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RESEARCH ARTICLES

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Amplitude and direction errors in kinesthetic pointing

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Abstract We investigated the accuracy with which, in the absence of vision, one can reach again a 2D target location that had been previously identified by a guided movement. A robotic arm guided the participant's hand to a target (locating motion) and away from it (homing motion). Then, the participant pointed freely toward the remembered target position. Two experiments manipulated separately the kinematics of the locating and homing motions. Some robot motions followed a straight path with the bell-shaped velocity profile that is typical of natural movements. Other motions followed curved paths, or had strong acceleration and deceleration peaks. Current motor theories of perception suggest that pointing should be more accurate when the homing and locating motion mimics natural movements. This expectation was not borne out by the results, because amplitude and direction errors were almost independent of the kinematics of the locating and homing phases. In both experiments, participants tended to overshoot the target positions along the lateral directions. In addition, pointing movements towards oblique targets were attracted by the closest diagonal (oblique effect). This error pattern was robust not only with respect to the manner in which participants located the target position (perceptual equivalence), but also with respect to the manner in which they executed the pointing movements (motor equivalence). Because of the similarity of the results with those of previous studies on visual pointing, it is argued that the observed error pattern is basically determined by the idiosyncratic properties of the mechanisms whereby space is represented internally.

Keywords Kinesthetic pointing · Force · Biological movement · Oblique effect · Space representation

Introduction

Even in the absence of vision, we are able to identify a hand position in space, move away from it, and then point back to that same position. The objective of this study is to investigate the influence of the movements by which we identify the target position in the kinesthetic modality on the subsequent pointing movement. In principle, the static cues relative to the target position at the end of the locating phase would seem to be sufficient for guiding the subsequent pointing movement. It is, however, impossible to exclude that critical information is also provided by kinesthetic cues during the locating motion and, possibly, during the motion away from the target position. In fact, early studies on motor memory have clearly demonstrated the importance of the locating phase when movements are restricted to one dimension (reviews in Laszlo 1992; Smyth 1984).

In these early studies, experimentators aimed at determining whether position or distance cues are privileged in the kinesthetic modality by varying the initial position of the *manipulandum* in the *position task,* which consists in placing the *manipulandum* in some previously identified position, and in the *distance task,* which consists in replicating the extent of a previous movement. If position cues prevailed over distance cues, reproduction errors in the position task should be independent of the initial position. Conversely, if distance cues prevailed over position cues, one should be able to reproduce a given distance from any initial position. The

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pattern of results does not fit this ideal dissociation. Errors in both tasks depend on many factors including the length (Imanaka and Abernethy 2002) and the average speed of the movement (Imanaka and Abernethy 1990). More importantly, changing the initial position between the specification of the criterion and the reproduction phase affected accuracy in both tasks, indicating that distance and position cues interact. An extensive study by Walsh et al. (1979) showed that participants undershoot the target when the initial hand position is moved away from the target, and overshoot the target when the initial hand position is moved closer to it. The presence of an interaction has led to the rejection of the idea that target position and distance are coded, stored and retrieved separately. Rather than asking which cue is encoded, it seems more sensible "to conceptualize the movement as it really is, that is, an entity involving a starting position, distance moved, and terminal location" (Walsh et al. 1979).

More recently, several studies have focused on the nature of the internal representation of the memorized target position (McIntyre et al. 2000; Soechting and Flanders 1992). Two views have emerged. On the one hand, the fact that proprioceptive signals from the arm depend on its posture has led some authors to suggest that the target position is initially represented in an intrinsic frame of references based on joint angles (Darling and Miller 1993; Soechting 1982). On the other hand, there are also reasons to believe that target position is represented in an extrinsic 3D frame of reference. In particular, only this second hypothesis is compatible with the observation that the spatial distribution of pointing errors is invariant, whether the same or different hands are used to locate and reach the target (Baud-Bovy and Viviani 1998). Moreover, postulating an extrinsic representation of the target provides a unified framework encompassing both kinesthetic and visuo-manual pointing (Vindras and Viviani 1998). Unlike earlier studies on motor memory, these more recent attempts to model sensorimotor transformations in kinesthetic pointing have not paid due attention to the preliminary locating motions. Even when the locating phase has been taken into account, only the gross parameters of the movement—such as length or direction—were analysed. For instance, it is not known yet whether, for a given amplitude and direction, pointing accuracy depends on the velocity and the shape of the path during the locating phase.

In this study we have adopted the view mentioned above that kinesthetic inputs associated with the locating and homing motion should not be artificially broken up into distinct cues (Walsh et al. 1979). Within this framework, we have chosen to investigate whether the covariation of velocity and path shape throughout the locating and homing phases is a critical factor for determining pointing accuracy. The choice is motivated by previous experiments showing that: (a) velocity and path shape in biological movements co-vary in the peculiar, highly constrained manner prescribed by the Two-thirds Power Law (Lacquaniti et al. 1983; Viviani and Flash 1995; Viviani and Schneider 1991); (b) dynamic visual stimuli that comply with the power law can be tracked (de'Sperati and Viviani 1997; Viviani and Mounoud 1990; Viviani et al. 1987), perceived (Viviani and Stucchi 1992), and anticipated (Kandel et al. 2000) more accurately than stimuli that fail to comply with the power law; (c) biological motions are perceived and tracked better than non-biological motions even in the kinaesthetic modality (Viviani et al. 1997). On the basis of these previous studies, we tested the prediction that the target position is encoded more precisely when the locating and homing motions mimic natural movements than otherwise. We used a robotic arm to drive the hand of the participant from a starting to a target position (locating phase), and then back to the first position (homing phase). Then, the participant had to reach again the target with a single active movement (pointing phase). Vision was prevented throughout the three phases. The experiments controlled the extent to which the first two phases mimicked natural, unconstrained movements. We also attempted to dissociate the role of these two phases by manipulating independently their cinematic characteristics.

Materials and methods

Participants

Eleven right-handed participants (three male, eight female) were tested in Experiment 1. Ten participants [four right-handed males, four right-handed females and two left-handed females (participants 9 and 10)] were tested in Experiment 2. All participants but one were 1st-year students at UHSR University, Milan, Italy, who were not paid for their services. Their age ranged from 19 to 54 years (mean: 23). Informed consent was obtained from all participants. However, they remained naive as to the ultimate goal of the study. The experimental procedures complied with the guidelines set by the Ethics Committee of the UHSR University.

Experimental procedure

In both experiments, a robot (MANUTEC R15, Siemens) drove passively the participants' right hand to the target position (*locating phase*) and away from it (*homing phase*). Then, the participants executed a voluntary movement toward the memorized target position (*pointing phase*). Experiment 1 tested 12 targets located 30° apart along the perimeter of a circle in the horizontal plane (diameter: 30 cm). Experiment 2 tested 20 targets located 18° apart along the same perimeter. The centre of the circular configurations of targets defined the origin of the workspace coordinates. Participants stood on a platform with the mid-sagittal axis aligned with the centre of the workspace at a distance that allowed them to reach all targets without flexing the trunk. The height of the platform was adjusted individually so as to bring the target plane to the height of the participant's abdomen. Participants were told that the goal of the experiment was to assess the accuracy with which they could reach the target. For the pointing phase, they were left free to choose whatever trajectory they felt more comfortable with. Participants wore earphones to receive instruction signals during the task.

Before the beginning of each trial, participants fully grasped a spherical handle (radius: 2.5 cm) with a pronated (palm-down) hand. The handle was attached to the robot arm through a 1-degree-of-freedom hinge joint, which allowed rotation around the vertical axis. The handle was positioned at the centre of the workspace. An acoustic signal instructed them to close their eyes at the beginning of the trial. In Experiment 1, the robot guided the participant's hand from the centre of the workspace to a starting position opposite the target position with respect to the centre of the workspace. Then, the robot drove the participant's hand to the target following a trajectory that varied across trials (see below) and, from there, back to the starting position with a standard motion (straight path, Gaussian velocity profile). In Experiment 2, the robot drove the hand to the target position from the centre of the workspace with a standard motion (straight path, Gaussian velocity profile) and then back to the starting position with a motion that varied across trials. In both experiments, the handle remained on target for 2 s. During this period a second acoustic signal reminded the participant to memorize the position reached. At the end of the homing motion, the participant released the handle, which was subsequently lowered by the robot. Two seconds later, a third acoustic signal instructed the participant to execute the pointing movement with the same hand configuration as during the grip. The participant maintained the hand at the final position reached at the end of this phase until a fourth and last signal indicated the end of the trial. At this point the participant opened his/her eyes and grabbed again the handle for the next trial. Participants were allowed to see the initial position of their hand before each trial. Several practice trials were administered at the beginning of the experimental sessions to familiarize the participants with the prescribed sequence of events.

The robot motion followed one of seven different trajectories during the locating (Experiment 1) or homing (Experiment 2) phase. Three trajectories had straight paths, and variable velocity profiles (i.e., Gaussian, lognormal, inverted lognormal). The other four trajectories had a curved path and Gaussian velocity profile (see Fig. 1). For the curved paths, two radius of curvature (200 and 300 mm) were combined with two directions of deviation relative to the straight line. In all cases, the movement lasted 1.5 s and the distance between the initial hand position and the target position was 30 cm. Because target positions and movement directions were uniquely related to each other, target positions will be identified by the angle of the movement direction. By convention, the direction angle 0° corresponded to the target at the nine o'clock position. The 12 (Experiment 1) and 20 (Experiment 2) target positions were combined with the 7 robot trajectories, yielding 84 and 120 different conditions respectively (no replication). The order of presentation of the conditions was randomized with the constraint that two consecutive trials should correspond to different targets and different trajectories.

Analysis of the force data

The forces that the hand applied to the handle were recorded by a strain gauge (Mini 40, Assurance Technology, sampling rate: 137.14 Hz) located between the robot arm and the hinge joint. Because the joint eliminated torques around the vertical axis, we recorded only the linear components $f_x(t)$ and $f_y(t)$ of the contact force in the horizontal plane. The components were filtered using a numerical Fast-Fourier Transform (FFT) filter (passband, 0–3.4 Hz, and stop-band, 6.9–68.6 Hz, with a linear roll-off between 3.4 and 6.9 Hz) and differentiated using a 16 points optimal Finite Impulse Response (FIR) differentiator (Rabiner and Gold 1975). By definition, the *force* and *jerk index* correspond to the time average over the duration of the locating or homing motion of the magnitude of the force vector and of its derivative, respectively.

