



Temporal coordination of the human head and eye during a natural sequential tapping task[☆]

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Abstract

The 'natural' temporal coordination of head and eye was examined as four subjects tapped a sequence of targets arranged in 3D 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. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Interest in the temporal coordination of head and eye goes back a long way, at least as far as 1921 when Dodge wondered whether gaze-shifts, which involve both the head and eyes, are integrated into a single unit of reaction. In other words, do synchronized rotations of head and eyes represent a centrally-programmed orienting response? Contemporary interest in human head/eye coordination began when Bartz (1966) published a report in *Science* in which he used EOG to record horizontal eye rotations and a helmet-mounted potentiometer to record horizontal head rotations of three subjects, who were asked to look at one of four, randomly-chosen, Nixie-tube targets. These targets appeared at randomly-chosen locations along the horizon-

tal meridian within a 110° field. Subjects were required to report the number displayed on the Nixie-tube. This requirement was imposed to encourage accurate gaze-shifts. It also had the virtue of making Bartz's task more 'natural' than most used later. Note that his subjects were asked to shift gaze to accomplish a useful purpose; namely, to find out which randomly-chosen number, 4, 5, 6 or 9, had come up on the Nixie-tube display on a given trial. Shifting gaze to get information is precisely the kind of thing humans do a lot. Shifting gaze simply to line it up with a light because it flashed is more characteristic of what is likely to happen in an oculomotor laboratory than in the work-a-day world.

Bartz's subjects were highly-practiced, i.e. their performance was recorded only after they had served in 19 daily practice sessions. Bartz noted that the limited prior work on head/eye coordination done before his own '...had shown that the eyes begin to move first, followed by the rotation of the head.' (p. 1644). His results confirmed this earlier finding. Bartz reported that 'After a latency period the eyes begin to move toward the stimulus while the head remains station-

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ary.’ (p. 1644). Note that the eyes of his subjects must have led appreciably. EOG recordings have relatively modest bandwidth.

The human head/eye coordination problem incubated for a few years until Gresty (1974) picked it up and shifted the emphasis from temporal coordination to a proposal made by Mowrer (1934) who said that the slow phase displacement of the eye, following the head movement, was due to the VOR. In this interim, Bizzi, Kalil, and Tagliasco (1971)² extended Bartz’s work to the monkey, using trained and, therefore, predictable, as well as unpredictable, target locations. Bizzi et al. (1971) reported that ‘Nonrandom target presentations,... reveal a different mode of eye–head coordination... the head moves before the target is

² Following up on Bartz (1966), Bizzi et al. (1971) inaugurated a series of head/eye coordination studies with monkeys. Recently, Freedman and Sparks (1997) published a relatively ‘natural’ study of the head/eye coordination of two rhesus monkeys, whose heads were not restrained. They reported: “RELATIVE TIMING OF EYE AND HEAD MOVEMENTS. In *all* [our italics] instances, changes in the direction of the line of sight were initiated by an eye movement; head movements that occurred before gaze shift onset did not alter gaze position. As a result, eye movement onset and gaze shift onset were identical. During the delayed gaze shift task, gaze latency (Fig. 3A) was relatively independent of movement amplitude... In contrast, the time from gaze onset to head movement onset decreased as a function of gaze amplitude (Fig. 3B) until, for gaze shifts larger than $\sim 40^\circ$, movements of the eyes and head began nearly synchronously” (p. 2332). The Freedman and Sparks (1997) study, and other monkey studies, were not discussed in the body of this paper because we are unwilling to assume that the monkey’s oculomotor performance, as studied to date, puts the monkey nearby on the continuum that includes human performance. Specifically, we are unwilling to assume that the ‘natural’ head/eye coordination of a monkey is likely to be observed when it is restrained in a primate chair, and after it has received fixation training with its head bolted to the chair. A long-standing skepticism about treating a monkey’s oculomotor performance as ‘natural’, when observed under such conditions, was confirmed by one of us (R.M.S.) in collaborations with A.A. Skavenski. Between 1985 and 1989, we recorded the ‘natural’ oculomotor performance of several Old and New World monkeys, who had been gentled, but never restrained or trained to ‘fixate’, before they came to College Park to have their eye movements recorded with the MRFM. All showed a natural preference for using saccades and saccade-like head movements, rather than smooth eye or head movements, to maintain gaze on stationary objects and to track moving objects (bits of banana moved back and forth in front of them). These naive monkeys also showed the well-known inclination to ‘downbeat nystagmus’; the fixating eye drifting up, causing a periodic pattern of downward saccades. On purely behavioral grounds, an unrestrained cat behaves more like an adult human when it comes to head/eye coordination, than an unrestrained, untrained monkey even when allowance is made for the fact that the cat has a smaller available range of coordinated motion. Knowing this, we decided to avoid the common practice of discussing human and monkey head/eye coordination as though they represented the performance of very similar creatures. In our view, this remains to be established (see Steinman, Haddad, Skavenski, & Wyman, 1973; Skavenski, Robinson, Steinman, & Timberlake, 1975, for a description of the training required to encourage a restrained monkey to fixate somewhat like a human being).

presented. A saccade follows the head movement by up to 150 msec.’ (p. 454). The potential importance of predictability of the target’s location on human head/eye coordination has received relatively little attention in the human head/eye coordination literature (see Corneil & Munoz, 1999; Corneil, Hing, Bautista, & Munoz, 1999, for exceptions) since Bizzi et al. (1971) called attention to its effect in the monkey.

Gresty (1974) was aware of this work with monkeys but neither considered nor studied the effect of predictability when he studied human head/eye coordination. Gresty, like Bartz, recorded the horizontal head and eye movements of eight subjects, who were ‘carefully acquainted with the experimental situation using examples of experimental conditions, but were given no opportunity to train in the situation.’ (p. 396). He also used EOG, a head-mounted potentiometer, and an array of 13 red LEDs, instead of Nixie-tubes, which meant that his subjects shifted gaze for shifting’s sake. The other major change in Gresty’s protocol was the addition of a condition in which the target was flashed for only 40 ms, extinguished for 1 s, and then re-illuminated. The dark interval was designed to reveal the operation of the VOR, free from the influence of visible targets. Passive head rotations were also included. Target location was hard to predict with both the continuously visible and flashed targets. This paper had relatively little to say about temporal coordination except that, ‘The fast dynamics of the eyes allow them to move before the head and they do so in a saccade of large amplitude... Most of the head movement takes place after the peak displacement of the eyes’. (p. 402). Therefore, with flashed targets, the eye tended to lead the head with both the highly practiced subjects and with the knowledgeable unpracticed subjects, regardless of whether the targets remained visible or disappeared. Moreover, the goal of the task also had little effect. The eye continued to lead the head when either gaze was shifted to acquire information or when gaze was shifted for its own sake.

