

## BIOMEDICAL PROGRAM RESEARCH: THE PRIMATE MOTOR SYSTEM

When The Johns Hopkins University Applied Physics Laboratory–Medical School Collaborative Biomedical Program was begun in the mid-1960s, one of the major facets was to engage the technical expertise of the engineers and physical scientists at the Laboratory to apply state-of-the-art technology to the solution of extant biological problems. A major accomplishment of this program has been the design and fabrication of unique instruments and systems that allow the exploration of specific research protocols designed to delineate the role of individual behavioral and physiological variables in studies of primate motor performance. The specific instruments provided through this collaborative program are summarized, as are the research results produced by their use over the past twenty years. The principal result of this research has been to delineate the role of the primate motor cortex in specifying and/or controlling upper-limb movements controlled by the proximal joints.

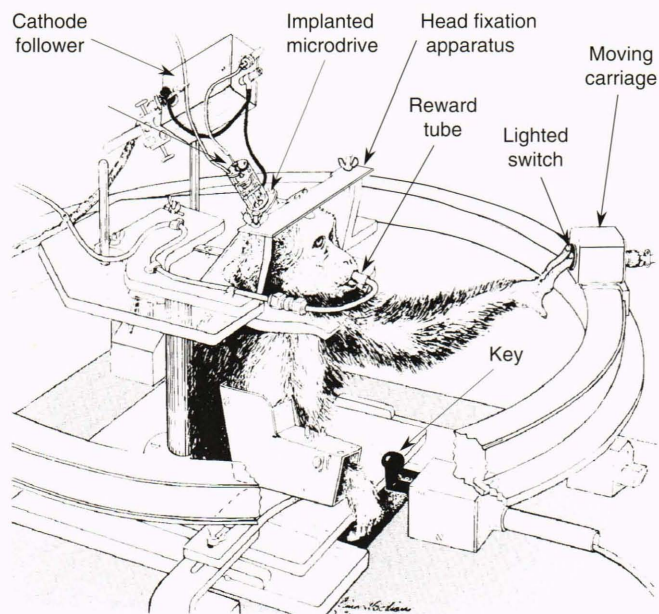
### THE EARLY YEARS: 1972–78

The contribution of The Johns Hopkins University Applied Physics Laboratory–Medical School Collaborative Biomedical Program (APL–MS–CBP) in providing special-purpose instruments and systems for biological studies of the primate motor system dates back to the early 1970s. At that time, John Chubbuck and his colleagues designed and constructed a sophisticated reaching apparatus to be used in experiments by Vernon Mountcastle and his collaborators. The need was for a device that would allow (1) reaching at various points in space, (2) reaching toward a target moving at various controlled speeds, and (3) control of the visual signals to initiate reaching. One of us (JTM) was then Director of the APL Biomedical Programs; the other (APG), who was then a postdoctoral fellow with Mountcastle, remembers the excitement caused by the arrival of the “electric train,” as the device was then called.

A schematic drawing of the device is shown in Figure 1. It consisted of a 69-cm-diameter ball bearing in which the inner race was fixed and the outer race was movable with respect to the monkey. Nylon balls separated the two races, resulting in sufficiently low friction for the movable race to be driven by a friction drive roller with adequate acceleration to bring this race, with its load, up to a prescribed velocity before entering the animal’s field of sight. A box containing a signal light and a push (response) button was attached to the outer, movable race. Four magnetic clutches that coupled the drive motor to the outer race controlled the angular rate and direction of motion of the signal light. The drive motor was a hysteresis motor run at constant speed so that its audio output would not become an input stimulus for the animal. Great care was exercised to avoid any other audible or visual cues to the animal that could have affected the results of the experiment. Using a DEC PDP11/20 minicom-

puter, William Talbot wrote computer programs to control the motion and status of the light (e.g., bright or dim, steady or flickering) and to specify the behavioral conditions for the delivery of the reward.

By using the electric train, monkeys were trained to move their arms and eyes toward the stationary or mov-



**Figure 1.** Drawing of a monkey reaching toward a lighted target in an apparatus used by Mountcastle et al.<sup>1</sup> for studies of the posterior parietal cortex. The animal has just released the key and has reached out to touch the lighted switch mounted on the moving carriage. The head fixation apparatus, implanted microdrive, cathode follower, and reward tube are also shown. (Reprinted, with permission, from Ref. 1.)

ing target. In a typical trial, the monkey depressed a telegraph key at lap level that turned on the light and caused the train to move. In some trials the train stopped, and after a period of time the light flickered (or dimmed), triggering the reaching movement of the monkey to it, followed by the delivery of a reward. In other trials, the train moved continuously at a specified speed, and at some time the light flickered, triggering the movement. Thus, reaching movements to different targets in space were obtained, and the relations of cell activity in an association area of the cerebral cortex (parietal area 7) to reaching were studied. The research performed with this device resulted in a fundamental paper that described the functional properties and quantitative studies of cells in the posterior parietal cortex of the behaving monkey.<sup>1</sup> The remarkable discovery from the studies was that a certain subset of cells in the posterior parietal cortex was activated with reaching; no one had suspected the presence of those cells in that cortical area, which was considered to have a higher-order sensory function.

