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Natural Oculomotor Performance in Looking and Tapping Tasks

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Abstract

A unique apparatus recorded eye and head movements of subjects as they tapped or only looked at sequences of 2, 4 or 6 nearby, 3-D targets. Each sequence was repeated 10 times to allow an opportunity for learning. A stereotypical pattern of movements was established after 2-3 repetitions. Subjects almost always looked at each target just before tapping it. Looking-only was more difficult than tapping in that it took more time and, unlike tapping, usually did not benefit from practice. The number of targets in a sequence affected time/target in both tasks. Sequence length and practice effects show that memory was involved. The persistent strategy of looking before tapping and the subjects' inability to tap a well-learned pattern with eyes closed, show that visual cues were also important. We conclude that motor planning occurred first at the level of the task and then at the level of specific motor programs. The relative difficulty of the less natural, looking-only task, in which the eyes worked without a meaningful cognitive or motor purpose, suggests that *efficient* eye movement programming requires a natural task of the kind eye movements evolved to serve.

Introduction

Until recently eye movements could only be studied accurately with the subject's head immobilized, a most

unnatural condition. Stimuli in most eye movement experiments were also unnatural, usually a single point of light seen in darkness that had to be fixated or tracked as it moved in steps, ramps or sinusoidal motions on the face of a CRT oriented at right angles to the line of sight. Occasionally, subjects were given two or more stationary points and asked to make saccadic steps from one to the next. These conditions and tasks are probably never encountered outside a laboratory. But, even in such unnatural situations, eye movement patterns have been shown to be governed by complex cognitive processes, rather than by simple reflexes or habits. For example: (1) sequences of saccades are pre-planned like many other motor sequences (Zingale & Kowler, 1987), (2) smooth pursuit is affected by expectations about future target motion (Kowler, 1989), (3) saccadic eye movements show speed-accuracy tradeoffs (Steinman *et al.*, 1973) and priming effects (Ross & Ross, 1980), and (4) smooth pursuit and saccadic eye movement subsystems share a single selective attentional mechanism with the perceptual system (Khurana & Kowler, 1987; Kowler, Doshier & Blaser, 1993). Findings such as these encouraged us to expect an even wider range of cognitive contributions to oculomotor behavior once eye movements could be studied under much more natural conditions -- conditions that might give cognition more room to operate. Our new work was also motivated by recent

evidence that oculomotor behaviors do not occur in isolation, but as integral parts of motor patterns which involve the head, torso and limbs (Collewijn *et al.*, 1992a,b; Kowler *et al.*, 1992). It has become quite clear that studying eye movements when only the eyes are able to move, gives a distorted and incomplete picture of how the oculomotor system operates (see Steinman, Kowler & Collewijn, 1990, for a summary).

The concentration on unnatural conditions and tasks in traditional eye movement research did not necessarily reflect the researchers' lack of appreciation of the complexity of the oculomotor system. Rather, until very recently, limitations of eye movement recording equipment made it impossible to do experiments that were both natural and accurate in the sense the measurement accuracy and precision was better than the accuracy and precision of the motor system under study. A unique apparatus, developed recently, eliminated this impasse, making it possible to measure with high precision, accuracy and time resolution, binocular eye and head movements of unrestrained, seated subjects.

A series of experiments, taking advantage of the new recording apparatus, was designed to be representative of everyday life situations in which coordinated visuomotor performance is used. All behaviors took place in a well-lit, visually rich environment, with 3-D targets located within arm's reach. The experimental tasks (tapping or looking at a sequence of targets) were designed to study spatial and motor memory, learning, planning, visual search and other cognitive activities involved in visuomotor performance.