Analysis of the cinematic data

An infrared camera located above the workspace recorded the horizontal position of a marker fixed on the metacarpal joint of the middle finger (ELITE system, sampling rate: 100 Hz, resolution: ~1 mm). The height of the hand was neither constrained nor monitored during the execution of the pointing movement. However, participants kept the height approximately constant throughout

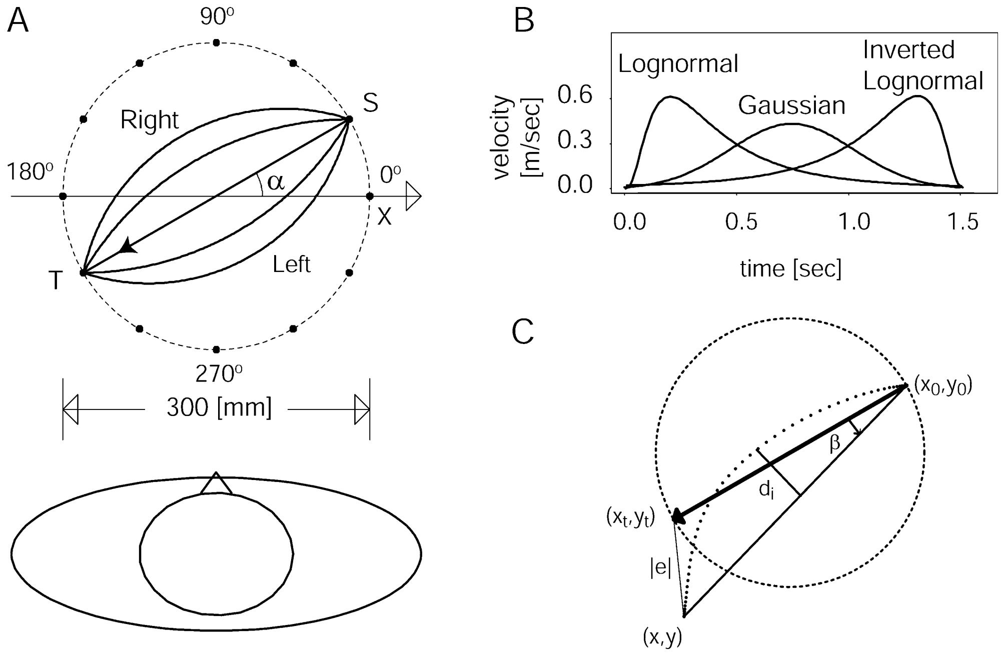

Fig. 1A–C Robot trajectories. **A** Target positions (*dots*) were located in the horizontal plane (only targets for Experiment 1 are shown). The direction of movement was defined by the angle (α) between the fronto-parallel axis and the line from the beginning (**S**) to the end (**T**) of the movement. The paths of the trajectories could be straight or curved, with a radius of curvature of 30.0 cm or 20.0 cm. **B** Velocity profile of the locating (Experiment 1) or homing (Experiment 2) movement. The straight path was combined with the three velocity profiles. Curved trajectories always had a Gaussian (bell-shaped) velocity profile. **C** Definition of the kinematic parameters. β Directional error (positive in the counter-clockwise direction); d_i distance of the *i*-th sample of the path from the line connecting the initial (x_0, y_0) and final (x, y) sample of the pointing movement; |e| amplitude of the error vector from the target (x_t, y_t) to the final position the trial. The coordinates of the marker position were low-pass filtered and differentiated by a model-based bandwidth selection algorithm that adjusted automatically the cut-off frequency to avoid high-frequency magnification during differentiation (D'Amico and Ferrigno 1990).

For every pointing movement, we computed the *error vector* $\boldsymbol{e}=(x-x_t, y-y_t)$ from the target position (x_t, y_t) to the end of the pointing movement (x, y) (Fig. 1C). The *directional error* β was defined by the angle between the line from the starting position (x_0, y_0) to the target, and the line from the starting position to the end of pointing movement. For each sample (x_i, y_i) of the pointing movement, we also computed the distance d_i from the straight line joining starting and final positions. By convention, the sign of d_i is positive when the sample (x_i, y_i) is to the right of the straight line (e.g. the trajectory in Fig. 1C), and negative otherwise. In order to discriminate straight from wavy trajectories that cross the line joining the starting and final hand position, we computed *signed* (λ) and *unsigned* (|λ|) *indexes of linearity* by averaging d_i and $|d_i|$ over the entire trajectory.

Finally, for each trial, we measured movement time (MT), peak velocity ($v_{\max}$) and peak acceleration ($a_{\max}$) during the pointing movement, and the time of occurrence of these peaks. The beginning and the end of each movement were identified by a standardized procedure. First, we computed the times at which the tangential velocity crossed a threshold value of 8 mm/s. The three longest intervals during which the velocity exceeded the threshold were identified as the locating, homing, and pointing phases. Then, the beginning and the end of each one of these phases were adjusted by lowering the threshold until 4 mm/s or until a minimum was encountered. All trials were visually checked and the times corrected manually if necessary. In the second experiment, technical problems caused the loss of 36 of the 1,400 recorded trials [1,400=7 (conditions) × 20 (targets) × 10 (participants)]. For each index, we interpolated the missing values at the angle α by using the available data for adjacent angles [quadratic polynomial fitted over the interval (α−80, α+80)]. The interpolation was performed separately for each participant and condition.

Statistical analyses

For both experiments, we analysed the effect of manipulating the cinematic characteristics of the locating or homing motion, the effect of movement direction, and the idiosyncratic differences among participants. The percentage of the total variance (R^2) explained by each of these factors was taken to indicate their strength (separate one-way ANOVAs with the participant, robot motion, and movement direction as factors).

In addition, we performed repeated-measure ANOVAs with movement direction, and velocity profile or path curvature as independent variables. Because the three velocity profiles were not systematically combined with the four possible paths, the effects of these factors were analysed separately. In the straight path conditions, for each index, we performed two-way, repeated-measure ANOVAs, with velocity profile and movement direction as within-participants factors (full factorial design). Similarly, we assessed the effect of the path and movement direction by analysing all robot motions with a Gaussian velocity profile (i.e., four curved plus one straight path) with another two-way repeated measure ANOVA. The degrees of freedom and tests of significance for the within-subject effects were adjusted by computing Greenhouse-Geisser's epsilon to account for possible violation of the sphericity condition (see Crowder and Hand 1995).

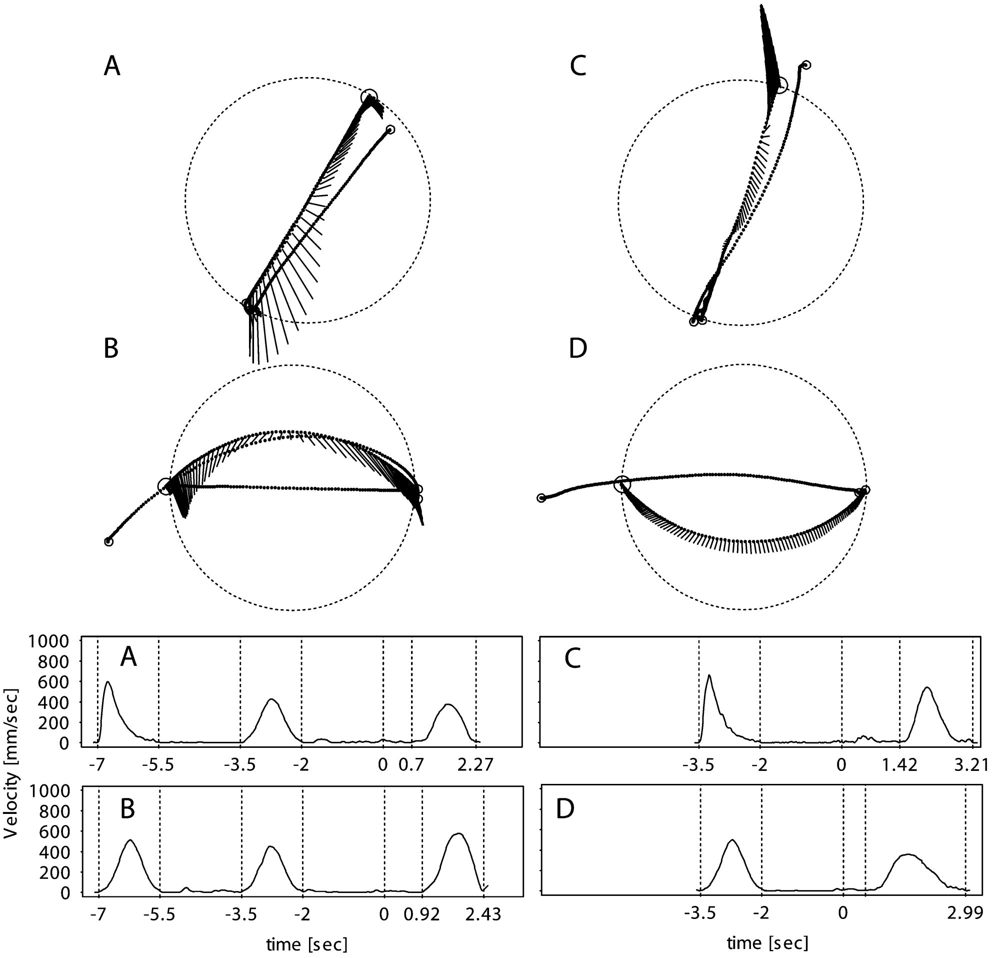

Fig. 2A–D Trial examples. Magnitude and direction of the interaction force between hand and robot handle during the locating or homing motion (*top panels*). Hand velocity during the trial (*bottom panels*). The origin of the time axis coincides with the Go signal for the pointing movement. **A** Example of a trial in Experiment 1 with lognormal velocity profile. Trial characteristics: target direction α=240°, movement extent L=27.7 cm, index of linearity λ=−2.6 mm, $\lambda_{\max}$=4.6 mm, directional error β=−9.0°. **B** Experiment 1 (same participant as in **A**), Gaussian velocity profile, α=0°, L=38.2 cm, λ=41.0 mm, $\lambda_{\max}$=97.0 mm, β=10.2°. **C** Experiment 2, lognormal velocity profile, α=252°: L=34.2 cm, β=−4°. **D** Experiment 2, Gaussian velocity profile, α=0°: L=38.9 cm, β=2.7°

