Human Performance in Visually Directed Reaching Results in Systematic, Idiosyncratic Error

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Abstract*

We study the performance of human subjects in a task which requires multi-jointed reaches to be made to targets spaced over a wide area. In accordance with established research, we find that subjects' reaches are not accurate when they cannot see either their hands or the targets. The errors subjects make are different at different targets, suggesting that they are due to an error in the planning of movements. However, contrary to existing models of this error, we find that it is highly idiosyncratic. This leads to the rejection of the most straightforward model of how reaching is learned, and poses problems which a future model must address.

Introduction

When humans reach to visually located targets without visual feedback, they make errors. The nature of these errors is a reflection of the way the motor system is controlled, and is the focus of this paper. We investigate visually directed reaches made under a variety of conditions, and find that subjects produce idiosyncratic errors which vary with the target's location. If the responses of a group of subjects is averaged together, the individual idiosyncrasies cancel each other, and the average error at any target is very small, approaching zero. The behavior of the group is thus not representative of any individual, suggesting that a model of motor control should attempt to explain the variations observed to exist between individuals.

Reaching, in the experiments described here, is the process of controlling the arm in order to position the finger in the environment. What variables are controlled, and how, is the topic of a variety of models. These models all assume that the final position of the finger is known, and that the motor system works to achieve this goal state. If the variables under control are joint angles or muscle lengths, then clearly a transformation of the visual target into an internal, postural one must precede movement planning. Even if the position of the hand is directly controlled, the joints and muscles must still be told what to do, and this requires that the desired hand position or trajectory be turned into desired postures.

Reaches made without visual feedback require a mapping from visual information about target location to an arm configuration. This mapping is ill posed since there are multiple arm configurations which can produce any single finger position. One way to learn an approximation of the mapping, called flailing or direct inverse modelling (Jordan and Rumelhart 1990), is to pick large numbers of arm configurations at random and then combine all random movements terminating in the same spatial region by a mechanism that approximates the average or *expected* values for each independent degree of freedom (Kuperstein 1988). These expected values can then be used to associate a unique arm posture with each visual location. These postures point to locations which approximate the associated visual locations but do not necessarily correspond to them exactly, resulting in an error field of four dimensions for targets in a plane that can be compared to experimental data. Prediction of minimum possible error from the flailing model does not depend on the details of the implementation of the model, as the properties sufficient to produce error predictions are embodied in the geometry of the arm and body and the description of the task.

The flailing model accounts to some degree for the gross quantitative properties of the error observed here, but it does not account for the idiosyncratic variations by subjects. The overall average magnitude of error predicted by the expected values is close to that seen in the experiments, differing by at most a factor of two from the observed error magnitude. Both observed and predicted error differ with target position, and not in any simple way. An individual subject will make different errors at different targets, but the direction of those errors is not consistently related to any outside variable. While this is true also for the predicted errors, the flailing model predicts that there is one unique actual response for each target, when in fact the responses are very different for each subject.

The specific expected values of a flailing model depend on the structure of the model arm and its task. Where Kuperstein's model was formulated using only a two-jointed artificial arm, we have attempted to construct a more realistic model. Using data from a kinesiology text (Luttgens and Wells, 1982) to establish the ranges of

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motion for the joints of the arm, we have modelled a reach as composed of thirteen independent variables. Expected values for errors in finger location after reaching to targets throughout the range of the arm are generated by simulated flailing. Since the arm almost never reaches to exactly the same place twice, the reaching space is divided into cells and all reaches terminating within a cell are grouped together for purposes of averaging. For each joint the angles of the postures which reach to a cell are averaged, computing a single angle. The posture resulting from all the average joint angles represents the expected values that would result from associational learning. The location of the finger tip resulting from the average posture for a cell is compared to the location of the center of the cell, resulting in a difference or error arising from the model. The mean magnitude of the errors made by the model is 1.75cm over the entire reachable surface, equivalent to approximately 2% of average arm length. The overall error magnitude is within the range of Kuperstein's original formulation of the flailing model and the available data from adult visually directed reaches.

Experiments

The flailing model predicts both large and small scale features of the error distribution, predicting that movements made to different targets should differ in their error, regardless of variable starting position and speed, and independent of the individual reacher. Our first two experiments examine the structure of the error distribution across a surface, the effect of starting position and individual difference. Our third experiment focuses on individual differences, studying three subjects' errors with respect to starting position and movement speed.

