Exp Brain Res (2005) 163: 503–514
DOI 10.1007/s00221-004-2204-7

RESEARCH ARTICLE

Henry Faineteau · Edouard Gentaz · Paolo Viviani

Factors affecting the size of the detour effect in the kinaesthetic perception of Euclidean distance

Received: 3 April 2004 / Accepted: 11 November 2004 / Published online: 10 May 2005

Abstract Three experiments investigated the mechanisms by which we estimate Euclidean distances on the basis of kinaesthetic cues. In all experiments, blindfolded participants followed straight and curvilinear paths with a stylus. Then, with a straight response movement, they estimated the distance between the end-points of the previously explored path. Experiment 1 was designed to validate the hypothesis—made on the basis of results from a previous study—that errors in the kinaesthetic estimations of distances (detour effect) originate from the difficulty to decompose the displacement vector into relevant and irrelevant components, which would become more severe at points of inflection. Using elliptic paths (no inflections), we demonstrated that errors are indeed reduced considerably. The role of the orientation of the work plane was investigated in Experiment 2 in which the same paths used in our previous study were oriented in the frontal rather than the horizontal plane. The results indicate that the detour effect is independent of the orientation. Moreover, despite the asymmetry that gravity introduces between upward and downward movements, errors in the two directions are almost identical. Experiment 3 addressed two issues. First, we demonstrated that introducing a delay between the exploration of the path and the response did not alter significantly the pattern of errors. By contrast, we demonstrated that errors are severely reduced when the number of paths to be explored is reduced by half. The results of the three experiments are discussed within the context of current theories of sensori-motor coding.

Keywords Detour effect · Frames of reference · Kinaesthesia · Space representation · Distance estimation

H. Faineteau
Faculty of Psychology and Educational Sciences,
University of Geneva, Geneva, Switzerland

E. Gentaz
Cognition and Development Laboratory (CNRS),
René Descartes University, Paris, France

P. Viviani
Faculty of Psychology and Educational Sciences,
University of Geneva, 40, Boulevard du Pont d'Arve,
1205 Geneva, Switzerland

P. Viviani (✉)
Faculty of Psychology, UHSR University, Milan, Italy
E-mail: viviani@pse.unige.ch
Fax: +41-22-379-9229

Introduction

The present study investigated the kinaesthetic estimation of the Euclidean distance (ED; straight-line) between the start- and end-points of curvilinear movements. This question has initially been raised in haptics by Lederman et al. (1985) who asked participants to trace with the index finger a path marked on a flat surface by raised dots. Afterward, subjects had to judge the ED. They reported that the ED between start- and end-points of a curvilinear path tracked by following haptic cues is increasingly overestimated when the length of the path exceeds twice the ED. More precisely, errors begin to increase only for paths covering relatively large portions of the working space, in the horizontal plane.

This question was examined (Faineteau et al. 2003) when the estimation was based only on the kinaesthetic cues in the absence of vision. Blindfolded participants followed straight and curvilinear paths in the horizontal plane with a hand-held stylus (encoding phase). Then, with a straight movement, they estimated the ED between the start- and end-points of the path (response phase). The results showed that small paths yielded an overestimation of the ED, the errors increasing with the length of curvilinear paths. By contrast, the results for large paths showed that ED was consistently underestimated independently of the detour. To interpret these results, we argued that errors arise because the kinaesthetic system is not able to separate the sagittal from the orthogonal (irrelevant) component of the displacement vector. In other words, we assumed that participants were unable to ignore the orthogonal component and to base the estimation solely on the sagittal component. We also made the additional hypothesis that the separation is more difficult for the small scale than for large scale paths because, in the former case, the points of inflection are clustered in a more limited portion of the workspace. Indeed, from the geometric point of view, inflections are simply defined as the points along the path where the sign of the curvature changes. Instead, from the point of view of controlling a tracking movement along the path, inflections are peculiar points where agonists become antagonists, and vice versa. Moreover, the balance between the components of the displacement changes at the points of inflections. Thus, it is possible that it is more difficult to separate the sagittal from the orthogonal component of the displacement vector when these changes are close in space and time. The first experiment was designed to test this hypothesis, by considering paths that do not have points of inflections.

In Faineteau et al. (2003), path exploration and response movements were carried out in the horizontal plane. In this plane, the balance between the radial and tangential components of the encoding movement was different for straight and curved paths (the *radial* component is along a radius that emanates from, and is orthogonal to, the main body axis; the *tangential* component is along a line that is orthogonal to one of the radii). In the first case, hand displacements had only a radial component in the straight ahead direction (backward *or* forward). In the second case, hand displacements resulted from a complex combination of radial and tangential components. This difference may be relevant for the performance in as much as the tactile-kinaesthetic space is known to present peculiar metric anisotropies (Davidon and Cheng 1964; Day and Wong 1971; Hogan et al. 1990; Liddle and Foss 1963). For instance, although the two directions are actually parallel, a 10-cm standard appreciated haptically along a radial direction extending from the right side of the body is subjectively equal to a distance of about 7.6 cm along the tangential direction orthogonal to the sagittal plane (Davidon and Cheng 1964). Radial components seem to have a special status, because both the perception of lengths and the size of the horizontal–vertical (H–V) illusion depend on the orientation of plane in which stimuli are presented (Day and Avery 1970; Deregowski and Ellis 1972). In particular, the H–V illusion occurs when the movements are executed in the horizontal plane, but disappears in the frontal plane. Moreover, the orientation of the work plane may also affect the perception of other spatial properties such as orientation (Gentaz and Hatwell 1995, 1996, 1998) and parallelity (Kappers 2002). Thus, the second experiment was designed to eliminate the radial component by having the task performed in the frontal plane. We reasoned that if the presence of radial movements increases the difficulty of separating the sagittal from the orthogonal component of the displacement vector, the detour effect should be reduced in the frontal plane.

The third experiment controlled the delay between the encoding and the response phases. In haptics, the accuracy with which a test bar can be set parallel to a reference in the horizontal plane increases when a delay is imposed before the response (Zuidhoek et al. 2003). In the proprioceptive modality, Rossetti and collaborators tested the introduction of a delay between the localization of target arranged along a circle in the vertical plane (sagittal or transversal) and the subsequent movement of the hand toward the remembered target position (Rossetti and Régnier 1995; Rossetti et al. 1996). When there was no delay between localization and pointing, the distribution of the end-points was elongated in the direction of the movement. Instead, when the delay was 8 s, the distribution tended to be elongated in the direction of the target array. All these experiments have been taken to suggest that immediate responses would depend on an egocentric frame of reference, whereas delayed responses would code the target position within an allocentric frame of reference, by taking into account the entire spatial layout of the targets. This distinction may be relevant also in the case of the detour task. Indeed, it could be argued that, if there is sufficient time to re-code the information acquired during the tracking phase in an external frame of reference, it becomes easier to disentangle the sagittal and orthogonal components of the tracking movement. If so, it follows that the detour path effect should be reduced when one increases the delay between encoding and response phases.