Results

Overview

The four upper panels in Fig. 2 show typical examples of the hand trajectory from the beginning of the locating (Experiment 1, A, B) or homing (Experiment 2, C, D) motion to the end of the pointing movement. Lines superimposed to the trajectories represent the force vector sampled every 0.02 s. During the robot motion, magnitude and direction of the force varied considerably, especially in trials with lognormal velocity profiles (Fig. 2A, C). The four lower plots show the tangential velocity of the hand during the trial. The time origin in these plots (t=0) is set at the acoustic signal instructing the participants to execute the pointing movement (2 s after the end of the homing motion). The average reaction time following the third acoustic signal was quite long (~0.8 s), reflecting the fact that the instructions emphasized accuracy rather than speed. Overshoots (as in Fig. 2B–D) were more frequent than undershoots (Fig. 2A). Directional errors occurred equally often in the clockwise (Fig. 2A, C) and counter-clockwise (Fig. 2B, C) direction. In general, the trajectories were fairly straight (Fig. 2A, C), even when the locating or homing motions were curved (Fig. 2D). Occasionally, however, a curved locating path was followed by a similarly curved pointing movement (Fig. 2B).

In the following, we first analyse the force applied to the handle during the locating and homing motion. The subsequent sections analyse the cinematic of the pointing movement (movement time, peak velocity, peak acceleration and path), which varied considerably from trial to trial, even within the same experimental condition. The fourth and last section deals with the effects of imposed motion and movement direction on pointing errors. In each section, we identify the most important experimental factors by computing the percentage of variance explained by the participant, the type of motion during the locating or homing phase, and the target position (see Table 1). We also tested the effects associated with the motion type and the target position with two-way repeated-measure ANOVAs (see Tables 2 and 3). Altogether, these analyses will establish the presence of a robust pattern of pointing errors, which is almost independent of both the kinematics

Table 1 Percentage of variance explained by each factor (one-way ANOVAs)

Variable	Phase	Participant	Mvt. condition	Mvt. direction
Contact force				
Force	Locating (L)	35^{**}	8^{**}	3
	Homing (H)	43^{**}	4^{**}	2
Jerk	L	12^{**}	44^{**}	11^{**}
	H	12^{**}	43^{**}	10^{**}
Kinematic				
MT	L	28^{**}	1	3^{*}
	H	34^{**}	1	2
Peak velocity ($v_{\max}$)	L	60^{**}	1	1
	H	57^{**}	1	4^{**}
Peak acceleration ($a_{\max}$)	L	53^{**}	1	1
	H	49^{**}	1	2
Linearity				
Signed (λ)	L	1	7^{**}	28^{**}
	H	1	28^{**}	7^{**}
Unsigned ($\lvert\lambda\rvert$)	L	15^{**}	2^{*}	9^{**}
	H	26^{**}	13^{**}	3^{*}
Pointing error				
Absolute ($\lvert e\rvert$)	L	9^{**}	2^{*}	10^{**}
	H	23^{**}	1	10^{**}
Amplitude (L)	L	14^{**}	1	11^{*}
	H	29^{**}	1	15^{*}
Directional (β)	L	1	1	28^{**}
	H	1	1	20^{**}
Degrees of freedom				
	Experiment	Subject	Motion	Direction
Hypothesis	Locating (L)	10	6	11
	Homing (H)	9	6	19
Residuals	L	913	917	912
	H	1,390	1,393	1,380

$^{*}P<0.01$, $^{**}P<0.001$

Table 2 Repeated-measure ANOVAs (*F* ratios and *P* values). df_h, df_e unadjusted degrees of freedom

Factor (df_h, df_e)	Force	Jerk	MT	$v_{\max}$	$a_{\max}$	λ	$\|\lambda\|$	$\|\mathbf{e}\|$	*L*	*B*
Experiment 1 (manipulation of the locating motion)										
Straight paths										
Velocity (2, 20)	27.9**	140.2**	-	4.5*	-	-	-	6.5*	6.4*	-
Mvt. direction (11, 110)	6.4**	49.7**	-	-	-	15.4**	4.7**	3.6*	3.7*	9.2*
Interaction (22, 220)	6.9**	30.2**	-	-	-	-	-	-	-	-
Curved and straight paths with Gaussian velocity profile										
Curvature (4, 40)	3.4*	32.7**	-	-	-	11.5**	-	4.9*	-	-
Mvt. direction (11, 110)	-	14.8**	2.5*	-	-	17.5**	4.9**	4.5**	5.3*	9.3*
Interaction (44, 440)	-	3.3**	-	-	-	-	-	-	-	-
Experiment 2 (manipulation of the homing motion)										
Straight paths										
Velocity (2, 18)	18.1**	135.2**	-	3.5*	-	-	-	-	8.1**	4.6*
Mvt. direction (19, 171)	2.8*	39.4**	-	3.1*	-	5.8*	-	4.4**	6.0**	4.0*
Interaction (38, 342)	3.7**	26.5**	-	-	-	-	-	-	-	-
Curved and straight paths with Gaussian velocity profile										
Curvature (4, 36)	6.7**	37.4**	-	-	-	9.5*	6.6*	-	-	-
Mvt. direction (19, 171)	-	17.0**	-	4.5**	-	5.8**	-	4.9**	5.9**	5.5**
Interaction (76, 684)	2.9*	-	-	-	-	-	-	-	-	-

-$P \geq .05$, $^{*}P<.05$, $^{**}P<.01$ with adjusted DOFs (Greenhouse and Geisser)

Table 3 Mean values for each movement condition. *Bold* denotes an effect of the velocity profile for straight paths or of the curvature for curved paths (see Table 3)

Robot motion	Force (N)	Jerk (N/s)	MT (s)	$v_{\max}$ (mm/s)	$a_{\max}$ (mm/s^2)	λ (mm)	$\|\lambda\|$ (mm)	$\|\mathbf{e}\|$ (mm)	*L* (mm)	β (deg)
Experiment 1 (manipulation of the locating motion)										
Straight paths										
Gaussian	**2.20**	**5.30**	1.74	**491.79**	1,717.24	0.05	6.21	**48.18**	**319.3**	1.23
Lognormal	**3.47**	**15.81**	1.68	**523.69**	1,910.73	0.97	5.84	**43.35**	**321.45**	1.76
Inverted log.	**2.42**	**11.69**	1.65	**499.37**	1,836.88	0.42	5.73	**40.28**	**310.3**	1.20
Curved paths										
Right	**2.27**	**6.93**	1.74	496.55	1,787.47	**4.38**	8.13	**48.11**	318.41	2.14
Slightly right	**2.25**	**5.82**	1.76	489.38	1,770.22	**3.13**	7.43	**45.07**	316.03	1.48
Slightly left	**2.17**	**5.75**	1.75	482.02	1,677.84	**−1.60**	6.65	**40.18**	315.15	0.44
Left	**2.57**	**7.02**	1.71	503.08	1,771.09	**−1.50**	6.92	**38.51**	314.58	0.90
Experiment 2 (manipulation of the homing motion)										
Straight paths										
Gaussian	**2.33**	**5.04**	1.71	**490.22**	1,753.62	−1.15	7.49	51.22	**328.12**	**0.13**
Lognormal	**3.15**	**16.82**	1.67	**513.59**	1,918.18	−0.79	6.70	48.33	**318.01**	**1.29**
Inverted log.	**2.88**	**12.30**	1.72	**476.31**	1,731.05	−1.11	7.03	46.47	**318.36**	**0.33**
Curved paths										
Right	**2.48**	**6.53**	1.73	495.62	1,820.82	**−11.11**	**15.30**	47.73	320.97	0.05
Slightly right	**2.22**	**5.74**	1.76	480.12	1,770.25	**−8.16**	**12.58**	46.91	321.05	0.48
Slightly left	**2.32**	**5.80**	1.77	480.09	1,702.63	**6.87**	**10.65**	49.06	322.86	0.35
Left	**2.48**	**6.63**	1.75	488.33	1,775.96	**10.81**	**14.07**	53.63	323.18	1.02

of the pointing movement and independent of the motion imposed by the robot during the locating or homing phase.

The force at the handle was affected by the velocity profile of the robot motion and by the direction of movement

The forces during the locating phase in Experiment 1, and during the homing phase in Experiment 2, were almost identical. In both experiments, the velocity profile of the robot motion strongly affected the time-average of the force magnitude and of its derivative (see Table 2). In the straight-path condition, both the initial peak of acceleration in the lognormal velocity profile and the peak of deceleration at the end of the motion in the inverted lognormal velocity profile produced correspondingly large peaks in the magnitude of the force (Fig. 2A, C). In contrast, when the robot followed the trajectory with a Gaussian velocity profile, the magnitude of the force remained small. This factor explained as much as 43% of the total variance of the jerk index (see Table 1). The factor had a lesser impact on the force index because some participants tended to pull the handle toward their body, which led to large variations in the level of static force applied by different participants. The effect of the curvature of the imposed motion on these indexes was less marked, but still statistically significant (see Table 2).

The direction of the motion also modulated the magnitude of the force and of its derivative in the straight path condition. In this condition, the force and jerk indexes peaked for the two directions (α=120° and α=300°) that correspond approximately to the axis of maximum inertia of the arm (see Fig. 3). The effect of motion direction was more conspicuous for the lognormal velocity profile than for the other velocity profiles, which explains the significant interaction between velocity profile and target direction (see Table 2). These results confirm that, during the locating and homing phases, there were important differences across experimental conditions at the mechanical level.

The variations of movement velocity were effectively compensated by corresponding variations of movement time

Because participants were free to choose the velocity of their pointing movements, and to vary it across trials, the range of movement times, peak velocities and peak accelerations was quite large. Moreover, the peak velocity and peak acceleration of the pointing movements were in general inversely correlated with movement time. Below, we show that this inverse relation holds true whether one considers the variability across participants (Fig. 4D), across movement directions (Fig. 4B), or the residual variability within each experimental condition (Fig. 4C).

