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13. ABSTRACT (*Maximum 200 Words*)

Natural patterns of head and eye movements were studied during inspection and manipulation of nearby target objects. Emphasis was placed on the study of natural tasks, that is, tasks in which subjects look at and handle real objects in a fully-lighted and highly-structured visual environment. These studies seek to determine how accurate binocular fixation must be in order to insure rapid and accurate manual performance in nearby 3-D space. The answer to this (and derivative) questions was 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. This research used unique instrumentation to examine fine-scale characteristics of coordinated human actions in nearby 3-D space. The upper body was free from artificial restraints, allowing an examination of natural 3-D search and action patterns. The research completed so far showed that observations made previously under less natural conditions have underestimated the capacity of the human oculomotor system and have obscured its preferred modes of operation.

14. SUBJECT TERMS

gaze-shift, gaze-accuracy, oculomotor compensation, visuomotor, VOR, cognitive processes, natural conditions, head-eye coordination

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Research Objectives

This line of research, when first funded by AFOSR in 1990, had two main thrusts: (i) It investigated the effectiveness of different compensatory oculomotor mechanisms that place and keep, *gaze* (the line-of-sight in space) on objects near enough to be touched. These compensatory mechanisms allow objects to be scrutinized and manipulated, and (ii) it investigated how oculomotor control and visually-guided manipulations are affected by both high- and low-level factors, *viz.*, sensory/perceptual, cognitive and volitional. The main problems that motivated this research will be described next.

If an individual wants to *maintain gaze* in order to examine an object very carefully, the oculomotor system must correct *gaze-errors* (differences between gaze and object position) caused by unavoidable changes of the position of the head relative to the object being examined. Oculomotor mechanisms must also compensate for head movements when gaze shifts from one object to another. Here, failure to compensate prevents gaze from falling directly on the intended object, causing an *initial gaze-shift error*. Such errors lead to inefficient search and manipulations because they make it necessary to make additional "corrective" saccades. This need slows search down and disturbs the fluency of ongoing, visually-guided manipulations.

Oculomotor compensation increases in importance as objects come nearer. When they are near enough to be reached, even very small changes of head position require relatively large compensatory eye movements. Potential compensatory oculomotor mechanisms include: (I) *VOR and LVOR* (the vestibulo-ocular *reflexes*) and (ii) *coordinating motor programs* (templates for generating coordinated head/eye/torso/hand motor actions). These templates might be brought to each novel coordinated motor task with movement size and/or direction already calibrated, or calibrated as the task is learned.

When this research began, very little was known about oculomotor compensation under the relatively natural conditions that would be employed for the first time in human oculomotor research , research that used instrumentation allowing an accurate examination of the human's ability to control gaze. Our conditions were *natural* in that an unrestrained, seated subject was required to look carefully at or manipulate nearby objects. These conditions are particularly important for humans, whose design, fabrication and use of tools have given them unmatched mastery of their environment. Despite this fact, little was known about the way humans perform visually-guided manipulations under such natural conditions.

Many of the experimental results produced by this grant could not be anticipated from knowledge accumulated in the large literature describing experiments done under unnatural conditions. Prior to the work done on this grant, most researchers studied subjects who viewed distant objects monocularly with their heads almost completely immobilized by biteboards or chinrests. What *was* known about compensatory eye movements when the research began?

It was known that *VOR* was relatively effective. It compensated 92 to 98% of the gaze error that could have been introduced, when large head oscillations (~ 40° p-p) were made while gaze was maintained on objects beyond reach (Steinman & Collewijn, 1980; Steinman, Levinson, Collewijn & Van der Steen, 1985). Its effectiveness with nearby objects was not known, nor was its operation during gaze-shifts among objects. There was also controversy about its operation beyond arms' reach. Some experts held that *VOR* was "switched-off" during gaze-shifts. Others held that it was "on", but unreliable. Still others held that it was "off," but that another, unnamed, mechanism compensated for head movements during gaze-shifts. (See Epelboim, Kowler, Steinman, Collewijn, Erkelens, & Pizlo, 1995, for a review of this controversy, as well as for details of the new research that will only be summarized below.)