The Bartz methodology and Gresty’s approach continued to be influential, and we find Barnes (1979) also using EOG, a head-mounted potentiometer, and LED targets flashed for long or short intervals. Barnes did not cite Bizzi et al.’s (1971) work with the monkey, did not include any predictable target locations, but did include both voluntary [active] and passive head rotations. At this point human head/eye coordination becomes more complicated. Namely, Barnes reported that the head led the eye in one of his conditions. The head (averaged over six subjects) led the eye by only 1 ms [sic] when the target, which was within 50° of the initial fixation point, appeared and remained visible. The eye led the head with more eccentric targets. It is important to note that Barnes (1979) also reported that ‘negative latencies [head leading eye] were observed 39 of 180

[22%] during continuous target presentation; 27 out of 180 [15%] for the target flashed condition.’ (p. 141). Therefore, overall, the eye was found to lead the head, but in Barnes’s experiment the head led on an appreciable number of trials, particularly with very eccentric targets.

The nature of human head/eye coordination continued to interest a number of investigators, with emphasis placed on the generation of saccades when the VOR was used to stabilize gaze. Gaze-shifts to unpredictable target locations were studied both during active and passive head rotations. Zangemeister & Stark (1981) found that the eye led the head when both moved in the same direction (see their Fig. 11). Head latency was reduced when the target’s location was predictable, but the eye still tended to lead the head. Biguer, Jeannerod, and Prablanc (1982) examined eye/head/hand coordination in a pointing task. Their experiment was more like natural human behavior than most described so far because gaze shifted to guide a pointing hand, a common task in everyday life. Biguer et al. (1982) introduce their work by claiming that ‘In normal conditions a subject will first orient his gaze, then his head, and finally his arm in the proper direction.’ (p. 301). Otherwise, this work was done within the tradition and with the methods introduced by Bartz: namely, (i) nine red LEDs arranged with 10° spacing about a central target, (ii) EOG was used to record binocular horizontal eye movements and (iii) a helmet-mounted potentiometer was used to record horizontal head rotations. Five ‘subjects were instructed to track the targets when they appeared, by eye, head and hand as quickly and as accurately as possible... the ocular saccade was always found to be the leading event in the reaching sequence... the onset of the head movement lagged behind that of the eye movement.’ (pp. 302–303). These authors also noted that subjects make relatively large pointing errors when they are not allowed to move their head and their eye toward the target.’ (p. 304). Therefore, the eye led the head in a relatively natural task that required coordination of the hand along with the eyes and head. The eye-first tendency emphasized in all of this research seems to be a rather robust characteristic of human subjects.

Much of the work described so far was summarized by Fuller (1992a), who reviewed publications through 1989 with both head-fixed and head-free humans, as well as with some other mammals. Ten of these papers dealt with free-headed humans. Eight of these used visual stimuli, which make them germane to the present paper. None of these eight experiments, however, can be described as either very natural or even accurate because: (i) head rotations were restricted to rotation about the vertical axis, (ii) head rotations might have been affected by friction within the potentiometer (a possibility played down by those who used them), (iii)

EOG, a relatively crude method, which is well known to be subject to several artefacts, was used to measure eye rotations, and (iv) the stimulating conditions were most often flashed targets that came on for variable intervals in otherwise dark environments, conditions quite different from those in which human beings perform most of their natural, coordinated, visuomotor acts. Fuller (1992a) expressed concern with these problems. He also raised the issue of the relevance of these papers for explaining human head/eye coordination during natural tasks in the real world. Fuller concluded that ‘The reliability or variability of different strategic patterns is highly dependent on the experimental design, which may become so constrained that the behavior no longer resembles that of the freely moving subject.’ (p. 111).

The problem of studying head/eye coordination under relatively realistic, natural conditions, had been solved for the rabbit by Collewijn (1977) well before Fuller’s review (1992). Collewijn solved the problem when he introduced the cube-surface field-coil, phase-detecting, magnetic eye/head recording system. Collewijn’s new method made it possible to record both head and eye rotations accurately while rabbits walked freely about in a relatively large field. Under these novel, rather natural conditions, rabbits, who did not make saccades when their heads were immobilized, showed themselves capable of ‘relatively invariant onset intervals’ (Fuller, 1992a, p. 109) between their saccades and head movements. Collewijn (1981) summarized his observations on the head/eye coordination of the freely-moving rabbit as follows: ‘It must be concluded that... most gaze changes are achieved by combined eye and head movements. In many of these, head and eye movements are both saccadic and initiated simultaneously.’ (p. 19).

Steinman and Collewijn (1980) used this rabbit instrumentation to record human gaze-control as the head was actively oscillated about its vertical axis, while distant objects, seen through a window on the 15th floor of the Medical faculty in Rotterdam, were fixated binocularly. They reported several features of human oculomotor performance that could not have been anticipated from more conventional observations made with the head restrained in a visually-impooverished environment usually used in more conventional laboratory experiments.

The handbook, which contains Fuller’s (1992a) review, also contains two papers (Collewijn, Steinman, Erkelens, Pizlo, & van der Steen, 1992; Kowler et al., 1992) which used Collewijn’s recording technique after it had been implemented in a much larger and more accurate phase-detecting instrument called the Maryland revolving field monitor (‘MRFM’). This instrument was scaled-up sufficiently to make it more comfortable for research with human subjects. These

papers examined the control of gaze during both natural and unnatural visuomotor tasks. Once again, it was shown that oculomotor performance under relatively natural conditions is different from performance under the constraints that were ubiquitous before Collewijn's important contributions to recording instrumentation. For example, in Collewijn et al. (1992), peak saccadic velocity was found to be higher when the head was entirely free, leading these authors to conclude that 'the main sequence parameters observed with the subject's head held on a bite board (or bolted to a metal frame) may be considered to reflect subnormal performance caused by the partial inhibition of the natural commands for shifting gaze.' (p. 418). Similarly, Kowler et al.'s (1992) paper examined natural eye movements during reading and scanning with the head free and found that having the head entirely free to move 'revealed a natural tendency to program head and eye movements concurrently in similar spatial and temporal patterns... during reading, and more vividly... during scanning unless... explicit efforts [were made] to avoid doing this.' (p. 426). Recently, Lee (1999) continued and extended these observations of free-headed reading.