A one-way ANOVA with the participant as the independent variable revealed that individual differences were highly significant for most cinematic indexes (inter-participants variability explained 30–60% of the total variance; see Table 1). In contrast, the direction and type of the robot motion during the locating or homing phase explained less than 5% and 1% of the total variance, respectively. For each participant in Experiment 1, Fig. 4A plots the average peak velocity versus the average movement time over all trials. There was a clear inverse relation between these variables (r=−0.84), which was confirmed by analysing the data for each direction separately. Thus, variations of peak velocity were accurately compensated by corresponding variations of movement time. Similar results were obtained for Experiment 2.

In spite of the considerable variability of movement speed, most pointing movements had very similar bell-shaped, slightly asymmetrical velocity profiles. On average, peak acceleration and peak velocity occurred at 27% and 47% of the movement time, respectively. The analysis revealed minor variations of the shape of the velocity profile across participants and trials. For each participant and condition, we tested shape invariance by computing the coefficient of correlation between the time-to-peak for velocity and acceleration. The values (ranging between 0.51 and 0.90) were lower than those reported in the literature (e.g. Gordon et al. 1994a, 1994b; Messier and Kalaska 1999). Generally, the velocity profiles of slow movements were more irregular than those of fast movements. Yet, even slow movements presented many

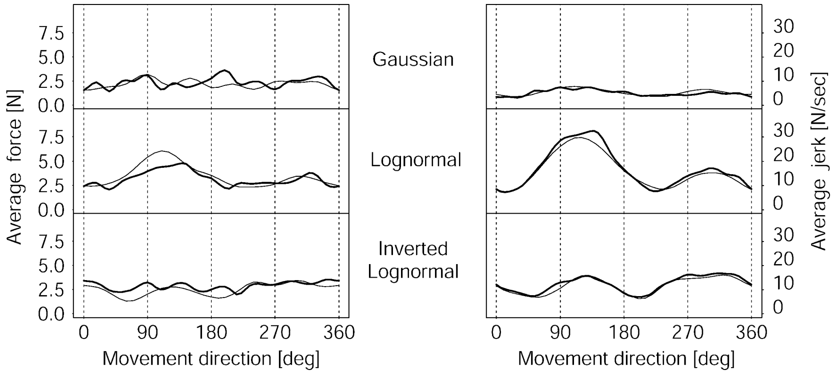

Fig. 3 Average force and average jerk in the straight path conditions. In this and in the following figures spline functions were used to interpolate the data (one data point for each target direction). Both force and jerk indexes were larger in the lognormal and inverted lognormal conditions than in the Gaussian condition. The results of Experiment 1 (*thin lines*) and Experiment 2 (*thick lines*) were very similar

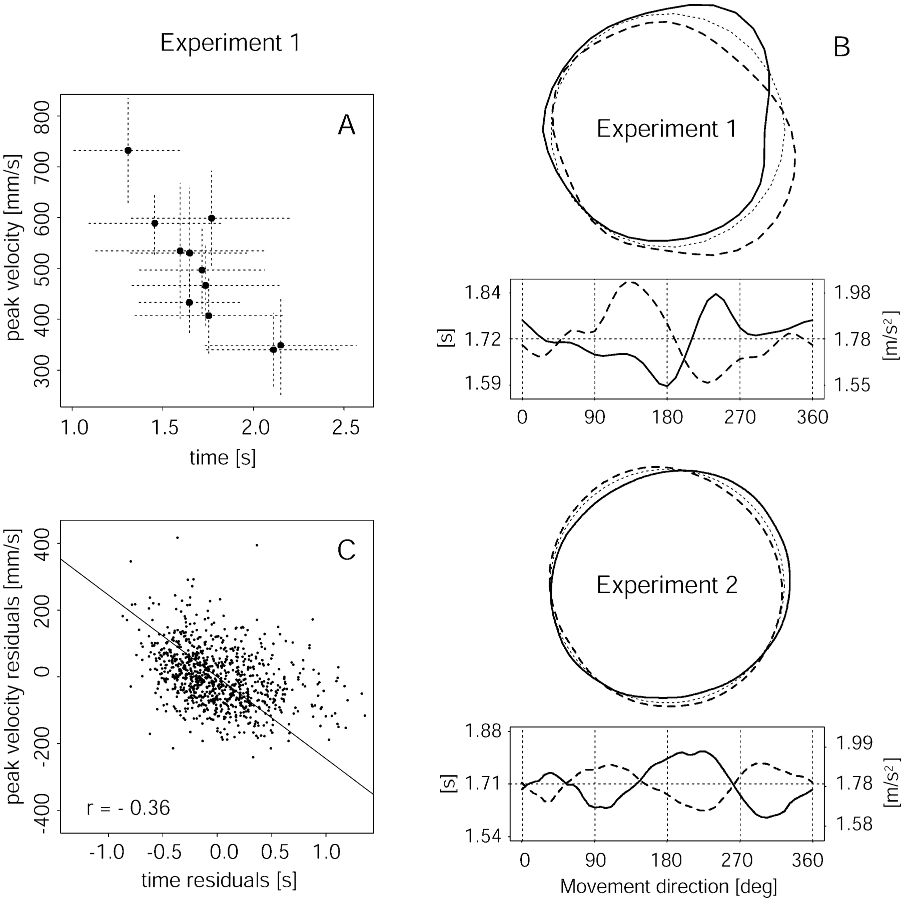

Fig. 4A–C Correlation between movement time, peak velocity, and peak acceleration. **A** Average movement time and peak velocity for each participant in Experiment 1. *Dashed lines:* ±1 standard deviation. **B** Polar and linear plots of movement time (*dashed lines*) and peak acceleration (*continuous lines*) as a function of target direction for both experiments. **C** Correlation between trial-to-trial residuals of the movement time and peak velocity in Experiment 1. In all cases, movement time was inversely correlated with peak velocity and peak acceleration

characteristic ballistic features. In particular, the inflections in the velocity profile were not accompanied by a change of direction of the movement, and it was possible to predict the distribution of peak velocity and acceleration times by assuming simply that the "width" of a bell-shaped template varied slightly from trial to trial.

The robot motion in the locating or homing phases had almost no effect on duration, peak velocity, and peak acceleration of the pointing movement. As noted above, the robot motion alone explained only 1% of the total variance of these variables (Table 1). The only significant effect was that of the velocity profile on peak velocity in the straight path conditions (Table 2). In both experiments, peak velocity and peak acceleration for the straight path conditions were greater for the lognormal profile than for the other two velocity profiles (Table 3). However, this should not be taken to suggest that participants attempted to mimic the features of the locating and homing motions. We found no evidence that participants attempted to reproduce the pronounced asymmetry of the lognormal and inverted lognormal velocity profiles (Fig. 2). In fact, the effect of the velocity profiles on peak velocity or peak acceleration of the pointing movement disappeared after normalizing the velocity profiles of the pointing movements to a reference movement time and amplitude (duration = 1.72 s; amplitude = 31.6 cm).

The direction of movement had small effects on cinematic variables. Peak velocity was modulated by the direction of movement only in Experiment 2 (see Table 2). The *P* values for peak velocity in Experiment 1, and for MT and peak acceleration in both experiments, were close to the critical value ($P<.1$). The polar and linear plots in Fig. 4B summarize the way in which the average movement time and the average peak acceleration varied across directions in a complementary fashion (data from both experiments pooled over participants). The corresponding curves for peak velocities (not shown) did not differ much from those for peak acceleration. Both the direction of maximum acceleration and minimum movement time coincided with the axis of least inertia of the arm (~240°), but the effect of direction was less systematic than that reported in the literature (Ghez et al. 1990; Gordon et al. 1994b) and varied among participants. In fact, two participants exhibited a pattern of directional anisotropy opposite to the one represented in Fig. 4B. In spite of these differences, an inverse relationship between movement time and peak acceleration was always present, indicating that these two variables covaried in a systematic manner.

Finally, over and above the main affect of the direction and motion type, velocity varied from trial to trial. This is shown in Fig. 4C for Experiment 1 by plotting the residuals for peak velocity against the residuals for movement time. Residuals were obtained from 3-way ANOVAs of velocity and movement time in which, participants, robot motion, and movement directions were the main factors, and interactions were not included. Time residuals accounted for 13% and 17% of the velocity residuals in Experiment 1 and 2, respectively.

The curvature of the pointing movements

On average, the maximum distance between the hand path and the straight line from the starting to the final position was 1.8 cm and 2.8 cm in Experiments 1 and 2, respectively. A one-way ANOVA of the unsigned index of linearity ($|\lambda|$) showed significant individual differences (see Table 1). The number of movements curved in either direction was roughly equal, because the signed index of linearity (λ) was not significantly different from zero.

In both experiments the analysis of the signed index of linearity (repeated-measure ANOVA) showed that pointing movements were straighter in the straight path condition than in the curved path condition (Table 2). Figure 5B and D show that movements following leftward-deviated locating paths were slightly deviated toward the left (thin dotted lines), whereas the opposite was true for rightward-deviated locating paths (thin continuous lines). The curvature of the pointing movements in the straight-path conditions followed closely the grand average (thick continuous line), reflecting the absence of interaction between path and movement direction.