Method

Subjects: Fourteen undergraduates from UCSD participated in the first experiment for partial fulfillment of course requirements, or for payment. Nine such undergraduates performed in the second experiment, although one was discarded when equipment failure was detected after the experiment. The third experiment employed three volunteer research associates who were naive to the hypothesis being tested.

Apparatus: Subjects were seated at a 160cm x 160cm x 77.5cm high table so that their sternums were abutted against a center mark. At the four corners of the table top were set microphones comprising a collection array for a three-dimensional audio digitizer (Graph Pen GP-6-3D-P). The subjects wore two small, Plexiglass-encased sound-emitters on their right index finger.

On the table, fifteen two cm target circles were selected to cover the reaching surface. These targets were selected to be within range of all the subjects. Mounted to the right of the subjects' chair was a large four sided box, open to the subject and the table, set at table level. In front of the subjects at an elevation of 15cm was an 8cm wide, 100cm long shelf. The experimenter sat behind the subject, in order to operate the digitizer.

Procedure: The subject's task was to move their right forefinger as fast as possible to land on a given target. The arm movement involved in this action was made ballistically, with no visual guidance or feedback. Subjects began each trial with their arm either inside the box to their right or beneath the shelf in front of them.

To initiate each trial, the experimenter identified one of the fifteen targets by reading aloud the number which labelled it. The subject was then given an indefinite period in which to orient to the target and prepare the movement. When ready, the subject shut their eyes and reached in one fast motion to place their finger on the target. When the movement ceased, the digitizer was activated and the position of the finger recorded.

After the experimenter told the subject that the recording had taken place, the subject was free to return their hand to the starting position, and only then to re-open their eyes. Since the box and shelf both obscured the hand from view, this assured that the subject could not see their hand for the entire experimental session.

Subjects in experiment one moved to each target four times from each starting position with a different random order within counterbalanced starting position blocks for each subject. This yielded 120 trials for each of the fourteen subjects. After the experimental session, the location of the targets were digitized by having the subjects tour the targets with their eyes open.

Experiment two was identical to experiment one, except that each of the eight subjects toured the targets both before and after the session.

In experiment three, an additional speed condition was added. Subjects were instructed to either move as quickly as possible (as above) or were told to take as much time as was needed to move as accurately as possible. Each subject moved to each target four times from each starting position in each speed condition with a different random order for each subject. This yielded 240 trials for each of the three subjects.

Results

These experiments showed that individuals produce systematic error when making visually directed reaches, and that the errors made at particular targets varied from individual to individual. Similarly, the errors made by any one individual varied from target to target. The observed idiosyncrasy in the error makes it difficult to conclude much about the group performance, but is in itself an important finding.

In order to determine if subjects made systematic error, a test of each mean response was made. For the first two experiments, a mean response was computed for each subject at each target for both initial positions. The third experiment included a speed condition, doubling the number of mean responses for each subject. Each subject made multiple responses in each condition, and so a mean response was calculated.

$$\text{mean response} = \left(\frac{\Sigma x}{n}, \frac{\Sigma y}{n} \right) = (\ \bar{x},\ \bar{y}) \qquad (1)$$

Considering each response as a vector directed from the target to the finger's location, the mean response is the vector average of all responses in a single condition. To establish a confidence level in the distance of the mean response from the target, the standard error of the mean was computed in each condition. To compute the standard error, we first computed the distance of the mean response from the target.

$$D = \sqrt{\bar{x}^2 + \bar{y}^2} \qquad (2)$$

The standard error is a measure of the dispersment of the individual data points around the mean. To measure this, we computed the distance of each individual response from the mean for that condition.

$$d = \sqrt{(x - \bar{x})^2 + (y - \bar{y})^2} \qquad (3)$$

The actual standard error was then computed, using the difference between the individual distances and the mean distance of error.

$$\sigma_d = \sqrt{\frac{\Sigma(d-D)^2}{n-1}} \qquad (4)$$

$$\text{SEM} = \frac{\sigma_d}{\sqrt{n}} \qquad (5)$$

Dividing the distance of the mean response by the standard error gives a Z score, which can be used to measure the certainty with which the distance is non-zero. If the mean response is far from the target, and the standard error is small, then there will be a high level of confidence in the mean response not being equal to zero, indicating that moving from one initial position to one target, that subject makes a systematic error.