The next research motor device designed and built under the APL-MS-CBP was dedicated to the study of reactions of the arm in response to torque perturbations.<sup>2</sup> The need was for a device that would deliver computer-controlled torque perturbations to the arm of a human subject holding against a constant load. The device that was designed could produce continuous forces up to 10 kg. The load applied by the motor mimicked both inertial and gravitational loads; the inertial component, derived from the moment of inertia of the torque motor, was equivalent to a mass of 2.8 kg. The presence of inertia prevented excessive accelerations and velocities; peak acceleration was about 6 m/s<sup>2</sup>, and peak velocity was about 0.2 m/s. Displacements used ranged up to  $\pm 10$  cm. These values were such that load perturbations could be produced in a time considerably less than the subject's reaction time.

The device consisted of a lightweight handle, which was grasped by the human subject. A steel cable connected the handle to a pulley mounted on the shaft of the torque motor. Instruction lights were mounted in the line of sight of the subject to provide visual cues, and strain gauges were installed in the handle to measure the tension in the cable. The experiment was conducted by producing an initial tension in the cable up to 5 kg, which represented about 10% of the maximal force that the subjects could resist. Then a perturbation was produced by increasing or decreasing this force by 50% to 70% of the initial force. A computer was used to program the motor current (load force) and instruction lights and to sample the experimental response variables.

A more sophisticated device, consisting of a ball-screw-driven moving member, was designed later for human subjects. That device allowed continuous and perturbing forces to be produced in both directions, and could interface both upper and lower limbs to the system. The perturbations were controlled in intensity and duration and were delivered unexpectedly under three different instructions: resist, assist, or ignore the perturbations. It was discovered that even though the perturbations were the same, the motor reactions differed, depending

on the instructions; sometimes short-latency responses occurred, other times long-latency and variable responses were given, and still other times responses inappropriate to the instructions occurred. Thus, the reactions were not reflex compensations, but rather the result of information processing according to the instructions.

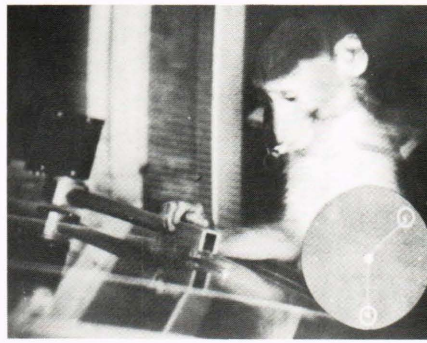
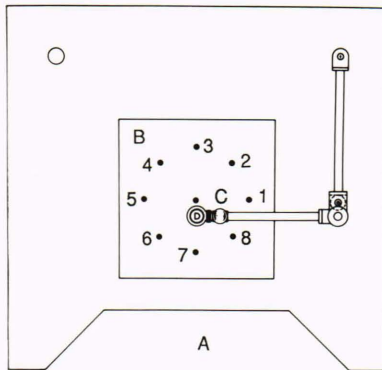
In an attempt to define the motor patterns that activate Betz cells in the red nucleus (a motor nucleus of the brain stem), another motor device designed and built under the APL-MS-CBP allowed monkeys to make various complex movements. A special combination of coordinated movements of the hand and the forearm, called the "twister" (used in changing gears on a motorcycle, for example), was found to be most effective in engaging the red nucleus.<sup>3</sup>

A simpler linear-motion device and a one-dimensional torquable handle (a handle able to produce motion about an axis) were constructed for studies of the basal ganglia.<sup>4</sup> The motor functions of these brain nuclei are shown by the symptoms of Parkinson's disease and involuntary movements resulting from lesions of parts of the ganglia. Visual instructions were given to monkeys by two rows of 128 (total of 256) closely spaced light-emitting diodes (LED's) (total length of 32.5 cm). The upper row indicated the target, and the lower row indicated the current position of a handle; the task was for the animal to move the handle so that the LED of the handle was aligned with the target. The activity of cells in the basal ganglia was found to be proportional to the amplitude of the movement. This relationship was, in a way, a positive image of the negative effect—the inability to make movements of large amplitude—as seen in Parkinson's disease.

## RESEARCH IN TWO-DIMENSIONAL ARM MOVEMENTS: 1978-PRESENT

Our own research into the motor cortex began with the hand-eye tracking device. Before our studies, research on the motor cortex, and the motor system in general, focused on movements about a single joint. We became interested in two-dimensional movements that would be triggered and guided by visual stimuli on the same planar working surface. The idea was that visually guided arm movements could best be studied when the visual stimulus and the movement share the same space, as usually occurs under natural conditions (i.e., under conditions of high stimulus-response compatibility).<sup>5</sup>

A schematic diagram of the two-dimensional device is shown in Figure 2. It consisted of a two-member movable manipulandum (a device that can be manipulated) in which the upper member was pinned to the fixed plane and rotated about that axis. The lower member rotated about a joint fixed to the lower end of the upper member so that all points on the stimulus plane were accessible to the distal end (point C in Fig. 2). (This device may be likened to the human upper arm and forearm, where the shoulder joint is the fixed axis.) Shaft encoders were installed within the "elbow" and "shoulder" joints. When zeroed at the beginning of each experiment, the shaft encoders provided input to a microprocessor that converted shaft angles to *x-y* positions on the plane every 10 ms



**Figure 2.** Left, schematic drawing of the two-dimensional hand-eye tracking apparatus. The monkey was sitting in a primate chair at A and grasped the articulated manipulandum at C to capture lighted targets (numbered dots) on surface B within the transparent plexiglass circle (D). Right, a monkey working in the device.

during each trial to a measured accuracy of 0.125 mm. The fixed plane on which the manipulandum was mounted was tilted toward the subject  $15^\circ$  from horizontal. The manipulandum moved in space just above and parallel to the plane so that its motion was essentially friction-free; the only opposing force was that of gravity.