Method

Apparatus

The "Maryland Revolving Field Monitor" or MRFM, is described next so as to provide an inkling of problems inherent in making accurate measurements of eye/head/arm coordination under natural conditions. The MRFM consists of 3 subsystems (Fig.1):

(1) The Revolving Field Monitor/sensor-coil subsystem (RFM) measures head and eye rotations. The RFM produces 3 mutually perpendicular, magnetic fields revolving at different frequencies. Each field is produced by two sets of ac-current-carrying, 5-element, coils mounted on a cubical frame -- a "cube-surface coil" that produces a spatially-homogeneous magnetic field within a large fraction of the frame's volume. Horizontal and vertical eye rotations are measured with silicone annulus-sensor coils (*Skalar-Delft*) attached to each eye by suction. Horizontal, vertical and torsional head rotations are measured with 2 sensor-coils mounted on the head. The angle between the plane of each sensor coil and the planes of each magnetic field is proportional to the phase difference between the ac-current induced in the sensor-coil and the phase of the ac-current induced in a reference coil associated with each field. The precision of angle measurement is better than 1 minarc with

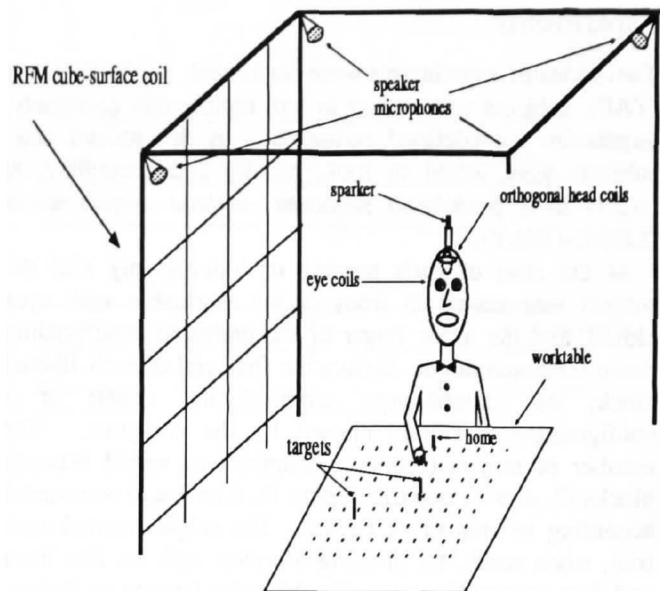


Figure 1. The Maryland Revolving Field Monitor apparatus (MRFM).

linearity < 0.01%. Sampling rate was set to 488 Hz.

(2) The Sparker Tracking Subsystem (STS) measures 3-D head translations. The "sparker", mounted on top of the head, emits bursts of sound at 61 Hz that are detected by 4 microphones mounted on a rectangular frame near the ceiling. STS computes the time of arrival of each spark's wavefront and outputs distances to each microphone (to 0.1 mm).

(3) The "Worktable" subsystem consists of a plastic table, with an 11 X 14 grid of equally-spaced wells into which rods topped with color LEDs (targets) can be placed. Tapping a target activates a microswitch, allowing the time of the tap to be recorded (to 2 msec). A well near the subject was designated the "home" position (see Fig 1).

Analyses

Outputs of the RFM and the STS were converted into worktable-coordinates to determine where the subject was looking with respect to the targets. To do this, three types of calibrations were performed: (1) Sparkers placed in worktable-wells calibrated "sparker-space"; (2) Sighting centers of each eye were measured with the head on a bite-board; (3) The positions of the sensor coils on the eyes and the relationship of the sparker to the eye and head coils was measured at the start of each experimental session. For each fixation (a relatively stable gaze position between gaze-shifts) the target with the smallest angle distance between binocular gaze direction and the target (gaze-error) was designated the fixation target. The subject was assumed to be fixating something other than one of the targets when the smallest gaze-error was greater than 10° (< 10% of fixations).

Experiments

Two series of experiments were performed. In the first task (TAP), subjects were asked to tap, rapidly and accurately, targets in a predefined sequence. In the second task, subjects were asked to look, rapidly and accurately, at targets in a predefined sequence, *without* tapping them (LOOK-ONLY).

