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System for projection of a three-dimensional, moving virtual target for studies of eye-hand coordination

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Abstract

Eye-hand tracking of moving visual objects in three-dimensional (3D) space is common in the behavioral repertoire of primates. However, behavioral and/or neurophysiological studies of this function are lacking mainly because devices do not exist that allow its investigation. We describe a device by which a spot of light can be presented in the immediate extrapersonal space of a subject and can be moved in various trajectories in 3D space. The target is a real image of a circular aperture produced by a system consisting of a light source, aperture, filters, several lenses and fold mirrors, and a large concave mirror to focus the final real image. Rapid, computer-controlled movement of the image is obtained by tilting a gimbal-mounted guide mirror (for x and y motion) and by translating a lens (for motion in the z direction). A second configuration of the system allows movement of a 3D image in the 3D space. Hand motion is monitored by means of a sonic, 3D, position-measurement system.

Keywords: Movement; Motor cortex; Psychophysics

We live in a three-dimensional (3D) world. The perception of the visual space that surrounds us as three-dimensional is the product of complicated neurophysiological processes (Collett and Harkness, 1982; Poggio and Poggio, 1984); however, the three-dimensionality of movements and forces generated by the arm is given, due to the multi-articulated construction of the skeleton and the multiple muscles attached to it. A basic question then is, how well does the 3D visual map correspond to the 3D motor map? How well can we match movement of a freely moving target in 3D visual space with movement of the hand following it? Everyday experience suggests that correspondence is indeed high, and the results of experiments in infants (Von Hofsten, 1983) suggest that a remarkable congruence within the 3D perceptual-motor space may be hard-wired and present before full control of the reaching movement has been attained.

A wealth of information has been accumulated recently concerning the control of discrete and free drawing arm movements in 2D or 3D space and their neural mechanisms (e.g., Abend et al., 1982; Atkeson and Hollerbach, 1985; Georgopoulos et al., 1986, Georgopoulos et al., 1989; Soechting and Terzuolo, 1987; Viviani and Cenzato, 1985). These behavioral and neurophysiological studies provide the proper theoretical, experimental, and neurophysiological basis for the investigation of visually guided eye-hand tracking of targets in 3D space and the effect of the intervention of additional cognitive processes. The main obstacle for the study of these functions has been the lack of a device that will make possible the presentation and control of freely moving visual targets in 3D space. The design of such a device is described in this paper. Traditionally hand movements have been directed to objects in space that are touched. The device that we have developed projects an image of the target and will allow, for the first time, the study of reaching and pointing in the absence of touch.

1. Description of the system

The 3D eye-hand tracking system employs two different optical systems to present images at various locations

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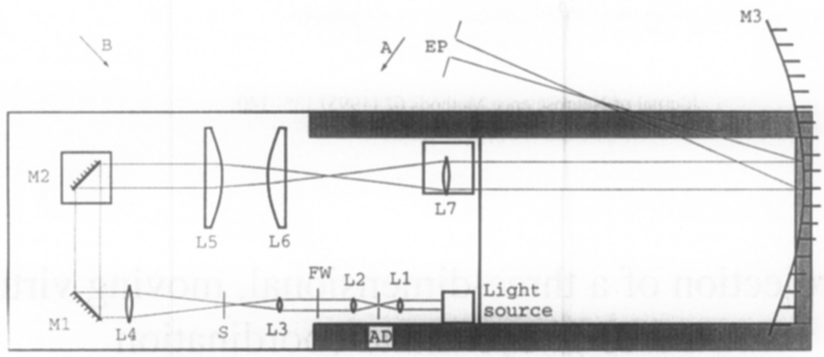

Fig. 1. Schematic of the optical system used to project and move a disk of light in a 3D volume. L = lens, M = mirror, AD = apertured diffuser, FW = filter wheel, S = shutter, EP = eye point.

within the volume of interest and a sonic tracker to measure hand position. In one system, a small, circular disk of light is projected into the volume of interest. This image is moved rapidly by using a mirror on two (piggy-back) rotary stages for pitch and azimuth and a lens on a linear stage for changing position of focus. In the second system, a real object is moved by a 3-axis translation stage so that its projected image moves in the target volume. The subject's task is to track the image with a pointer held in his fingers so as not to occlude the image to either eye. Since the image is in free space, the subject does not physically contact an object and therefore only visual cues are used. Hand motion is measured in 3 dimensions by means of a sonic, 3D, position-measurement system.

