Perceptual distortion contributes to the curvature of human reaching movements.

Daniel M. Wolpert
Zoubin Ghahramani
Michael I. Jordan

Department of Brain and Cognitive Sciences
Massachusetts Institute of Technology

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Abstract

Unconstrained point-to-point human arm movements are generally gently curved, a fact which has been used to assess the validity of models of trajectory formation. In this study we examined the relationship between curvature perception and movement curvature for planar sagittal and transverse arm movements. We found a significant correlation ($p < 0.0001$, $n = 16$) between the curvature perceived as straight and the curvature of actual arm movements. We suggest that subjects try to make straight-line movements, but that actual movements are curved because visual perceptual distortion makes the movements appear to be straighter than they really are. We conclude that perceptual distortion of curvature contributes to the curvature seen in human point-to-point arm movements and that this must be taken into account in the assessment of models of trajectory formation.

Introduction

There are several invariant features of point-to-point human arm movements: trajectories[1] tend to be gently curved, smooth and have bell-shaped velocity profiles (Bernstein 1967; Morasso 1981; Abend et al. 1982; Flash and Hogan 1985; Atkeson and Hollerbach 1985; Uno et al. 1989). The nature of this trajectory curvature in relation to the parameters of the movement has often been used to evaluate the predictive power of models of trajectory planning (e.g. Uno et al. 1989) and control (e.g. Flash 1987). In this paper we first discuss the three main explanations for the curvature which have been proposed before suggesting a fourth possibility which we have evaluated empirically.

The first explanation is that the reference trajectories[2] are indeed curved. Uno, Kawato and Suzuki (1989) suggested this possibility based on their minimum torque change model. This model is based on an optimal control formulation in which a 'cost function' is chosen in order to evaluate the performance of the system under control (Bryson and Ho 1975). The cost function is usually defined as the integral of an instantaneous cost over a certain time interval, and the aim of the planner is to minimize the value of this cost function. Uno et al. (1989) proposed a cost function which is the integral of squared torque change summed over all the joints. Minimum torque change predicts gently curved arm trajectories, with the form of the curvature depending on the position of the arm within the workspace. Uno et al. (1989) showed that there is a reasonably good correspondence between the predictions of the minimum torque change model and actual hand trajectories. Recent experiments by Wolpert et al. (1993), however, show that under conditions

[1] The *trajectory* refers to the path and speed of the movement where the *path* is the sequence of positions through which the hand passes.

[2] The *reference trajectory* is the centrally specified desired trajectory. The actual achieved trajectory need not be the reference trajectory due to factors such as imperfect control and joint limitations.

of altered visual feedback, in which the perceived curvature of arm movements is increased, subjects adapt their trajectory planner so as to produce visually straighter movements. This suggests that the cost function is specified in extrinsic visual space—a result incompatible with the minimum torque change hypothesis.

The second possibility is that the reference trajectory is straight but that imperfections in the control system lead to curvature which is dependent on the dynamics of the arm. For example, the minimum jerk hypothesis, originally proposed by Hogan (1984) for one joint and by Flash and Hogan (1985) for multi-joint movements, states that the cost to be minimized is the first derivative of Cartesian hand acceleration or 'jerk.' The reference trajectories produced by this model are straight lines in space. Models such as minimum jerk, in which only the kinematic aspects of the movement are determined, require a controller that produces motor torques to follow the reference trajectory. Imperfections in such a controller could lead to curved trajectories.

The third possibility is that the central nervous system, rather than directly computing torque, specifies the trajectory in terms of an intermediate representation, such as a series of equilibrium positions (Flash 1987) or desired muscle lengths (Bullock and Grossberg 1988). The actual trajectory produced then depends on the dynamics of the arm. This possibility differs from imperfect control in that it is this intermediate representation, rather than the outcome, which is matched to the reference trajectory.

Finally, we suggest a fourth possibility—the curvature seen is due to visual perceptual distortion. Under this hypothesis subjects try to make visually-straight movements but misperception of the curvature of the path followed by the hand leads to perceived straight-line motion when the hand is, in fact, making a curved movement. The current study was designed to evaluate this fourth alternative.