At the start of each tapping or looking-only trial the subject was seated in front of the worktable with eyes closed, and the index finger of the preferred hand holding down the home target. Before the first trial of each 10-trial block, the experimenter arranged the targets in a configuration randomly chosen by the computer. The number of targets (sequence length) was varied between blocks (2, 4 or 6) and trial length (3, 6 or 9 sec) was varied according to number of targets. The subject started each trial, when ready, by pressing a button with his free hand and then opened his eyes. The order for tapping or looking was specified by target color and was not changed in this series of experiments. For the longest sequence (6) the order was: release the home target, yellow, green, red, flashing yellow, flashing green, flashing red, home. For set sizes 2 and 4, the order was the same with the sequence ending on the home target after only 2 or 4 targets. At sequence end, the subject kept his eyes closed until starting the next trial. Each target configuration was seen for the first time at the start of the first trial in a block.

Results

All 4 subjects reported that tapping targets was very different from only looking at them: the tapping task was easy and even fun, but the looking task was effort-full and even somewhat annoying. Subjects also thought that they used different scanning patterns in the two tasks. Namely, they did not look at every target after the first 2 or 3 repetitions in the tapping task, but that they did look at every target when required only to look.

A new notation, called a "look-tap diagram", was developed to check these subjective impressions. Fig. 2 shows look-tap diagrams for a block of 10 TAP trials (top) and a block of 10 LOOK-ONLY trials (bottom) for subject CE. Each diagram represents 1 trial. Time is on the abscissa. Each horizontal line represents one target, with the first target in the sequence at the bottom. The symbols drawn on each line show when a target was looked at or was tapped, with circles representing tapping and rectangles representing looking. The width of each rectangle represents how long the subject looked at the target. Sometimes two or more rectangles appear adjacent to each other on the same line. This occurs when the subject made small saccades while keeping his gaze on the same target.

The look-tap pattern shown in Fig. 2 was very typical. Errors in scanning order occurred during the first 1 or 2 repetitions, as the subject had to find the targets. After that,

subjects looked at each target in order in both tapping and looking tasks. Interestingly, even in the earlier repetitions most saccades landed near targets, demonstrating the efficiency of search -- eccentric vision was used to find targets and foveal vision to confirm their color. When tapping, all subjects almost always (on 93% of all trials) used the strategy of shifting gaze to the next target and continuing to look at it until just before tapping it. In the rare instances where the subjects did not look at the target just before tapping it, the skipped target was usually located in the row nearest to the subject where it could be tapped while the arm was closest to the body. This look-before-tap pattern remained the same even on the very rare trials (<2%) that had errors in the tapping sequence, as in repetition 7 in Fig. 2. When the arm made a mistake, so did the eyes. This implies that the errors arose from improper target selection, not from any difficulty in coordinating the arm and the eyes.

The subjects were quite unaware of having looked at each target in the tapping task, believing that they often skipped looking at targets. Their impression that scanning patterns were different in the two tasks did not agree with the behavioral facts as outlined above. Was their impression that looking-only was more difficult than tapping also erroneous? To compare task difficulty, we examined the total time needed to complete the sequence divided by the number of targets. This measure (time/target) is shown in Fig. 3a as a function of the repetition of a sequence. Tap times were not only considerably shorter than looking-only times, but for 3 of the 4 subjects, only the tapping performance became faster with practice. For 3 of the 4 subjects, time/target decreased by nearly a factor of 2 for tapping and not at all for looking-only. The fourth subject, RS, improved in both, evidently finding a strategy for looking efficiently that eluded the other subjects. But even for RS, tapping times remained shorter than looking-only times after practice.

The shorter time/target for tapping was genuine and not due to tapping errors (i.e., a speed-accuracy trade-off). Subjects made very few errors (<2%) in tapping sequences, and nearly all of these errors occurred during the first 3 repetitions. The subjects actually made more sequencing errors when looking only, with almost all of these errors due to extra fixations embedded in an otherwise correct looking sequence. These data confirm the subjective impressions that "looking-only" -- the basis of most of our knowledge about saccades obtained in the laboratory -- is inherently artificial and not representative of what we do with the eyes in everyday life.