We analysed the curved path conditions for each participant separately. First, we computed the mean

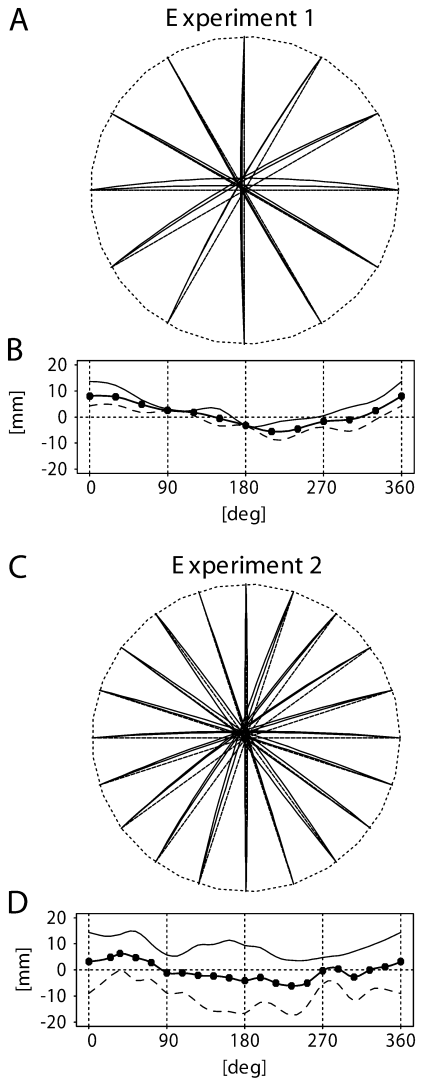

Fig. 5A–D Effect of target direction on path curvature for Experiment 1 and 2. **A, C** The paths are represented by arcs of circle with the same (signed) index of linearity (λ) as the actual data (λ-values averaged over all conditions). **B, D** Average index of linearity as a function of target direction. The results for the pointings following curved locating motions are plotted separately. *Thin continuous* and *dashed lines* correspond to average curvature of pointings following locating motion deviated toward the right and left respectively. The average linearity index over all conditions (*thick continuous line*) was used to define the arcs of circle in **A** and **C**

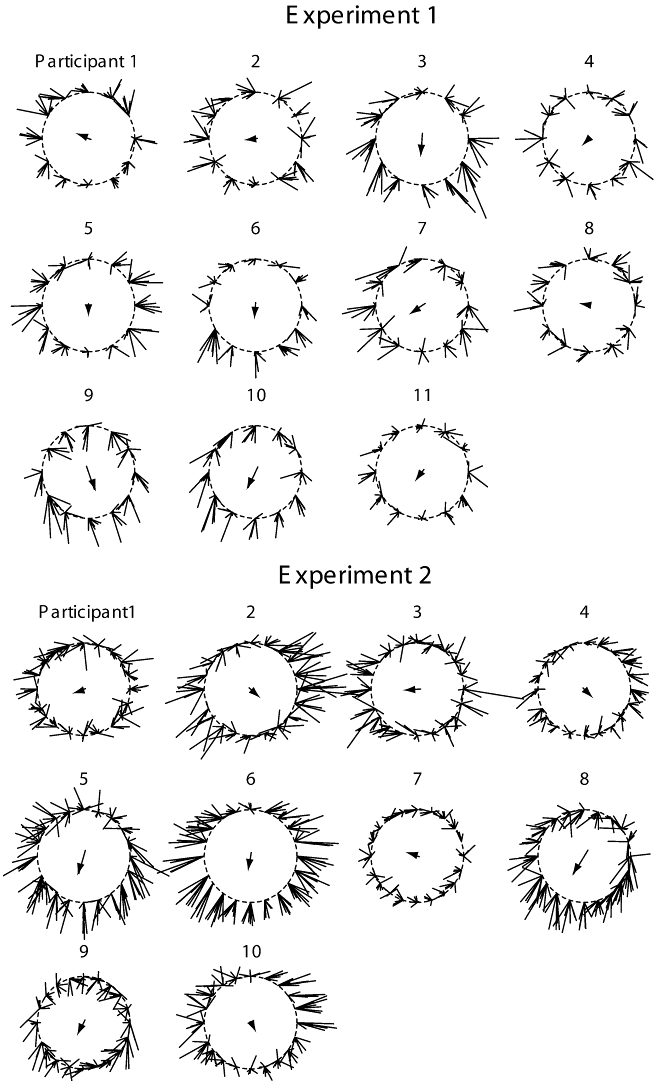

Fig. 6 Movement endpoints for all participants and both experiments. *Solid lines* connect targets and endpoints for straight and curved paths, respectively. The *centre vector* is the mean of all error vectors (amplitude is doubled for visual clarity)

value of the signed linearity index for both directions of the curvature of the robot motion. The difference between the means was highly significant for one participant in Experiment 1 and six participants in Experiment 2 (*t*-test, $P<.001$). Across participants the average difference was 5.3 in Experiment 1 and 18.6 in Experiment 2, indicating that there were more participants who mimicked the path of the robot motion in Experiment 2 than in Experiment 1. However, the individual variability in the signed linearity index was large in both experiments (standard deviation: 7.95 mm in Experiment 1 and 8.95 mm in Experiment 2).

Finally, in both experiments the curvature of the pointing movements depended also on the direction of movement in both experiments (Table 2). Maximum curvature (negative or positive) occurred for movements along the axis of minimum inertia of the arm, i.e. when targets could be reached by a simple rotation of the forearm (60 or 240 degrees, Fig. 5). The bent was similar for both directions, except for 3- and 9-o'clock targets for which movements to the left were more curved than movements to the right. In Fig. 5A (Experiment 1) and Fig. 5C (Experiment 2), path curvature for each direction is summarized by arc of circles with a bent that corresponds to the average value across all conditions (thick continuous line in Fig. 5B, D).

Pointing errors

Figure 6 shows the set of final hand positions for all participants and both experiments. In Experiment 1 the average absolute error over all conditions ranged from 3.1 cm to 6.0 cm (mean 4.3 cm). The corresponding range for Experiment 2 was between 2.6 and 7.6 cm (mean 4.9 cm). We broke down pointing errors into amplitude and directional components. Individual differences explained at least 14% of the total variance of the movement length, but only 1% of the total variance of the directional error (Table 1). In contrast, the direction of movement explained between 10% and 15% of the total variance of the movement length and between 20% and 30% of the total variance of the directional error. In both experiments, the velocity profile and/or path used by the robot to move the participant's hand toward the target (Experiment 1) or away from it (Experiment 2) explained less than 2% of the total variance.

The salient features of the error distributions were common to all participants, including the two left-handed individuals tested in Experiment 1. First, almost all participants tended to overshoot the targets. In Experiment 1 individual averages of movement amplitude (*L*) varied from 30.1 cm (for participant 9) to 34.3 cm (for participant 3). In Experiment 2, movement length varied from 29.0 (for participant 9) to 36.6 cm (for participant 6). In addition, the extent of the overshoot depended on target direction ($P<.05$ in both experiments, Table 2). Figure 7 illustrates this point by plotting the amplitude of the movement as a function of target direction for each condition (middle panels) and each participant (bottom panels). The overshoot was maximum along the lateral directions (i.e., 0° and 180°). The upper panels in Fig. 7 summarize the amplitude/direction relationship by show-

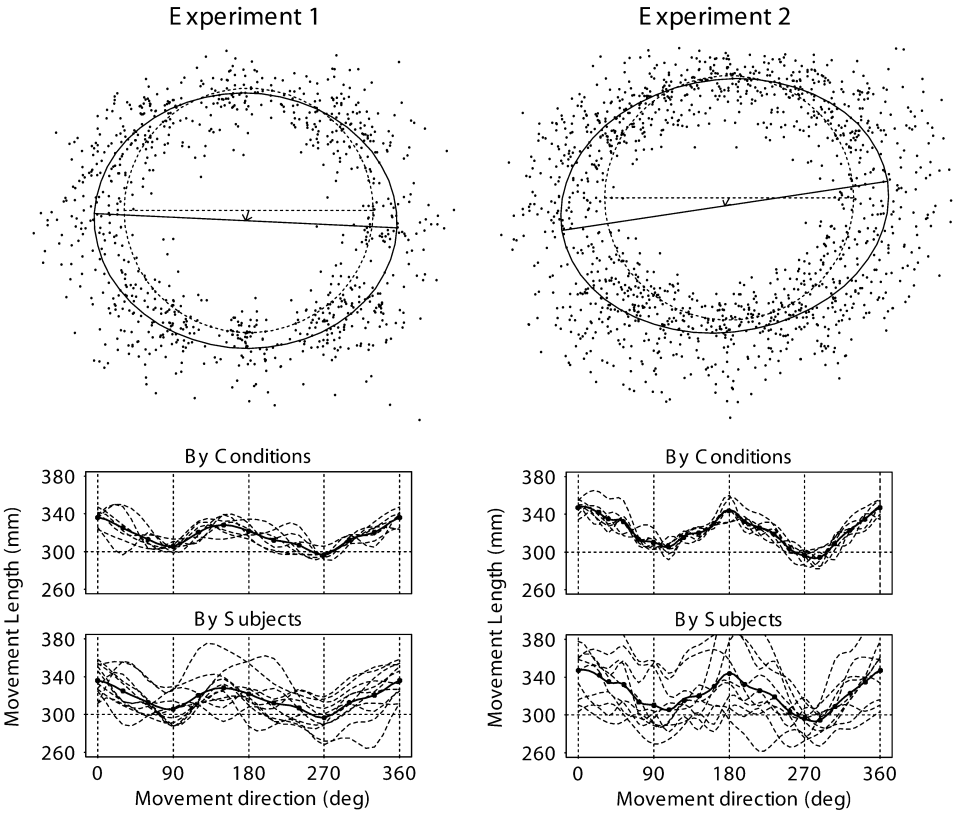

Fig. 7 Effect of target direction on the amplitude of the pointing movements in the two experiments. *Top* Spatial distribution of the endpoints for all trials and all participants. An ellipse was fitted to the data points. Note that the major axis of the ellipses is shifted toward the body of the participant and tilted. *Middle dotted lines* represent the average amplitude as a function of target direction for each condition (all participants). The *solid line* is the average across conditions. *Bottom Dotted lines* represent the average amplitude as a function of target for each participant (all conditions). In both panels, the lines are spline interpolations of the data points (*filled dots*)

ing the ellipses that fit best the movement end-points for each trial (Gander et al. 1994; Bookstein 1979). The axis of maximum elongation of the ellipse was tilted away from the lateral axis by –2.7° in Experiment 1 and 8.5° in Experiment 2. The tilt angle varied between −14.4° and 22.1° when separate ellipses were fit to the data points for each participant.

Second, there was a tendency to point closer the body, and slightly to the left of the targets. For most participants, the mean error vectors averaged across movement directions and conditions were directed toward the left side of the body (see the arrows at the centre of the plots in Fig. 6). This bias caused the movements directed away from the body (270°) to be shorter than those directed toward the body (90°), and the overshoots to be larger for the movements directed toward the left (0°) than toward the right (180°). The population ellipses in Fig. 7 also reflect this tendency.

