrusts of our grant. Effort was also expended in other intellectually satisfying areas while these activities were ongoing. Specifically,

<u>Other Activities:</u>

1) Epelboim, collaborating closely with Kowler, wrote up and submitted for publication a description of a series of experiments, showing quite clearly that the low velocity oculomotor control subsystem (slow control) is not position sensitive and seems, therefore to be responsible for minimizing drift velocity exclusively (contrary to claims that have been made). This work satisfied Epelboim's "masters or research competency" requirement. The manuscript was accepted by Vision Research in August and should appear in the next (February) issue of this prestigious journal (perhaps in time for a xerox or reprint to be appended to this Annual Report).

2) In November, Pizlo, whose doctoral research was partially supported by this grant, published the machine vision section of his Ph.D. thesis in CVGIP: IMAGE UNDERSTANDING (see appended reprint) and 2 mss based on psychological sections of his thesis are in final stages of preparation for submission to the Computational Vision or Psychophysics Sections of Vision Research.

3) Epelboim and co-workers continued working in their spare time on the reading research reported at last years ARVO Meeting and in last year's Annual Report. Currently, a manuscript covering this very provocative work is in the works and should be ready for submission fairly soon (progress depends on free moments and these can be few and far between). This ms contains new data obtained since the ARVO material was prepared. Pizlo and Erkelens stayed on a few days in June after Collewijn went home to permit their reading eye movements to be recorded. These subject were interesting because both can read well in their native languages (Polish and Dutch), but they can also read English well. Both read spaced and unspaced text in both languages with Erkelens reading unspaced English almost as well as he read unspaced Dutch. He read unspaced text in both languages very well indeed!

Edwards, who joined our group in July as the Research Associate with advanced math skills, also allowed Epelboim to add another native English reader to her population. Her sole prior native English reader was Steinman. Epelboim is native in Russian and learned English as a second language. Edwards read unspaced text very well, more like Steinman than Epelboim as one might expect given their similar backgrounds. This line of research is ready to be disseminated to a wider audience than attends ARVO. It almost certainly will take years of fighting with referees and editors to get this material published because our observations on reading unspaced text renders most, if not all, prior eye movement research and theory pretty silly -- a state "specialists" in this active field will be slow, probably even unwilling, to accept. Epelboim and I are looking forward to many heated exchanges about our reading experiments.

4) Collewijn, when he was in residence last Spring, agreed to finish analyzing one important set of measurements made in Maryland just before the current grant began and to have this material ready for submission during 1993, hopefully before our renewal application is due. He met this commitment and will be able to report preliminary results in April at a Neural Control of Movement Meeting. A draft of this material for submission to an appropriate journal should be ready within the next few months (see the appended abstract). This material is important for our grant, not only because considerable time and effort was expended on it during the past two years, but also because it provides important baseline data for our current and future work. These experiments studied binocular gaze-shifts over the entire oculomotor range that were made when the head was stabilized artificially. All of our current and future work will be done with subjects free to move naturally, but the results of this prior research allow us to relate our current work with the head free to our prior work and to the work of other laboratories, where accurate eye movement measurements can only be made with the head restrained because of instrumentation limitations.

5) Edwards, who joined us as a Research Associate in July, has been primarily concerned advancing and coordinating all of our analysis needs. Edwards, who comes to us with background and math skills developed in his work in Atomic Physics, prepared a detailed description of the theory underlying our unique instrument, the Maryland RFM, and has derived all of the trigonometric relationships required to analyze data obtained with this instrument. Edwards, since joining us, built on the original trigonometric analyses developed primarily by Pizlo in collaboration with Erkelens to develop complete documentation that will be used to guide our present and future collaborative work (see the appended document: "The Maryland Revolving-Field Monitor: Theory of the Instrument and Processing Its Data").

This document is almost in its final form, awaiting a) additional suggestions for revisions from our "team" and b) the entry of the final, definitive values for our worktable space calibration matrix, being calculated as I write. Edwards' next project will be an error analysis of our instrument, which will allow us to plan realistic and cost effective improvements and also prevent us from undertaking experiments beyond the current capabilities of our instrument (this error analysis will constitute the body of Volume 2 of the document described just above). During his spare time (e.g., while waiting for email comments from collaborators elsewhere) Mark has used our SUN and other computer resources to advance his career in Physics. His efforts in this direction resulted in 2 publications in the Physical Review during this past year (see appended reprints); he has another theoretical project underway at present.

Full Publications in Reviewed Journals

Dell'Osso, L., Van der Steen, J., Steinman, R., and Collewijn, H. (1992) Foveation dynamics in congenital dynamics: I. Fixation. Documenta Ophthalmologica, 79, 1-23, 1992

Dell'Osso, L., Van der Steen, J., Steinman, R., and Collewijn, H.,(1992) Foveation dynamics in congenital dynamics: II. Smooth pursuit. Documenta Ophthalmologica, 79, 25-49.

Dell'Osso, L., Van der Steen, J., Steinman, R., and Collewijn, H.,(1992) Foveation dynamics in congenital dynamics: III. Vestibulo-ocular reflex. Documenta Ophthalmologica, 79, 51-70.

Edwards, M. A. (1992) Calculation of multiphoton-ionization Green's function using the Wentzel-Kramers-Brillioun approximation. Physical Review A1, 45, 409-417.

Edwards, M. A. (1992) Calculation of multiphoton-ionization Green's function using the Wentzel-Kramers-Brillioun approximation. II. Physical Review A1, 46, 7228-7234.

Book Chapters Published

Collewijn, H., Steinman,R., Erkelens, C., Pizlo, Z. and Van der Steen, J. (1992) The effect of freeing the head on eye movement characteristics during 3-D shifts of gaze and tracking, In THE HEAD-NECK SENSORY MOTOR SYSTEM, edited by Berthoz, A, Vidal, P, and Graf, V, Oxford University Press, London, pp. 412-418.

Kowler, E., Pizlo, Z., Zhur, G., Erkelens, C., Steinman, R. and Collewijn, H. (1992) Coordination of head and eyes during the performance of natural and unnatural) visual tasks, In THE HEAD-NECK SENSORY MOTOR SYSTEM, edited by Berthoz, A, Vidal, P, and Graf, V, Oxford University Press, London, pp. 419-426.

Articles in preparation or in press:

Collewijn, H., Steinman, R.M., Erkelens, C. J. (in prep.) Binocular gaze-shifts: coordination of vergence and version. Should be submitted to Journal of Physiology (London) by June 1993.

Epelboim and Kowler E. (in press) Slow control is driven by velocity, not position, signals. Should appear in February issue of Vision Research.

Epelboim, J., Booth, J., Airey, D. and Steinman, R. (in prep.) Reading unspaced text. Should be submitted to Vision Research or Perception & Psychophysics by June 1993.

Pizlo, Z. (in prep.) Shape constancy in human beings and computers based on a perspective invariant. Should be submitted to the Computational Vision Section of Vision Research by April 1993.

Pizlo, Z., Rosenfeld and Epelboim, J. (in prep.) Exponential model of the time-course of size processing. Should be submitted to Psychophysics or Computational Vision Section of Vision Research by April 1993.

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