The stimulus area (tangent screen) of the plane was a 25 cm by 25 cm area immediately in front of the human subject's position at point A. The stimulus could be presented in two ways: first, as a fixed display of nine LEDs, where eight were arranged in a circle around the ninth; and second, as a back-projected laser spot, controlled by movable galvanometers, so that it could be placed at any position within the stimulus-display area. Tangent screens could easily be changed, and the "shoulder" joint could be mounted on the left side of the working surface for use with the left hand. The basic task was as follows: A light appeared on the tangent screen, and the subject was required to grasp the manipulandum at C and move it so that the target circle D was over the target light. After a randomly determined period of time, that light was turned off, and another light appeared elsewhere on the tangent screen. The subject then moved the distal end of the manipulandum to capture that target and hold it for another randomly determined time, after which the trial ended. (In some experiments, capture was not required, only motion through or past the target.) A computer presented stimuli and collected data, which were stored in digital form.

We have used the two-dimensional device in both behavioral studies of humans and neurophysiological studies of monkeys to investigate visuomotor coordination and cognitive processing of visuomotor information. In the following section, we briefly summarize the main findings of these studies.

## BEHAVIORAL STUDIES

### Spatial-Motor Learning

In a reaction time task, monkeys were trained to move the articulated manipulandum over the planar working surface (Fig. 2) toward lighted targets. The major descriptor of this motor learning was a dramatic reduction in the spatial variability of the hand trajectories, which was exponential with practicing time, similar to learning curves in general.<sup>6</sup>

### Effects of Spatial and Temporal Uncertainty

The spatial uncertainty was varied by presenting the same target for many trials, as against presenting it in a random sequence among other targets. The reaction time did not change, but the trajectory variability increased with increasing spatial uncertainty. In contrast, temporal uncertainty (i.e., when the target will appear) did not have any significant effect and did not interact with the effects of spatial uncertainty.<sup>6</sup>

### Modification of Aimed Movements after Change of Their Target

Is a hand movement aimed at a target modifiable or not modifiable before its completion? Previous work in experimental psychology has shown that if two separate responses (e.g., pushing a button with the left or right hand) are required following the presentation of two different stimuli (e.g., a red or blue light), and if the two stimuli are presented in quick succession (e.g., within a reaction time), then the reaction time to the second stimulus is prolonged substantially, depending on the interstimulus interval (the psychological refractory period; see Ref. 6 for a review of the literature). We did not observe such a delay for movements aimed at a target. Thus, when the target of the movement changes during the reaction time, the hand moves first toward the first target for a period of time proportional to the time for which the first target stays on, and then it changes direction and moves to the second target. This finding shows that the stimulus-response processing is very efficient for aimed movements, and that the trajectories of these movements can be modified readily during the course of the reaction time or movement (on-line).<sup>6,7</sup>

### Strategy Underlying the Modification of Aimed Movements

How is the effective, on-line modification of aimed movements being achieved? Interruption of the movement at various points along its trajectory requires accurate calculation of the braking forces to be exerted by the hand; such a calculation is fairly complicated because the forces depend on the time of change, and the dynamic conditions at the time of interruption must be known. Human subjects and monkeys alike, however, use a simple and effective strategy to achieve the behavioral goal of going to the target that is on as soon as possible: they

use large braking forces that are always effective in stopping the hand, reversing the direction of its movement, and bringing it to the second target. These forces are excessive and mechanically inefficient when the first target stays on for only a short period, but they practically eliminate all major computations. Thus, the solution given is behaviorally successful; it requires minimal computations; and it is very effective mechanically, although inefficient from the viewpoint of mechanical energy.<sup>7</sup>

### The Making of Movements at an Angle from a Stimulus Direction

We studied the capacity of human subjects to move at a certain angle from a stimulus direction, for example, to move 70° clockwise from targets presented randomly on a circle. We found that the reaction time was a linear function of the amplitude of the angle, suggesting that the subjects may perform a mental rotation of an imagined movement direction, that is, from the stimulus to the response orientation.<sup>8</sup>

### Visuomotor Memory Scanning

In studies of visuomotor memory scanning, fourteen human subjects performed a modified Sternberg memory-scanning task. First, they made a series of two to six movements in different directions from a central point toward peripheral lights on a planar working surface (list trials). Then, after a warning signal, one of the previous list stimuli, except the last, was presented again (test trial). Subjects were instructed to move in the direction of the stimulus that had been presented next in sequence in the list. The mean reaction time in the test trials increased as a linear function of the number of movements  $S$  in the list: mean reaction time (ms) =  $105 + 205.8S$  ( $2 \leq S \leq 6$ ). This finding suggests that the task involves memory scanning of visuomotor list items.<sup>9</sup>