The contribution of the *LVOR* (the Linear VOR) was also unclear. This compensatory mechanism is a new addition to the oculomotor literature (Paige, 1989; 1991). It is not as well established as the *VOR*. A compensatory mechanism for head translations, like the *LVOR*, becomes very important with near objects because small translations of the head require large compensatory rotations of the eye . Translational components, associated with head rotations, are also contribute to gaze errors when objects are within reach. It is clear that the *VOR*, alone, cannot provide complete compensation.

Motor programs could also compensate for bodily movements. A new motor program might have to be learned during each novel task, or, it might be brought to the task in the form of calibrated head/eye/torso/arm maps. These might allow a novel task to be executed by invoking a known strategy and making only parametric adjustments specific to the particular situation. For example, the subject might say to himself, "the farthest object can be reached while sitting upright", or, alternatively, "it is too far, lean forward to reach it". The presence of such strategies and calibrated motor programs might allow *VOR, LVOR* to be "switched-off" during gaze-shifts as has been proposed (see above).

Note, however, that the availability of one or another of these compensatory reflexes does not, in itself, preclude the existence of other compensatory mechanisms. All could be available and useful. This research program began by making a simplifying assumption. Namely, that the vestibulo-ocular reflexes, *if available under the natural conditions studied*, would be sufficient and could, therefore, serve as the primary, perhaps even only, compensatory mechanisms. Beginning with this assumption was useful because it allowed concentration on the second goal, *viz.*, to find out how motor programs, used to accomplish purposeful manipulations, are affected by high- and low-level factors. Finding out how existing motor programs *also* contributed to establishing and maintaining gaze could be postponed.

This assumption can be justified. Namely, if the vestibular reflexes are available, compensatory motor programs, pre-calibrated or not, would be redundant, perhaps superfluous. The assumption that *both* motor programs and vestibular reflexes would be available goes counter to the criterion most oculomotor scientists prefer. Most believe that biological control systems tend to be as simple as possible, so once reflexes can do the job on-line, why add the capacity to learn novel motor programs to accomplish the same thing?

With this consideration in mind, the first experiment examined the availability of the vestibular compensatory mechanisms under natural, but until then never studied, conditions. This experiment led to the publication by Epelboim *et al.* (1995 a) cited above. A publication on the dynamics of vergence and version was also published by Collewijn, Erkelens & Steinman(1995). A paper by these authors on binocular trajectories (an extension of this research) was published in 1997. Both papers deal with the nature, rather than the availability, of the oculomotor compensatory reflexes. They examined the manner in which the high and low velocity subsystems interact when gaze shifts among objects within arms' reach. These publications solved some existing problems, but, raised a host of new questions. Some are motivating ongoing research.

Experiments bearing on the second thrust were run concurrently, *i.e..*, studies of the effects of low- and high-level factors on visually-guided manipulations. These experiments have produced a number of publications beginjning with Epelboim, Steinman, Kowler, Edwards, Pizlo, Erkelens & Collewijn (1995 b) These papers derived from Dr. Epelboim's doctoral dissertation, which won the Bartlett Award for the best Ph.D. dissertation completed in the Department of Psychology at the University of Maryland in 1995 when her degree was awarded. Highlights of this research will be described next.

Highlights from Publications Between 1997 and April 2001

The effectiveness of compensatory reflexes during and between gaze-shifts: **(a)** The gaze of unrestrained subjects was recorded as they shifted gaze among three widely-separated targets, all within arms' reach. These initial gaze-shift errors were compared to errors observed when an unexpected push, produced a head movement during the gaze-shift. This was done by having an experimenter, seated behind the subject, push the subject at unpredictable times in unpredictable directions as gaze was shifted in time to a metronome. The metronome made it possible for the experimenter to predict when a gaze-shift would make the head move. The experiment required that the head was moving relatively fast *while* gaze was actually shifting. This seldom happened because saccades are very fast. Even the relatively large saccades (31°- 59°) required in this experiment took less than 100 ms to complete. This made it very unlikely that a head movement would occur during a gaze-shift. A large number of saccades were necessary to gather an adequate number of what were called, "golden" observations. Two subjects ran about 100 trials (≈900 saccades each) before a suitable sample of golden gaze-shifts was recorded.