The endpoints of oblique pointing movements were attracted by the diagonals

The average directional error (β) over all target directions and conditions was fairly small. Across participants, it varied between 0.1° to 2.3° (mean: 1.3° in Experiment 1 and 0.6° in Experiment 2). Thus, there was a slight tendency to point to the left of the target. Ghilardi et al. (1995) reported a similar counterclockwise bias for pointing movements towards visual targets.

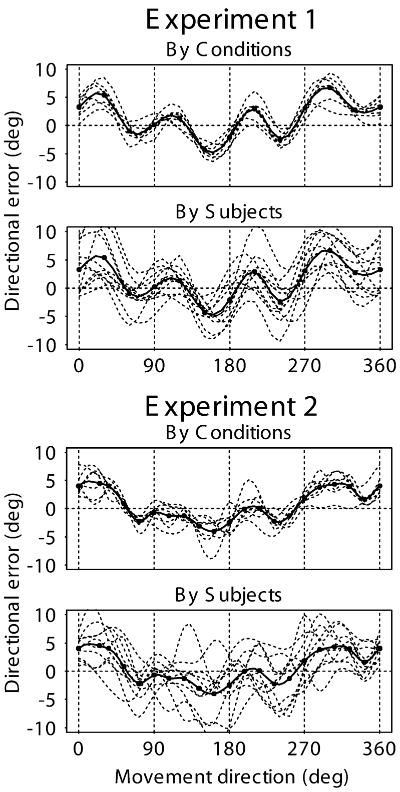

Fig. 8 Effect of target direction on directional errors in the two experiments. Directional errors for each condition (*top*) and each participant (*bottom*)

The new finding was that directional errors were affected by target direction ($P<.05$ in both experiments, see Table 2), the error varying by as much as 6° between directions. Errors followed a consistent pattern, which repeated itself in each quadrant. The bias was positive in the first half of the quadrant (counterclockwise rotation) and negative (clockwise rotation) in the second half. Thus, the perceived position of the targets tended to be attracted by the diagonal axes (i.e. 45, 135, 225 and 315°). For instance, in Experiment 1, pointing movements directed toward the 30° and 60° targets ended up on average at 34° and 58°, respectively.

The pattern of directional errors in Fig. 8 suggests the superposition of a highly regular oscillation with period of $\pi/2$ and a slower oscillation of period 2π. We factored out the latter effect by recomputing the directional errors after subtracting from the endpoints of each participant the corresponding mean pointing error. In addition, we also removed the (small) systematic counterclockwise bias mentioned above by subtracting from each endpoint the average directional error across movement directions. Figure 9 shows the result of this procedure for Experiments 1 and 2.

The spread of the end-points for each target was not uniform across directions (top part of Fig. 7) suggesting that directional errors also depended on movement direction. To quantify the variability of the directional error, we first eliminated the between-subject variability by subtracting the individual average directional error from the original data. Then, we computed the standard deviation for each movement direction separately by pooling the data in all participants and all conditions. As shown in the bottom plot of Fig. 9, the variability of the

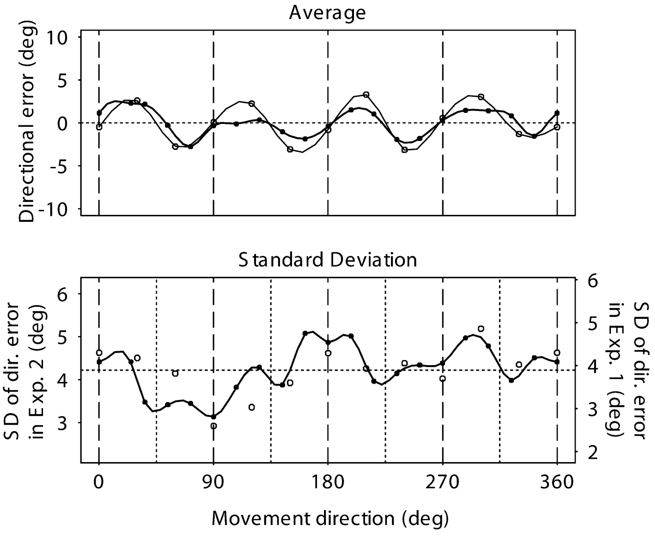

Fig. 9 Directional errors. *Top* Directional error after removal of the translation component in Experiment 1 (*thin line*) and 2 (*thick line*). Data from all participants in all conditions. *Bottom* Variability (standard deviation) of the directional error for each target direction (Experiment 1: *empty dots;* Experiment 2: *solid dots*). Data from all participants in all conditions

directional error was smaller for movements directed toward the body, suggesting the body provided a stable reference for locating the target. Note that such a reference did not prevent the occurrence of a systematic bias toward the diagonals. It simply allowed one to reach the same (biased) position with greater reliability.

Locating and homing motions had a limited effect on the pattern of pointing errors

The velocity profile of the locating or homing motions had a statistically significant effect on the average length of the subsequent pointing movement (Table 2). The fact that in Experiment 1 the amplitude of the pointing movements varied *pari passu* with the peak acceleration of the locating motions may suggest that the initial acceleration imposed on the arm contributed to the estimate of the target distance (Table 3). However, the inference is not well supported by the results of Experiment 2, in which the longest pointing movements were actually observed after homing motions with the Gaussian velocity profile. As concerns pointing accuracy, we found that directional errors were affected only by the velocity profile of the homing motion. By contrast, absolute errors were affected only by the velocity profile of the locating motion (Table 2). Although the effects of velocity reached statistical significance, they were all quite small (viz. ~1.1 cm for movement length, ~1.1° for direction and ~0.8 cm for absolute error) and explained only 1% of the total variance (Table 1).

Manipulating the curvature of the path of the locating or homing motion had an even smaller effect on pointing errors. Although the path of the locating motion affected the absolute error (Table 2), neither the difference between mean movement amplitudes (~0.2 cm), nor that between movement directions (~1.0°) was sufficiently large to reach significance. Finally, there was no evidence of interaction between movement direction and velocity or path curvature (the curves in the middle panels of Fig. 7 are almost parallel; see also Table 2). In short, the pattern of errors seems fairly independent from the mechanical interactions that take place during the locating or homing motions. This conclusion was verified further by regressing the average absolute error against average force or average jerk for each participant. In all cases but one (participant 1 in Experiment 1), the percentage of variance explained by either the average force or the average jerk remained below 4%.

Effect of the kinematics of the pointing movement on accuracy

In both experiments, pointing movements with a rightward bend ($\lambda>0$) tended, on average, to end up to the left of the target ($\beta<0$) and vice versa (Table 1). In fact, a linear regression analysis revealed that approximately 7% of the total variance of the directional error was explained by the curvature of the pointing movement. However, the suggested effect of the sign of the curvature of the pointing movement on directional errors was actually much weaker than the effect of the direction of the target, which accounted for 28% (in Experiment 2) and 20% (in Experiment 1) of the total variance. Aside from this marginal tendency, the pattern of error was largely unaffected by the geometry and kinematics of the locating and pointing movements. This was verified by repeating the analyses reported in Figs. 7 and 8 on more homogeneous groups of trials. First, we ranked all pointing movements according to their movement time, and divided them into four equal groups (N = 231), with an equal contribution of all directions (Fig. 10A). Figure 10B shows that, for all groups, average amplitude and average directional error followed the same overall patterns already shown in Figs. 7 and 8, respectively. Thus, errors were

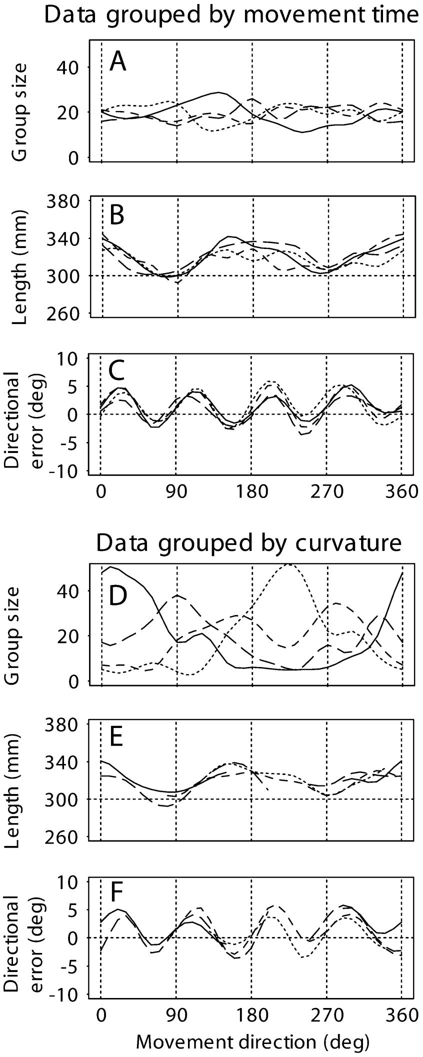

Fig. 10A–F Effect of movement speed and path linearity on pointing errors. Pointing movements were divided into four groups by using movement time (*top panels*) and linearity index (*bottom panels*) as criteria. Amplitude and direction of the movements were averaged for each group. Note that group size was almost balanced only when movement time was used as grouping criterion independent of the velocity of the pointing movement. Second, we divided again all pointing movements in four groups according to their signed linearity index. In this case, the sample size was not distributed evenly across directions (Fig. 10D) because, as noted before, movements to the right tended to have a right bend (λ>0), and movements to the left tended to have a left bend (λ<0). However, it was still possible, within each group, to compute the average amplitude (Fig. 10E), and the average directional error (Fig. 10F) for each direction (only means based on more that 10 values were retained for analysis). The same pattern emerged again for all groups, which implies that the distribution of errors is also independent of the curvature of the pointing movements.