Natural visuomotor behaviors often involve sequences of movements. Figure 3a shows that longer sequences required more time/target. The effect of sequence length diminished somewhat with practice. Sequence length effects demonstrate that an individual response depends on properties of the sequence in which it is embedded, and

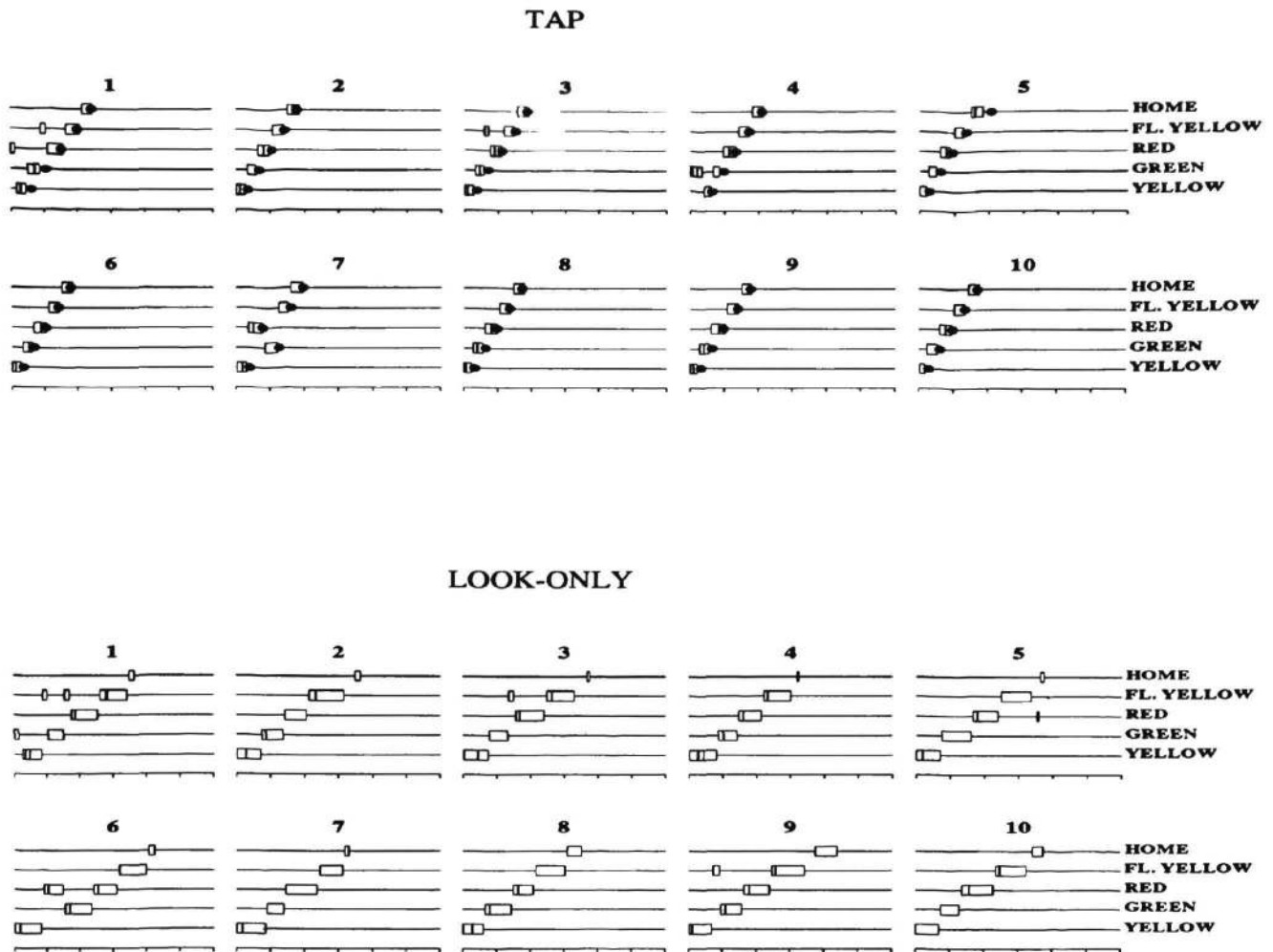


Figure 2. Look-tap diagrams for a block of 10 TAP trials (top) and a block of 10 LOOK-ONLY trials (bottom) for subject CE with 4 targets. See text for explanation of notation.

imply that at least some aspects of the entire sequence was planned as a whole before execution began (Sternberg *et al.*, 1978; Zingale & Kowler, 1987). These results, as well as the learning effects, illustrate the role of memory in the performance of the tapping task.