## NEUROPHYSIOLOGICAL STUDIES

### Directional Selectivity of Single Cells in the Motor Cortex and Area 5

We recorded the activity of single neural cells in the motor cortex and area 5 of the parietal cortex of monkeys while the animals made movements in various directions on a planar working surface. In both cortical areas the results were similar: The activity of single cells is tuned broadly around a preferred direction, so that the frequency of discharge is highest with movements in a preferred direction and decreases progressively with movements made farther and farther away from the preferred direction. The intensity of cell discharge is a linear function of the cosine of the angle formed between the direction of the movement and the cell's preferred direction. The preferred directions range throughout the two-dimensional directional continuum. These findings indicate that a single cell is engaged for many movements. Since the same directional tuning function applies to both the motor cortex and area 5, these two areas seem to "talk" the same language in the directional domain; the main difference is that the motor cortex is activated about 100 ms earlier than area 5.<sup>10</sup>

### Neuronal Population Coding of Movement Direction

The broad tuning of single cells indicates that a cell participates in many movements; conversely, the implementation of a particular movement involves the activation of a whole population of neurons. How is the direction of movement coded uniquely in the discharge of the neuronal ensemble? We postulated that each cell makes a vectorial contribution (votes) along the axis of its preferred direction, and that this contribution is weighted by the amount of change in cell activity during a movement in a particular direction. The outcome of the population operation (the population vector) can then be visualized as the sum of the weighted cell vectors. Indeed, we found that the population vector pointed in or near the direction of the movement.<sup>11</sup> Moreover, when the population vector was calculated every 20 ms during the reaction time, it predicted well the direction of the movement that unfolds later.<sup>12</sup>

### Motor Cortical Prediction of Movement Direction during an Instructed Delay Period

Suppose movement is delayed for a period of time and is emitted later in response to a "go" signal. Would the population vector during the delay period predict the direction of the coming movement? Indeed, we found that it would, suggesting that the motor cortex is involved in the processing of directional information, even in the absence of immediate movement.<sup>13</sup>

### Movement Direction versus Movement Endpoint

The effects of movement direction on cell activity were dissociated from those of the endpoint of the movement in experiments in which monkeys moved to the same endpoint, starting from various points in two-dimensional space. We found that the cell activity still varied with the direction of movement.<sup>14</sup>

### Effects of Change in Target Location on Cell Discharge in the Motor Cortex

When the target of the movement changes location during the reaction or movement time, the activity of cells in the motor cortex also changes promptly. This result is most probably the neurophysiological basis for the behavioral finding that the movement is modified accordingly, as described previously. The duration of cell response to the presentation of a target is a linear function of the time that the first of two targets stays on, and the duration of the movement toward the first target is also a linear function of the duration of the cell response. These findings indicate that the motor cortex is a faithful processor of information in the temporal domain.<sup>15</sup>

### Motor Cortical Mechanisms during Spatial-Motor Transformations

In a natural situation, a visually guided movement of the arm is toward the target. In specific experiments, however, instructions can be given to a human subject such that the movement results from a transformation of visually given information. In this study, the direction of movement in two-dimensional space was required to be

at an angle from a visually defined reference direction that changed from trial to trial. Under this condition, the reaction time of human subjects increased linearly with the angle,<sup>8</sup> suggesting that a mental rotation from the stimulus direction to the movement direction might underlie performance in this task. This hypothesis could be tested because the directional motor intention could be visualized as the neuronal population vector. Indeed, recordings of the motor cortex of animals revealed that the neuronal population vector pointed first in the direction of the stimulus and then rotated gradually and counterclockwise to point in the direction of the movement (Fig. 3). This finding supports the mental rotation hypothesis and underscores the usefulness of the population analysis in general and the population vector in particular as meaningful tools for analysis and interpretation of brain events related to mental transformations. The important idea behind these studies is that brain activity can be interpreted meaningfully and then used as a probe to gain insight into the brain correlates of cognitive functions.<sup>16</sup>

### RESEARCH IN THREE-DIMENSIONAL ARM MOVEMENTS: 1986-89

The two-dimensional device proved extremely useful in studying behavioral and neural aspects of two-dimensional arm movements. These movements were con-