In the same year that these papers were published, Land (1992) published a paper in *Nature* in which he showed that he could predict human head/eye coordination during driving. This was an interesting contribution in part because Land points out that understanding the human being's natural way of coordinating head and eye can be observed when the coordination required can be done in the manner Land dubbed, 'unthinkingly'. Driving a real car safely on a real street in real traffic benefits from confining attention to the task at hand. It discourages observing, or attempting to modify, one's natural propensity for coordinating the head and eyes. Land performed his study by recording a view of the driver's gaze superimposed on a view of the scene with a head-mounted videocamera. His rationale was as follows: 'If there are 'natural' patterns of oculomotor coordination that emerge in every day situations these should be detectable from the predictable way that the head and eye co-vary. An appropriate and severe test of the system's predictability would then be that the amplitudes and time courses of both the eye and the head movements involved in every change of gaze would be dictated uniquely by the sizes of the gaze changes themselves.' (p. 318). He found that 'in the records... there were a few occasions when the head led the first eye movement of a series by up to 150 ms, but strict synchrony (20 ms or less) was far more common' and went on to conclude that 'under circumstances where eye and head movements are generated unthinkingly, the two motor systems receive the same command at almost the same time. This seems to be the 'default' condition of the mechanism that directs

gaze. We can of course override it consciously by either making or suppressing head movements. Most of the time, however, the rules indicated here probably apply.' (p. 320).

Smeets, Hayhoe, and Ballard (1996) picked up this problem. They also looked at coordination while subjects performed a visuomotor task 'unthinkingly'. Their task was also natural but quite different. They examined gaze-shifts while subjects manipulated objects. These manipulations required subjects to make gaze-shifts of about 30° as they made a reproduction of a model located in the visual field. Smeets et al. (1996) introduced their study by pointing out that what we know about human head/eye coordination 'is based mainly on studies in highly artificial laboratory conditions. Simple tasks in artificial laboratory conditions are well suited to studying basic mechanisms of neural control. However, when we use such experiments to study the interaction of such mechanisms, their results sometimes tell us more about the experimental constraints than about the control mechanisms we want to study (Steinman, Kowler, & Collewijn, 1990). Our approach is therefore to study humans who are performing natural tasks, having their attention focused on the task, instead of on the variables we want to study.' (p. 434).

Smeets et al. (1996) recorded the position and orientation of the head and the hand with a 3-D electromagnetic system. The position of the left eye was recorded with a head-mounted IR camera. The accuracy of their latency measurements was between 16 and 20 ms if they 'averaged many trials'. Four subjects were required to make reproductions of DUPLO building block models. Smeets et al. (1996) reported the following pattern of results: 'The horizontal movements of gaze, head and hand followed a coordinated pattern: *a shift of gaze followed by a movement of the head* [our italics], which (in general) preceded the movement of the hand. The exact timing and amplitude of the head movement relative to the saccade depended on movement of the hand.' (p. 437). They go on to conclude that 'contrary to Land's (1992) conclusion... that even under circumstances where the gaze is shifted unthinkingly, eye and head can receive different commands at different times.' (p. 440).

By 1992, the year in which Land published his driving experiment, the development of the MRFM had progressed to the point where it became possible to study gaze-control very accurately under the conditions that are arguably the most significant for the human's success as a species. Namely, the human's ability to manipulate and fashion objects held in the hands. In other words, to fashion and work with objects that are well within arms' reach. Measuring gaze accurately under these conditions required measuring translations of the head, as well as head and eye angles, very

accurately. The Smeets et al. (1996) experiment (described above) clearly falls into this category of significant, natural experiments with respect to the nature of the task. Its temporal and spatial resolution was less than what was possible with the MRFM, but it was sufficient to add some useful information to the human head/eye coordination problem. The coordination of the head and eye depended on what the hand was going to do, but does the eye continue to lead the head whenever the hand manipulates nearby objects?

Data that would answer this question had already been collected (1992) and analyzed for other purposes (Epelboim et al., 1995). In these experiments, subjects were seated with heads and torsos completely free as they either looked at (LOOK-ONLY) or tapped rods (TAP) in a specified sequence, arranged nearby in 3D space. The TAP task resembled activities humans are often called upon to do in the real world under natural conditions. It was also rather similar to what Smeets et al. (1996) had asked their four subjects to do. No explicit instructions were given as to how the head and eyes should be coordinated in either task. Both tasks encouraged the subjects to perform ‘unthinkingly’. They were required to complete the sequence as fast as they possibly could without making any errors in the order in which the tapped or looked at the sequence of rods.

The present paper reports the results of additional analyses of the database that has produced four publications so far, viz. Epelboim et al. (1995, 1997); Epelboim (1998), and Malinov, Epelboim, Herst, and Steinman (2000).³ All dealt with the control of gaze under relatively natural conditions. They described: (i) visual search, gaze-shift accuracy and the function of gaze-shifts, (ii) gaze-shift dynamics, (iii) gaze and retinal-image-stability, and (iv) the size of binocular saccades, how well saccade size matched in the two eyes, and saccadic vergence. The present paper describes the temporal coordination of the head and eye when these subjects tapped a sequence of targets. Head/eye coordination was not analyzed for the conditions in this database in which subjects LOOKED-ONLY at targets because all four subjects tended to sit very still, keeping head movements to a minimum. There was not sufficient head movement to make an analysis of the temporal coordination of head and eye interesting. The TAP task was quite different. The head and eye made many coordinated movements. We found that *the head tended to start moving before the eyes*, a result at odds with

much of the prior literature on human head/eye coordination, including the only two papers (described just above) that studied human head/eye coordination under rather comparable, relatively natural, conditions.

