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Speed-accuracy trade-off in the performance of pointing movements in different directions in two-dimensional space

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Abstract Nine healthy subjects performed 2D pointing movements using a joystick that controlled a screen cursor. Continuous visual feedback was provided until movement completion. Three variables were systematically manipulated: (1) target distance, (2) target size and (3) target direction. A four-way factorial ANOVA was used to analyze the effects of these fixed factors and of the random factor of subject on several movement parameters. Movement time increased with increasing distance and decreasing target size and as predicted from Fitts' law. The target direction did not affect movement time. In contrast the direction, distance and size of the target significantly affected the movement time until the first zero crossing on the speed record reflecting the time to bring the arm into the vicinity of the target. Movements on the lateral axis of the horizontal plane (horizontal movements) resulted in a decrease in initial movement time compared to movements on the anterior axis of the horizontal plane (vertical movements). A significant effect of target distance and direction but not target size was observed for the magnitude of maximum acceleration, maximum speed and maximum deceleration. Horizontal movements had a larger maximum acceleration, speed and deceleration. Furthermore the maximum speed and deceleration occurred earlier in time for these horizontal movements. Finally the number of secondary peaks on the speed record increased with decreasing target size and was not affected by the target distance or target direction. In conclusion our results indicate that different movement parameters are affected by target distance, size and direction. The crucial distinction was between parameters affected by target size and direction. These parameters did not overlap. Target direction affects the first part of movement execution while target

size affects the final part of movement execution. Thus a clear segmentation of movement execution in two phases is supported by these results. The implications of these results for theoretical models of speed-accuracy trade-off are discussed.

Key words Pointing movement · Speed-accuracy trade-off · Movement direction · Human · Motor control

Introduction

The execution of a fast and accurate pointing movement results in the observation that speed and accuracy are inversely related (speed-accuracy trade-off). When the accuracy of the movement (defined as the specified target width) is manipulated then movement time is related to the required distance and accuracy of the movement through the equation:

$$MT = a + b \log_2 (2 \times \text{targetdistance} / \text{targetwidth})$$

MT is movement time and a and b are regression coefficients (Fitts 1954; Fitts and Peterson 1964). This formulation, often referred to as "Fitts' law," has been verified for a variety of different experimental conditions using different parts of the body for accurate pointing (see Plamondon and Alimi 1997 for review). When the accuracy of the movement is allowed to vary then variability of the end point of a pointing movement increases with increasing distance and decreasing time to movement completion (Schmidt et al. 1979). Other models constructed to explain the speed-accuracy trade-off resulted in reformulations of Fitts' law to fit certain sets of experimental data (Crossman and Goodeve 1983; Jagacinski et al. 1980; Hoffman 1991; MacKenzie 1989; Meyer et al. 1988; Plamondon 1995a, 1995b; Burdet and Milner 1998). One issue that has not been addressed by these models concerns the generality of Fitts' law for movements in different directions in two-dimensional space (Georgopoulos et al. 1981; Hermann and Soechting 1997). It has been shown that the direction of movement

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affects the accuracy of the movement when no visual feedback is provided and the accuracy is measured as the amount of end-point variability of the movement (Gordon et al. 1994b). Furthermore, the effects of target direction and distance on end-point variability are independent, suggesting that direction and distance are separately specified by the motor system (Gordon et al. 1994a).

The first aim of this study was to investigate the effects of direction of a pointing movement on the speed-accuracy trade-off. Thus the distance and size of the target were also systematically varied. Visual feedback of the pointing movement was continuously available.

The study of arm movements in two-dimensional and three-dimensional space has resulted in the following major observations: (1) the movement trajectory is close to a straight line and (2) the velocity curve of the movement is bell shaped (Georgopoulos et al. 1981; Morasso 1981; Soechting and Laquanity 1981; Abend et al. 1982). The execution of accurate pointing movements results in a velocity profile that has more than one peak. It has been proposed that a rapid and accurate movement can be decomposed in two phases: (1) the initial adjustment phase and (2) the current control phase. During the first phase, a large, bell-shaped velocity peak helps to bring the arm to the vicinity of the target while the secondary small peaks that follow help to accurately reach the target location (Woodworth 1899). However, there is disagreement as to the actual nature of and processes underlying the two phases. The first peak has been proposed to reflect the transport phase. Several groups have proposed that the magnitude of this peak is proportional to the movement speed while its shape remains invariant (Hollerbach and Flash 1982; Atkeson and Hollerbach 1985; Soechting 1984). However, when the accuracy of the movement is manipulated the shape of the initial velocity peak is affected (Marteniuk et al. 1987; MacKenzie et al. 1987). More specifically, the decelerating phase of the velocity peak is prolonged for more accurate movements. The smaller peaks appearing at the end of the velocity record might reflect a different process that is used to fine-tune the accuracy in reaching (Soechting 1984). These smaller peaks disappear when viewing the arm is not permitted (Chua and Elliott 1993, 1997), thus indicating a visual feedback control. Other models propose that the final velocity peaks need not reflect a feedback process (Plamondon 1995a, 1995b; Plamondon and Alimi 1997). Finally it has been proposed that the whole movement trajectory is under feedback control in the sense that the ongoing motor response is constantly compared with the goal of the movement (or its internal representation) (Prablanc and Martin 1992).