Analyses of both subject's data showed that vestibular compensation *was* effective, albeit: variable; sometimes compensating on only one meridian, and (ii) compensating by varying amounts in the presence of similar head velocities. Vestibular reflexes also established gaze following a gaze-shift as well after a passive displacement as it did when no passive head displacement was introduced. Initial gaze-shift errors were also "normal" also showing on-line vestibular compensation. These initial errors were normal in the sense that they were similar to errors following saccades of similar size with the head on a biteboard (Collewijn, Erkelens & Steinman, 1988 a, b).These findings make it reasonable to assume that compensatory vestibular reflexes are likely to operate during visually-guided manipulations. This assumption, however, must still be tested. This can be done by introducing unexpected, passive displacements while tapping or some similar manipulation is performed.

(b) In another paper, Epelboim (1998) showed that the average retinal image velocity is relatively low (< 1.5°/s), when a subject sits with the head free, while maintaining gaze on a nearby object. Velocities like this are low enough to prevent them from having adverse effects on visual acuity (Westheimer & McKee, 1975; Murphy, 1978; Steinman *et al.*, 1986; Steinman & Levinson, 1990). This finding was new, but more reassuring than surprising. Human scrutiny of small, nearby objects would be inconvenient, to say the least, if the head had to be immobilized before gaze could be maintained. So, common sense, buttressed by subjective impressions, led to the expectation that compensation would be good, when a human being maintained gaze on nearby objects. But, prior to this experiment, the degree to which gaze could be maintained had only been measured accurately with distant targets. It is reassuring, even if not surprising, to know that vestibular compensation is also functionally effective when objects are near. Here, great demands are made on compensatory reflexes. These demands include the need to compensate for even small head translations. Compensation is not needed to maintain gaze when the target object are far away, the only condition studied previously.

Effect of Low- and High-Level Factors on Visually-Guided Manipulations: (a) Virtually nothing was known about visuomotor coordination under the natural conditions employed because, until very recently, binocular gaze could not be measured *accurately* and *precisely*, while nearby objects were manipulated with the head free to move naturally. The criterion for *accurate* and *precise* measurement used is the same as the criterion used elsewhere in experimental sciences. Namely, accurate measurements of head and eye angular orientations and head translations (variables needed to estimate gaze with the head free) must be made *in engineering units on a scale finer, and with instruments less variable, than the performance being measured.* At its limit, human oculomotor performance is exquisite. Average absolute gaze-error during maintained fixation and its standard deviation are both only about 2 to 3 minarc when the head cannot move. Knowing this, measurements were needed that were better by at least a factor of two, *i.e.*, 1 to 1½. Meeting this criterion required some effort, expended over many years. We met this criterion for measuring eye and head angles by 1988, two years befor AFOSR support became available, but meeting it for measuring head translations was not met until 1992, two years after AFOSR became available. Analyzing the data collected in 1992 required the development of considerable novel software. Our first publications describing human oculomotor control with nearby targets under relatively natural conditions first appeared in 1995, only 5+ years ago. So, we are still very close to the threshold of this new data realm. There are surely many additional discoveries to be made.

Highlights of those made so far are: (i) just looking at a sequence of targets, solely with the objective of fixating each target accurately, and looking at a similar sequence with the objective of tapping the targets, are fundamentally different tasks. The seemingly more complicated task, using vision to guide tapping, was easier, more pleasant and took less time to complete than the task in which the subject did much less; namely, fixated each target in a sequence for its own sake; (ii) visual search (using a saccade to find the next target) is a separate and different saccadic activity than looking from one target to the next in the sequence in both kinds of tasks, (iii) looking for its own sake, looking to guide tapping, and visual searching is synergistic, they interact in beneficial ways, and (iv) subjects almost always look at the target they are about to tap before tapping it, but are convinced that they do not do this often once the particular target pattern has been learned.