2. Methods

Binocular eye/head movements were measured while subjects tapped (TAP) sequences of 3D targets (colored LEDs) located on a worktable in front of them. The angular separation of targets was random, varying between about 1.5° and 35° of visual angle. The distance from the subjects’ eyes to the targets varied from about 50 cm to 90 cm, depending on where the targets were and how much each seated subject moved. All targets were arranged before the beginning of each trial and were stationary and visible throughout. Eyes were closed between trials. Each target configuration was tapped ten times before a new randomly-generated configuration was presented. See Epelboim et al. (1995) for additional procedural details.

The temporal relations between the onset- and offset-times of head rotations and saccades (relative to the head), which met the following two criteria for a coordinated head/eye movement, were examined: (1) the head and eye moved in the same direction; and (2) the horizontal components of both the head and eye were larger than 10°. The criterion used for saccade and head onset and offset was a horizontal velocity = 20% of its peak. This criterion was chosen because Smeets et al. (1996), the prior experiment most closely related to ours (see above), had used ‘a very conservative threshold to detect the onset of movement... velocity surpassed 50% of its maximum value.’ (p. 436). We also desired a conservative criterion, but were able to set it lower (20%) because our temporal resolution was much better, viz. ~ 2 , rather than 16 ms. Head and eye movements were considered to begin simultaneously if their onset occurred within ± 8 ms of each other, also a conservative value, i.e. four times our resolution limit. In all, 2729 ‘coordinated’ head/eye movements met these criteria (N/Subject: ZP = 637, HC = 649, RS = 720, CE = 723). The MRFM data used in these analyses consist of angular positions measured to 1 minarc with successive samples separated by 2.04 ms. Examples of the different kinds of head/eye coordinations observed can be found in Figs. 1–4.

3. Results

The overall pattern of head/eye coordination was strikingly similar for all four subjects.

³ See Epelboim et al. (1995) for a description of the MRFM; the kind of data it generates, and the design of the TAP and LOOK-ONLY experiments. The performance of the four subjects, who served in these experiments, can be visualized at: <http://brissweb.umd.edu>.

3.1. Onset of eye and head

The head of all four subjects moved before the eye more often than the eye moved before the head. The head led 48% of the time (range = 46–52%). The mean head lead was 22.78 ms (S.D. = 16.85). The head and the eye started moving simultaneously 37% of the time (range = 35–40%). The mean when they started simultaneously (± 7 ms) was 5.54 (S.D. = 2.64). The eye led the head only 15% of the time (range = 13–18%). The mean eye lead was 33.25 (S.D. = 20.70). The differences

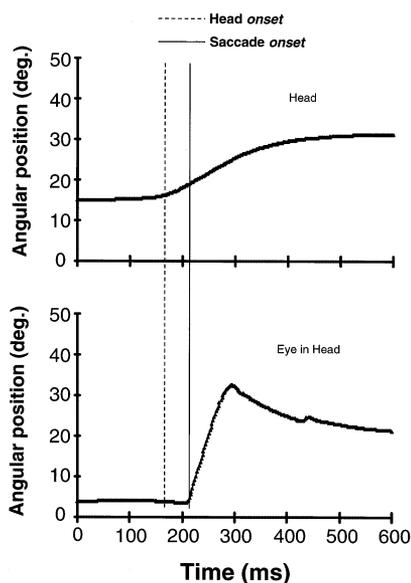


Fig. 1. Example of an head/eye coordination at the onset of movement in which the head led the eye. Top: head movement. Bottom: eye movement.

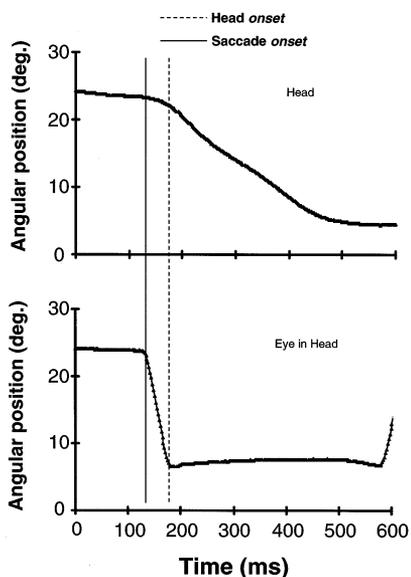


Fig. 2. Example of an head/eye coordination at the onset of movement in which the eye led the head. Top: head movement. Bottom: eye movement.

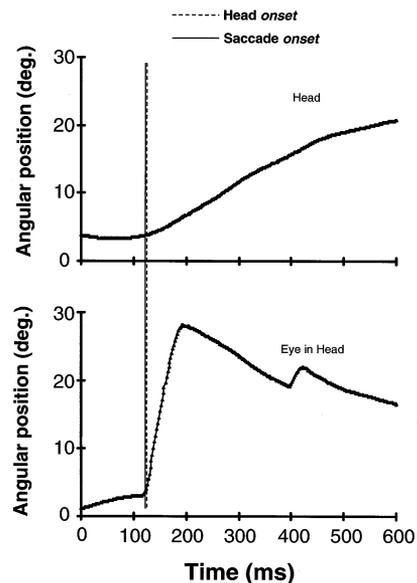


Fig. 3. Example of an head/eye coordination at the onset of movement in which the eye and head move simultaneously. Top: head movement. Bottom: eye movement.

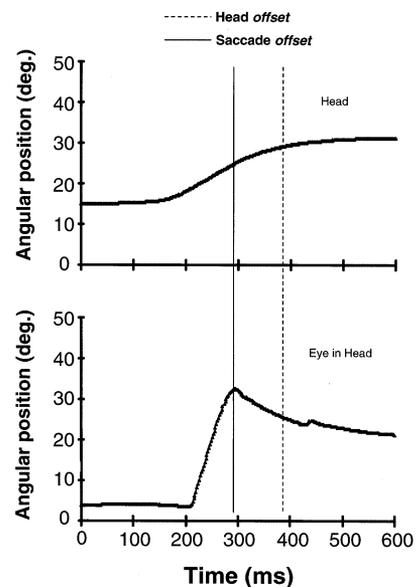


Fig. 4. Example of an head/eye coordination at the offset of movement in which the eye stopped moving before the head. Top: head movement. Bottom: eye movement.

among the three groups of proportions of coordinated head/eye movements, summarized in Fig. 5, were all statistically significant ($\chi^2 = 463.2$, $df = 2$, $P < 0.0001$), which means that we can conclude that the head is most likely to lead, and that the eye is least likely to lead, during coordinated head/eye movements under the natural conditions studied.