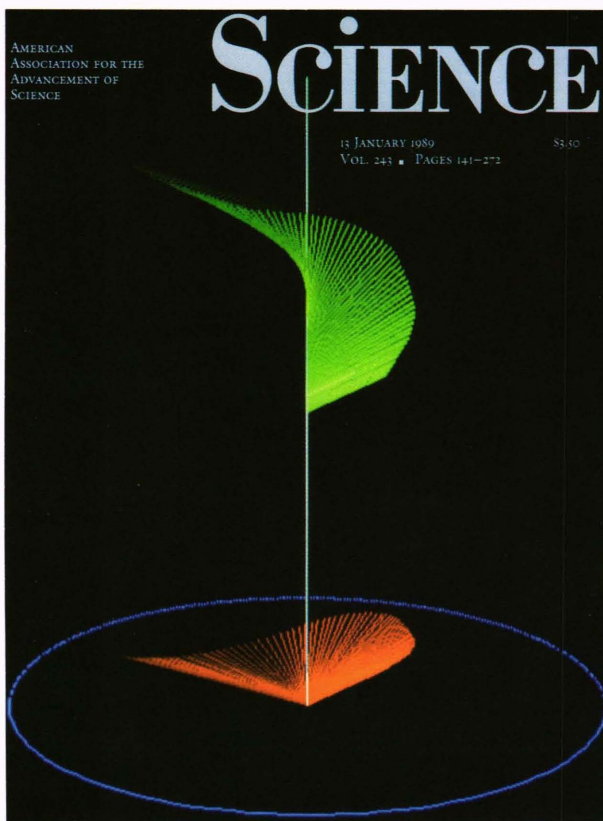
strained to a planar working surface, though, and it could be argued that the results might also be constrained to that condition. For example, would cells also be directionally tuned in three-dimensional space? Would the population coding also hold for free-reaching arm movements? Examining these questions required a device that would allow free-reaching movements to targets in three-dimensional space. Such a device was designed and constructed under the APL-MS-BP in 1986.

The device consisted of a cubical enclosure with a back plate (Fig. 4) that contained a 19 by 25 array of holes (475 total). Stimulus-response elements consisting of red buttons that could be lighted and microswitches to detect the pushing of the buttons were mounted in the ends of 45-cm-long hollow stainless steel rods. The rods could be placed within any of the backplate holes for lateral positioning; the length of the exposed rod determined the depth positioning. The lighted stimulus-response elements were turned off after the depression of buttons with a force of about 200 g. The light-control and switch-monitoring circuitry could accommodate up to thirty-two lights at any one time; the lights could be turned on and off as well as dimmed in any combination, as commanded by the experiment control computer. During a trial, a center light came on first, and the animal was required to depress and hold the colored button (switch) for a period after which that light went off and a peripheral light came on. The animal was required then to move to the peripheral light and press the switch, after which the trial ended. Movements of the animal's arm were recorded using a sonic tracking system. A spark gap was attached to the wrist and was discharged every 10 ms, producing a sonic wave that was received by at least three of eight sonic receivers located at the corners of the cubical work volume. A separate microprocessor selected signals from three of the receivers and calculated the  $x$ ,  $y$ ,  $z$  coordinates of the animal's wrist each time the spark gap was excited. An experiment control computer was interfaced to the experimental apparatus to present stimuli and collect data.

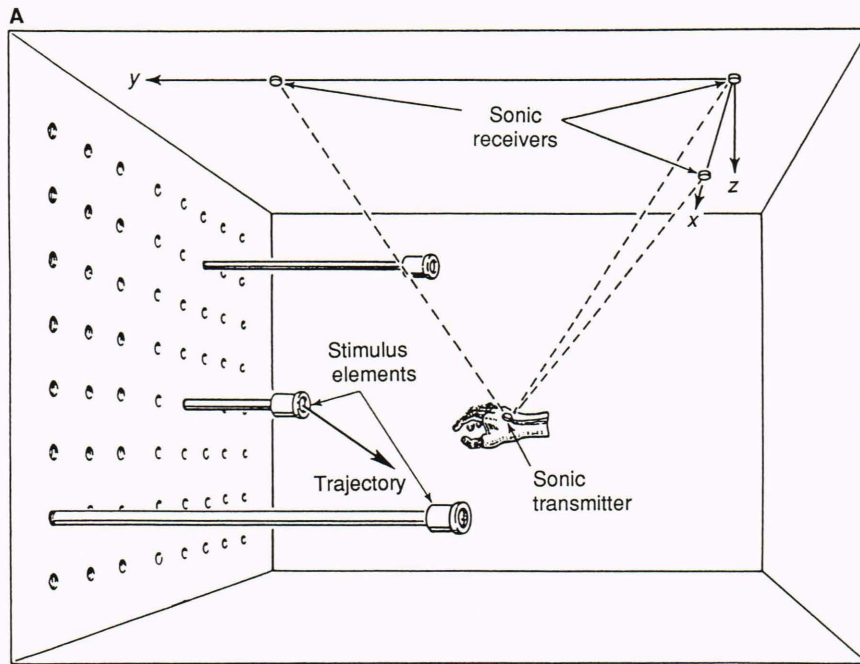
The results of our studies with the three-dimensional device confirmed our previous findings with the two-dimensional device and generalized the directional coding of arm movements to three-dimensional space. Thus, single cells are broadly tuned with respect to the direction of movement in three-dimensional space, and the directional tuning can be described by a cosine function. Moreover, the population coding of movement direction was found to hold for free-reaching movements in three-dimensional space<sup>17-19</sup> (see Fig. 5). Finally, the population vector also predicts the direction of movement when the movement starts from different points in three-dimensional space; it therefore represents a generalized ensemble operation for coding the direction of movement in space.