Experiment 1

In Experiment 1, the estimation of the ED of half-elliptic paths in the horizontal plane was investigated. If the presence of points of inflection increases the difficulty in estimating the ED, the detour effect should be reduced with paths that do not have points of inflection.

Method

Participants

In total, 12 Geneva University students (6 males, 6 females) participated in this first experiment for payment. All participants were right-handed with a Bryden score of 5 (Bryden 1977). Informed consent was obtained from all participants, who remained naive, however, as to the expected effects of the experimental manipulations. The experimental protocol was approved by the Ethics Committee of the University of Geneva.

Apparatus

Movements were recorded with the help of a 63×46-cm digitizing table (WACOM, Neuss, Germany, UltraPad model UD-1825, sampling rate: 200 samples/s; spatial resolution: 100 lines/mm). The recording implement was a stylus with the size and weight of an ordinary ball-pen. Participants were seated in front of the table placed horizontally, with the trunk kept in the full upright position by a tightly fitting seat. The height of the seat with respect to the work plane was adjusted individually to achieve a comfortable posture. The table was mounted on rails, and could be moved laterally by the experimenter. On the table was placed a Plexiglas board in which several paths with rounded edges had been grooved (Fig. 1). Width and depth of the grooves matched the size of the tip of the stylus so that participants could track the paths accurately and smoothly by holding the stylus with the usual writing grip. There were 12 test paths (A–L) separated into three sets (S1: A, B, C, D; S2 : E, F, G, H; S3: I, J, K, L). Each set included one straight and three curved paths. The straight paths (A, E and I) were 7.5, 15 and 22.5 cm long for S1, S2 and S3, respectively, and were parallel to the sagittal axis of the participant. In all sets, the curved paths corresponded to the same parametric equations:

$$x = a\cos\theta \quad y = b\sin\theta$$

The corresponding values for the major (a) and minor (b) axes are indicated in Table 1. With these parameters, the ED between the end-points was equal to the length of the straight paths (i.e., 7.5, 15 and 22.5 cm, respectively). The curved paths follow a half-elliptic trajectory. Thus, the length of the paths E, F, G and H, in S2, and those of the paths I, J, K and L, in S3, were two and three times, respectively, that of the corresponding paths A, B, C and D in S1. Near the left edge of the table there was an additional 45-cm vertical straight path, which was used for recording the responses (see later).

Experimental conditions and procedure

Participants were blindfolded throughout the experiment. In each trial, there was an "encoding phase" followed by a "response phase". In the encoding phase, the experimenter guided the stylus-holding hand of the participant into the groove at one end of a path. At a sound signal, the participant had to track the path to the other end-point with a smooth, uninterrupted movement and stop there for 1 s. At the end of the encoding phase, the experimenter raised vertically the participant's hand and placed the response path under the stylus by moving the table to the right by the appropriate amount. Between the end of the encoding phase and the beginning of the response phase, which was prompted by a sound tone, 3 s elapsed. In the response phase, the participant had to move along the response path through a distance that she/he estimated to be subjectively equal to the ED between the end-points of the path tracked in the encoding phase. The response movement was always performed in the direction opposite to that of the encoding movement (with respect to the trunk). Participants knew that, because the response path was always aligned with the sagittal axis, the task was equivalent to that of reaching again the same spatial location where the encoding movement had began. However, we did not explicitly frame the task as one requiring to reach the same starting position again. When the participant was satisfied that the distance traveled was equal to the ED, she/he lifted the stylus from the groove. This stopped the recording and terminated the trial. No stringent time constraints were imposed on either the encoding or the response movements.

There were two experimental conditions, each performed by a randomly chosen group of ten participants. In one condition, the start point for the encoding phase was close to the body, and the hand was moving outward. In the other condition, the start point for the encoding phase was far from the body, and the hand was moving inward. Each path was traced eight times. Thus, there were 96 trials in each condition [8(trial)×4(path length)×3(scale)], which were administered in a different pseudo-random order to each participant. No feedback was provided concerning the accuracy of the responses. An experimental session lasted about 1 h, including a short rest period.

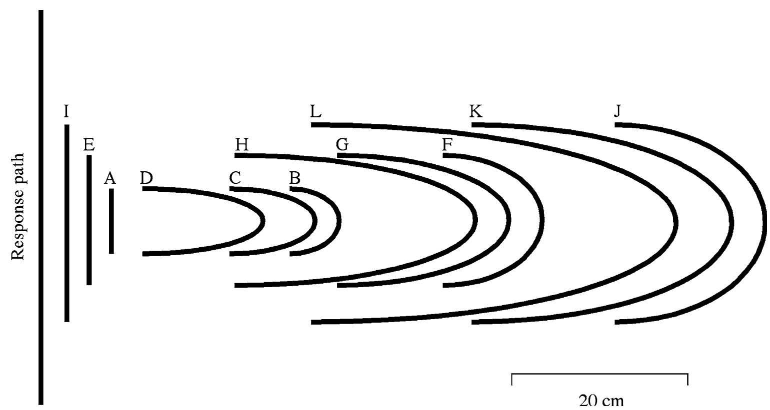

Fig. 1 Experiment 1. Outlay of the work plane. Each scale (S1: A, B, C, D; S2: E, F, G, H; and S3: I, J, K, L) included one straight and three half elliptic paths. The straight paths (A, E and I) were 7.5, 15 and 22.5 cm long, respectively, and were parallel to the sagittal axis of the participant. The length of the curved paths in the three sets was equal to two, three and four times the length of the corresponding straight paths, respectively (B = 15 cm, C = 22.5 cm, D = 30 cm, F = 30 cm, G = 45 cm, H = 60 cm, J = 45 cm, K = 67.5 cm, L = 90 cm). Responses were given by following the 45-cm vertical path on the left side of the board

Table 1 Experiment 1. Characteristics of the test paths (A–L)

Pathway	A	B	C	D	E	F	G	H	I	J	K	L
ED (b)	7.5	7.5	7.5	7.5	15	15	15	15	22.5	22.5	22.5	22.5
Major axis (a)	–	5.70	9.88	13.86	–	11.40	19.75	27.73	–	17.09	29.63	41.59
Detour = length/ED	1	2	3	4	1	2	3	4	1	2	3	4
Eccentricity	–	0.75	0.93	0.96	–	0.75	0.93	0.96	–	0.75	0.93	0.96
Length	7.5	15	22.5	30	15	30	45	60	22.5	45	67.5	90

Data processing

The beginning of the response phase was identified as the first sample for which movement velocity exceeded a threshold of 0.1 cm/s. The end of the phase was identified as the first sample after which the movement velocity amplitude remained below the same threshold value for more than 1 s. The response amplitude was then computed by subtracting the *y* coordinates of the initial and end-points (accuracy: 0.25 mm). Because both encoding and response movements were spatially constrained, their kinematics were fully described by their velocity. Velocities were computed by smoothing the raw data with a double-exponential filter (cut-off frequency = 8 Hz) and applying an optimal algorithm (minimax, finite impulse response) for numerical derivation (Rabiner and Gold 1975).