We studied the velocity profiles of movements in two-dimensional space by manipulating the accuracy and distance of the movement. We expected from previous observations (Gordon et al. 1994a; Ghez et al. 1994) that the velocity would be affected by the direction of movement. This effect has been explained by the hypothesis that different initial inertia due to the position of the arm

is not compensated by the initial force the subject applies for different movement directions. This initial inertia anisotropy results in different initial accelerations. The second aim of this study was to investigate the interaction of movement direction with movement amplitude and movement accuracy on the velocity profile. Preliminary results of this study have been reported (Smymnis et al. 1998).

Materials and methods

Nine healthy subjects, seven male and two female [mean age 33.2 years, standard deviation (SD) 7.8 years], participated in this study. They were recruited from the staff and medical students at the Neurology Department of Aeginition Hospital. We received informed consent from all subjects after explaining to them the experimental procedure. The hospital ethics committee had approved the experimental protocol.

Each subject sat comfortably in front of a computer screen placed at a distance of 70 cm from his/her forehead. The subject's head rested on a head cushion mounted on the chair.

The subject rested his/her hand on a joystick handle that could move freely. The movement of the joystick was almost frictionless. The joystick was a commercially available analog model that was modified for the purposes of this experiment. More specifically a spherical ball was attached to the joystick shaft that was used by the subjects to grasp the handle. The two potentiometers (X, Y) of the joystick were modified to measure potential as an output (instead of resistance) and the center of the two potentiometers was calibrated to zero potential (maximum potential was ± 5 V). The joystick was positioned on a horizontal surface at waist level approximately 20 cm in front of the subject. The joystick handle was centered with respect to the body axis of the subject. Joystick movement controlled the X, Y position of a cursor on the computer screen. Data were sampled at 200 Hz using an analog 12-bit A/D converter (PCL-812PG, Advantech Co.) The ratio of joystick movement to cursor movement on the screen was 0.27, meaning that a 23-mm movement of the upper end of the joystick handle corresponded to a 85-mm movement of the cursor. For this range of small movements of the joystick, the joystick and the arm moved in a horizontal plane. All distance measurements in this study represent joystick handle displacement that is the actual distance that the hand moved.

The subject performed pointing movements so that the cursor entered visual targets appearing on the screen. Each trial started when a target circle (diameter = 2.3 mm) appeared at the center of the screen. The subject moved the cursor within this target circle a variable distance and waited for a period of 3–4 s after which a peripheral target circle appeared. The subject was instructed to move the cursor as fast as possible to enter the peripheral target circle and maintain that position for 0.5 s. The following conditions constituted trial errors for which a tone of 200 Hz lasting 0.2 s was delivered:

1. The subject initiated the movement by exiting the center target before 0.1 s had elapsed after the peripheral target presentation (anticipation error).
2. The subject failed to initiate the movement by exiting the center target within 1 s after the peripheral target presentation (latency error).
3. The subject did not enter the peripheral target circle within 0.5 s from movement initiation measured as the time when the subject's movement exited the center target circle (movement time error).
4. The subject moved the cursor outside of the peripheral target before 0.5 s had elapsed from the time that the cursor had entered the peripheral target circle (target pass error).

After the completion of the trial the screen was blank for 1 s before the center target was turned on again.

The peripheral target circle was defined by the following parameters: (1) four different distances from the center of the center target to the center of the peripheral target (5.75 mm, 10.35 mm, 14.95 mm, 19.55 mm), (2) four different sizes (diameters of 2.3 mm, 3.5 mm, 4.6 mm, 5.8 mm), (3) four different directions in 2D space (right, corresponding to a right movement of the joystick handle; left, corresponding to a left movement; up, corresponding to a forward movement away from the body; and down, corresponding to a backward movement towards the body). Thus, 64 combinations of target distance, size and direction were used. Three repetitions of all combinations (192 trials) had to be performed without error for task completion. Only four subjects completed the task. The others stopped at about 200 movements without completing the full set of correct trials.

For each trial we recorded the X , Y position data for the joystick movement. After smoothing using a running average of five consecutive values, the X , Y joystick position data were used to measure the instantaneous speed of movement (measured as the speed between two consecutive points X_1 , Y_1 and X_2 , Y_2) as follows:

$$\text{Distance} = ((X_2 - X_1)^2 + (Y_2 - Y_1)^2)^{1/2}$$

The instantaneous speed then was this distance in millimeters divided by the sampling interval (0.005 s). Figure 1 presents a single trial record. The actual trajectory is plotted on the upper part and the instantaneous speed record is plotted on the lower part of this figure. We used the instantaneous speed record of each trial to calculate the kinematic variables of interest. The instantaneous speed record started at the appearance of the peripheral target circle. The first three non-zero values were taken to indicate that a movement had started. The first one of these values was used to mark the onset of the movement. The time for the initial phase of the movement was measured from the onset of the movement to the time that a single zero value on the speed record was encountered again (see Fig. 1). The total movement time was measured as the time from the onset of the movement to the time when the instantaneous speed was stabilized to zero for at least 0.4 s during the period that the cursor remained in the peripheral target circle (see Fig. 1). If the cursor was moving in the target circle and did not stop for least 0.4 s before the end of the target hold period (set at 0.5 s), the trial was discarded from further analysis. This was a

strict criterion for including trials because subjects had to keep the handle perfectly still within the target circle. We repeated the analysis using a less strict criterion. Thus trials were excluded when the subjects kept the cursor still during the last 0.1 s of the 0.5-s waiting period. Using this more relaxed criterion we permitted a small amount of movement within the target circle to be included in the total movement time. The “maximum speed” was the maximum value of the instantaneous speed record. The time from the onset of the movement that maximum speed occurred was also calculated (see Fig. 1).