Gaze accuracy will be considered next. Subjects usually required two or more saccades to reach each target. In Fig. 3b the open bars show binocular gaze-errors for the first saccade and the filled bars show gaze-errors after the final

saccade made to each target. Gaze-errors were not significantly affected by sequence length or practice within the block of 10 trials, so Fig. 3b shows data averaged over these conditions. Gaze-errors, even after corrections, were smaller in the looking-only than in the tapping task. This suggests that some of the additional time taken in the look-only task might have been used to improve saccadic accuracy. However, we doubt that such a speed-accuracy trade-off explains these gaze-errors because tapping

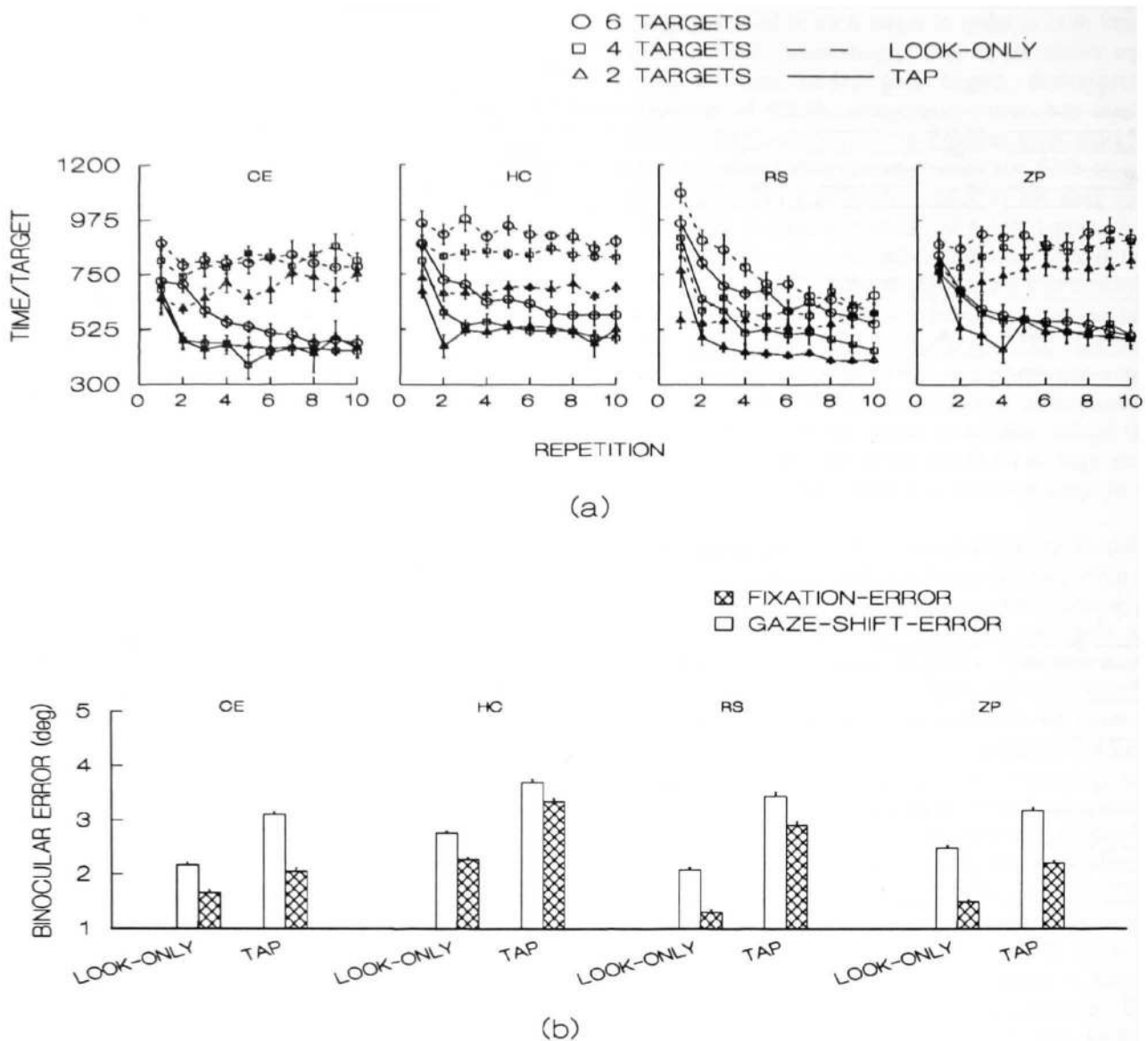


Figure 3. (a) Time/target as a function of repetition in a sequence for TAP (solid lines) and LOOK-ONLY (dashed lines). (b) Mean (SE) gaze-shift errors (open bars) and fixation-errors (filled bars).

continued to become faster with practice (Fig. 3a) while gaze-errors did not change. Even RS, who did get faster with practice when only looking, did not do so by increasing his gaze-errors.

Perhaps gaze-errors were larger during tapping because the subjects did not have to pay attention to their gaze-accuracy. They only needed to pay attention to the accuracy of their taps. This difference in the allocation of attention may be the reason that subjects were under the impression that they had skipped looking at targets more often than proved to be

the case, and also why they tolerated larger gaze-errors when they tapped. Gaze came only as near to the target as required to perform the tapping task.

But why look directly at the target at all during tapping? The tapping task was simple and made only modest demands on visual acuity. The strategy of looking at each target before tapping it was so pervasive that we are encouraged to assume that it had some utility. If subjects had been able to learn the sequence of arm movements, looking would not have been necessary after the first few repetitions. We were,

however, able to show that such learning did not occur. We found that the tapping could not be done with the eyes closed (the subjects groped around for the targets). Tapping was better with the targets illuminated in an otherwise darkened room, but it took an additional 50 to 100 msec/target to complete the sequence than when the room lights were on. Finally, we moved 1 target by one grid space after 7 repetitions with a target configuration, and the subject tapped the modified