Results

The kinematics of the encoding and response movements depended on the path. Table 2 reports, for both types of movement, mean and standard deviation of the average velocity computed for all participants and all trials. In the encoding phase, the pattern of average velocities resulted from the combination of two factors: (1) the true ED (S1 5.26 cm/s, S2: 7.74 cm/s, S3 8.93 cm/s) and (2) the path length (1×ED 4.12 cm/s, 2×ED 6.91 cm/s, 3×ED 8.75 cm/s, 4×ED 9.46 cm/s). Encoding movements were slightly faster when they started from the distal than from the proximal position, but the effect was not statistically significant. In the response phase, the average velocity also resulted from the combination of two factors: (1) the true ED (S1 2.16 cm/s, S2 3.19 cm/s, S3 4.05 cm/s) and (2) the encoding direction (distal starting point 3.39 cm/s, proximal starting point 2.88 cm/s). The accuracy of the distance estimation was measured by the relative errors, i.e., the difference between the estimated and actual ED divided by the actual ED, with negative and positive values indicating underestimation and overestimation, respectively. Statistical analysis was patterned after the experimental plan by taking into account three factors: the scale (S1, S2 and S3), the path length (1×ED, 2×ED, 3×ED, 4×ED) and the direction (starting point for the encoding movement: distal or proximal). An ANOVA [3(scale)×4(path length)×2(direction) with repeated measures on the two first factors] demonstrated that the two movement directions during the encoding phase produced the same pattern of errors ($F_{1,10}$ = 1.735, $P > 0.25$). Thus, Fig. 2 summarizes the effects of scale and path length by averaging the data over trials, participants and directions. There was a significant main effect of the scale factor ($F_{2,20}$ = 1.8, $P = 0.003$), with an overestimation for small (S1) paths (mean error = 0.039) and an underestimation for larger (S2 and S3) paths (mean error: S2 = 0.080, S3 = −0.092). One-tailed *t* tests comparing the mean value of each condition (averaging over directions) with zero showed that the scale effect is present for each path that belongs to larger scales (S2 and S3, excepted for the path E).

Globally, the effect of path length was also significant ($F_{3,30}$ = 11.85, $P = 0.003$), with a general tendency to underestimate the ED (mean error 1×ED = −0.018, 2×ED = −0.104, 3×ED = 0.045, 4×ED = −0.010). Post-hoc analysis (Newman–Keuls test with 0.05 alpha level) showed that, in S1, values of mean error did not sig-

Table 2 Experiment 1. Mean (M) and standard deviation (SD) for all participants and all trials of the average velocity of the encoding and response movements as a function of path (A–L) and starting point (*distal*; *proximal*)

		S1				S2				S3			
		A	B	C	D	E	F	G	H	I	J	K	L
Velocity of encoding phase (cm/s)													
Distal	M	3.350	4.948	6.517	7.322	4.500	6.960	9.799	10.397	5.497	9.127	10.451	11.524
	SD	1.285	1.900	2.324	2.605	1.605	2.370	3.006	3.565	2.124	2.709	3.395	3.465
Proximal	M	2.790	4.536	5.946	6.672	3.926	6.847	9.586	9.939	4.662	9.030	10.203	10.940
	SD	1.231	2.011	2.087	3.118	1.861	3.027	5.130	4.766	2.500	5.267	5.280	5.654
Velocity of response phase (cm/s)													
Distal	M	2.424	2.193	2.365	2.179	3.443	3.119	3.490	3.663	4.576	4.391	4.273	4.546
	SD	0.798	0.784	0.935	0.875	1.159	1.181	1.309	1.378	1.626	1.391	1.238	1.572
Proximal	M	2.011	1.888	2.101	2.135	3.061	2.980	2.741	3.045	3.606	3.523	3.854	3.618
	SD	0.650	0.581	0.753	0.772	1.060	1.011	1.097	0.974	1.543	1.220	1.329	1.288

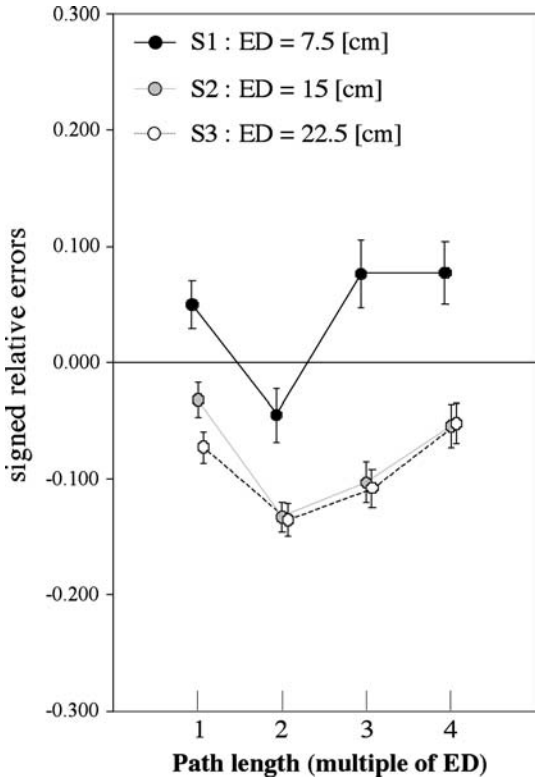

Fig. 2 Experiment 1. Mean and standard errors of signed relative errors in Euclidean judgements as a function of scale and path length (negative and positive values indicate under- and overestimation, respectively). Data are pooled for participants trials and encoding direction

nificantly differ among paths A (mean error = 0.050), C (mean error = 0.076) and D (mean error = 0.077). However, the mean error for path B (mean error = –0.045) significantly differed from those for paths A, C and D. In S2, the mean errors did not differ significantly among paths F (mean error = –0.133), G (mean error = –0.103) and H (mean error = –0.054). However, the mean error for path E (mean error = –0.032) differed significantly from path F, but not from paths G and H. In S3, no mean error was significantly different from the others (mean errors I = –0.072, J = –0.135, K = –0.108, L = –0.052). All interactions were not significant. The scale×length path interaction ($F_{6,60} = 1.62$, $P > 0.15$) was not significant.