The acceleration record was derived by differentiation of the instantaneous speed record. From this record we measured the maximum acceleration as well as the minimum acceleration, which was measured as the positive maximum deceleration. We also measured the time from the onset of the movement that the maximum deceleration occurred (see Fig. 1).

Finally, we measured the number of peaks on the speed record. These were measured using the same procedure that was used to define the maximum speed. The first peak on the speed record was by definition the peak where the maximum speed occurred. The first zero value after this peak was used as the new start and the next peak on the speed record was detected and so forth until the end of the movement (see Fig. 1).

The data from nine subjects were pooled together; thus a total of 1994 movements were analyzed. We excluded 472 movements (23.7%) in which an error had occurred as these were analyzed separately (see “Study of the errors” below). The speed records and trajectories of the 1522 correct movements were visually inspected. We excluded 516 trials in which the subject made small movements while inside the target circle. We repeated the analysis using a more relaxed criterion for the definition of the movement end. For this analysis we excluded 23 trials from the original 1522 correct trials. We also excluded 31 trials in which subjects produced step movements to the target; thus the speed record did not have a clear large first peak. Thus using the strict criterion for the definition of the movement end point we analyzed a total of 975 correct movements, while using the more relaxed criterion we analyzed 1468 correct movements. Table 1 shows the number of movements for each subject for each of the four levels of each parameter that was manipulated (target distance, size and direction). The sum of trials is 975. The data for each parameter (e.g., time to maximum deceleration) were submitted to a four-way factorial analysis of variance (ANOVA) with target distance, target size and

Fig. 1 A typical example of a single trial is depicted. The positional record (X , Y position) is depicted in the top part. The two circles represent the center and peripheral targets. The instantaneous speed record is depicted in the lower part of the figure. All the kinematic parameters that were measured in this study are marked on the instantaneous speed record (see “Materials and methods” for a detailed description of the parameters)

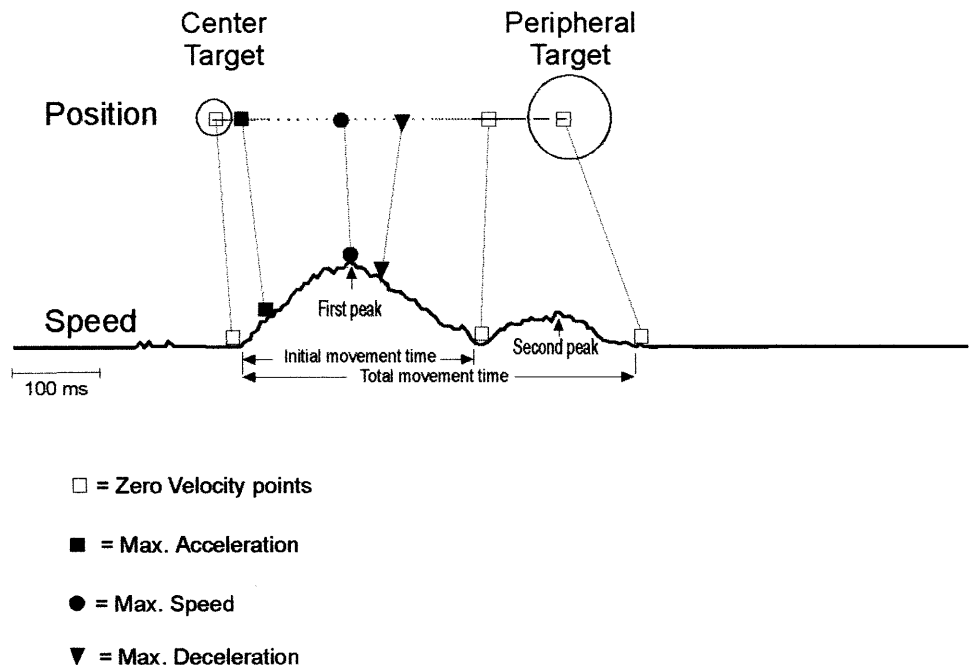


Table 1 Number of trials used in the data set after the application of all exclusion criteria ($N = 975$ trials) are separately presented for each of the fixed factors representing target manipulation (distance, size, direction). For each factor the data are divided by the number of different levels of manipulation and further divided by the number of subjects that participated in the study. The number of trials for each level for each subject is thus plotted in each of the table cells

	S1	S2	S3	S4	S5	S6	S7	S8	S9	Total
Size										
2.3 mm	26	22	32	27	28	28	38	38	39	278
3.46 mm	26	17	38	18	33	25	38	30	36	261
4.6 mm	23	16	36	24	26	25	29	27	29	235
5.75 mm	22	22	28	18	16	17	28	21	29	201
Distance										
5.75 mm	21	21	29	20	32	29	32	27	36	247
10.35 mm	23	13	37	26	27	25	39	31	37	258
14.95 mm	26	21	36	20	18	23	36	26	30	236
19.55 mm	27	22	32	21	26	18	26	32	30	234
Direction										
Forward	28	21	36	22	27	24	27	30	32	247
Left	26	13	35	18	26	28	35	30	33	244
Backward	20	21	36	25	23	21	36	22	31	235
Right	23	22	27	22	27	22	35	34	37	249
Totals	97	77	134	87	103	95	133	116	133	975

target direction as the fixed factors and subject number as a random factor (Statistica software, version 5.1, 1997 edition, Statsoft Inc.). The mean and variance for each level of the fixed factors were significantly correlated for all indices, thus violating a basic assumption for the applicability of the ANOVA analysis (Snedecor and Cochran 1988). We thus submitted the data for each index to a logarithmic or a square root transformation to maximally reduce the correlation between means and variances (Snedecor and Cochran 1988). The results of the ANOVA presented for each parameter correspond to the transformed data while for presentational clarity the original values were used for tables and graphs. We used the 0.01 significance level to define significant effects in these ANOVA analyses. Post hoc analyses were used to evaluate differences between mean values for each factor.