1.1. Disk optical projection system

A block diagram of the optical system is shown in Fig. 1 and a photograph of the system (taken from arrow A in Fig. 1) is shown in Fig. 2. It consists of a light source, an aperture, filters, several lenses and fold mirrors, and a large concave mirror to form an image of the aperture in the target volume. The motion of the image is obtained by tilting a gimbal-mounted guide mirror (providing pitch and

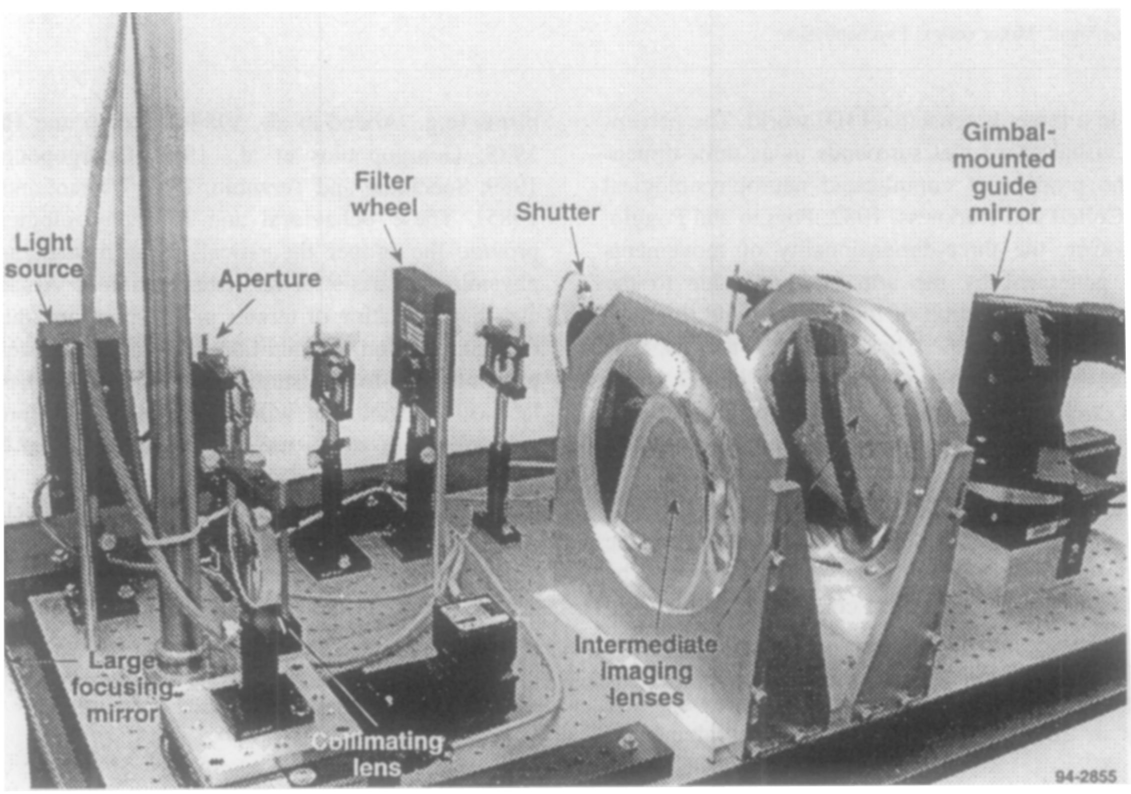

Fig. 2. Photograph of the disk projection system. This photograph was taken in the direction indicated by the A arrows in Fig. 1.

azimuth mirror motion for x and y image motion) and by translating a lens (for image motion in the z direction).