We tested whether signed errors correlated with the average velocity of either the encoding or the response movements. Coefficients of linear correlation were computed for each path by pooling the data for all trials and all participants. No trend emerged for the encoding movement, the average correlation across paths being $r = -0.047$ and $r = -0.160$ for the distal and proximal starting point conditions, respectively. However, errors depended on the average velocity in the response phase, faster responses being associated with larger overshoots. The correlation was significant for most of the paths (Table 3), the average across all paths being $r = -0.315$ for the distal starting point condition and $r = -0.352$ for the proximal starting point condition. Exceptions were the straight paths A and E (for both starting points), the path F when the starting point was proximal, and the paths G, H, K and L when the starting point was distal.

Experiment 2

In Experiment 2, we wanted to investigate whether movements executed in the frontal plane influence the kinaesthetic perception of ED. If the presence of radial movements increases the difficulty to separate the sagittal from the orthogonal component of the displacement vector, the detour effect should be reduced in the frontal plane. Moreover, orientating the work plane vertically breaks the radial symmetry of the movements with respect to gravity. In the vertical plane, upward encoding movements involve a higher level of muscle activation than those in the reverse direction. Thus, if active forces have a role in perceiving the spatial consequences of the displacements, as suggested by Gentaz and Hatwell (1996), one should find a significant difference between ED estimations with upward and downward encoding movements.

Method

Participants

In this experiment, 10 Geneva University students (3 males, 7 females) participated for payment. None of them had participated in Experiment 1. All participants

Table 3 Experiment 1. Correlation between encoding movement velocity, response movement velocity, and signed relative Euclidean distance (ED) errors as a function of path (A–L) and starting point (distal, proximal)

	S1				S2				S3			
	A	B	C	D	E	F	G	H	I	J	K	L
Correlation between encoding movement velocity and ED error												
Distal	–0.134	–0.118	–0.097	–0.159	–0.196	0.140	0.071	0.044	0.264	0.262	–0.302*	–0.342*
Proximal	–0.021	–0.051	0.005	0.391**	0.034	0.034	0.351*	0.164	0.282	0.034	0.364*	0.334*
Distal	0.236	0.416**	0.511**	0.289*	0.202	0.432**	0.264	0.235	0.337*	0.446**	0.205	0.208
Proximal	0.186	0.439**	0.345*	0.559**	0.037	0.171	0.393**	0.326*	0.507**	0.388**	0.409**	0.464**

Probabilities for t tests (comparing r values to 0) are as follows: * $P < 0.05$, ** $P < 0.01$

were right-handed with a Bryden score of 5 (Bryden 1977). Informed consent was obtained from all participants, who remained naive, however, as to the expected effects of the experimental manipulations. The experimental protocol was approved by the Ethics Committee of the University of Geneva.

Apparatus

The apparatus and the data processing were those used in Experiment 1. There were 6 test paths (A–F) separated into two groups (S1 A, B, C; and S2 D, E, F), differentiated by a scale factor (Fig. 3). Each group included one straight and two variable-curvature paths. The straight (1×ED) paths (A and D) were 7.5 cm and 22.5 cm long for S1 and S2, respectively, and were parallel to the sagittal axis of the participant. In both groups, the curved portions of the paths had the same parametric equations:

$$x(\phi) = (c_1 \cos(8\phi) + c_2) \sin(\phi) \qquad (\phi = 0, \pi)$$
$$y(\phi) = (c_1 \cos(8\phi) + c_2) \cos(\phi) \qquad (\phi = 0, \pi)$$

For paths B and C, the constants (in mm) in the equations were: $c1 = 3.81$, $c2 = 33.69$. The corresponding values for E and F were: $c1 = 11.43$, $c2 = 101.07$. With these parameters, the ED between the end-points was equal to the length of the straight paths in the group (i.e., 7.5 cm and 22.5 cm, respectively). Two horizontal straight segments were added to the curved portions of the paths so as to make the length of the curved paths in the two groups equal to two (2×ED) and three (3×ED) times the length of the corresponding straight paths (B = 15 cm, C = 22.5 cm, E = 45 cm, F = 67.5 cm). Thus, the length of the paths D, E and F in S2 were three times that of the corresponding paths A, B and C in S1. Near the left edge of the table, there was an additional 45-cm vertical straight path, which was used for recording the responses.

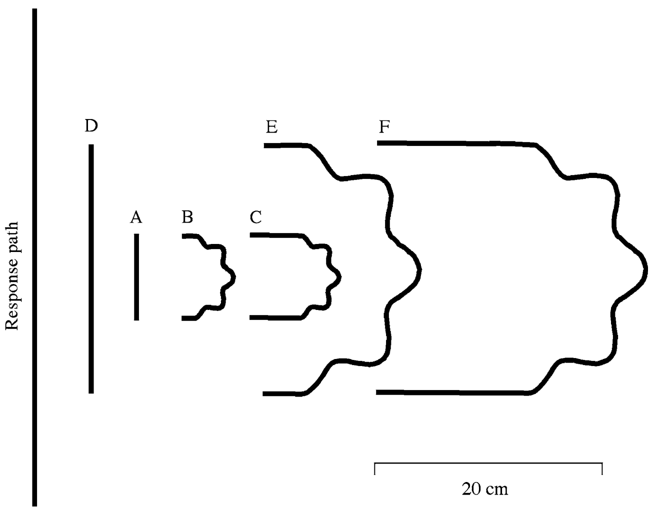

Fig. 3 Experiments 2 and 3. Outlay of the work plane. Each scale (S1 A, B, C; and S2 D, E, F) included one straight and two variable-curvature paths. The straight paths (A and D) were 7.5 cm and 22.5 cm long, respectively, and were parallel to the sagittal axis of the participant. The length of the curved paths in the two sets was equal to two and three times the length of the corresponding straight paths, respectively (B = 15 cm, C = 22.5 cm, E = 45 cm, F = 67.5 cm). Responses were given by following the 45-cm vertical path on the left side of the board

Experimental conditions and procedure

The board with the paths was positioned vertically in front of the participant. The end-points of the paths were always in the body mid-sagittal plane. After the encoding phase, the table was moved to the right by the appropriate amount so as to place the response path in the mid-sagittal plane of the participant. The start point was either in the bottom position (hand moving upward) or in the top position (hand moving downward). Each path was traced in both directions, the response movement being always in the opposite direction with respect to the encoding movement.

Throughout the experiment, participants were blindfolded. The trials included two phases: (1) an "encoding phase" and (2) a "response phase". Between the end of the encoding phase and the beginning of the response phase, 3 s passed. The procedure was the same as in Experiment 1. Once the path was encoded, participants were asked to estimate the ED between the start- and end-points.

Each path was traced eight times in each direction. Thus, there were 96 trials [8(trial)×3(path length)×2(scale)×2(direction)], which were administered in a different pseudo-random order to each participant. No feedback was provided concerning the accuracy of the responses. An experimental session lasted about 1 h, including a short rest period.