Results

The mean values and standard deviations for all parameters measured from the speed record (see “Materials and methods”) for all movements included under the strict criterion definition of the movement end point ($N=975$) are presented in Table 2.

Effects of target distance

The increase in target distance resulted in an increase in the time that maximum speed was reached ($F = 45.5$, $P < 0.001$). The difference of the mean time of maximum

speed for the maximum distance (19.55 mm) minus the mean for minimum distance (5.75 mm) was 82.15 ms. There was a significant interaction of distance and subject ($F = 3.01$, $P < 0.01$), indicating a significant variability from subject to subject for this effect. The increase in target distance resulted also in a significant increase in the time of maximum deceleration ($F = 115$, $P < 0.001$), initial movement time ($F = 272$, $P < 0.001$) and total movement time ($F = 311$, $P < 0.001$) (see Fig. 2). There was a difference in mean time of 140.8 ms for the time to maximum deceleration, 201 ms for the initial movement time and 213.2 ms for the total movement time between movements to the smallest target distance and movements to the largest target distance. The interaction of subject effect and target distance effect was not significant for these three parameters, indicating a common effect of target distance for all subjects. We repeated the ANOVA analysis using the larger data set (1468 trials, see “Materials and methods”). The effect of target distance was significant for the time to maximum speed ($F = 98.4$, $P < 0.001$), time to maximum deceleration ($F = 109$, $P < 0.001$), initial movement time ($F = 220$, $P < 0.001$) and total movement time ($F = 202$, $P < 0.001$).

There was a significant increase in maximum acceleration with increasing target distance ($F = 16.2$, $P < 0.001$). There was a 7.33% increase in the magnitude of mean maximum acceleration when subjects moved to the target at the largest distance compared to the mean when

Table 2 Means, standard deviations and number of observations for each of the kinematic variables that were measured

Parameter	Number of observations	Mean	Standard deviation
Time of maximum speed	975	109.35 ms	65.24 ms
Time of maximum deceleration	975	173.1 ms	106.08 ms
Initial movement time	975	281.59 ms	104.02 ms
Total movement time	975	312.44 ms	119.94 ms
Maximum acceleration	975	2360 mm/s ²	690 mm/s ²
Maximum speed	975	63 mm/s	22 mm/s
Maximum deceleration	975	1800 mm/s ²	500 mm/s ²
Number of peaks	975	1.13	0.35

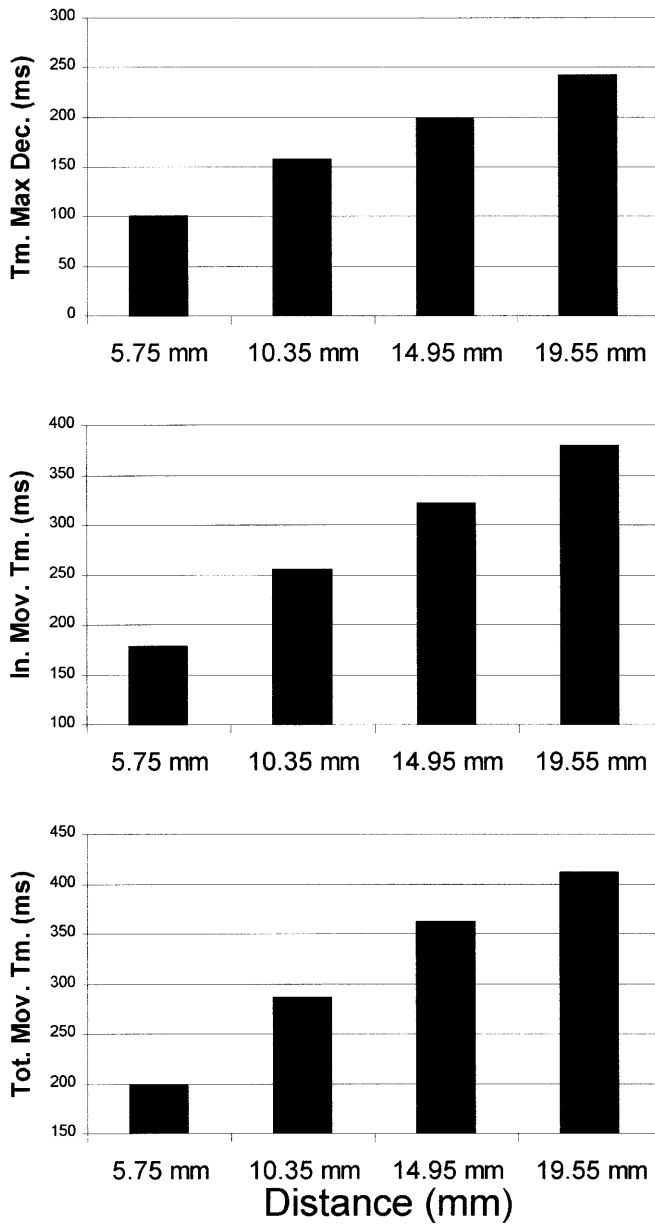


Fig. 2 Mean values (ms) of the time of maximum deceleration (*Tm. Max. Dec.*), initial movement time (*In. Mov. Tm.*), as well as the total movement time (*Tot. Mov. Tm.*), for the four target distances used in this study (target distances are presented in millimeters on the X-axis)

they moved to the smallest target distance (see Fig. 3). Increasing the target distance resulted also in a significant increase in maximum speed ($F = 367, P < 0.001$) and maximum deceleration ($F = 58.3, P < 0.001$). The difference for movements to the largest minus movements to the smallest target distance was 25.1% for the magnitude of mean maximum speed and 13.44% for the magnitude of mean maximum deceleration (see Fig. 3). There was no significant interaction of subject effect with the effects for target distance for these three parameters, indicating a common effect of target distance for all subjects. We repeated the ANOVA analysis using the larger