The light source is a quartz halogen lamp with its own separate power supply (Oriel model 63200). A condenser lens (L1) focuses the lamp filament onto an apertured diffuser (AD). The apertured, back-lit diffuser acts as the illuminated object for the optical system — the real image of which is ultimately projected into the subject's view.

An apertured 100-mm focal-length achromat lens (L2, Melles Griot) collimates the light from the diffuser so that a beam passes cleanly through the filter wheel (FW) aperture that follows. A second 100-mm achromat (L3) refocuses the beam to an intermediate aerial image. Following this second achromat and while the beam is small enough in diameter, the light passes through the aperture of the computer controlled shutter (S, JML electronics, model SDS16550).

A 82-mm-diameter, 300-mm focal-length achromat lens (L4, Melles Griot) is used to recollimate the beam to a larger beam diameter. A turn mirror (M1) folds the larger-diameter beam to the motorized gimbal mirror (M2) that provides the two lateral dimensions of the image motion.

After the motorized mirror, the beam passes through a pair of 10″-diameter plano convex lenses (L5, L6, focal length = 385 mm from J.R. Cumberland) in an arrangement resembling a Ramsden eyepiece to create another intermediate aerial image. These lenses provide that the beam is centered on the final lens for the range of angular positions of the motorized guide mirrors. A final 300-mm focal-length achromat (L7), that is mounted on a translation stage to provide the third (longitudinal) dimension of target motion, collimates the beam (nominally) and directs it to the very large, spherical mirror (M3) mounted off the edge of the table.

Finally, the beam is focused by the large spherical mirror (Glass Mountain Optics, Austin, TX; 500-mm focal length) to a real aerial target image of about 5 mm diameter that is located about 50 cm from the mirror. The system is designed for an unobscured range of image motion (for human subjects) within a cube approximately 100 mm on a side and within the subject's reach (i.e., nominally 50 cm from the subjects eyes). To achieve the stereoscopic viewing, a chin rest is used to fix the head position such that both of the subject's eyes are illuminated by the system for all target positions. To minimize the visual clutter from the mirror that can distract the