Modelling the pointing errors

The leftward bias and the lateral stretching of the endpoints are reminiscent of the pattern of errors described in a previous study (Baud-Bovy and Viviani 1998) in which the participant's right hand was moved from an initial position close to the participant's body to targets located in front of him. In that study, we showed that errors could be explained by a bias in the perceived orientation of the arm and forearm. We tested whether this explanation accounts also for the present results. Because arm posture was not recorded, we computed the orientation of arm (η) and forearm (ζ) relative to the *y*-axis under the simplifying assumption that the both body segments remained within the horizontal plane:

$$\eta = \arctan\left(\frac{x_e}{y_e}\right) \quad \zeta = \arctan\left(\frac{x - x_e}{y - y_e}\right)$$

The elbow position $(x_e, y_e)=[l_a \cos(\phi-\xi), l_a \sin(\phi-\xi)]$ was derived from the hand position (x, y) alone, after computing the angle between the *x*-axis and the shoulder-hand direction as $\phi=\arctan(y/x)$, and the elbow flexion angle as $\xi=\arctan(l^2-l_a^2-l_f^2/2l_a l)$. In this formula $l=\sqrt{(x^2+y^2)}$ is the shoulder-hand distance, and arm and forearm lengths were set to $l_a=26$ and $l_f=31$ cm, respectively. We assumed that the centre of the workspace was located 35 cm in front of the shoulder, and 20 cm to its left (Fig. 11).

Figure 11A shows the targets (empty circles) and the average endpoints over all participants and conditions (filled circles) in Experiment 1. The data points in the left panel of Fig. 11B describe the relationship between the arm orientation angle η at the end of the locating phase, and the same angle at the end of the pointing phase. The right panel of Fig. 11B describes the analogous relation for the forearm orientation angle ζ. As in Baud-Bovy and Viviani (1998), we fitted linear psychophysical functions to these two sets of orientation angles (continuous lines), and used the values predicted by the psychophysical function to compute the perceived hand position in space. The corresponding errors were then decomposed into amplitude and directional components (Fig. 11C). Com-

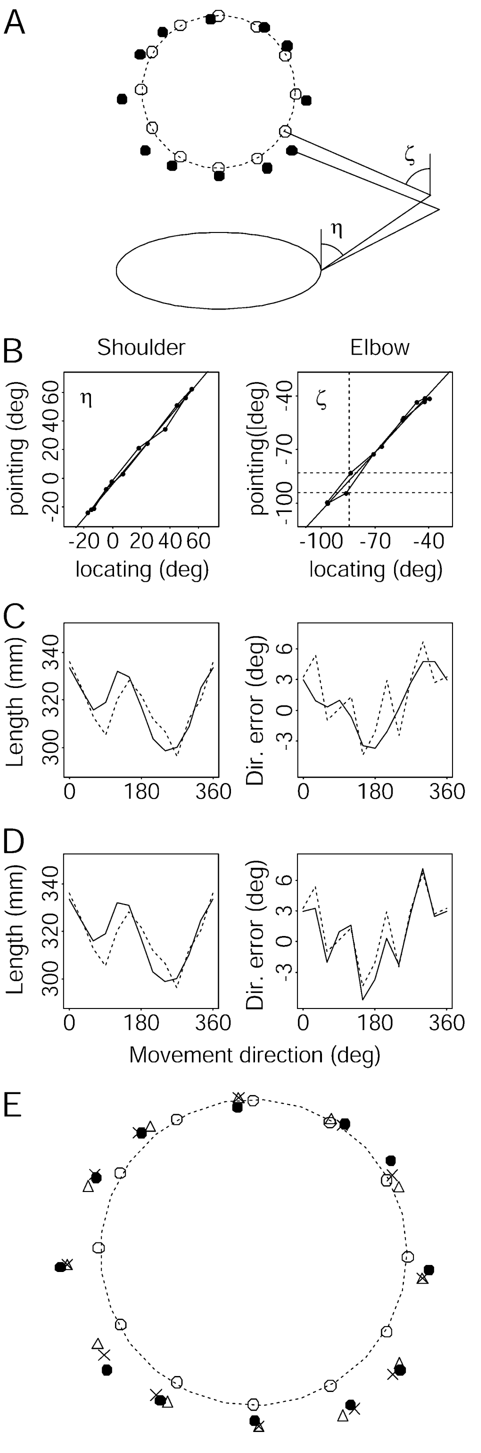

Fig. 11A–E Modelling systematic errors. **A** Targets (*empty circles*) and average endpoints (*filled circles*) in Experiment 1 (all participants in all conditions). The postural angles η and ζ relevant to the model are indicated in a schematic representation of the arm. **B** The relation between the postural angles at the end of the locating (*x*-axis) and pointing (*y*-axis) phase. Angle values were computed from targets and endpoint positions (see text). Linear psychophysical functions were fitted to the data points (*black dots*). **C** Movement amplitudes and directional errors (*dotted lines*) compared with model predictions (*continuous lines*). **D** Movement amplitudes and directional errors (*dotted lines*) compared with the predictions of the complete (*continuous lines*). **E** Endpoints predicted on the basis of the psychophysical functions alone (*triangles*), and by the complete model, which includes a direction-dependent bias (*crosses*) paring the predictions (continuous line) to the actual data (dotted line) shows that the two peaks of the movement amplitude are reasonably predicted. By contrast, the four peaks of the directional error are not predicted. As indicated in the right plot of panel B, the reason for the failure is that directional errors cannot be modelled by linear psychophysical functions. Indeed, the angle (η) of the forearm at the end of the locating motion is identical for the 30° and 120° target (vertical dotted line), whereas, to fit the data, the perceived orientation angle should take two different values (horizontal dotted lines). A more accurate account of the results can be obtained by including a source of directional error $D(\alpha)=K\ \sin(4\alpha)$ that depends explicitly on the target angle α. Thus, the final hand position (x, y) was expressed by:

$$x = l_a \sin(\eta) + l_f \sin(\zeta) + D(\alpha)\sin(\alpha)$$
$$y = l_a \cos(\eta) + l_f \cos(\zeta) - D(\alpha)\cos(\alpha)$$

where η and ζ are the perceived orientation angles predicted by the linear psychophysical functions, and the value of the constant K in the error term $D(\alpha)$ was set so as to optimize the fit to the data (Fig. 11D). This more complex model (crosses) fits much better the final hand positions than the simpler model based on the psychophysical functions alone (triangles).

Discussion

The experiments showed that errors in kinaesthetic pointing follow a well-defined pattern, which is basically impervious to manipulations of the passive displacements by which the target position is identified, and also fairly independent of the kinematics of the active movement itself. In both experiments, participants overshot targets along the lateral axis. In addition, oblique movements were attracted towards the closest diagonal. First, we discuss the reasons for such a robust behaviour. Then, we address the question of why the error distribution has the observed characteristics.

Invariance of the errors with respect to homing and locating motions

We wanted to ascertain whether, in the absence of vision, the kinematics of the locating and homing motions affect the kinaesthetic encoding of the target position. Magnitude and direction of the contact force between hand and robot differed considerably across conditions (Fig. 2), the magnitude being largest in conditions that differed most from natural movements. Instead, the average movement amplitude varied by less 11 mm (about 3% of the movement extent), and the average directional error varied less than 2° (Table 2). In particular, the amplitude was unaffected by the path curvature, suggesting that participants managed to discount the path detour in estimating the Euclidean distance of the target from the initial hand position.

In both experiments, the velocity profile imposed by the robot had a significant—albeit small—impact on the length of the pointing movement. However, the interpretation of this effect is subject to caution. On the one hand, velocity and length of the pointing movements were positively correlated—a common finding in the case of active movements (e.g. Adamovich et al. 1999). Thus, the kinematics of the robot could have influenced the velocity of the pointing, rather than amplitude per se. On the other hand, the effect was not consistent across experimental conditions. The longest pointing movements were associated with the lognormal velocity profile in Experiment 1, and with the Gaussian velocity profile in Experiment 2.

There were two other differences between the two experiments: (1) absolute errors were affected by velocity and curvature of the locating motion (Experiment 1), but not by the corresponding parameters of the homing motion (Experiment 2); (2) conversely, the direction of the pointing depended on the velocity profile of the homing motions, but not on the velocity profile of the locating motion. Over and above these differences, it remains that manipulating the robot motion had a far smaller and less systematic impact on errors than the direction of the pointing movement itself. Contrary to our expectations, pointing accuracy did not improve when the kinematics of the locating motion resembled that of natural movements (i.e. a straight path and a bell-shaped velocity). Moreover, errors were not related to the time-average of the contact forces during the imposed displacement. Apparently, the general notion that stimuli that mimic the kinematics of actual biological gestures are perceived more faithfully than other stimuli (Beardsworth and Buckner 1981; Johansson 1977; Liberman and Mattingly 1985; Prinz 1997; Viviani et al. 1997; Viviani and Stucchi 1992) cannot be generalized to the case where one has to perceive a spatial location on the basis of kinaesthetic cues alone. In fact, the robustness of the pattern of pointing errors with respect to the robot motion is in keeping with the results of a previous study showing that pointing accuracy does not depend on whether the same posture was adopted during the locating and pointing phases (Baud-Bovy and Viviani 1998).

These results do not imply that proprioceptive information acquired during the locating and homing phases is neglected, or that pointing movements are driven only by the positional information gathered while the hand is on target. Indeed, previous studies (Baud-Bovy and Viviani 1998; Helms-Tillery et al. 1994) have shown that participants tend to replicate the arm posture achieved at the end of the locating phase. In the present study, we found that the path of the locating and homing motion had a significant influence on the trajectory of the pointing movement (see Fig. 5). In particular, there were instances (see Fig. 2B) in which pointing movements attempted to mimic the path of the locating motion. Although accuracy was no better in these trials than in others, this occasional strategy demonstrates that a memory trace of the locating motion is available, and can be brought to bear in planning the subsequent pointing movement. Moreover, there is evidence that pointing errors can actually be affected by the manner in which the target position is identified and reached. For example, large deviations of the locating path from a straight-line result in a misestimation of target distance ("detour effect"; Fainetеau et al. 2003; Lederman et al. 1985). Similarly, movements tend to overshoot the targets when the locating motions are slower than the pointing movements, and to undershoot the targets in the opposite case (Imanaka and Abernethy 1990). However, it should be stressed that all the studies mentioned above manipulated the locating movements to a larger extent than we did. For example, the detour effect emerges when the path of the locating movement is at least twice as long as the straight path. Moreover, the most significant effects on pointing accuracy were observed by manipulating the initial position of the hand (Imanaka and Abernethy 2002; Walsh et al. 1979), which was not a controlled variable in our experiments.