### RESEARCH IN MULTIDIMENSIONAL ISOMETRIC FORCES: 1988-PRESENT

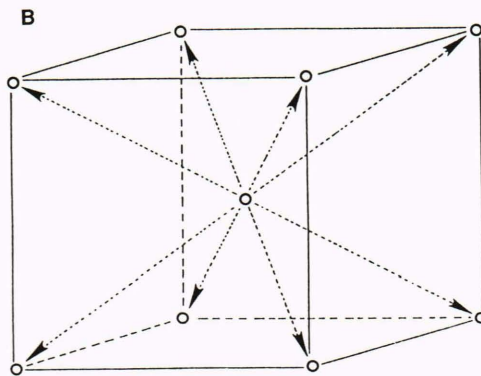
All the studies summarized in the foregoing sections deal with arm movements. Questions arise of how the neural system solves the complicated biomechanical



**Figure 3.** Rotation of the neuronal population vector. (Reprinted, with permission, from *Science* 243 [cover photo]. © 1989 by the American Association for the Advancement of Science.)



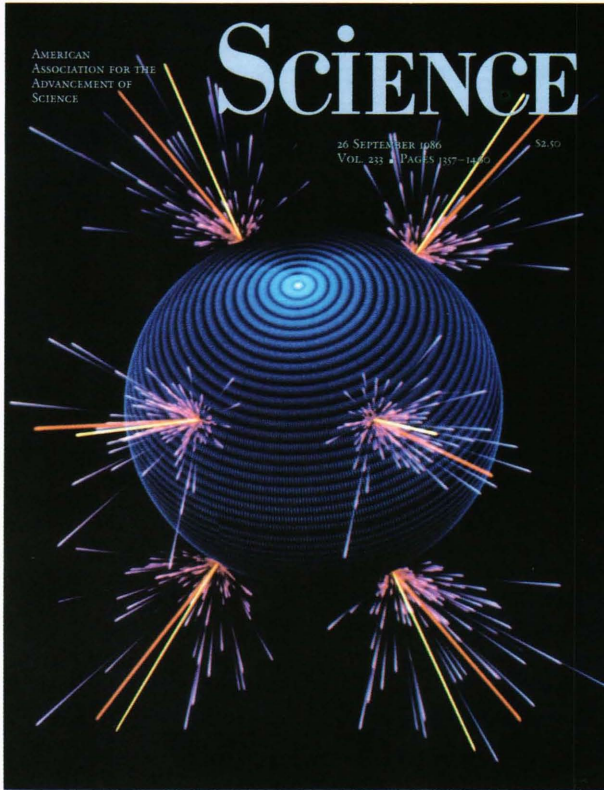
**Figure 4. A.** Schematic diagram of the three-dimensional reaching apparatus. **B.** Layout of the target lights and switches.



problem of the dynamics of the moving arm with its changing loads, joint angles, location of center of gravity, and segment interactions. To gain insight into these questions, we wanted to extend our investigations by requiring human subjects to exert isometric forces, a situation in which the variables just mentioned would be fixed. We discussed with our APL collaborators the design of a device that would allow the exertion and measurement of visually guided isometric forces in three dimensions. Two problems had to be addressed: first, how to indicate to the subject a three-dimensional direction in visual space, and second, how to monitor and feed back to the visual display the force exerted by the subject. We solved the display problem by creating random-dot stereograms;<sup>20</sup> our APL colleagues solved the isometric manipulandum problem.

The isometric force device consists of two parallel plates in the shape of equilateral triangles; three force

sensors are mounted between the plates at the corners. A handle is rigidly mounted to the load-spreading plate, which distributes the applied forces to the sensitive members of the load cells. Since the entire force range of the load cells involves displacement of only 40 to 120  $\mu\text{m}$ , no perceptual motion occurs at the top of the handle where the human subject's hand rests. This circumstance requires that the load-spreading plates be exactly parallel and extremely rigid to avoid distortion when loads are applied. The load-cell power supplies and preamplifiers are located in a separate chassis close to the load cells with coarse trim adjustments; all other electronic systems are mounted in the experiment control console. The resolved and digitized force values are presented to the experiment control computer via a standard parallel interface; the computer selects the sampling rate and reads the digitized data. Provision is made to indicate whether any data were missed during the time al-



**Figure 5.** Neuronal population coding of three-dimensional arm movements. (Reprinted, with permission, from *Science* 233 [cover photo]. © 1986 by the American Association for the Advancement of Science.)

located for reading. Three full-scale values of force (500, 1000, and 2000 g) are used; the load cells have a 23-kg overload rating for safety.

We have completed a series of behavioral studies on human subjects with the isometric force device and are now beginning neurophysiological studies with behaving animals. The main results of the human studies are summarized in the following sections.