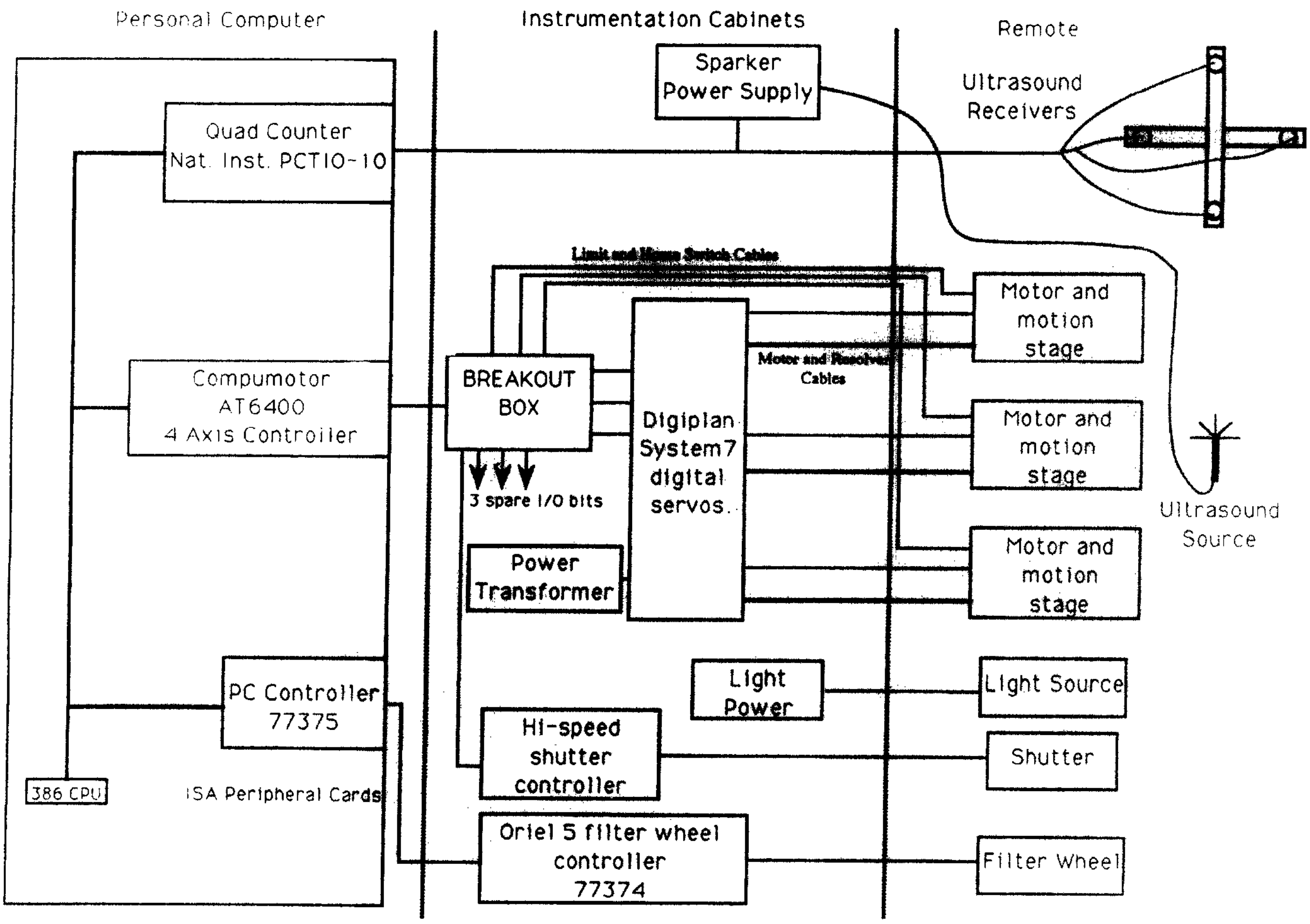

Fig. 3. Block diagram of the electronic components used in projection system.

subject, the room should be darkened. Selective illumination of the hand can be accomplished with a narrow light beam.

The entire apparatus is enclosed within a light tight box (except for the exit port for the beam and the large spherical mirror) and contained in a dark room for which the illumination can be controlled by the experimenter. The image is a bright disk in a dark surround. An optional fixed-position background image can be employed to provide better depth cues. To accomplish this, a background reference surface with a circular opening can be placed in the rear focal plane of lens L7 (Fig. 1) and attached to the lens translation stage so that its imaged is fixed in the viewing volume. The relative illumination of this reference surface and the disk target can be adjusted to meet the experimenter's requirements.

The mechanical pieces in the system are typically off-the-shelf post-mounting components. Notable exceptions are the adapters to the motors, the mirror holder for the guide mirror, and the lens cell for the large-diameter lens pair following the guide mirror — all of which were custom made. Most of the general optical components are held in adjustable post-mounted holders (Melles Griot). The posts fit into collars that are mounted on flat aluminium bases which can be held directly to the optical quality breadboard table.

1.2. Control of spot position

The guide mirror is mounted on two piggy-backed rotary tables (Daedal, Model 20505) which are aligned to form a 2-axis gimbal system. These stages are driven by a 2000 steps/rev. servomotor via a 36:1 reducing gear and are limited by switches to move over an approximately 12° sector. These stages thus have an 18 arc-sec resolution per motor step. The focusing lens is mounted on a linear translation table (Daedal, Model 105021) that has 2″ of travel and the 4 pitch lead screw advances the stage 0.25″ per shaft revolution for a resolution of 3.1 μm per motor step.