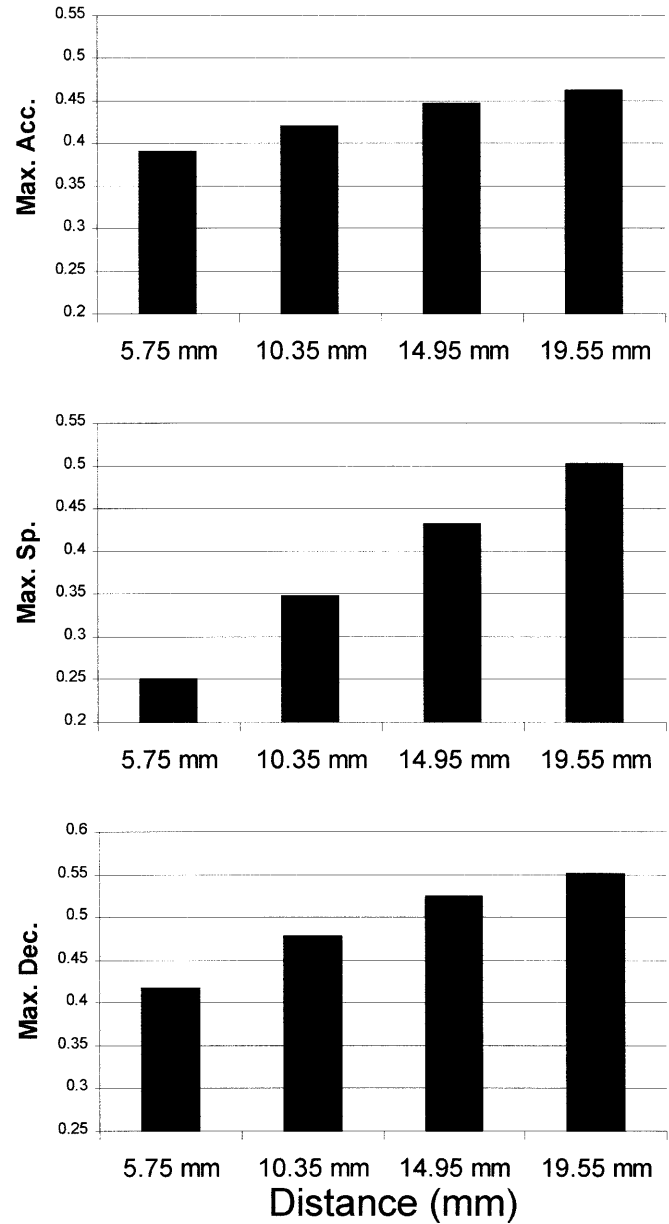


Fig. 3 Mean values of the magnitude of maximum acceleration (*Max. Acc.*), maximum speed (*Max. Sp.*), and maximum deceleration (*Max. Dec.*), for the four target distances used in this study (target distances are presented in millimeters on the X-axis). The magnitude measures (Y-axis) were normalized to the maximum value for each parameter

data set (1468 trials, see “Materials and methods”). The effect of target distance was significant for maximum acceleration ($F = 30.5, P < 0.001$), maximum speed ($F = 702, P < 0.001$) and maximum deceleration ($F = 110, P < 0.001$).

In conclusion the increase in target distance resulted in a later occurrence of maximum speed and maximum deceleration. The initial movement time and the total movement time increased with increasing distance as predicted from Fitts’ law. The magnitude of maximum acceleration, deceleration and speed increased with increasing target distance.

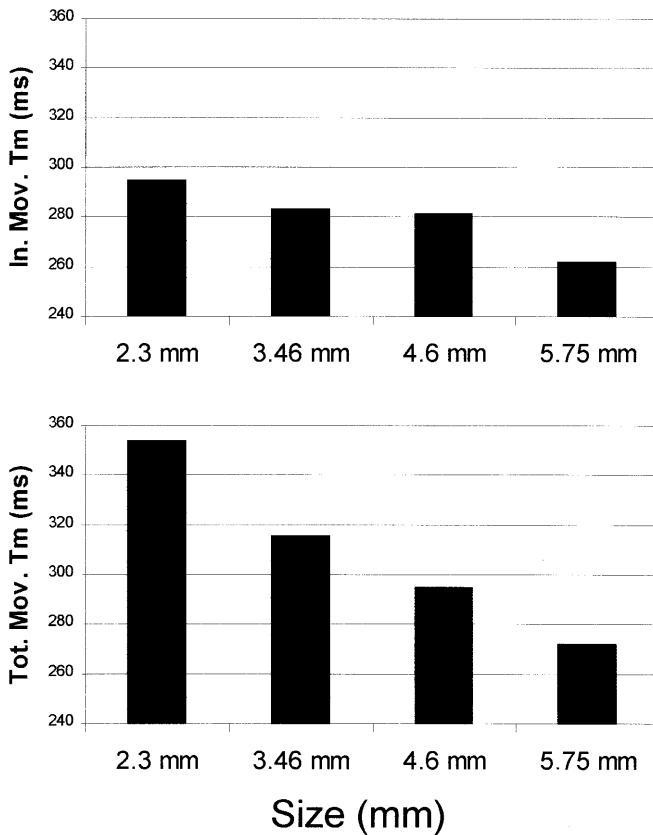


Fig. 4 Mean values (ms) of the initial movement time (*In. Mov. Tm.*), as well as the total movement time (*Tot. Mov. Tm.*), for the four target sizes used in this study (target sizes are presented in millimeters on the X-axis)