Fig. 6A shows the distribution of the three types of coordinated head/eye movements: the eye leading, eye and head starting simultaneously and head leading. The

data were pooled over the four subjects because individual differences were modest. Fig. 6B plots the proportion of the data that fell near (± 20 ms) our temporal resolution limit (~ 2 ms). The head can be seen to be likely to lead the eye even when ‘simultaneous’ is defined as stringently as our instrumentation allowed.

Fig. 7A shows the distribution of gaze-shift sizes for the three classes of head/eye relationships (head leads, simultaneous and eye leads). It is shown separately for each subject to illustrate how very similar their performance was with respect to this parameter. Their ages, sizes and builds varied considerably but their performance did not. Apparently, constraints inherent in tapping randomly-configured rods on a 46×59 cm² worktable had a larger influence on performance than the individual differences among the subjects’ ages and physiognomies. The mean gaze-shift, averaged over all four subjects, was 42.6° , S.D. = 15.06.

Fig. 7B shows the distribution of individual subject’s gaze-shift directions (leftward or rightward) for the three classes of head/eye relationships (head leads, simultaneous and eye leads). All four subjects were about equally-likely (within $\sim 2\%$) of making gaze-shifts to the left and to the right, viz. 48.3% went left and 51.7% went right. These leftward and rightward saccades were quite similar in size. The mean left saccade-size, averaged over the four subjects, was 42.5° , S.D. = 15.0, and the mean right saccade-size was 42.6° , S.D. = 15.11.

It is clear that performance in the tapping task was not subject to appreciable individual differences. The nature of the task, rather than individual subjects’ propensities, had the larger influence on the way all four coordinated their head and eyes. On the whole, the head led the eye, or the head and eye started moving simultaneously. The eye was least likely to initiate a gaze-shift during this relatively natural tapping task.

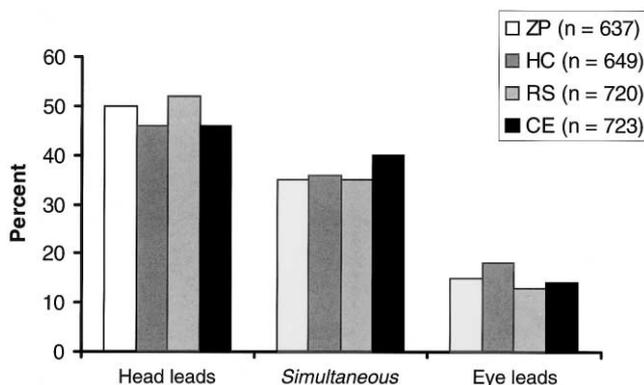


Fig. 5. Proportion (%) of coordinated head/eye movements in which the head led the eye, the head and eye moved simultaneously and the eye led the head. The performance of each subject is shown separately.

Note that gaze-shift-sizes varied over quite a large range, about 68% were between 27° and 57° .

3.2. Offset of eye and head

The eye of all four subjects always stopped moving before the head. On average, the head stopped 136 ms after the eye. The earliest head movement stopped 24 ms after the eye and the latest stopped 487 ms after the eye.

4. Discussion

4.1. Comparison with other ‘natural’ experiments

We undertook this analysis primarily to determine: (i) whether the eye started moving before the head as had been reported by Smeets et al. (1996) when vision guided a hand that was copying a model, or (ii) whether the head and eye started moving simultaneously as had been reported during driving by Land (1992). We found neither. We found that the head was more likely to start moving before the eye when a sequence of rods was tapped. The eye was least likely to move first. If the head did not lead, head and eye were more likely to begin moving simultaneously. The finding that the eye was least likely to lead in our tapping task is at odds with most prior work on human head/eye coordination. Furthermore, the coordination of all four subjects in our tapping task was similar. Such uniformity was also rare in prior work, where considerable inter- and intra-subject variability had been reported (Smeets et al., 1996, see their Fig. 5B); Land, 1992). Individual differences in gaze-shift dynamics in our tapping task were also not large (see Fig. 4 in Epelboim et al., 1997). The relatively modest inter-subject variability observed in our tapping task suggests that characteristics of this task placed constraints on head/eye coordination that were not imposed by copying models or by driving. In summary, the head/eye coordination of the subjects, who served ‘unthinkingly,’ in three experiments, explicitly designed to be as ‘natural’ as possible, differed quite widely both with respect to the nature and variability of the temporal relationship between the head and eye.

4.2. Comparison with less ‘natural’ experiments

A number of rather elaborate studies of head/eye coordination in humans under less natural conditions have been published since Fuller’s (1992a) review (cited above). The degree to which they shed light on more natural conditions is unclear, but highlights of a few will be described here for comparison with our results.

Ron, Berthoz, and Gur (1993) used Bartz’s (1966) technique, i.e. binocular EOG and a head-mounted