Results

The kinematics of the encoding and response movements depended on the path. Table 4 reports, for both types of movement, mean and standard deviation of the average velocity computed for all participants and all trials. In the encoding phase, the pattern of average velocities resulted from the combination of three factors: (1) the true ED (S1 3.83 cm/s, S2 6.55 cm/s); (2) the path length (velocity was higher for C than for B, and higher for F than for E) and (3) whether the path was straight or curved (C 4.47 cm/s, D 5.94 cm/s; both paths had the same length). In the response phase, the average velocity depended only on the true ED (S1 2.45 cm/s, S2 4.52 cm/s). Thus, in both phases, larger movements were executed at higher velocities. However, despite this spontaneous velocity compensation, the duration of the movement increased with its size.

The accuracy of distance estimation was again measured by the relative errors. Statistical analysis was patterned after the experimental plan by taking into account three factors: the scale (S1, S2), the path length

Table 4 Experiment 2. Mean (M) and standard deviation (SD) for all participants and all trials of the average velocity of the encoding and response movements as a function of path (A–F) and starting point (*downward*; *upward*)

Path	A		B		C		D		E		F	
Start	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up
Velocity of encoding phase (cm/s)												
M	3.745	3.971	3.287	3.347	4.773	4.406	5.732	6.200	6.449	6.319	7.164	7.029
SD	1.699	1.820	1.238	1.123	2.039	1.516	2.152	2.686	2.307	2.147	2.849	2.515
Velocity of response phase (cm/s)												
M	2.687	2.656	2.585	2.384	2.851	2.760	4.609	4.881	4.765	4.644	4.655	4.756
SD	0.292	0.231	0.286	0.222	0.312	0.288	0.405	0.485	0.462	0.466	0.476	0.483

(1×ED, 2×ED, 3×ED), the direction (hand moving upward, hand moving downward).

An ANOVA [2(scale)×3(path length)×2(direction), with repeated measures on the three factors] demonstrated that the two movement directions during the encoding phase produced the same pattern of errors ($F_{1,9}=0.09$, $P>0.25$). Figure 4 summarizes the effects of scale, path length and encoding direction by averaging the data over participants and trials. There was a significant main effect of the scale factor ($F_{1,9}=12.21$, $P<0.01$), with an overestimation for small (S1) paths (mean error = 0.213) and a near absence of errors for large (S2) paths (mean error = 0.008). One-tailed *t*-tests comparing the mean value of each condition (averaging over encoding directions) with zero showed that the ED for each path of S1 was significantly overestimated (A $t_{159}=5.327$, $P<0.001$; B $t_{159}=6.369$, $P<0.001$; C $t_{159}=10.295$, $P<0.001$). Mean relative Euclidean errors for paths within S2 did not differ significantly from zero,

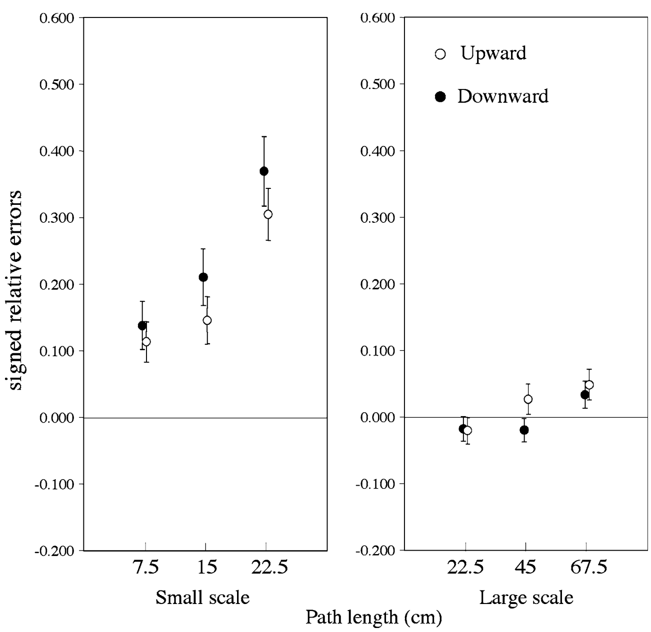

Fig. 4 Experiment 2. Mean and standard errors of signed relative errors in Euclidean judgements as a function of scale, path length and encoding direction (negative and positive values indicate under- and overestimation, respectively). Data pooled over participants and trials

except for the longest path (D $t_{159}=-1.388$, $P=0.167$; E $t_{159}=0.248$, $P>0.25$; F $t_{159}=-1.63$, $P=0.008$).

Globally, the effect of path length (pooled over S1 and S2) was also significant ($F_{2,18}=13.66$, $P<0.001$). However, because there was a significant scale×length path interaction ($F_{2,18}=7.65$, $P=0.039$), the length effect was different across scales. Post-hoc analysis (Newman–Keuls test with 0.05 alpha level) showed that in S1, the errors tended to be lower ($P=0.087$) in path A (mean error = 0.126) than in path B (mean error = 0.178) and lower in path B than in path C (mean error = 0.337). In fact, in group S1, there was a significant linear tendency between errors and path length ($F_{1,9}=12.9$, $P<0.01$). By contrast, in group S2, errors did not differ significantly among paths (mean errors: D = –0.019, E = –0.004, F = –0.041). In sum, the over-estimation tended to increase with path length in S1, whereas the accuracy of the estimations remained stable with path length in S2.

We tested whether signed errors correlated with the average velocity of either the encoding or the response movements. Coefficients of linear correlation were computed for each path by pooling the data for all trials and all participants. No trend emerged for the encoding movement, the average correlation across paths being $r=-0.013$ and $r=0.003$ for the downward and upward encoding conditions, respectively. However, errors depended on the average velocity in the response phase. There was a significant correlation for all paths and both directions ($P<0.001$ in all cases), the average across paths being $r=0.502$ for the downward encoding condition and $r=0.464$ for the upward encoding condition. Thus, response velocity increased as a function of the size of the response.

Experiment 3

In Experiment 3, we addressed the questions of whether the introduction of a delay between the encoding and response phases would affect the performance in the kinaesthetic estimation of ED. Delay time was varied across the conditions, being either 3 s—as in experiments 1 and 2—or 12 s [comparable to the conditions used by Rossetti et al. (1996) and Zuidhoek et al. (2003)]. As in Experiment 2, the work plane was oriented vertically. However, we tested only the ED condition for which a significant detour effect had been found (set of paths S1). By doing so, it was also possible to test the hypothesis that the overestimation of the ED is partly due to a range effect (overshooting short distances and undershooting long distances). The range effect has been interpreted as a natural tendency to produce response movements with an amplitude close to the mean amplitude of all movements performed in a given experimental context (Wilberg and Girouard 1976). The same ED was estimated both in Experiment 2, in which the other ED was also tested, and in experiment 3, in which it was the only tested distance. Thus, if our hypothesis is correct, the ED in Experiment 3 should be less overestimated than that in Experiment 2.