Effects of target size

The decrease in target size resulted in a significant increase in initial movement time ($F = 7.09, P < 0.01$) and total movement time ($F = 45.5, P < 0.001$) (see Fig. 4). There was no effect of target size on the time of maximum speed and the time of maximum deceleration. The mean value of the initial movement time for the maximum target size (5.75 mm) differed from the mean value of the initial movement time for the minimum target size (2.3 mm) by 33.25 ms. The mean value of the total movement time for the maximum target size differed from the mean value of the total movement time for the minimum target size by 81.68 ms. We repeated the ANOVA analysis using the larger data set (1468 trials, see “Materials and methods”). The effect of target distance was significant only for total movement time ($F = 11.7, P < 0.001$).

The decrease in target size resulted in a small (3.22% difference between movements to the largest and movements to the smallest targets) but significant decrease in maximum speed ($F = 5.28, P < 0.01$). There was no significant interaction with subject for all the significant main effects for target size. We repeated the ANOVA analysis using the larger data set (1468 trials, see “Mate-

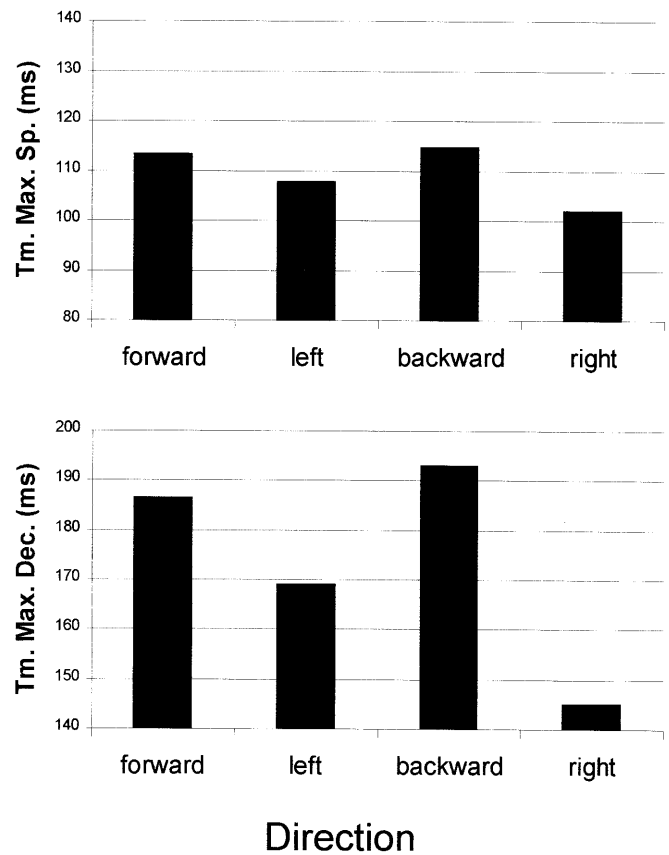


Fig. 5 Mean values (ms) of the time to maximum deceleration (*Tm. Max. Dec.*) of the time to maximum speed (*Tm. Max. Sp.*) and for the four target directions used in this study (target directions are presented on the X-axis)

rials and methods”). The main effect of target size on maximum speed was not significant for this larger data set. No other effect was significant.

In conclusion the smaller target sizes resulted in a larger movement time especially the total movement time as predicted from Fitts’ law. The effects of target size on the magnitude of maximum acceleration and deceleration were not significant, while there was a small but significant effect on maximum speed that disappeared when the larger data set was used for the ANOVA.

Effects of target direction

The target direction effects on the time to maximum speed and the time to maximum deceleration are plotted in Fig. 5. There are significant differences in the time of maximum deceleration for different directions of movement ($F = 9.05, P < 0.001$). The time of maximum speed and the initial movement time were also different for different movement direction although the differences did not reach the 0.01 level of significance. The total movement time was not affected by the target direction. We computed the mean value for the time to maximum de-