#### Directional Performance of Force Production

Directional accuracy in the two-dimensional isometric task was slightly lower than that in the movement task; the reaction time was not significantly different. The small difference in accuracy could be attributed to the different stimulus-response compatibility, that is, the physical separation of the manipulandum (hand) and display (eye). Systematic distortion of the display (by tilting the two-dimensional plane) did not result in degradation of performance until the plane was tilted by 80° (almost horizontal).<sup>21</sup>

#### Directional Performance with Change in Stimulus Information

In the standard experiment, the human subject's response cursor was visible throughout the trial. In experiments in which the response cursor at the center was turned off when the target appeared, the directional accuracy decreased and the reaction time increased. This

result may be interpreted as caused by a decrease in the amount of information supplied to the subject by the stimulus, resulting in a longer time to prepare a response and a significantly less precise response.<sup>21</sup>

#### Directional Accuracy in the Presence of a Bias Force

In the experiments involving a bias force, a static force was applied to the manipulandum, requiring the subject to compensate throughout the trial. The directional accuracy and the reaction time did not differ significantly from the experiments without the bias force. This result may have at least two explanations; the neurophysiological experiments will be designed to distinguish between the two hypotheses, which could not be distinguished by the behavioral data.<sup>22</sup>

#### Directional Accuracy during the Force Recruitment Time

Directional accuracy was computed at various levels of force intensity (from 50 to 200 g-force). Performance accuracy increased with force intensity for all experimental conditions studied, suggesting that the direction of the produced force is continually compared with the motor command produced by the neural system and corrected.<sup>22</sup>

#### Directional Accuracy in Three-Dimensional Force Production

Stimuli (targets) were produced in three dimensions by means of the stereographic display, and human subjects were required to produce forces to move their response cursors near or through the target. Naïve (unpracticed) subjects could not perform well in this task, so several subjects performed a long series of trials. All subjects exhibited a typical learning process in which directional errors decreased in an approximately exponential manner with practice. Other results were essentially the same as in the two-dimensional task; that is, directional accuracy improved during force development.<sup>23</sup>

#### Experiments in Continuous Motion

Human subjects were asked to exert forces on the manipulandum handle so as to trace continuous trajectories (circles, ellipses, and lemniscates) in force space in specified planes, for example, in the plane normal to the line of gaze. Results of these experiments were compared with those of Viviani and Terzuolo,<sup>24</sup> who in 1982 found a piecewise linear relationship between the tangential velocity and the radius of curvature in spatial figures believed to result from central neural constraints. Our results verify that such a relationship also exists in force space; that is, when the force trajectory is most curved, the tangential velocity is lowest. Thus, our observations support the notion that central neural constraints give rise to this relation.<sup>25</sup> Further analysis will be done on the spatial characteristics of the force trajectories.

With the isometric manipulandum, we were able to study dynamic force production under conditions of constant (static) load; however, knowledge of the behavior of neural cells under static conditions cannot necessarily

predict their behavior under dynamic conditions. Our APL colleagues designed and fabricated a more sophisticated device to improve our capability to dissociate muscle pattern and direction in a dynamic manner while recording cellular response. In this device, an isometric manipulandum is mounted atop a two-axis system that provides motion and force readout. A torque motor is mounted on each of the two axes of motion and allows the injection of forces of variable duration, direction, and magnitude on the manipulandum handle during the reaction time or the movement time (Fig. 6). In addition to the outputs of the isometric system, shaft angle encoders read out the angular position of each shaft.

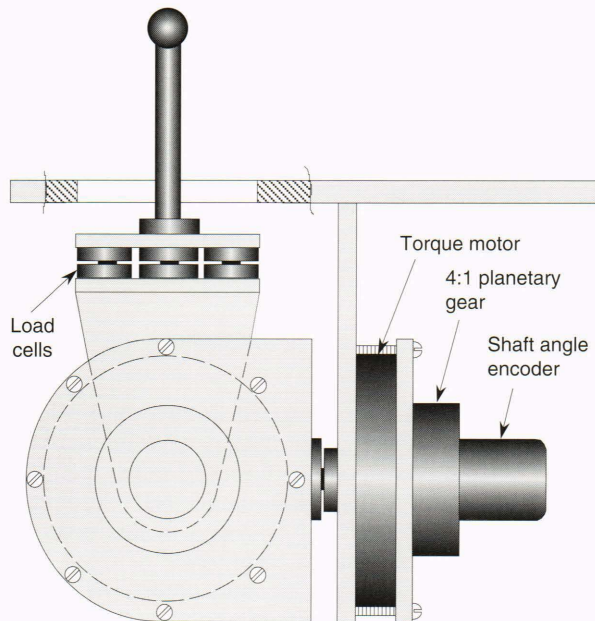


Figure 6. Schematic diagram of the torquable manipulandum.

We have just started using this torquable manipulandum and hope it will help us answer questions concerning the directional control and correction of trajectories, as well as the interplay between force and movement. Time constants of the motors and circuitry with a fast parallel interface allow almost instantaneous interaction with the display or the human subject. The torque capability of the motors is such that forces up to 120 g-force can be produced at the manipulandum handle.

### THE FUTURE: REACHING OUT TO TOUCH AN UNTOUCHABLE TARGET

To extend our studies into the domain of continuous, spatiotemporal control of three-dimensional, visually guided arm movements (a problem that has not been investigated previously), a new device has been designed and will be fabricated by our APL colleagues. It will allow the presentation and free motion of a visual target in three-dimensional space by using an optical system to present a real point image within the volume of interest (the subject's extrapersonal space). The human subject's task will be to capture and/or follow the image with his finger; since nothing can be physically contacted, only visual cues will be available to the subject. Hand motion will be measured in three dimensions by a sonic position measuring system.