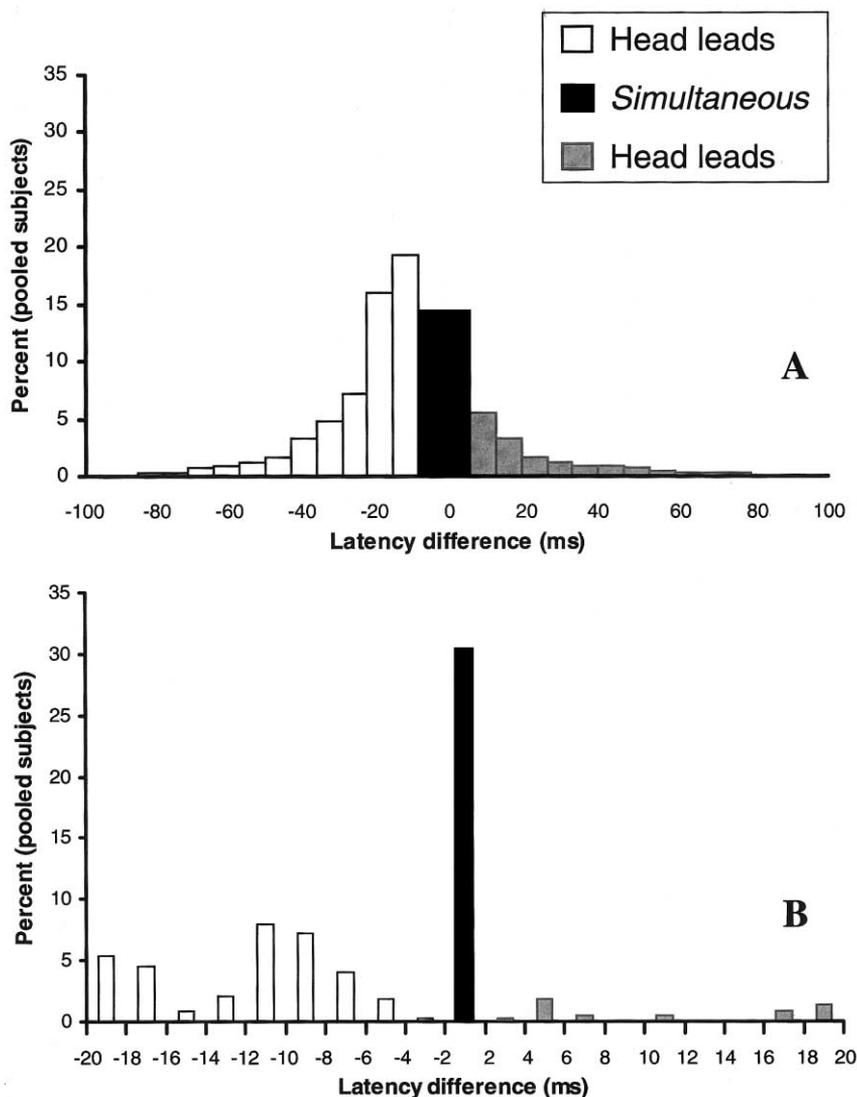


Fig. 6. (A) Distribution (%) of coordinated head/eye movements (7 ms bins) in which the head led the eye, the head and eye moved simultaneously, and the eye led the head. Latency difference was calculated as head-onset minus eye-onset, the convention introduced by Guitton and Volle (1987). The data were pooled across subjects because individual difference were small (see Fig. 5). (B) Distribution (%) of coordinated head/eye movements near (± 20 ms) the temporal resolution limit, viz. 2 ms. This distribution shows when the head led the eye, the head and eye moved simultaneously, and the eye led the head with respect to the smallest temporal interval that could be measured.

potentiometer, to measure the horizontal eye and head rotations of four subjects following motion of a red laser spot. Subjects were 'instructed to follow the stimulus pattern 'as quickly and accurately as possible and to remain fixating at the last flash offset until the target reappeared at the initial position' (p. 597). The authors introduced their paper by saying that 'Variations in eye-head latency have been shown to be dependent on the displacement, predictability and visibility of the target.' (p. 596). They employed a pair of flashed targets that always went in the same direction, either increasing or decreasing in eccentricity. They proposed that if 'in the head free conditions, the eye and head are tightly coupled... any modification of an eye saccade [caused by flashing a pair] would be accompanied by a

concomitant change in head movement.' (p. 596). They found that 'in response to two successive flashes in the same direction in total darkness, head movement preceded eye movement.' (p. 606). They also called attention to their 'most important new finding that in response to two sequential flashes, some eye and head movements were dissociated: the initial head motion was towards the first flash offset, whereas the concomitant eye saccade was to the second flash offset... [a] finding contrary to the current belief that tight eye-head coupling is a phenomenon throughout the phylogenetic scale.' (p. 609). Ron et al.'s (1993) experiment stands out as probably the only example of reports of the head leading the eye consistently, prior to our results.

Volle and Guitton (1993) used EOG to record binocular horizontal eye movements, but used the amplitude detection, magnetic field method with a sensor coil taped on the forehead to measure rotations of the head (the head coil was calibrated by having the subject rotate the head while wearing a calibrated, helmet-mounded potentiometer). Targets were 17 red LEDs separated by 10° within a $\pm 80^\circ$ field. The main difference between this and prior work was the fact that they studied gaze shifts with the visual axis straight ahead relative to the body (as prior workers had), but they also studied gaze shifts with the head offset from the straight ahead by various angles. They found that for relatively small eccentricities, i.e. 40° or less ‘ocular saccades are very fast: they bring the visual axis on or close to the target before head movement has contributed much to the gaze displacement... [for eccentricities] $> 50^\circ$... head motion contributes increasingly more to gaze displacement... [the authors go on to note

that]. Despite the fact that subjects were not specifically instructed to move their heads, they had a strong propensity to do so even when head motion was not necessary.’ (p. 469).

More recently, Goossens and Van Opstal (1997) used the phase-detecting technique introduced by Collewijn (1977) for the study of freely-moving rabbits, to publish unusually accurate measurements of human head/eye coordination with both visual and auditory input used to define the location of 84 LED targets arranged at spherical polar coordinates with the LED at the origin located ‘at the straight-ahead position’. Subjects initiated trials under both aligned and unaligned conditions. In the former, the subject’s head and gaze was directed to the LED in this straight-ahead position. In the unaligned condition, before the trial began the head and eye were aligned to different directions. The subject was required to maintain this direction of the head when shifting gaze to a randomly-selected LED in the

