Exp Brain Res (1994) 98:153–156

RESEARCH NOTE

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Perceptual distortion contributes to the curvature of human reaching movements

Received: 17 September 1993 / Accepted: 3 November 1993

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.

Key words Trajectory planning · Visual perception
Motor control · Curvature perception · Human

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; Atkeson and Hollerbach 1985; Flash and Hogan 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 that 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 et al. (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 that 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 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 multijoint 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

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[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

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, that 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.

Materials and methods

Eight naive, normal, right-handed students of the Massachusetts Institute of Technology 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 (Fig. 1a). 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 Video Graphics Array (VGA) screen (640 × 480 pixels) with an LCD projector (Sayett Media Show) onto a horizontal rear projection screen suspended 26 cm above the tablet (Fig. 1a). One pixel measured 1.2 × 1.2 mm on the screen. A horizontal, front-reflecting, semisilvered 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

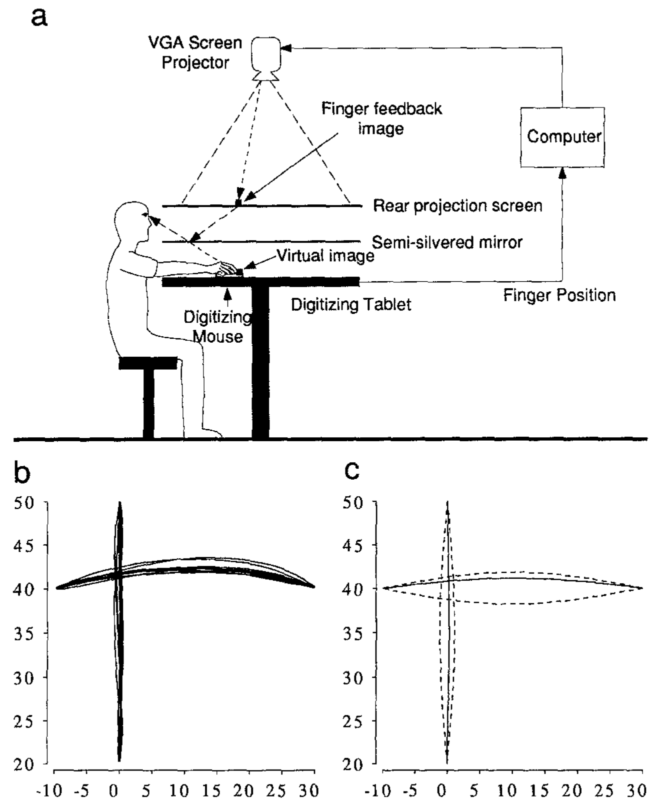

Fig. 1 **a** Experimental apparatus for measuring arm trajectories in the horizontal plane under virtual visual feedback. The position of the finger was captured on-line by a PC which computed the position of the visual feedback; this was output to a VGA screen projector. The position of the finger was 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** 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 centimeters relative to the head position. **c** The *dashed lines* show the paths of the extreme 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 **b**, 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 semisilvered 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 mean 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 perfomed 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 (Fig. 1b).

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-ms minimum-jerk trajectory between two targets. On each movement, by adding a semisinusoid 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 Fig. 1c), 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 to the intertarget line at 100 evenly spaced points along the intertarget line. The resampled paths were averaged for each subject and direction of movement. As a robust measure of curvature we used the mean 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.

[4] By approximating the subjects' curved motion as a sinusoid, the mean 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

For each subject and direction of movement the perceived curvature was compared with the mean 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 1 and an intercept significantly different from 0.

Results

The subjects produced sagittal movements that were approximately straight and transverse movements that were generally curved outwards, away from the body (Fig. 1b; see Fig. 1c for the curvature that this subject would perceive as straight). The mean movement durations were 1001 ms for the sagittal movements and 1105 ms for the transverse movements.

Figure 2 shows a plot of actual movement curvature (M_c) against the perceived curvature of movements (P_c). A linear regression for the data gives $M_c = 2.22\, P_c + 0.78$ ($r = 0.72$, $P < 0.0001$, $n = 16$). Separate linear regression

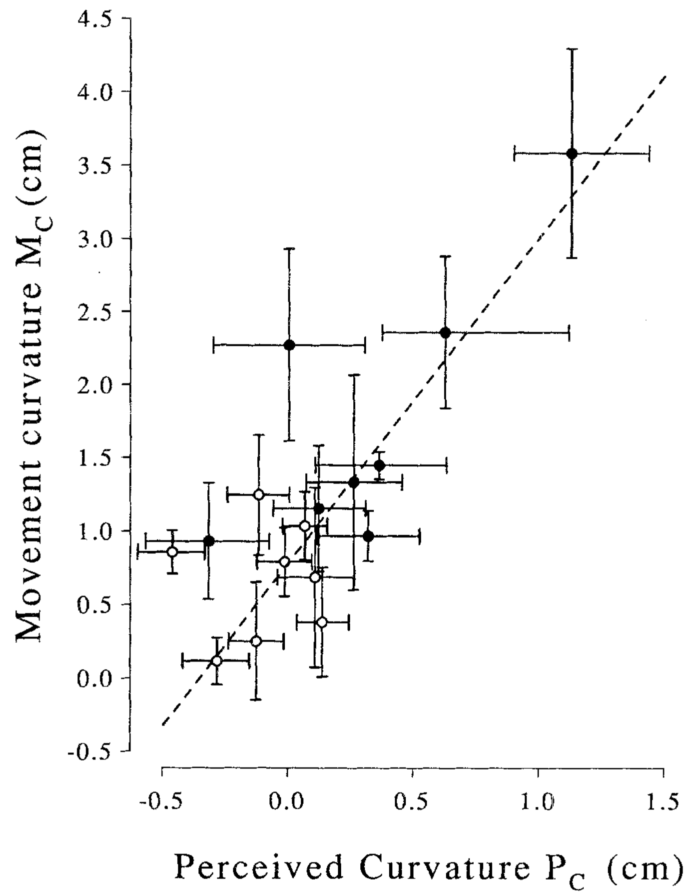

Fig. 2 The relationship between perceived and actual curvature for sagittal (*hollow circles*) and transverse (*filled circles*) movements. *Error bars* show 95% confidence intervals. The maximum likelihood regression line for the full data is shown

for the transverse and sagittal data give $M_c = 2.05 P_c + 0.93$ ($r = 0.71$, $P < 0.0001$, $n = 8$) 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 1 ($P < 0.0001$) and the intercept is also significantly different from 0 ($P < 0.0001$).

Discussion

We have studied the relationship between movement curvature and perceived curvature across eight 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 0 and a slope of 1. The slope, however, is significantly different from 1 ($P < 0.0001$), and the intercept is also significantly different from 0 ($P < 0.0001$). The nonzero intercept suggests that even when subjects 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 that takes into account the entire trajectory.

It is interesting to compare these results with the classic studies on static curvature perception. There is an extensive literature, reviewed by Foley (1980), on the apparent frontoparallel 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 is, 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.

Acknowledgements We thank Chris Miall for helpful comments on this paper and to Elizabeth Johnston for pointing us to the visual psychophysics literature. This project was supported in part by grants from the McDonnell-Pew Foundation, ATR Human Information Processing Research Laboratories, and Siemens Corporation; by grant IRI-9013991 from the National Science Foundation; and by grant N00014–90–J–1942 from the Office of Naval Research. Daniel M. Wolpert was supported by a grant from the Office of Naval Research; Zoubin Ghahramani was supported by a grant from the McDonnell-Pew Foundation; Michael I. Jordan is a NSF Presidential Young Investigator.

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