Method

Participants

In this experiment, 20 Geneva University students (3 males, 17 females) participated for payment. None of them participated in the previous experiments. All participants were right-handed with a Bryden score of 5 (Bryden 1977). Informed consent was obtained from all participants, who remained naive, however, as to the expected effects of the experimental manipulations. The experimental protocol was approved by the Ethics Committee of the University of Geneva.

Experimental conditions and procedure

The apparatus, the stimuli (Fig. 3) and the data processing were the same as in Experiment 2. Only the small scale paths were tested (A = 7.5 cm, B = 15 cm, C = 22.5 cm).

In this experiment, the delay between the encoding phase and the response phase was a controlled variable. There were two conditions defined by the delay between the encoding and response phases, which was either 3 s (“3-s delay condition”) or 12 s (“12-s delay condition”). It should be noted that the 3-s delay condition was the same as the “no-delay” conditions of Experiments 1 and 2. Each path was traced eight times in each direction. Thus, there were 48 trials in each condition [8(trial)×3(path)×2(direction)], which were administered in a different pseudo-random order to each participant. The two delay conditions were tested in separate sessions in successive days. To check the presence of learning effects, for half the participants, the 3-s delay condition was tested first, and the 12-s delay condition was tested another day. For the other half, the reverse order was applied. An experimental session lasted about 45 min, including a short rest period.

Results

Table 5 reports, for both movement directions (upward, downward), mean and standard deviation of the average velocity computed for all participants and all trials. In the encoding phase, the average velocity increased with the path length (A 2.62 cm/s, B 2.88 cm/s, C 3.66 cm/s).

As for Experiment 1, the accuracy of the distance estimation was measured by the relative errors. Statistical analysis was patterned after the experimental plan by taking into account the delay condition (3-s delay, 12-s delay), the path length (1×ED, 2×ED, 3×ED), the order of the experimental sessions (3-s delay condition before the 12-s delay condition, 12-s delay condition before the 3-s delay condition), and the direction (hand moving upward, hand moving downward).

A preliminary analysis of variance on signed relative errors showed that the experimental session order had no effect ($F_{1,18} = 0.053$, $P > 0.25$) and did not interact with any other factor. Consequently, results were collapsed across order of testing. An ANOVA [3(path)×2(direction)×2(delay condition), with repeated measures] demonstrated a significant effect of the path factor ($F_{2,38} = 8.738$, $P = 0.002$). Globally, signed errors increased only for the longest path (mean error: A = –0.004, B = –0.003, C = –0.073). Pooling over delay conditions, pre-planned contrasts demonstrated that

Table 5 Experiment 3. Mean (M) and standard deviation (SD) for all participants and all trials of the average velocity of the encoding and response movements as a function of path (A–C), delay condition and starting point (*downward*, *upward*)

	Path	A		B		C	
	Start	Down	Up	Down	Up	Down	Up
Velocity of encoding phase (cm/s)							
3-s delay	m	2.668	2.721	3.065	3.040	3.850	3.746
	sd	1.242	1.146	1.299	1.181	1.683	1.147
12-s delay	m	2.431	2.666	2.745	2.704	3.441	3.610
	sd	1.251	1.127	1.124	1.027	1.496	1.477
Velocity of response phase (cm/s)							
3-s delay	m	2.001	1.818	1.964	1.897	1.956	1.888
	sd	0.844	0.734	0.813	0.775	0.768	0.722
12-s delay	m	1.633	1.460	1.616	1.452	1.738	1.517
	sd	0.698	0.663	0.688	0.635	0.886	0.731

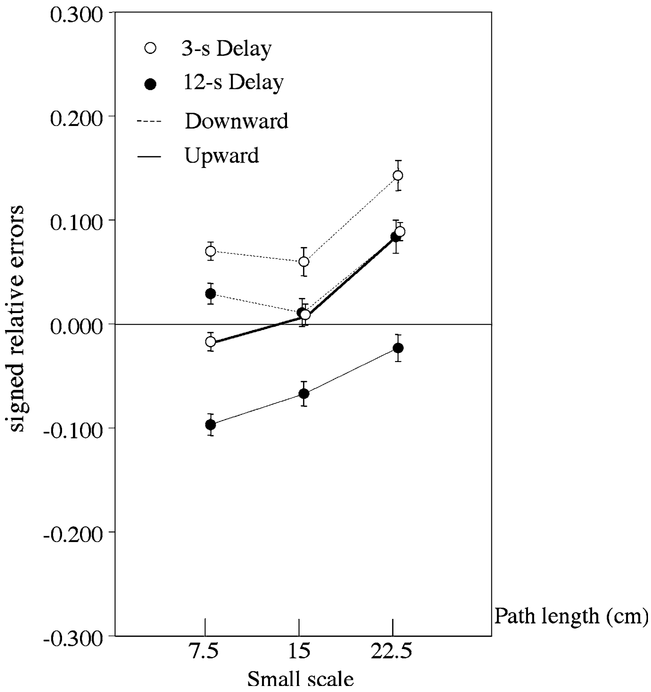

Fig. 5 Experiment 3. Mean and standard errors of signed relative errors in Euclidean judgements as a function of scale, path length, encoding direction and delay condition (negative and positive values indicate under- and overestimation, respectively). Data are pooled for participants and trials

errors were not different between A and B ($F_{1,19}=0.098$, $P>0.25$), and smaller for B than for C ($F_{1,19}=25.61$, $P<0.001$).

The delay also had an effect ($F_{1,19}=9.462$, $P=0.006$), estimates of the ED being globally overestimated in the 3-s delay condition (mean error = 0.059). However, in the 12-s delay condition, upward encoding movements led to underestimation of ED (mean error = –0.062), and downward movements to an overestimation (mean error = 0.041). Finally, an effect of direction was also significant ($F_{1,19}=17.31$, $P=0.001$). When the encoding direction was downward, ED was systematically overestimated (mean error = 0.066); for upward encoding movements, ED was underestimated for paths A and B, and slightly overestimated for path C. In order to check in which delay condition performances were more sensitive to the encoding direction, separate analyses were carried out. An ANOVA [3(path)×2(direction), with repeated measures] was conducted for each delay condition and showed that the encoding direction effect (Fig. 5) was much more marked in the 12-s delay condition ($F_{1,19}=23.29$, $P<0.001$) than in the 3-s delay condition ($F_{1,19}=4.73$, $P=0.042$). No interaction was significant.