The perceptual-motor system is noisy, and this noise, even if unbiased, can be expected to produce error in reaching. In order to compare the observed results to the result of noise, we ran a Monte Carlo experiment. Unbiased error follows from two assumptions, first that the error has mean zero and second that it is distributed with equal variance in all directions around the target. Data was generated from these two assumptions. For each of 850 separate simulated targets, eight simulated reaches were made. Error in the X and Y dimensions was generated separately, with a single value being selected from each of two normal distributions of equal variance and each with mean zero. For each target a simulated mean response and standard error was computed in the same manner as for the observed data, leading to a judgement of confidence in the mean response error being non-zero. Overall, more than one third of all mean experimental responses (276 out of 835) were more than 95% likely to not be zero for the observed data. This compares with only 0.35% more than 95% likely for the Monte Carlo experiment.

While there were a large number of non-zero errors, the average across subjects of all responses at each target was not discernible from zero for all three experiments. This suggests that few of the non-zero responses contained the same systematic error, as otherwise the mean across subjects would show a bias. To investigate the possibility that the biases were idiosyncratic, a pairwise comparison of all non-zero mean responses at each target was made. The likelihood that any two means were drawn from the same distribution was computed to determine how different each mean response was from the others. If the likelihood that two means come from the same distribution is less than five percent, then the difference between the means was taken to be significant.

Overall, there were 907 pairwise comparisons possible, of which 768, or 85%, proved significant. This percentage was nearly constant across the three experiments, as 84% (495/587) of the comparisons in experiment one, 86% (197/230) in experiment two and 84% (76/90) in experiment three were significant. The source of these differences was predominantly the difference between one subject and another, rather than one subject reaching from two different initial positions.

Discussion

The results of these experiments demonstrate that there is a mechanism governing visually directed reaching which produces different systematic error for each individual. Reaching is a complex operation, and many factors could contribute to the systematic error. Factors such as the veridicality of visual and proprioceptive perception, the appropriate use of feedback signals and an accurate representation of the target for arm control are all candidates, but only the last is a possible source of error in these experiments. The flailing model predicts systematic error due to an inaccurate representation of the target, but it predicts the same error for each individual. Without extensive modification the flailing model cannot account for the observed reaching behavior.

Given that many factors participate in the control of movements, what is the source of the error observed in the experiments? We postulate a control structure with four basic components, any of which could introduce error into a reach. The first step in making a movement is acquiring the spatial target, which involves visual perception and memory. The perception of the visual target must then be transformed into a desired posture. A feedforward attempt to reach the desired posture is then begun, and, conditions permitting, feedback can be used to correct the reach. Visual information about hand position can be used directly, or indirect feedback can be produced from the proprioceptively perceived arm posture by a feedback controller using a forward model of the arm's kinematics.

Perceptual errors will result in a reach directed to the wrong spatial location, as will memory errors in the time between acquisition of the target and completion of the movement. If the inverse kinematics employed by the feedforward controller are incomplete, the commanded posture will not lead to the desired location. Once the motor system tries to achieve the desired posture, the interaction of the arm with the environment can introduce more errors in the execution of the command. Inaccurate direct feedback about posture can result in the arm taking on a posture different from the desired one. If the forward model used for indirect feedback is incomplete, then this is one last source of error which could cause reachers to believe their hands are not where they really are.

These four types of error: perception of the goal, noise in the plant, inaccurate feedback control and incorrect transformation of the perceived goal into an internal one, each are candidates for explaining the observed errors. Before considering each of these in turn, we can distinguish between two general classes of error which can be introduced into the movement system. Systematic error in reaching must be the result of a bias by one or more of the elements of movement control. Random error, or noise, introduced into the system will effect motor performance on any given reach, but will disappear when multiple reaches are averaged together. This is true whether the noise comes from vision, proprioception, motor execution or a control command.

The perception of the goal can introduce error through either perception or memory, as mentioned above. Any systematic error in visual perception will be transparent to the motor control system, since motor behavior operates in the visual world. This means that if an individual always perceives targets to be to the left of where they are, say, then they will also perceive their hand to be to the left. The result of seeing the hand and the target in the same space is to negate any biases in the visual system, as is made clear through experiments in which the visual world is displaced, but where motor control quickly adapts (Harris, 1965). Foley and Held (1972) showed that large systematic errors result from reduced visual information about target location. Since the experiments presented here do not change the relation between the visual and motor systems, perceptual mistakes cannot account for the observed biases in responses. Systematic error can also be observed if movement is delayed for an extended time (Schoecting and Flanders 1989, vonHofsten and Rosblad 1988). This is most likely due to the forgetting of target location, a process which can introduce biases into the goal command. However, in the experimental paradigm presented here, subjects are not required to remember the target location for longer than it takes them to voluntarily initiate movement. They are allowed to keep their eyes open until they begin moving, and so have little chance to forget the target location before making the movement.