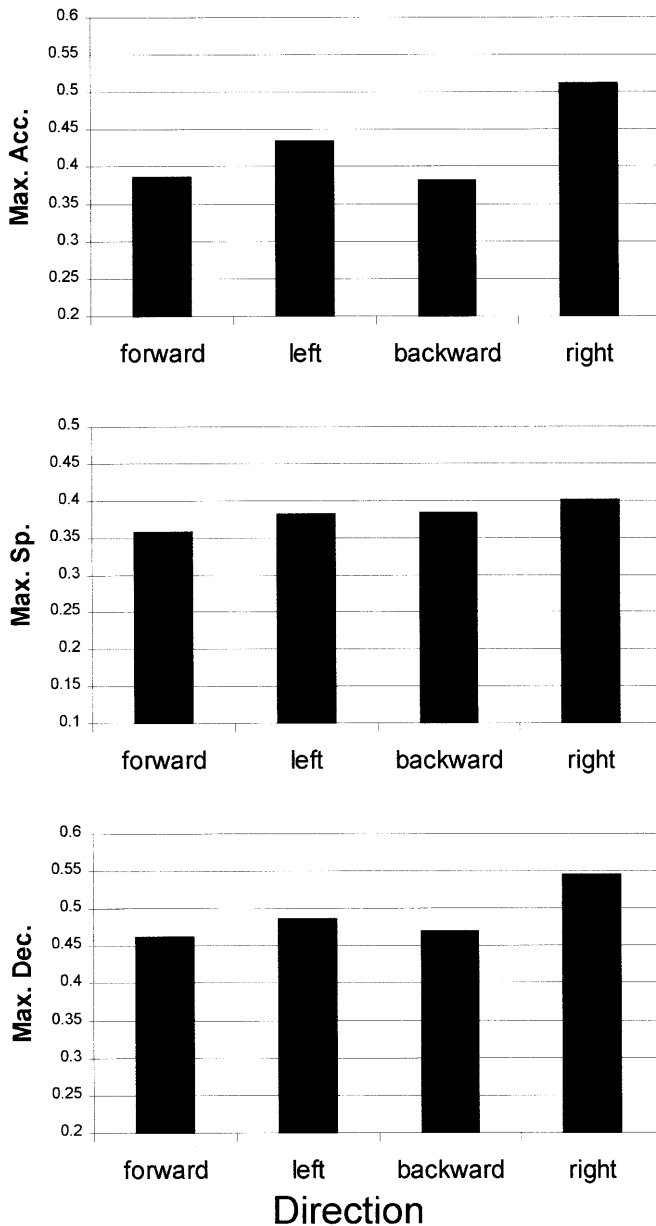


Fig. 6 Mean values of the magnitude of maximum acceleration (*Max. Acc.*), maximum speed (*Max. Sp.*) and maximum deceleration (*Max. Dec.*) for the four target directions used in this study (target directions are presented on the *X*-axis). The magnitude measures (*Y*-axis) were normalized to the maximum value for each parameter

celeration for the left and right movements (horizontal axis movements) and the mean value for the forward movements and the movements toward the body (vertical axis movements). The difference of the mean for the vertical axis movements minus the horizontal axis movements was 32.62 ms. The target direction effect did not have a significant interaction with subject. We repeated the ANOVA analysis using the larger data set (1468 trials, see “Materials and methods”). The effect of target direction was significant for the time to maximum speed ($F = 5.5, P < 0.001$), time to maximum deceleration ($F =$

12, $P < 0.001$) and initial movement time ($F = 6.15, P < 0.01$). The effect of target direction on total movement time was again not significant.

There was a significant effect of target direction on the magnitude of maximum acceleration ($F = 29.7, P < 0.001$), the magnitude of maximum speed ($F = 5.93, P < 0.01$) and the magnitude of maximum deceleration ($F = 58.3, P < 0.001$) (see Fig. 6). Movements in the horizontal axis resulted in a 8.9% increase in the magnitude of maximum acceleration and a 5% increase in the magnitude of maximum deceleration. There is also a smaller (2.1%) increase in the magnitude of maximum speed. The interaction of these significant effects of target direction with the subject was not significant. We repeated the ANOVA analysis using the larger data set (1468 trials, see “Materials and methods”). The effect of target direction was significant for maximum acceleration ($F = 42.9, P < 0.001$), maximum speed ($F = 8.62, P < 0.001$) and maximum deceleration ($F = 23.6, P < 0.001$).

In conclusion, movements on the horizontal axis resulted in a larger amplitude of maximum acceleration, speed and deceleration and the braking of the initial movement (until the first zero crossing on the speed record) was sooner. However, the total movement time was not affected by target direction. Thus target direction does not affect the speed-accuracy trade-off measured by the total movement time.