A block diagram of the digital control system is shown in Fig. 3. All three moveable stages are driven by digital servo motors. The servo motors are AC brushless motors with incremental encoder feedback. A low EMI (electromagnetic interference) power stage drives each motor in order to minimize interference with neural recordings. The motor commands are computed on a dedicated personal computer (Everex PC). The AT6400 Indexer board is located within the IBM-compatible computer. This board receives position commands from the PC and generates the necessary pulse and direction signals to command the digital servo for each motion stage. The Digiplan System 7 digital servo system performs the servo control for each

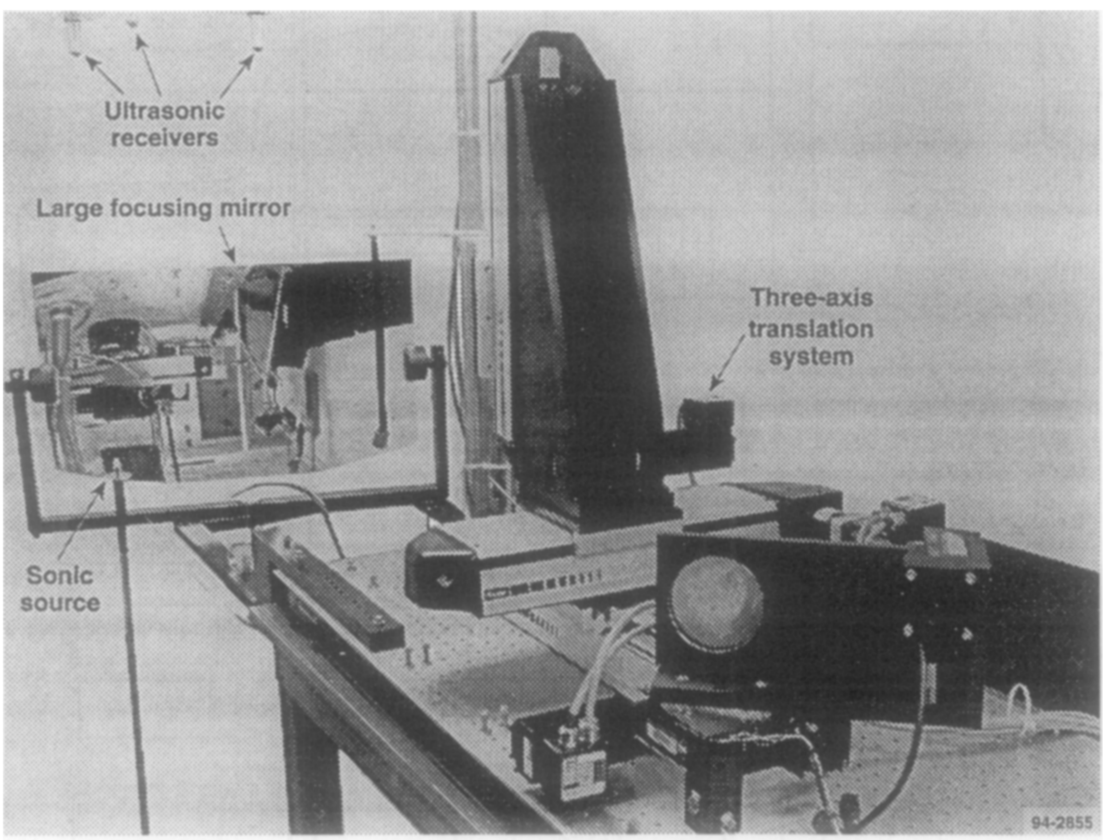

Fig. 4. Photograph of the revised optical system used to project an image of a real object. This photograph was taken in the direction indicated by the B arrows in Fig. 1.

stage of the system. Programs to generate spot position movement profiles are generated on the PC.