Other analyses showed that gaze-shift-dynamics were adjusted differently in each task. This result suggests that the objective (purpose or goal) of a given task sets the parameters of oculomotor mechanisms to produce optimal, *i.e.*, efficient performance. Subjects were not aware of doing this, implying that the required parameter values were determined and conveyed to the oculomotor "plant" automatically. This was true both for shifting gaze and for maintaining gaze in place. In the latter, the task's purpose determined and set parameters of *slow control* (Steinman *et al.*, 1973) to allow the amount of retinal image slip to be different, but optimal, optimal in the sense that it led to efficient performance of the particular task.

In some tasks, slow control actively maintained the direction of gaze between gaze-shifts, but in others gaze moved with the head, *i. e.,* slow control was not active. Both the head and eyes moved differently in different tasks. The nature of their coordination depended on what the subject was asked to do. The advantages inherent in doing this, as well as the appropriate parameter-settings needed by the oculomotor “plant” were brought into the experimental setting by the subjects. These adjustments were made without either training or conscious effort. This kind of adaptability comes very naturally and the humans’ capacity to perform automatically in this flexible manner is probably responsible, in no small part, for his exceptional success at manipulations, ranging from chipping flints to fabricating watches, to say nothing of the manipulations performed these days during microsurgery.

More recent additions to our knowledge about the coordination of head and eye under natural conditions make it increasing clear that one cannot predict natural head-eye coordination on the basis of information collected under less natural conditions. Abstracts taken from two papers (the first published last year and the second, in press) make this point. Namely:

> "We determined how saccades were used in the experiments described in Epelboim *et al.*, (1995), where unrestrained subjects looked at or tapped nearby targets. We report: (i) the size of binocular saccades, (ii) how well saccade size matched in the two eyes, and (iii) saccadic vergence. A representative sample (3375 saccades) was measured: 83% were < 15°, 53% were < 5°. Only two were "microsaccades". Saccade sizes were very similar in the two eyes. These results imply that subjects *prefer* avoiding large saccades. They can do this simply by re-orienting the head appropriately. Subjects under-verged by 25-35% and performed well. None experienced diplopia."

> "The "natural" temporal coordination of head and eye (on the horizontal meridian) was examined as 4 subjects tapped a sequence of targets arranged in 3-D on a worktable in front of them. The head started to move before the eye 48% of the time. Both the head and eye started to move "simultaneously" (within 8 ms of each other) 37% of the time. The eye started to move before the eye only 15% of the time. Gaze-shifts required to perform the tapping task were relatively large, 68% of them were between 27° and 57°. Gaze-shifts were symmetrical. There were almost as many lefts as rights. Very little inter- or intra-subject variability was observed. These results were not expected on the basis of prior studies of head/eye coordination performed under less natural conditions. They also were not expected given the results of two rather similar, relatively natural, prior experiments. We conclude that more observations under natural conditions will have to be made before we understand why, when and how human beings coordinate head and eyes as they perform everyday tasks in the work-a-day world."

Summary and Overview of where this research program stands 5 years after we began to publish data based on "natural" experiments follows:

The Bottom Line is that the key to achieving accurate gaze control may lie in the ability of human beings to call upon one or the other compensatory subsystem at different times and/or to varying degrees. This capacity is built-in. Choosing a particular objective (goal or purpose) sets the parameters in the oculomotor plant without any explicit efforts on the subject's part. Evidence for the ability of the human being to juggle the contribution of different subsystems to control gaze seems to be most pronounced when gaze is studied under conditions approximating conditions in the natural world. It may be here, and only here, that the nature and full extent of the human capacity to produce effective motor control becomes most apparent (see Herst et al., in press, for support of this claim).

List of discoveries made in these studies of natural oculomotor performance with nearby targets: (i) cyclopean gaze, on average, is more accurate than either eye; (ii) subjects show no sign of a "dominant eye"; (iii) microsaccades are rarely made, at best "once in a blue moon"; (iv) vergence tends to be 25%-45% *beyond* the attended plane; (v) subjects fixate no more accurately than a given task demands; (vi) parameters in the "Plant" adjust to high-level task demands, such as objectives or goals; and (vii) the head is most likely to begin to move before, or at the same time, as the eye.