Errors in motor function are similar to errors in perception, in that systematic failures would be overcome by learning. If one's elbow always extended farther than desired, the extension command would be reduced to produce the desired movement. While we have not presented the mechanism for these corrections explicitly, they lie implicit in our discussion of learning through association. In addition, the ability to achieve desired postures is well documented in the context of posture duplication. If an individual moves a finger to a certain angle, and the finger is then displaced, the finger can be returned to the initial angle with a high degree of accuracy (Kelso and Holt 1980, Bizzi, et al 1982). This indicates that motor system can achieve its desired postures well.

Both visual perception and motor execution are essentially accurate, so we must look to the control mechanisms which govern reaching for the source of its errors. There are two potential proprioceptive feedback systems which can operate during movement. The first is direct feedback, which compares afferent information about the current posture with the desired posture to help achieve the desired posture. Success in duplicating postures points to the veridicality of this system. The second use of postural information is for indirect feedback effecting the desired hand position itself. Using a model of the forward kinematics of the arm, an indirect feedback controller maps posture into hand position. Actual hand positions can be compared to desired ones, and new desired position commands sent. This replicates the process by which visual feedback produces accurate reaches. If the forward map is inexact, then the computed hand position will not be the actual one and 'corrective' signals will result in additional error. There is evidence, reviewed by Olson and Hanson (1990), to suggest that the forward mapping is in fact inexact. Researchers have found varying degrees of constant error and directional biases in experiments involving perception of hand position from postural information. A failure to locate the position of one's hand after a passive movement indicates that proprioception is only poorly transformed by the forward map used by a feedback controller. However, the high speed required for the movements in our experiments and the inability to correct movements suggest that a closed loop system does not underlie fast visually directed movements. Thus, the possible errors due to feedback cannot appear in at least our first two experiments.

In order to produce fast movements, a feedforward controller is a necessity. The transformation from desired hand position to desired posture is potentially a source of error due to the properties of the inverse kinematics of a redundant manipulator like the arm. The excess degrees of freedom of the arm means that there is no unique mapping from hand position to arm postures. The flailing model describes how a mapping between desired spatial locations (targets) and postures can be formed, and provides expected values for the errors made during visually directed reaching. In the experiments we collected data which can be directly compared to the model's predictions.

As a model of average performance, the expected value model makes a little progress toward explaining the observed data. It predicts successfully the magnitude of error and the dependence of error on differences in target location. The model does not predict the individual biases, which were a major result of the experiments. Our experimental finding of an average overall error magnitude of 4% of arm length for visually directed reaching is in line with other findings (Olson and Hanson 1990). The flailing model predicts an overall expected value error of approximately 2% of arm length, which Kuperstein's implementation approached with a 4% error. When the flailing model is tested at only the experimental targets the predicted error increases to nearly 8% of arm length, suggesting that the inverse transformation is about as accurate as individual subjects.

The failing of the flailing model lies in its determinacy. Since predictions come from geometric properties of the arm and from principles of association taken to be constant between individuals, all individual difference must be explained only be differing bodily geometries. However, the observed individual performance differences are much greater than the model can accommodate, especially inasmuch as individual differences extend to sensitivity to initial position and movement speed. In order to account for individual difference, there must be parameters of the model which are free to vary during learning, and which do not deterministically relate to the history of the learning period. This requirement stems from our assumption that many learning trials are required for the acquisition of reaching skill, and that these trials are essentially identical across individuals.

What then do these comparisons say about the flailing model as a theory of how people make visually directed reaches? The gross characteristics of the data, which are matched by the model, suggest that a feedforward inverse transformation is applied by people when they reach. The model makes predictions detailed enough to be rejected, but by the same token it demonstrates that theoretical model at this level should and can be held closely to complex aspects of the data for comparison. Attempts have been made to identify a variable responsible for the idiosyncratic differences (eg., Foley and Held 1972, Jeannerod 1988), but none have been satisfactory. The prevalence of idiosyncratic error in our experiments leads us to conclude that it is real, and that it must be explained.

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