Using these components, we are able to achieve 300 mm/s motion of the spot in the x–y plane (tangent to the plane of the face) and in the z plane (perpendicular to the face).

1.3. Second optical system for projection of a 3D image

The spot projection system can be converted into a second optical system that allows projection of the image of a real 3D object. The only optical component in this new system is the large focusing mirror. The final focusing lens and large eyepiece optics are removed from the optical bench to make room for a 3-axis translation table onto which is placed the 3D object to be imaged. The object is illuminated and is moved in a 3D volume. Its image is projected via the focusing mirror into the target volume. This optical system has the advantage that real, 3D objects can be visualized which makes the task of depth localization easier and the volume range can be larger. The disadvantage of this technique is that target motion is much slower than the disk projection system. A photograph of the system with the 3-axis translation system in place is shown in Fig. 4 (from the viewpoint of B in Fig. 1).

Each stage of the 3-axis translation system has 10 in. of range. The belt-driven stages (Daedal, Model 506101) are mounted on top of each other with the bottom stage moving the object along the sight axis, the middle stage moving the object horizontally, and the top stage moving the object vertically. The bottom two stages have a 5:1 reduction gearhead and a resolution of 9 μm per motor step. The top stage has a 3:1 reduction gearhead and a resolution of 15 μm per motor step. The stages use the same motors and servos as those used in the disk projection system. If desired, image rotation could be accomplished by manual or motorized rotation of the object.

1.4. Three-dimensional position measurement system

A sonic position measurement system was available from a previous application (Guier et al., 1987) and was adapted for this system. It is used to track the 3D position of a sparker held by the subject's fingers. A high-voltage ultrasound source (Type GP-6-3D from Science Accessories, Stratford, CT) is discharged at rates as fast as 100 Hz on command from the computer to produce a sonic signal. This source is part of the pointer used by the subject to track the image. The sonic signal is detected by four ultrasonic receivers located on the corners of a square and positioned 3 ft. above the center of the target volume. The sonic distances are determined by measuring the sonic wavefront transit time from the sparker to the receivers. The outputs from the ultrasound pre-amplifiers are thresholded by comparators with adjustable thresholds to allow some flexibility when operating in noisy environments. The sonic signal from each receiver is used to stop a 5 MHz counter associated with that receiver by means of a counter/time board (National Instruments, model PC-T10-10) located within the PC. The X, Y, Z coordinates of the spark gap are calculated by the PC from these transit times; the 5 MHz clock limits the resolution to 0.07 mm.

The actual distance represented by these sonic delays is a function of the speed of sound which varies with environmental factors (mainly temperature). It thus is necessary to calibrate the tracker system to avoid geometric distortions in the computed positions. A calibration rod which attaches to the sonic receiver frame, has two slots at fixed positions into which the sonic source is placed in order to obtain each channel's electronic delay as well as the current speed of sound. Previous engineering tests (Guier et al., 1987) on the tracker system revealed that the absolute error is less than 0.3 mm and the repeatability is also 0.3 mm. The tracker performance is thus within the required experimental accuracy of 1 mm.

1.5. Software

The software to operate the system was programmed in Borland's Turbo C and operates as a stand-alone application under DOS. It pulls together signals going to and from the sonic trackers, motion stages and shutter. This process was accomplished by continuously polling the motion stages to report the mirror position (and thus the beam position) and setting up software interrupts from the sonic tracker to report the tracker position when it is turned on. When an experiment is conducted (or replayed), a 3D display is presented showing the position of the light beam and sonic tracker at all times.

On start-up, a menu is presented that gives the operator several choices. He can run an experiment, replay the results of an experiment, calibrate the system, or send test and reset messages to different parts of the system to make sure it is operating correctly.

Calibration is a simple procedure that is necessary for proper operation of the system. Because heat and humidity affect the sonic tracker greatly, this part of the calibration should be run daily. Calibration of the motion stages and mirror assembly need only be done when the system is moved.