Invariance of the kinematics of the pointing movements

At a gross level of description, most pointing movements displayed the typical features of ballistic movements, i.e. an almost straight path, and a bell-shaped velocity profile. There was no attempt to correct the hand position at the end of the approach phase by small submovements (Adamovich et al. 1999; Baud-Bovy and Viviani 1998). Moreover, peak velocity and peak acceleration of the pointing movements were inversely correlated with movement duration, indicating that the general features of the pointing movements were defined early on in the movement. Finally, although duration and average speed varied across trials, the shape of the velocity profiles was almost constant.

There was a small influence of the curvature of the locating or homing motion on the curvature of pointing movements. Even after discarding the trials that clearly corresponded to an attempt to reproduce the locating motion (see above), we found that movements were on average slightly deviated from the straight line in the same direction as the locating or homing motion, suggesting that the processes responsible for the trajectory formation are influenced by the memory trace of previous movements. We also observed small deviations of the pointing path from the straight line that depended on target direction. Movements perpendicular to the axis of the forearm, which could be executed predominantly by an axial rotation of the upper arm, were more curved than those that had the same orientation as the forearm axis. Perhaps, executing slightly curved trajectories simplifies the inverse kinematics problem (Atkeson and Hollerbach 1985; Cruse and Brüwer 1987; Haggard and Richardson 1996). Alternatively, these deviations may result from uncontrolled dynamic interactions between the limb segments during the execution of the movement (Flash 1987).

For some participants, and movement time, peak velocity and peak acceleration varied systematically with movement direction. However, these effects were less marked than previously reported (Gordon et al. 1994a, 1994b). In addition, several participants did not exhibit the expected pattern of directional anisotropy with lower acceleration peaks along the directions of maximum arm inertia. This discrepancy might be due to the fact that we did not specify the speed at which the pointing movements should be executed. In fact, constraining speed may be instrumental in producing velocity profiles that bear the mark of biomechanical factors (Gordon et al. 1994b).

The velocity profile of the pointing movement never reflected the early acceleration or late deceleration peaks of the locating or homing motion in the lognormal and inverted lognormal conditions. Like Adamovich et al. (1999), we found a tendency to increase movement length with movement speed (see also Imanaka and Abernethy 1990). However, the size of the effect was limited. On average, movement length increased only by 3% in spite of a twofold variation of movement duration. Thus, the tendency to produce longer movements at faster speeds is best viewed as a flaw in the processes that permits participants to select and execute pointing movements of different duration, quite independently from their length. The overall picture is that, because final accuracy was emphasized, participants were able to change the speed of the pointing movements across trials without affecting much the amplitude of the pointing movement.

Where do errors come from?

The lateral stretching of space suggested by the error distribution is often observed in the kinaesthetic (Adamovich et al. 1998; Baud-Bovy and Viviani 1998; Rao and Gordon 2001), but not in the visual, modality (Vindras and Viviani 1998). Adamovich et al. (1998) argued that the stretching is a *motor effect* arising in the course of the pointing phase. They also argued that in the visual modality the effect is cancelled by an opposite contraction of space along the same lateral axis akin to the "range effect" (Poulton 1975). The different error distribution in the visual and kinaesthetic case can be explained more parsimoniously by assuming that the lateral stretching is instead a *perceptual effect* specific to the kinaesthetic channel.

Converging evidence suggests that visual and kinaesthetic pointing are planned using extent and direction of the required displacement as control parameters (Gordon et al. 1994a, 1994b, 1995; Vindras and Viviani 1998). In the kinaesthetic modality, movement extent must either be estimated directly, or derived from positional information. The first possibility seems in contradiction with the so-called "radial-tangential" illusion. For example, the length of laterally oriented rods appears shorter than the length of sagittally (or radially) oriented rods (Cheng 1968; Davidon and Cheng 1964; Day and Wong 1971; Deregowski and Ellis 1972; Reid 1954; vonCollani 1979). Thus, if distances were perceived directly, lateral targets should have been undershot rather than overshot. Alternatively, we assume that in the absence of vision, extent and direction are derived from kinaesthetic estimations of the postural angles. We suggested (Baud-Bovy and Viviani 1998) the existence of a systematic bias in the perceived postural angles of the arm, which translates into an error in the perceived positions of the hand, and, therefore, in the plan for the movement to be executed. Because the pointing movement itself is essentially ballistic, the error is ultimately transferred to the final position. By incorporating these postural biases in a model of the performance, we were able to predict the overshooting of the lateral targets without invoking a specific motor error.

The tendency for oblique movements to deviate towards the diagonals (Fig. 9) has also been observed in visuomanual pointing (Gordon et al. 1994a, 1994b, 1995; Gourtzelidis et al. 2001; Sainburg et al. 1995; Smyrnis et al. 2000). Gordon et al. (1995) argued that the deviations towards the axis of least inertia of the limb (which corresponds approximately to the 45° diagonal) arise from an inadequate compensation of the inertial properties of the arm, whereas the deviations along the orthogonal direction are due to interaction torques (Gordon et al. 1995). Our results do not sit well with a biomechanical interpretation of the directional anisotropy, because directional errors were independent of the kinematics of the movements. In particular, if the clustering of the endpoints along the axis of maximum inertia resulted from interaction torques, the effect should have increased with speed. Instead, there was no difference among groups of trials with different average velocity (Fig. 10B, C), or with different indexes of linearity (Fig. 10E, F).

The same pattern of systematic deviations occurs in the estimation, judgement and reproduction of the orientation of visual stimuli. In his extensive study on visual estimation of orientation, Reese (1953) reported that constant errors were least for the vertical and horizontal orientations, intermediate at 45° (mid-quadrant), and maximum at 30° and 75° (see Howard 1982). Yakimoff et al. (1989) found a systematic deviation toward the 45-degree oblique when participants were asked to place a line in a dot pattern that was not aligned with the vertical or horizontal axes. Deviations towards the diagonals were also reported by Dick and Hochstein (1989) in one experiment where participants reported the subjective orientation of a tilted bar by telling the time that the bar would mark on a clock face. In the kinaesthetic modality, several studies have shown that vertical and horizontal orientations are perceived more accurately than oblique orientations (Appelle and Countryman 1986; Gentaz and Hatwell 1995, 1996; Lechelt and Verenka 1980). Unfortunately, no study has analysed separately the constant and variable component of the error at a number of orientations sufficiently large to describe fully the pattern of directional errors.

Because similar directional errors occur both in pointing tasks, and in estimating, judging and reproducing visual orientations, one and the same mechanism might be involved in all cases. In discussing the origin of the biases in the perception of orientation—which are sometimes referred to as “oblique effect” (Appelle 1972), Essock (1980) proposed a distinction between “class 1 effects” reflecting the basic functioning of the sensory system, and “class 2 effects” attributed to the higher-level encoding or memory processes involved “in identifying, remembering, matching, categorising or comparing the orientations of visual or somato-sensory stimuli” (Essock et al. 1997). In our experiments, biases in the perceived postural angles would qualify as “class 1 effects”, whereas directional errors would originate from a “class 2 effect”, which, as suggested by Gourtzelidis et al. (2001), might include a representational component. Specifically, there would be an (unconscious) tendency by the participants to categorize the circular workspace into quadrants delimited by the horizontal and sagittal axes (Huttenlocher et al. 1991). If so, the perceived position of oblique directions would drift towards a default (or prototype) position placed at the “centre of mass” of the quadrant (i.e. along one diagonal axis) whenever the true position of a point in the workspace is insufficiently specified by sensory inputs. Indeed, a model based only on postural biases could not explain the tendency for the endpoints of oblique pointing movements to be attracted by the diagonals (Fig. 8). To obtain a satisfactory fit of the data (Fig. 11), we had to incorporate in the model also a tendency to be attracted by the centre of mass of the quadrants.

Principles of equivalence

We suggest that the most parsimonious way of explaining the remarkable consistency with which positions are reached across variations in the manner in which they are identified, is to invoke the notion of equivalence between different hierarchical levels. The scheme we advertise assumes that kinaesthetic inputs, as well as efferent commands, give rise to a dynamic representation at the sensorimotor level wherein each movement preserves its specific identity. Within the context of a pointing task, a principle of *perceptual equivalence* is at work by virtue of which many of these representations are treated as equivalent. In this view, the input to the motor planning stage is not a set of parameters of one specific representation, but rather the abstract invariant that characterizes a class of equivalence over perceptual representations. The fact that the position reached at the end of the pointing movement is almost independent of the kinematics of the movement suggests that a further principle of *motor equivalence* is also at work between the representational and sensorimotor levels, which groups under one class all (potential) movements with a given endpoint. If there is no reason to do otherwise, any one motor solution within the class can be freely selected and implemented.

The principles of perceptual and motor equivalence do not imply that the representation of the target position is accurate, or that the actual endpoint coincides with the estimated target position. Thus, the scheme is compatible with both the presence of considerable variability in the performance, and the presence of a systematic pattern of errors. In fact, we have already argued that distortion occurs at the sensorimotor and representational levels. Specifically, the lateral stretching of the endpoints was credited to a bias in the psychophysical relationship between actual and perceived joint angles, and directional errors were credited to the peculiarities of an amodal representation, which is also responsible for the estimation and reproduction of visual orientations.

Our scheme does not exclude the possibility that the selection of a motor solution within a class of motor equivalence is biased by the specific representation instantiated within the sensorimotor level. Therefore, it can account for the occasional tendency by the pointing phase to mimic certain aspects of the locating phase such as replicating the arm posture achieved at the end of the locating movement. It should be stressed that the distinction between sensorimotor and representational levels, which may be debatable in the case of stimulus-driven movements, makes sense in the case of kinaesthetic pointing, where the coding and execution phases are necessarily separated in time. Because the endpoint distribution for kinaesthetic (Rossetti et al. 1996; Rossetti and Régnier 1995) and visual targets (McIntyre et al. 1997, 1998) depends on whether the motor response is immediate or delayed, pointing toward memorized targets is likely to be subserved by a different set of processes than stimulus-driven movements.

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