configuration 3 more times. If the arm's motor program included the exact locations of the targets, the subjects should have taken more time before tapping the relocated target because the initial arm movement would be inaccurate. This did not happen. Moving a target a small distance (~ 5° on average) had no effect on total time to complete the sequence nor on the time before the relocated target was tapped. These results suggest that, even after practice, subjects relied on visual cues (obtained from the fovea) rather than on memory for determining the exact locations of the targets. However, performance did depend on the properties of the sequence and on practice (Fig. 3a), showing that memory played some role, perhaps in specifying the general locations of the targets or providing rough estimates of arm trajectories.

Conclusion

Tapping a sequence of targets might on the face of things seem harder than just looking at them because more activity is required and because the movements of the arm must be coordinated with movements of eye and head. But, we found that all these additional requirements made the task easier, not harder. Tapping not only felt easier than looking-only but sequences were completed faster, performance was more receptive to the benefits of learning and practice, and the requirements for accurate gaze-shifts were relaxed. These results suggest that motor planning is hierarchical, occurring first at the level of the task -- that is, "orient to the target" -- and subsequently at the level of specific motor programs for eyes, head and limb. These specific plans are derived from the higher, task-level plans, which incorporate the spatial and temporal constraints needed to ensure coordination of the individual movements (e.g., Lashley's, 1951, shared spatial map and temporal clock). Our results suggest that looking, in and of itself, does not constitute such a high-level plan. Access to efficient routines for the generation of saccadic sequences may require simultaneous performance of a "real" task (tapping, reading, counting, searching) in which eye movements are used to satisfy the kind of real visual need that eye movements evolved to serve. Once this is accepted, understanding how eye movements work will require a radical revision in traditional laboratory approaches. It becomes essential to study eye movements in conjunction with other cognitive and/or motor acts to determine their nature and function. The MRFM apparatus makes this line of research practical.

Acknowledgements

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