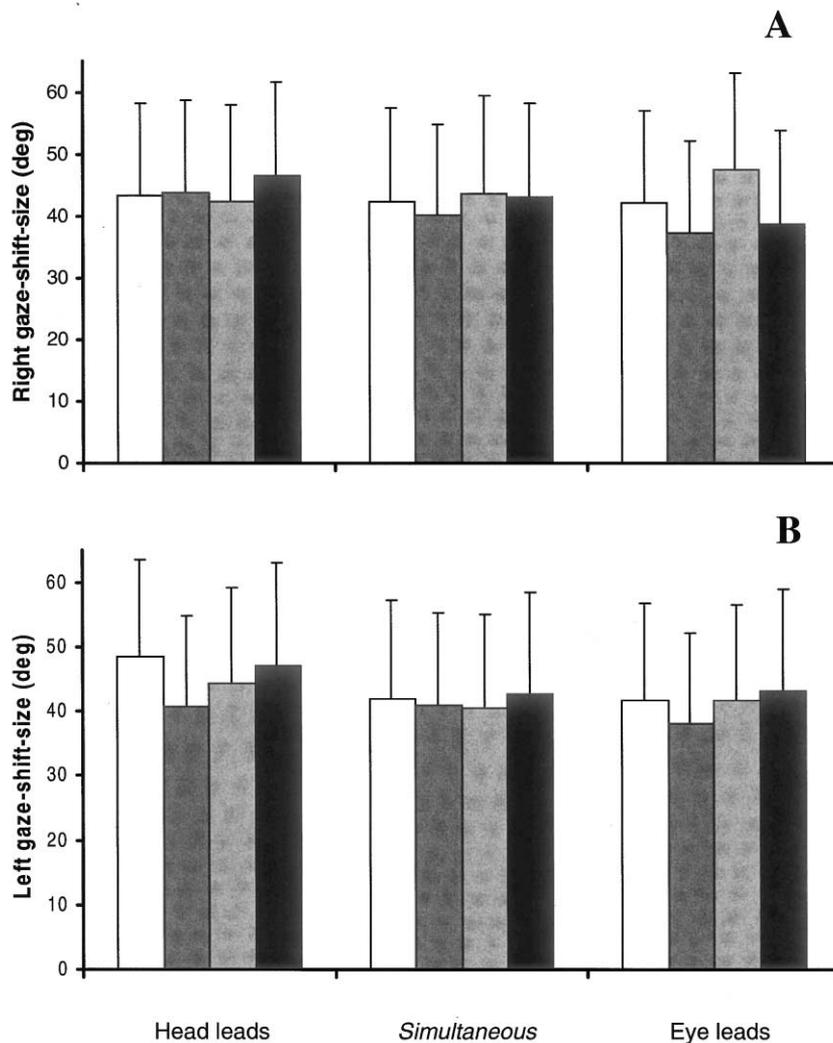


Fig. 7. (A) Mean right gaze-shift-size ($^\circ$) and standard deviations when gaze-shifts went to the right and the head led the eye, the head and eye moved simultaneously, and the eye led the head. The performance of each subject is shown separately. (B) Mean left gaze-shift-size and standard deviations when gaze-shifts went to the left. See Fig. 5 for the color code of each subject.

array. Subjects were explicitly instructed to ‘make orienting responses towards peripheral targets as fast and as accurately as possible... [and] not to move their body...’ (p. 545). The LED targets were beyond the reach (0.85 m) of all but the longest human arms.

Goossens and Van Opstal’s (1997) reported that ‘In response to the visual stimulus, gaze is initially displaced by a saccadic eye movement only. After a delay of about 50 ms, a saccadic head movement starts contributing’ (p. 547). This was observed in both the aligned and unaligned conditions. Therefore, once again, the eye still tended to lead the head, the most frequently reported result since Bartz began the modern work in 1966.

Corneil et al. (1999) and Corneil and Munoz (1999) also made very accurate measurements by using the magnet field-sensor coil technique to measure head and eye movements. They studied four subjects who were able to move around freely while they looked at (or near) LED’s, or towards auditory ‘noise bursts’, while a second stimulus, of the other modality, was presented either near where the target was presented (their ‘enhancer’ condition) or away from where the target was presented (their ‘distractor’ condition). They selected their four subjects to meet ‘criteria for head movers (Fuller, 1992b).’ (Corneil et al., 1999, p. 1392). The Corneil et al. (1999) report has little direct relevance to the present work because it examined gaze shift dynamics and accuracy when distractions were introduced during gaze shifts. The authors were primarily interested in whether the gaze-shift could be reversed in midflight. Corneil and Munoz (1999) is more germane because it examined head-onset latency under the conditions described in Corneil et al. (1999). The goal of this aspect of their experiments was to ‘identify and analyze early head movements (EHMs) that occurred before the initiation of a correct gaze shift (CGS).’ (p. 1407).

Corneil and Munoz (1999) observed that ‘...subjects sometimes move their head in the direction of the target before the gaze shift begins.’ (p. 1406). They grouped these ‘early head movements’ into ‘correct’ or ‘incorrect’, depending on whether the head oriented towards the target or towards the distractor. The group of ‘correct’ early head movements is closet to our situation in which gaze is shifted towards the next target in a tapping sequence. Corneil and Munoz (1999), do present some data that can be compared with ours. They report that, overall subjects, the average percent of early head movements with a visual target and auditory stimulus in the same location, i.e. an auditory ‘enhancer’, was 33%. The percentages for the four individual subjects were 34, 79, 19 and 1%. The 33% overall average tabulated is hardly representative. We found ‘early head movements’, i.e. the head leading the eye, on average, 48% of the time, and our subjects’

percentages of early head movements ranged from 46% to 52%. Our subjects were much less variable.

Corneil and Munoz (1999) concluded that ‘...a simple examination of eye and head onset times is not a sufficient approach to fully understand eye-head coordination during gaze shifts. Future studies will require more complicated experimental protocols, such as employing multiple stimuli to tease apart different facets of orienting commands, and more sophisticated experimental techniques, such as combining extracellular recording of electromyographic neck muscle activity in behaving animals, to further understand the decomposition of orienting signals in to the final movement commands for the eye and head.’ (p. 1419). We agree that more studies are needed to understand the temporal coordination of the human head and eye, but we suspect that simpler, and more natural, rather than more complicated, experiments may be a better way to go. This possibility will be emphasized below.

Recently, Stahl (1999) also published a rather elaborate, relatively unnatural, but accurate experiment on human head/eye coordination. The rotating magnetic field-sensor coil technique, introduced by Collewijn (1977), recorded head and eye angles. An elaborate ‘stimulus paradigm [that] was designed to evoke a quasi-natural pattern of eye-head coordination [was also used because] earlier investigations... strongly potentiated head movements.’ (p. 42). A 180° array of LEDs was used to create 76 possible target eccentricities. A complex pattern of target placements were presented throughout each trial, with a set of two to five ‘peri-test’ targets being presented $\pm 0-2^\circ$ from an eccentric target whose eccentricity could be somewhere $\pm 50^\circ$ of the starting fixation position. Stahl’s (1999) intention was to emulate what he believed to be the ‘natural’ human scanning pattern, the kind that might be employed during a ‘bird-watching hike through a field’. Stahl (1999) said that, ‘We designed our stimulus to parallel the natural pattern of visual search in which large saccades to new objects of interest are followed by series of smaller saccades as the details of the object are inspected.’ (p. 52). It requires more than a little optimism to believe that the manner in which a human being will track a series of LEDs that appear unpredictably at varying distances from where gaze resides in an otherwise dark, impoverished environment resembles the manner in which a human being will actually search the highly-structured, illuminated world in which a bird-watcher takes a hike to look for birds. Despite such obvious differences between natural bird-watching and the stimuli provided in this experiment, Stahl (1999) felt ‘that our stimulus paradigm’s more natural distribution of [required] saccade sizes and lack of any instructions regarding head alignment improved the laboratory approximation of natural eye-head coordination.’ (p. 52). Ten subjects served in this experiment.