The layout of the optical system is shown in Figure 7. It consists of a light source, filters, several lenses and mirrors, and a large concave mirror to focus the final real point image, whose intensity and color may be varied. The position of the image in the human subject's extrapersonal space is varied laterally by tilting the gimbal-mounted guide mirror and longitudinally by translating the collimating lens. The optical components will be selected to produce an image size of 5 mm and a usable volume for motion of 30 cm by 30 cm by 30 cm.

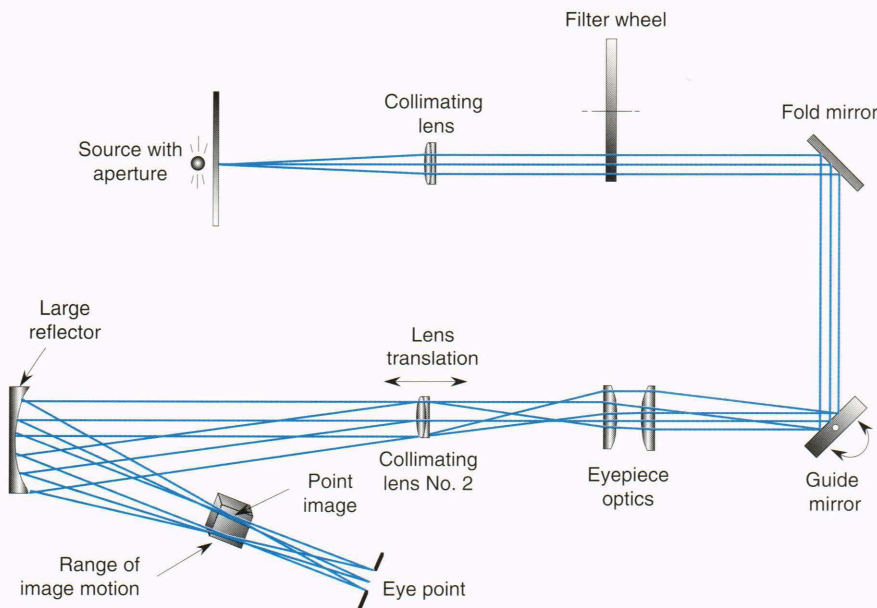


Figure 7. Optical layout of the device providing a virtual target for reaching.



A computer code for optical design and ray tracing was employed to evaluate the proposed optical system. Prescriptions for the lens elements and mirrors and their relative locations are entered into the computer model, and the program calculates exact ray trajectories through the system. Tracing marginal rays through the optical system guarantees that the system is unvignetted for image points within the target volume. The ray tracing also shows that the spot size criterion is met.

The two-axis gimbal system rotating the guide mirror and the linear translation table on which the collimating lens is mounted will be driven by digital servo motors. Velocity and acceleration parameters of available digital motors will allow achievement of velocities of up to 300 mm/s in all three planes, and also will allow bringing the spot from zero to maximum velocity in less than 30 ms. A dedicated personal computer will be used to compute the spot motion commands for input to an indexing controller, and the controller will generate the pulse commands to the digital servo power stages that control the three digital servo motors. An experiment control computer will download spot movement profiles to the dedicated personal computer via an RS-232 communication channel.

The position measurement system will be a modification of a three-dimensional (sonic) position measurement system developed previously. A spark gap is attached to the human subject's finger and is discharged on command from the experiment control computer, producing a sonic signal. The signal is detected by four ultrasonic receivers placed above the work space, and the  $x$ ,  $y$ ,  $z$  coordinates of the spark gap are calculated from the sonic delays by a microprocessor-based system. Engineering tests revealed that, under ideal conditions, the absolute error was less than 0.3 mm and the repeatability was on the order of 0.3 mm. Under laboratory conditions, it is anticipated that the location of the spot will be on the order of 1 to 2 mm.

Data from the position measurement system and current position information regarding the mirror drive stages will be transmitted to the experiment control computer. The computer can calculate the instantaneous positions of the spot and the subject's finger, and these data will be stored on-line in digital form. Care will be taken to ensure that the digital drive circuitry and the position measurement system do not interfere with the recording of single-unit activity. This system will allow future investigations in several areas, including continuous movement tracking in three-dimensional space, testing additional cognitive loads in discrete and continuous movements, intercepting a moving visual stimulus, and tracking and intercepting when stimulus information is limited or intermittent.

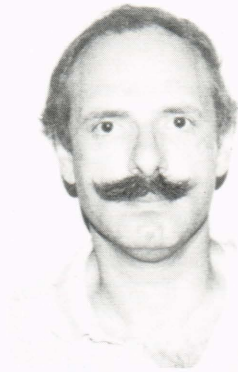
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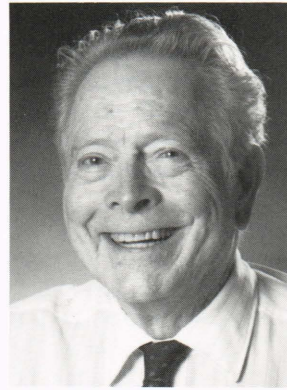
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