Additional Published Research: We also devoted some effort to research on a problem that grew out of teaching an undergraduate perception course. These efforts led to the publication of a paper on apparent motion. It should have an important effect on the teaching this subject in the future. It could also lead to important new information about the perception of motion itself. The abstract of this paper follows:

> "Max Wertheimer (1880-1943), the founder of the Gestalt School of Psychology, published a monograph on the perception of apparent motion in 1912, which initiated a new direction for a great deal of subsequent perceptual theory and research. Wertheimer's research was inspired by a serendipitous observation of a pure apparent movement, which he called the φ-phenomenon to distinguish it from optimal apparent movement (β), which resembles real movement. Wertheimer called his novel observation "pure" because it was perceived in the absence of any object being seen to change its position in space. The φ-phenomenon, as well as the best conditions for seeing it, were not described clearly in this monograph, leading to considerable subsequent confusion about its appearance and occurrence. We review the history leading to the discovery of the φ-phenomenon, and then describe: (i) a likely source for the confusion evident in most contemporary research on the φ-phenomenon, (ii) the best conditions for seeing the φ-phenomenon, (iii) new conditions that provide a particularly vivid φ-phenomenon, and (iv) two lines of thought that may provide explanations of the φ-phenomenon and also distinguish φ from β."

We also have a paper in press on depth perception which shows that the Bishop Berkeley's time-hallowed claim that vergence can provide a clew to depth is unfounded even when objects are very close to the observer where vergence angles are quite large (> 3°). One hopes that this paper (Logvinenko, Epelboim & Steinman, in press) may also have some effect on the teaching of perception. Removing "vergence angle" from the list of "cues to depth" might even prove to have some practical significancein the design of optical devices.

Uniqueness of Approach: This research was made possible by unique instrumentation (the Maryland Revolving Field Monitor, MRFM) developed and available only at the University of Maryland, College Park. See Edwards *et al.* (1994) for full details, or Epelboim *et al.* (1995) for a briefer treatment. This kind of research probably cannot be done anywhere else with anything like comparable accuracy and precision in an unrestrained subject. Being able to make these measurements allows us to look, for the first time, at characteristics of human visually-guided motor performance with sufficient spatial and temporal resolution to examine the finest performance details as new skills are learned and preserved.

The approach is also somewhat unusual because the limits of sensory and motor capacity are studied. No attempt is made to establish populational norms. In almost all cases, subjects, who know the purpose of the experiment and the relevant literature, participate in these experiments. The data of each individual are reported separately. Individual differences are explained, whenever possible, never obscured by averaging across subjects. This approach is common in the visual science community, but less so in the diverse group studying eye movements. This approach also follows as a natural consequence of using instrumentation that provides accurate measurements of gaze , *i.e.*, this instrumentation requires: (i) attachments to the eyes: It is "invasive," so scientifically-educated, mature adults are best able to give "informed consent"; (ii) short recording sessions (<40 minutes) that more often than not must be replicated a number of times; (iii) careful, time-consuming, psychophysical calibrations of the sighting centers of each eye within the apparatus, and (iv) commitment to participating in experiments that sometimes take more than a year to complete.

Summary of this Project: This research used a unique instrumentation to examine, until now hidden, fine-scale characteristics of coordinated human actions in nearby 3-D space. The upper body is free from artificial restraints, allowing one to see natural 3-D search and action patterns. The research completed on this grant has made it clear that observations made with the restraints used in other studies of eye movements underestimate the capacity of the oculomotor system, and obscure its preferred modes of operation.The exceptional motor skills developed by our species have been a major contributor to the control human beings now exercise over many aspects of their environment.