Methods

Eight naive normal right-handed MIT students participated in this study. Each subject participated in both a production experiment and a perception experiment. To assess the curvature of their arm movements each subject performed a session of sagittal and of transverse movements. To assess their perception of curvature each subject also participated in a two-alternative forced choice experiment that required judging the direction of curvature (leftward vs. rightward, or inward vs. outward) of a moving cursor spot.[3] To make the production and perception experiments as similar as possible we chose to display the subjects' finger position as a virtual cursor spot projected at the exact position of the finger.

Arm Movement Recording

Subjects sat at a large horizontal digitizing tablet with their head supported by a chin and forehead rest (Figure a). The subject's finger was mounted on the cross hairs of a digitizing mouse which could be moved along the surface of the digitizing tablet (Super L II series, GTCO, MD); the subject had no direct view of his arm which was covered by a screen. The digitizing tablet's coordinates were sampled at 185 Hz by a PC as (x, y) coordinate pairs; the accuracy of the board was 0.25 mm.

The targets and the feedback of finger position were presented as virtual images in the plane of the digitizing tablet (and therefore in the plane of the finger tip). This was achieved by projecting a VGA screen (640 x 480 pixels) with an LCD projector (Sayett Media Show) onto a horizontal rear projection screen suspended 26 cm above the tablet (Figure a). One pixel measured 1.2 x 1.2 mm on the screen. A horizontal front-reflecting semi-silvered mirror was placed face up 13 cm above the tablet. The subjects viewed the reflected image of the rear projection screen by looking down at the mirror. By matching the screen-mirror distance to the mirror-tablet distance all projected images appeared to be in the plane of the finger (when viewed in the mirror) independent of head position. Targets were presented as 5.5 cm hollow squares and the finger position was indicated by a 7 mm filled white square (cursor spot). The position of the finger was used on-line to update the position of this cursor spot at 50 Hz.

[3] Curvature is, strictly speaking, a geometric entity—a property of the path traced out by the moving cursor spot. Note, however, that the cursor does not leave an actual physical trace as it moves—the subject must estimate the curvature from the kinematics of the moving cursor spot.

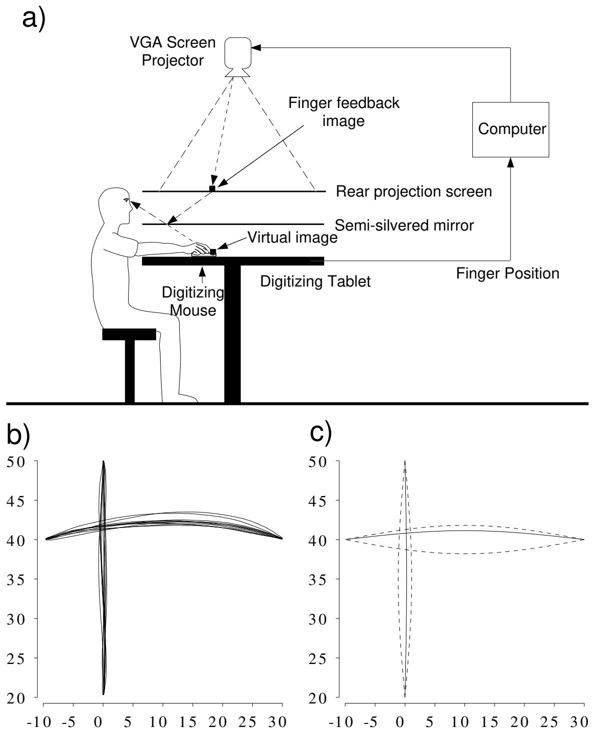

Figure . Figure . a) Experimental apparatus for measuring arm trajectories in the horizontal plane under virtual visual feedback. The position of the finger was captured on-line by a PC which computed the position of the visual feedback; this was output to a VGA screen projector. The position of the finger was displayed on the rear projection screen as a white filled square. The subject saw the virtual image of this cursor spot in the plane of his finger. b) Shows an example, for one subject, of the finger paths during trials in the absence of visual feedback. For clarity the end points of the transverse and sagittal movements have been aligned to their respective targets. The axes are in cm relative to the head position. c) The dashed lines show the paths of the extremal stimuli (and therefore the range) used in the curvature perception experiment. The solid line shows the 50% threshold path calculated from the mean of the probit analysis. This represents the path that the subject, whose movements are shown in c), would regard as straight.