We tested whether signed errors correlated with the average velocity of either the encoding or the response movements. Coefficients of linear correlation were computed for each path by pooling the data for all trials and all participants (Table 6). In the 3-s delay condition, results showed that the encoding direction influenced the correlation between the signed errors and the average velocity of the encoding movements. Across paths, the average of the coefficient of linear correlation was $r=0.246$ for downward encoding condition ($P<0.001$), and $r=0.046$ for upward encoding condition ($P>0.10$). More precisely, a significance level of 0.05 was reached for each of the three paths in the downward encoding condition, whereas it was not reached for any path in the upward condition. In the 12-s delay condition, the average across paths of the coefficient of linear correlation was $r=0.274$ for the downward encoding condition, and $r=0.117$ for upward encoding condition. More precisely, a significance level of 0.05 was reached for the paths B and C in the downward encoding condition, and for the paths A and C in the upward condition.

There was a positive correlation between signed errors and the average response velocity, for all paths, and both delay conditions. In the 3-s delay condition, the average across paths of the coefficient of linear correlation was $r=0.427$ for downward encoding condition and $r=0.330$ for the upward encoding condition ($P<0.001$). In the 12-s delay condition, the corresponding values were higher, namely $r=0.540$ and $r=0.494$ for upward and downward encoding conditions ($P<0.001$). A significance level of 0.01 was reached in all cases.

We compared the data obtained in Experiments 2 and 3 to test whether the performance in the 3-s delay condition was affected by the context. The experimental context differed across experiments 2 and 3 by the number of EDs to estimate. In the latter experiment, the small-scale paths (S1) were the only stimuli proposed

Table 6 Experiment 3. Correlation between encoding movement velocity, response movement velocity and signed relative Euclidean distance (ED) errors as a function of path (A–C), delay condition and starting point (*downward*, *upward*)

Path	A		B		C	
	Start Down	Up	Down	Up	Down	Up
Correlation between encoding movement velocity and ED error						
3-s delay	0.183*	0.007	0.254**	0.065	0.301**	0.066
12-s delay	0.112	0.160*	0.233**	−0.020	0.476**	0.211**
Correlation between response movement velocity and ED error						
3-s delay	0.492**	0.327**	0.464**	0.311**	0.285**	0.394**
12-s delay	0.494**	0.578**	0.549**	0.500**	0.480**	0.504**

Probabilities for t tests (comparing r values to 0) are as follows: * $P<0.05$, ** $P<0.01$

whereas, in the former experiment, they were presented in conjunction with the larger paths (S2). An ANOVA [3(path)×2(direction)×2(experimental context), with repeated measures on the two former factors] demonstrated a significant effect of the experimental context ($F_{1,28}=5.741$, $P=0.023$), indicating that ED estimations were less accurate when two EDs were tested in the same experiment (mean error: Experiment 2 $=0.214$; Experiment 3 $=0.059$). However, because there was a significant experimental context×path length interaction ($F_{1,28}=5.31$, $P=0.029$), the effect of the context was different across paths. Pair-wise comparisons for each path demonstrated that when participants had to estimate two EDs, Euclidean errors increased significantly (two-tailed t-tests for independent samples: A $t_{58}=2.24$, $P=0.029$; B $t_{58}=2.61$, $P=0.011$; C $t_{58}=-3.39$, $P=0.001$).

General discussion

In these experiments, we investigated four factors potentially relevant for the kinaesthetic estimation of the ED in the path integration task. Specifically, we examined the well-known detour path effect, i.e., the erroneous estimation of the ED that occurs when the path from the initial to the final point is not straight. The following factors were considered: (1) the presence of points of inflection in the path, (2) the presence of a radial component in the movement during the encoding phase, (3) the delay between the encoding and response phases and (4) the number of EDs tested in one experimental session.

In Experiment 1, for each of three EDs, we tested 4 paths with a length of one, two, three and four times the ED. The set of 12 paths included all the lengths already considered in a previous study (Faineteau et al. 2003). However, unlike the paths in that study, the trajectories were half ellipses with no points of inflection. The results showed that EDs were generally underestimated for large scale paths (S2 and S3) and overestimated for small scale paths (S1). The scale did not have a graded effect in so far as the results for S2 and S3 were virtually identical, and quite different from those for S1. This behavior is not what one would expect from a range effect. Rather, it may be taken to indicate a rather sharp transition between the mode of accessing kinaesthetic information within a limited portion of the workspace, and the mode that sets in for larger portions of the workspace.

The new result was that the detour path effect, which was very conspicuous in the presence of points of inflection (Faineteau et al. 2003), disappeared when the paths had no inflections. For all paths, the estimated EDs were independent of the length of the detour. In our previous report, we argued that the detour effect arises because, at the points of inflection, it is difficult to isolate the component of the encoding movement that is parallel to the response movement (at points of inflection the balance between components changes). Whereas a veridical ED would require integrating only the parallel component over time, we supposed that the estimated distance is inflated by the (spurious) contribution of the orthogonal component. The fact that the detour effect occurred only with small scale paths suggested that filtering out the orthogonal component becomes difficult as the points of inflection get closer in time and space. The disappearance of the detour effect for the small scale stimuli when there are no points of inflection is in keeping with this hypothesis. It is worth noting that also in the haptic modality the detour effect has been demonstrated only for paths that have inflections (Lederman et al. 1985).

In Experiment 2, the conditions were the same as in the on-axis condition in the experiment by Faineteau et al. (2003), except for the plane orientation (vertical instead of horizontal). The change of orientation had two consequences. On the one hand, in the frontal plane, the encoding movement never has a radial component. Thus, comparing the results in the two planes would permit one to ascertain whether the presence of both radial and tangential components in the encoding movement was detrimental for the estimation of the ED. The results showed that the ED for small scale paths was overestimated, the errors increasing with the length of the detour. By contrast, there was no detour effect for large scale paths. In this case, estimations were more accurate and results showed that errors did not differ from zero except for the longest path. Even though errors for S1 were higher than those reported previously (Faineteau et al. 2003), and those for S2 were almost null, the general trend of errors as a function of path length is similar in the two studies. Thus, because the detour effect is independent of the work plane orientation, the presence of a radial component does not seem to have a significant impact on kinaesthetic accuracy.

On the other hand, performing the task in the vertical plane permitted one to address the question of the role that active forces may have in perceiving the spatial consequences of the displacements. In the immediate-response condition adopted for this experiment, upward and downward encoding movements resulted in very similar patterns of errors, which seems to exclude the hypothesis that the voluntary effort to raise the hand provides a richer array of kinaesthetic information than downward movements. At least in the context of our task, the results do not support the active versus passive distinction suggested by previous studies on kinaesthetic positioning (Paillard and Brouchon 1968).