In order to make experiments easier to conduct, a command language was designed that allows the experimenter to specify experiment parameters in a more general way. With this command language, experimenters can create complex experiment scenarios with easy English-like commands. Experimenters can use commands like `SPOT` to turn the light beam on for a specified amount of time, `GO` to send the light beam to a location in space, and `GETDATA` to get tracking data from the sonic tracker for a specified amount of time. Before the program actually executes the experiment, it checks to make sure the experi-

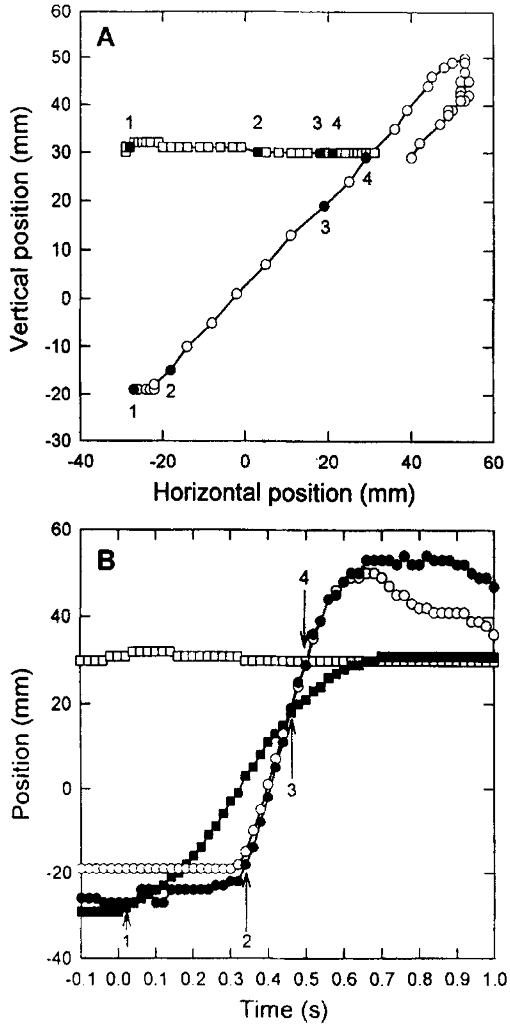

Fig. 5. Results from initial psychophysical experiments with the disk projection system. The subject attempted to intercept a stimulus that moved from left to right at constant velocity. A: trajectories of light spot (squares) and finger position (circles). B: time course of motion in the X (filled symbols) and Y (open symbols) dimensions for the stimulus (squares) and the response (circles).

ment file is valid (e.g., Do tracking times make sense? Can the motors move the beam fast enough to execute the experiment?)

When an experiment is conducted, a data file is created that reflects the results. This file contains, at every sample, the 3D position of the tracker, the 3D position of the light beam, and the clock time in milliseconds. This file can then be replayed visually later for more in-depth analysis of the data.

2. Results from preliminary experiments with system

Preliminary evaluation of this instrument involved psychophysical experiments with naive human volunteers. Four different experimental protocols involving both discrete and continuous movements were presented using the disk projection system to produce the motion and a single sparker attached to the subject's finger to measure the response. An example of data collected from a simply X–Y interception experiment is shown in Fig. 5. At the start of the experiment, the subject positioned his finger on a target in the lower left part of the X–Y space, and the stimulus light spot was 50 mm directly above. After a wait period, the stimulus moved horizontally across the space at a constant velocity. Instructions to the subject were to intercept the stimulus simultaneously in both X and Y. The trajectory of the movement for one subject is shown in Fig. 5A, and the time course of the response is shown in Fig. 5B. At time point 1, the stimulus started moving to the right. This subject waited more than 300 ms before initiating a movement. At time point 2, he began motion in X and Y at approximately equal velocities. At time points 3 and 4, his finger position matched the light spot position in X and Y, respectively. These results demonstrate the utility of this system for producing a moving light stimulus and for tracking the position of the subject's response.

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