Calibration

Prior to each experiment the position of the digitizing mouse cross-hairs relative to projected pixel position was calibrated over a grid of 16 points on the tablet. By illuminating the semi-silvered mirror from below the virtual image and the cross-hairs of the digitizing mouse could be lined up by eye. A quadratic regression of x and y pixel position on x and y hand position was performed and this was the used on-line to position the targets and cursor spot. The correlation of the fit was always greater than 0.99. Cross-validation sets gave a average calibration error of 1.5 mm.

Experimental Design

In the movement curvature experiment the subjects were asked to reach "naturally" between two stationary targets which were alternately illuminated. The subjects' task was to move their finger so as to place the cursor spot within the illuminated target. Apart from placing the cursor spot within the target there were no accuracy or time constraints. As we wished to study naturally produced movements the subjects were given no instructions as to the path their hand should take—in particular they were not instructed to move in a straight line.

Each session consisted of 60 movements; the first 40 movements were performed with the cursor spot continuously displayed. The last 20 movements of each session were performed with the cursor spot eliminated during the movement. The subjects' movement curvature was assessed in two sessions. The subjects were required to make sagittal movements between targets at (0,20) and (0,50) cm relative to the their head position and transverse movements between targets positioned at (–10,40) and (30,40) cm (Figure b).

In the curvature perception experiment the subjects participated in a two-alternative forced choice (2AFC) paradigm to assess their ability to judge the curvature of the movement of the cursor. During this perceptual task the subjects made no movement but observed the cursor spot making a 600 millisecond minimum-jerk trajectory between two targets. On each movement, by adding a semi-sinusoid of variable amplitude to the straight line trajectory, the cursor path was curved either to the left or right of the straight line between the targets. The subjects had to decide in which direction the cursor spot had curved. We tested ten different amplitudes of the sinusoid (the range is shown in Figure c), evenly spaced about zero; each amplitude was repeated 15 times in a pseudorandom order. Two cursor spot movement directions were tested in this task—sagittal outwards and transverse rightwards.

Analysis

To assess the curvature of the arm movements we analyzed the last 20 trials of each movement session, which were performed without visual feedback. We chose to analyze movements in the absence of visual feedback as they represent the feedforward outcome of the trajectory planner. The paths were first scaled and rotated so as to align the start and end point of the movements. This was necessary both for statistical purposes and to ensure that movement curvature could be assessed independently of inaccuracy resulting from the absence of visual feedback. The trajectories were then spatially resampled by linearly interpolating the actual paths to find the perpendicular distances of the inter-target line at 100 evenly spaced points along the inter-target line. The resampled paths were averaged for each subject and direction of movement. As a robust measure of curvature we used the averaged midpoint deviation (M_c)—the perpendicular distance of the finger at the midpoint of the movement from the inter-target line[4].

Movement times were also calculated by defining the start and the end of the movement with a 10 cm s^{-1} velocity threshold. The movement times were averaged across subjects for each direction of movement.

To assess curvature perception we calculated the amplitude of the sinusoid (P_c) at which the subjects perceived the cursor as moving in a straight path. The 2AFC data was analyzed using probit analysis (Dobson 1990); a cumulative Gaussian function was fit to the forced choice data to calculate the mean. The 95% confidence limits of the mean were also estimated from the psychometric function.

For each subject and direction of movement the perceived curvature was compared with the average midpoint deviation of the corresponding movement. All movement curvature was regarded as positive and the corresponding perceived curvature was given a positive sign if it was in the same direction as the movement curvature and a negative sign otherwise. As both M_c and P_c had error measures, we fit linear regressions numerically using maximum likelihood for the sagittal, transverse and combined data. To test the hypothesis that all the curvature seen in the movements was due to perceptual distortion (i.e. $M_c = P_c$) we tested whether the full data regression had a slope significantly different from one and an intercept significantly different from zero.

Results

The subjects produced sagittal movements which were approximately straight and transverse movements which were generally curved outwards, away from the body (Figure b; see Figure c for the curvature which

[4] By approximating the subjects' curved motion as a sinusoid the average midpoint deviation can be shown to be exactly equal to the standard definition of curvature: $\ddot{y}/(1+\dot{y}^2)^{3/2}$, where derivatives are taken with respect to x. This obviates the need to calculate first and second derivatives which can introduce noise into the measurement.

this subject would perceive as straight). The average movement durations were 1001 ms for the sagittal movements and 1105 ms for the transverse movements.