Intra-subject variability was relatively low but inter-subject variability was large and the reasons for such ‘variability in head movement tendencies is unknown’ (p. 52). Stahl also reported that ‘Head movements occasionally preceded gaze saccade onset by up to a few tens of milliseconds.’ (p. 43), a result reported first by Barnes (1979) and subsequently noted in a number of relatively unnatural, experiments on human head/eye coordination.

4.3. Conclusion

There have been two classes of experimental approaches to the study of the temporal coordination of the human head and eyes. The majority of these experiments fell in the first class, which were done under highly unnatural conditions with subjects required to shift gaze to suddenly illuminated or flashed targets that appeared in unpredictable locations in otherwise dark environments with the head restricted, more or less, to motions about its vertical axis. Until relatively recently many of these experiments used a rather crude method (binocular EOG) for recording eye movements as well. In most conditions, in most of these experiments, the eye was found to start moving before the head. A tendency for the head to lead the eye occasionally when the appearance of a target was predictable was also noted. Large subject-to-subject variability, and even within subject variability, has been notable in this work, a fact that has been taken as a tribute to the flexibility of the human beings’ motor control systems. It could also suggest something quite different. Namely, the use of experimental designs poorly-suited for examining how these control systems evolved to perform reliably and efficiently. We have acquired a lot of information during the last 35 years about how individuals perform in a variety of analytical experiments that require movement of both the head and eyes. We are still very far from understanding the general principles underlying the way in which the head and eyes cooperate in the performance of natural tasks. During the last two decades instrumentation that evolved from Collewijn’s (1977) study of the freely-moving rabbit has made it possible to measure head/eye coordination accurately with few restrictions, but there have been few studies to date that have exploited these opportunities by requiring subjects to perform real tasks under truly natural conditions. If successful completion of these tasks requires concentration, if they are performed ‘unthinkingly’, and if they fall within the realm of significant human activities, like crafting tools, or performing surgery, it will become possible to observe the way head, eyes and hands actually are meant to work together reliably and efficiently.

We already know something about experimental conditions that impose a natural limit on the likelihood of

a human being’s head participating in a gaze-shift. Recall that head/eye coordination was not analyzed in the LOOK-ONLY experiments described by Epelboim et al. (1995) (see Section 2). It was not analyzed because all 4 subjects sat very still, keeping their head movements to a minimum. One could say that they almost froze their heads in space (their performance can be visualized at <http://brissweb.umd.edu>). These subjects had not been instructed to hold the head still, but all four adopted this strategy when asked to look as accurately as possible at the same kind of target sequences they were required to tap. Epelboim et al. (1995) described this result as follows: ‘Subjects reported that looking-only was more difficult than tapping... These differences were evident in the spontaneous comments made by the subjects as the data were collected. All four reported that tapping the targets was relatively easy and fun, whereas sitting and looking at the targets in sequence seemed very unnatural, pointless, and required more effort.’ (p. 3408). N.B. that three of the four subjects (HC, CE & RS) were highly experienced eye movement subjects. They had been fixating and tracking stationary and moving targets for as many as 42 years before they participated in the TAP and LOOK-ONLY experiments. Almost all of their prior experimental participation had been unnatural. They had performed with the head immobilized on a biting board or chin rest. Once the head is supported artificially there is no need (and apparently no likelihood) of discovering how important it is to hold one’s head as still as possible when required to fixate accurately. Note also that the fourth subject (ZP), who had participated in fewer prior eye movement experiments, adopted the same strategy as the very experienced eye movement subjects for coordinating his head and eye. He kept his head quite still. It is also important to note that there was very little within or between subject variability when these subjects looked accurately at a sequence of targets. All four seemed to know, and acted on the fact, that keeping the head immobile would make it easier to perform this task. In other words, there seemed to be a natural propensity for doing this just as there was for leading with a head movement when they shifted gaze to guide their tapping of similar target sequences. Studying other natural tasks, which might allow coordinated movements of the head and eyes, might be the best way to discover additional propensities for coordinating head and eyes. Knowing what these natural human propensities are might eventually allow us to understand the principles underlying the selection of specific behaviors.

We conclude by claiming that now that natural experiments can actually be done, it is time to do them, rather than to continue to simulate quasi-natural conditions based on information obtained under highly restricted, unnatural conditions. Judging by the

widespread success of human beings in performing a variety of difficult, visually-guided motor tasks, one should be able to observe a relatively reliable, universal repertoire of coordinated actions, rather than continuing to observe the plethora of individual differences that permeate most of the existing literature on human head/eye coordination.

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Biographies

Julie Epelboim (1964–2001) died of cancer on January 10, 2001, about 6 months after it had been diagnosed. Her death deprived the visual science community of one of its most promising and productive young scientists. Dr Epelboim made important contributions to the study of the role of cognitive processes in human oculomotor control and to the use of eye movements to infer cognitive processing.

Dr Epelboim was born in Moscow, emigrated to the United States with her family in 1977, attended Carnegie Mellon University, and received her BSc in Applied Mathematics with Majors in Computer Science and Psychology in 1988. From 1990 to 1995, she attended the University of Maryland at College Park, receiving her PhD in Psychology for her dissertation, ‘*Cognitive and Motor Coordination in Visuomotor Tasks*’, under the direction of Professor Robert M. Steinman. 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 Professor Patrick Suppes. 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 during her first year in residence at NIST.

Dr Epelboim’s more important publications are listed below, where it is evident that scientists from a variety of backgrounds had an opportunity to collaborate with her during her brief career. We, her main collaborators, decided to publish this obituary because we wanted our colleagues, who did not have the good fortune of working with her, to know that science suffered a great loss with her untimely death.

James R. Booth
Han Collewijn
Andrew N. Herst
Eileen Kowler
Patrick Suppes

Mark Edwards
Casper J. Erkelens
Zygmunt Pizlo
Azriel Rosenfeld
Robert M. Steinman

Publications

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