Finally, Experiment 3 allowed us to assess the role of two factors: (1) the time interval between the encoding and the response phases and (2) the importance of the context (one ED versus two EDs). Not surprisingly, having tested only small scale paths, a detour effect was still clearly present. However, the tendency to overestimate the ED with increasing path length was weaker than in Experiment 2, possibly because only one set of paths was tested. Both for downward and upward encoding movements, increasing the response delay from

3 s to 12 s resulted in a uniform reduction of the amplitude of the response. In the former case, errors remained positive; in the latter, overshooting turned into undershooting. When the hand is maintained for 12 s in an upward position, the anti-gravitational forces elicited by this posture provide cues that result in a reduced perceived ED. We cannot be specific about the nature of these cues.

By comparing the results of Experiment 3 in the 3-s delay condition with the analogous results from Experiment 2 (obtained with the same delay), it appears that the experimental context had a significant effect on global accuracy. Indeed, the mean signed errors for small paths in Experiment 2 (two EDs tested) were as much as three times larger than those in Experiment 3 (one ED tested). Moreover, also the variability of the relative error was higher when two sets of paths were tested instead of one.

The experimental context interacted with the effect of the direction of the encoding movement (upward or downward). Unlike in Experiment 2 (small scale paths), the upward encoding movements in Experiment 3 resulted mostly in an underestimation the ED, whereas downward encoding movements clearly overestimated the ED. The experimental context also affected the relationship between encoding velocity and accuracy. In Experiment 2, there was no correlation between the velocity of the encoding movements and the accuracy of the responses, while, in Experiment 3, velocity and accuracy were correlated for downward movements in the 3-s delay condition (Table 6).

To conclude, we addressed the question of the system(s) of representation that is(are) involved in the performance of the task. In a recent paper, Klatzky and Lederman (2003) presented evidence that at least three types of representation are potentially relevant for kinaesthetic pointing tasks in which angles, positions and distances have to be estimated. Specifically, they assume that a kinaesthetic representation of movement in terms of sensory inputs is translated first into an extrinsic representation where reference is made to a location in external space and, finally, to a configural representation where salient landmarks are identified in terms of angles and relative distances. Each representation may be called into play according to the requirements of the task. The authors, however, do not rule out the possibility that, quite independently of these representations, tasks such as that investigated here call for ad-hoc, movement-based strategies. Our results seem to confirm this last suggestion. On the one hand, separating the displacement vector into a component parallel to the direction from the start to the end-point, and a component orthogonal to this direction (see above), may well be construed as a movement-based heuristics that does not rely on an explicit representation of locations. On the other hand, the fact that increasing the delay between the encoding and the response phases did not alter consistently the performance does not support the hypothesis suggested by Zuidhoek et al. (2003) of a transition from an egocentric to an allocentric view point within an extrinsic representation of the landmarks. Finally, the fact that eliminating the radial component of the encoding movement also failed to produce a significant change in performance runs again counter to the notion that directions relative to an egocentric reference may play a role in distance estimation. However, unlike Klatzky and Lederman (2003), we cannot exclude that the heuristics utilized in our task draws on information that pertains to the kinaesthetic level of representation. Indeed, the main clue for detecting an inflection during a movement is the inversion of the role between agonist and antagonist muscle synergies, which is likely to be signaled by the sensory inputs from the effectors. The confirmed observation that the detour effect does not occur when the encoding movements span a large portion of the workspace is in keeping with the suggestion (see "Introduction") that the accuracy with which movement components can be separated is affected by the presence of inflections only when they are close in space and time.

Acknowledgements This work was supported by FNRS Grant 31-55620.98 to P.V., Cognitique Program Grant COG 78B (French Ministry of Research) to E.G., and by research funds from UHSR University. We thank the CERN (Geneva) technical services for manufacturing the boards used in the experiments.

References

Bryden MP (1977) Measuring handedness with questionnaires. Neuropsychologia 15:617–624

Davidon RS, Cheng MH (1964) Apparent distance in a horizontal plane with tactile-kinesthetic stimuli. Quart J Exp Psychol 16:277–281

Day RH, Avery GC (1970) Absence of the horizontal-vertical illusion in haptic space. J Exp Psychol 83:172–173

Day RH, Wong TS (1971) Radial and tangential movement directions as determinants of the haptic illusion in an L figure. J Exp Psychol 87:19–22

Deregowski J, Ellis HD (1972) Effect of stimulus orientation upon haptic perception of the horizontal-vertical illusion. J Exp Psychol 95:14–19

Faineteau H, Gentaz E, Viviani P (2003) The kinaesthetic perception of Euclidean distance: a study of the detour effect. Exp Brain Res 152:166–172

Gentaz E, Hatwell Y (1995) The haptic "oblique effect" in children and adults' perception of orientation. Perception 24:631–646

Gentaz E, Hatwell Y (1996) Role of gravitational cues in the haptic perception of orientation. Percept Psychophys 58:1278–1292

Gentaz E, Hatwell Y (1998) The haptic oblique effect in the perception of rod orientation by blind adults. Percept Psychophys 60:157–167

Hogan N, Kay BA, Fasse ED, Mussa-Ivaldi FA (1990) Haptic illusions: Experiments on human manipulation and perception of "virtual objects". Cold Spring Harbor Symp Quant Biol 55:925–931

Kappers AM (2002) Haptic perception of parallelity in the midsagittal plane. Acta Psychol (Amst) 109(1):25–40

Klatzky RL, Lederman SJ (2003) Representing spatial location and layout from sparse kinesthetic contacts. J Exp Psychol Hum Percept Perform 29(2):310–325

Lederman SJ, Klatzky RL, Barber PO (1985) Spatial and movement-based heuristics for encoding pattern information through touch. J Exp Psychol Gen 114:33–49

Liddle D, Foss BM (1963) The tactile perception of size: some relationships with distance and direction. Quart J Exp Psychol 15:217–219

Paillard J, Brouchon, M (1968) Active and passive movement in the calibration of position sense. In: Freedman SJ (ed) The neuropsychology of spatially oriented behavior. Dorsey Press, Homewood IL, pp 35–55

Rabiner L, Gold B (1975) Theory and application of digital signal processing. Prentice-Hall, Englewood Cliffs, NJ

Rossetti Y, Régnier C (1995) Representations in action: pointing to a target with various representations. In: Bardy BG, Bootsma RJ, Guiard Y (eds) Studies in perception and action III. Lawrence Erlbaum, Mahwah NJ, pp 233–236

Rossetti Y, Gaunet F, Thinus-Blanc C (1996) Early visual experience affects memorization and spatial representation of proprioceptive targets. Neuroreport 7(6):1219–1223

Wilberg RB, Girouard Y (1976) Distance perception affected by retention of the stimuli in short-term memory. Can J Psychol 30(2):63–71

Zuidhoek S, Kappers AM, van der Lubbe RH, Postma A (2003) Delay improves performance on a haptic spatial matching task. Exp Brain Res 149(3):320–330