Figure shows a plot of actual movement curvature (M_c) against the perceived curvature of movements (P_c). A linear regression for the data gives $M_c = 2.22P_c + 0.78$ ($r = 0.72$, $p < 0.0001$, $n = 16$). Separate linear regression for the transverse and sagittal data give $M_c = 2.05P_c + 0.93$ ($r = 0.71$, $p < 0.0001$, $n = 8$) for the transverse data but no significant effect at the $p = 0.05$ level ($n = 8$) for the sagittal data. The slope of the combined data is significantly different from one ($p < 0.0001$) and the intercept is also significantly different from zero ($p < 0.0001$).

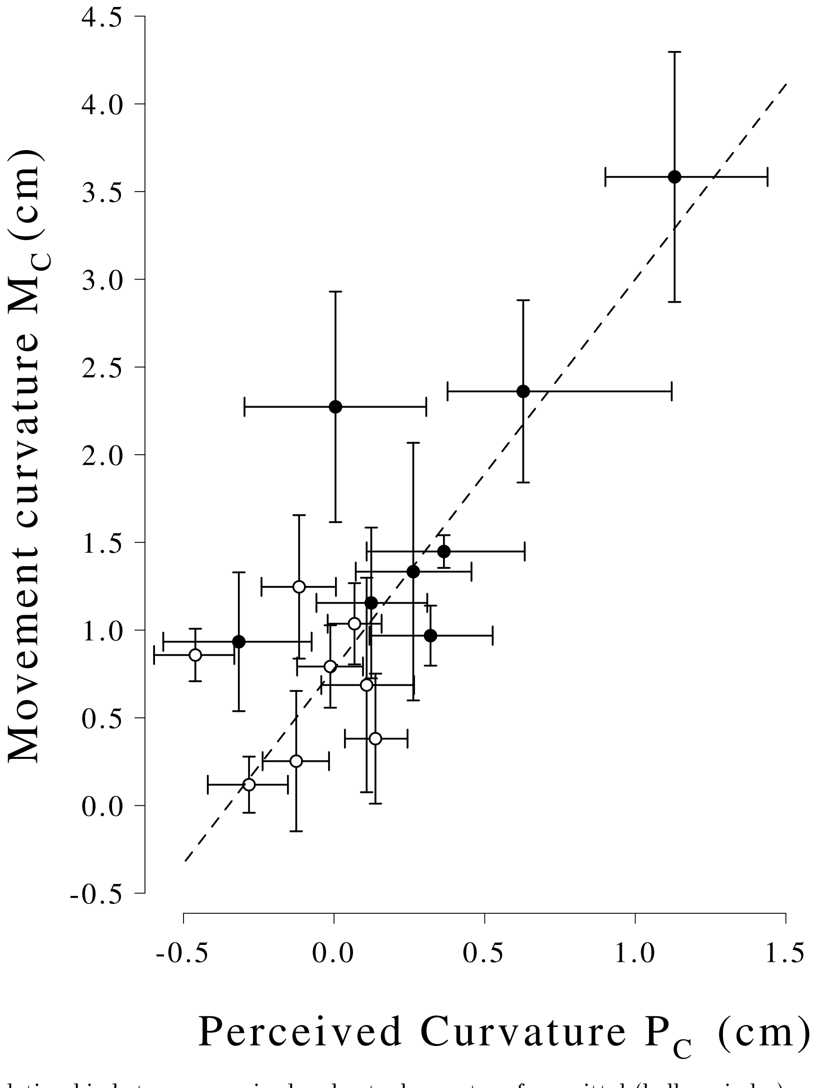

Figure . The relationship between perceived and actual curvature for sagittal (hollow circles) and transverse (filled circles) movements. Error bars show 95% confidence intervals. The maximum likelihood regression line for the full data is shown.

Discussion

We have studied the relationship between movement curvature and perceived curvature across 8 subjects and two directions of movement. We have not assessed the effects of visual perceptual distortion during the production of movements as we only analyzed trajectories performed in the absence of visual feedback. These results, therefore, address the effect of the misperception of curvature on the feedforward planning of trajectories. Even though the cursor spot movement duration in the perception study was somewhat shorter than the subjects' actual movement durations the results showed a highly significant linear relationship ($p < 0.0001$, $n = 16$) between perceived curvature and movement curvature. Although one must be careful in assigning causality on the basis of such a linear relationship we suggest that this perceptual distortion of curvature contributes to the movement curvature.