This laboratory studies the development of such skills at a level of analysis sufficient to see all of their potentially important details. Knowledge, based on such studies, should be useful as well as intellectually satisfying, in the long run. The long range goal is to understand how sensory/perceptual, cognitive and motor processes, both reflexive and learned, work together during visually-guided manipulative tasks -- tasks performed within arms' reach, the region in which the exceptional skill and creativity of human beings are manifest. Said even more simply, the long range goal is to find out how specific signals, plans and decisions are used to make human manipulations efficient, adaptable and, occasionally, even creative. When this goal is reached, that is, when the knowledge needed to emulate a human operator is available, it should be possible to develop electromechanical surrogates, capable of performing similar tasks skillfully in novel environments.

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Robert M. Steinman, D. D. S., Ph. D., Professor of Psychology and PI, University of Maryland. *Fellow, American Psychological Society, 1994. UMCP Chapter, Sigma Xi, Lifetime Contribution to Science Award, 1996.*

Michael Stepanov, a Graduate Research Assistant, who had made good progress towards his Ph.D., while supported by a prior AFOSR Grant, was forced him to take a terminal Masters in 1997 to take a job in industry that provided an income sufficient to support his family in Russia. He is now doing very well and meeting this need as a Senior Engineer in Optical Technologies at the *Ciena Corporation.*

Tatiana I. Forofonova, M.D., Ph.D., D. Med. Sc., joined the grant as a "Visiting Senior Research Scientist" in March 1996. She joined the lab to learn about eye movement research and basic visual science. In Moscow, she practiced as a laser surgeon as well as being active in a wide range of administrative, research, teaching and clinical activities. She was a very useful addition to this project. Her ophthalmology training made her exceptionally adept at handling the SKALAR silicone annuli used in our research. She got her "green card" in July 1996, and then participated on the grant as a "Senior Research Scientist" (on a part-time, hourly basis). In 1998, Dr. Forofonova took a position that made better use of her medical clinical background. She is now the Director of Ophthalmic Imaging at the University of Medicine and Dentistry of New Jersey.

Ilya Malinov, who was supported as a graduate Research Assistant, completed his graduate education with a M. S. degree in August 2000 and found a computer system engineering job in the Silicone valley. We agreed that a career in academe was not suited to his temperament despite a number of technical skills that seemed to make this attractive to him, as well as to us, when he joined the lab as a Graduate Student.

Active Participants, who received No Remuneration from this Grant:

Julie Epelboim, Ph. D. From 1990-1995, she attended the University of Maryland at College Park, receiving her Ph.D. in Psychology for her dissertation, "Cognitive and Motor Coordination in Visuomotor Tasks". Prior AFOSR and AASERT Grants provided partial support for her while she got her Ph.D.. Between 1995 and 1998 she was a NIH-NRSA Postdoctoral Fellow at the Center for the Study of Language and Information at Stanford University, where she studied "Mathematical Modeling of Cognitive Processes" under the direction of Prof. Patrick Suppes, who is a NAS Fellow and National Medal of Science Winner. Shortly after completing her postdoctoral work at Stanford she won a NRC Research Associateship at the Intelligent Systems Division of the National Institute for Standards &Technology. She died of cancer on January 10, 2001 during her first year in residence at NIST.

Zygmunt Pizlo, Ph. D. (E.E., Warsaw), Ph. D. (PSYC, UMCP), is currently an Associate Professor of Psychological Sciences at Purdue University. He was partially supported by a prior AFOSR Grant when he earned his UMCP doctoral degree in Psychology. He won the 1994 Young Investigator Award from the Society for Mathematical Psychology on the basis of publications derived from his doctoral dissertation.. He is the "theoretical" member of the group that has begun to work on motion perception.

Filip Pizlo, the son of Zygmunt, is an undergraduate Computer Science Major at Purdue University. H e made important intellectual, as well as technical, contributions to our work on the phi-phenomenon. He will continue to collaborate with as in our future research on motion perception.

Sally Bogacz contributed to several aspects of our research while she was supported on an AASERT training grant associated with our AFOSR Grant. She completed her Ph. D. in December 2000 winning our department's Bartlett Award for doctoral research. Dr Bogacz is currently seeking a research position in the metropolitan Washington, D.C. area.