Separate analyses of the transverse and sagittal movements showed a strong linear effect of perceptual distortion on movement curvature ($p < 0.0001$) for the transverse direction but no effect for the sagittal direction. As the perceived curvature is clustered around zero for the sagittal subset of the data we suggest that the lack of correlation seen represents low variability in the "independent" variable (P_c). Combining the transverse and sagittal data increases the range of this independent variable thus revealing a linear relationship.

If visual perceptual distortion were the sole reason for the curvature of the movements we would expect the regression of movement curvature against perceived curvature to have an intercept of zero and a slope of one. The slope, however, is significantly different from one ($p < 0.0001$) and the intercept is also significantly different from zero ($p < 0.0001$). The non-zero intercept suggests that even when subject are able to perceive curvature correctly they still make gently curved movements, possibly in accordance with one or more of the hypotheses discussed in the Introduction. The slope of 2.22 is surprising as it suggests that the increase in movement curvature seen is larger than can be explained by the increase in perceptual distortion alone. This may be due to our simple measure of curvature as the midpoint deviations; subjects may use a more sophisticated internal measure which takes into account the entire trajectory.

It is interesting to compare these results with the classical studies on static curvature perception. There is an extensive literature, reviewed in Foley (1980), on the apparent fronto-parallel plane (AFPP)—the surface which subjects report as visually flat. In these studies the subjects view a horizontal array of vertical rods. One rod is fixed and the subjects' task is to set the other rods so that they all appear to lie in a plane parallel to a vertical plane through the eyes. These studies report that at far distances the subjects set the rods on a surface convex to them and at near distances they are set on a surface increasingly concave to them. Usually the apparent plane corresponds to the physical plane at only one viewing distance. The viewing distance used in our experiment corresponds to the near distance of the AFPP task. Our finding of convex cursor movements in the transverse direction being perceived as straight are, therefore, in accord with the static AFPP results.

We suggest, in conclusion, that the subjects' desired hand trajectory is a straight line, but that misperception of the curvature of the movement contributes to the curvature seen in normal movements. In other words, the curved hand movements are perceived as straighter than they really are, thereby appearing closer to the desired hand trajectory. These results suggest that the comparison of models of human trajectory formation must take into account the perceptual process by which trajectories are evaluated.

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References

Abend, W., Bizzi, E., and Morasso, P. (1982). Human arm trajectory formation. *Brain*, 105:331–348.

Atkeson, C.G. and Hollerbach, J.M. (1985). Kinematic features of unrestrained vertical arm movements. *J.Neurosci.*, 5:2318–2330.

Bernstein, N. (1967). *The coordination and regulation of movements.* Pergamon, London.

Bryson, A.E. and Ho, Y.C. (1975). *Applied optimal control.* Wiley, New York.

Bullock, D. and Grossberg, S. (1988). Neuromuscular realization of planned arm movement trajectories. *INNS.Abstr.*, -.

Dobson, A.J. (1990). *An introduction to generalized linear models.* Chapman and Hall, London.

Flash, T. (1987). The control of hand equilibrium trajectories in multi-joint arm movements. *Biol.Cybern.*, 57:257–274.

Flash, T. and Hogan, N. (1985). The co-ordination of arm movements: An experimentally confirmed mathematical model. *J.Neurosci.*, 5:1688–1703.

Foley, J.M. (1980). Binocular distance perception. *Psych. Rev.*, 87:5:411–434.

Hogan, N. (1984). An organizing principle for a class of voluntary movements. *J.Neurosci.*, 4:2745–2754.

Morasso, P. (1981). Spatial control of arm movements. *Exp.Brain Res.*, 42:223–227.

Uno, Y., Kawato, M., and Suzuki, R. (1989). Formation and control of optimal trajectories in human multijoint arm movements: Minimum torque-change model. *Biol.Cybern.*, 61:89–101.

Wolpert, D.M., Ghahramani, Z., and Jordan, M.I. (1994). Are arm trajectories planned in kinematic or dynamic coordinates? an adaptation study. *Experimental Brain Research In Press.*