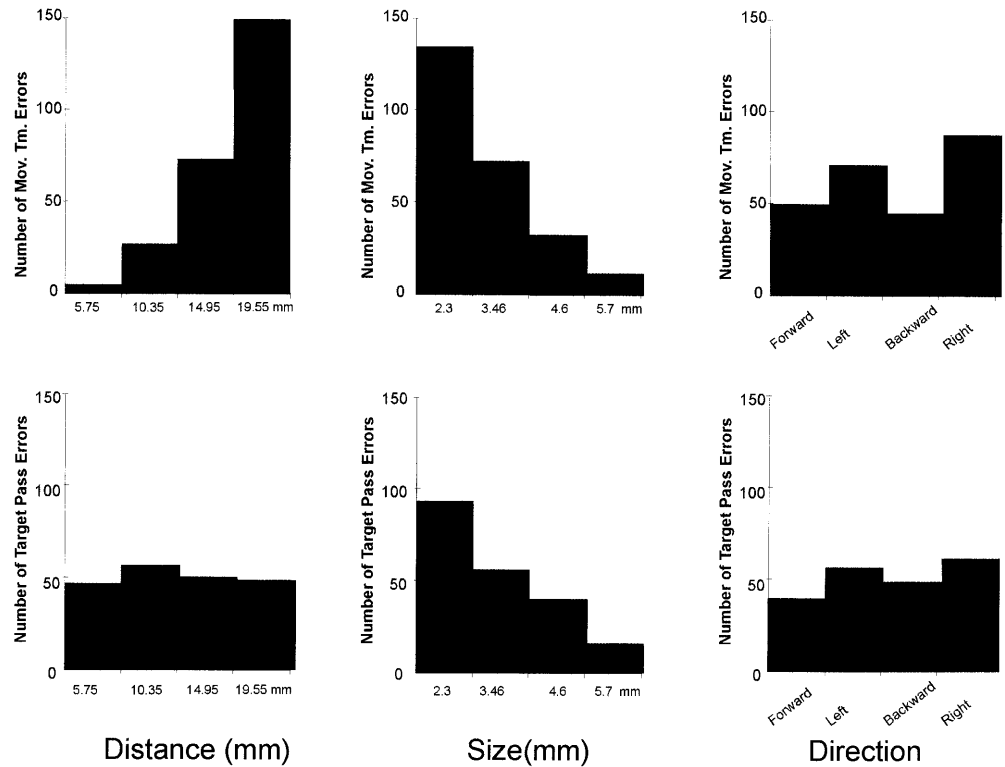
Interaction effects

We examined the two-way interaction terms in the ANOVAs between the three fixed factors, namely target distance, target size and target direction for all parameters measured. No interaction term reached the 0.01 level of significance. There was one interaction between target size and target direction in the case of the total movement time that reached the 0.05 level of significance ($F = 2.28, P < 0.05$). This significant interaction was due to the fact that movements to the smallest target towards the right had a larger total movement time than movements to the smallest target in all the other directions. The same results were observed by repeating the ANOVA on the larger data set (1468 trials, see “Materials and methods”).

Number of peaks on speed record

In 13.5% of movements the first peak of maximum speed was followed by a second smaller peak and only in three cases by a third peak before the movement came to a complete stop. We performed the same four-way ANOVA on the number of peaks on the speed record. There was a significant main effect of target size ($F = 21.9, P < 0.001$) and target distance ($F = 3.17, P < 0.05$). The decrease in the target size resulted in an increase in the number of peaks on the speed record. There was also an increase in the number of peaks with increasing target

Fig. 7 Each column of this figure shows the distribution of errors for each of the different factors that were manipulated in this study (target distance, size and direction, values marked on the X-axis of each histogram). In the first row the distributions of movement time errors are depicted while in the second row the distributions of target pass errors are shown



distance. The target direction had no effect on the number of peaks. There were no significant interaction effects at the level of 0.01 but there was a significant two-way interaction of target distance with target direction at the level of 0.05 ($F = 2.8$, $P < 0.05$). This interaction effect resulted from the fact that a second peak was observed more often for movements to the right target at close distance. This effect was evident only for the smallest distance movements. The ANOVA results on the larger data set showed the same significant effect of target size ($F = 5.12$, $P < 0.01$) and target distance ($F = 4.55$, $P < 0.05$). The same interaction effect was also significant ($F = 2.11$, $P < 0.05$).

Study of the errors

The error rate was 23.7% in this experiment. Two types of errors together constituted 97% of the total number of errors, namely movement time errors and target pass errors (see "Materials and methods"). The effects of target distance, target size and target direction on the numbers of both types of errors were examined (Fig. 7). The effects of target distance and target size were straightforward. A significant increase in movement time error rate occurred for an increase in target distance and a decrease in target size ($X^2 = 189.48$, $P < 0.001$ and $X^2 = 138.88$, $P < 0.001$, respectively). Interestingly the directional axis also had an effect on movement time error rate with more errors for movements in the horizontal axis ($X^2 = 17.9$, $P < 0.001$). The effects of the three factors of target distance, size and direction on the number of target pass

errors are shown in the bottom row of Fig. 7. Only the effect of target size was significant ($X^2 = 86$, $P < 0.001$).

Discussion

This study examined the effects of distance, accuracy and direction of a pointing movement on several kinematic parameters. The total movement time increased with increasing target distance and decreasing target size as expected from Fitts' law, but it was not affected by target direction. In contrast the initial movement time was significantly affected by target direction as well as by target distance and target size. Specifically the initial movement time for directions on the horizontal axis was reduced. In addition the times of occurrence on the speed record of maximum speed and maximum deceleration were significantly altered by target direction as well as by target distance whereas they were not affected by target size. Thus decreasing target distance or moving in a horizontal axis resulted in an earlier occurrence of maximum speed and maximum deceleration. Target direction, target distance but not target size significantly affected the magnitude of maximum speed, maximum acceleration and maximum deceleration. The directional effect was an increase in the magnitude of these parameters when subjects made movements on the horizontal axis.

Methodological considerations

The task used in this study involved a visuomotor transformation from a vertical screen to a horizontal move-

ment of a joystick. The use of a joystick to control a cursor on a vertical screen has been extensively used in the study of arm motor control (see Plamondon and Alimi 1997 for a review). This visuomotor transformation did not affect the accuracy characteristics of arm movements (Gordon et al. 1994b). When complex visuomotor transformations were introduced in the interface between the visual display and the actual arm movement, the parameters that the subject used for control were accurately described in the hand space and not in the visual display space (Graham and MacKenzie 1995; MacKenzie and Graham 1997). Thus the visual to motor transformation used in this study was not expected to affect the kinematic parameters measured.

Our design was such that very small movements of the arm were magnified on the screen by a factor of approximately 3. A similar magnification was also used in the study of Gordon et al. (1994a) using small wrist movements, and the characteristics of errors in pointing did not change, suggesting that pointing accuracy was not affected by this manipulation. In a study of three-dimensional reaching movements (Soechting and Flanders 1989), in one of the conditions the subjects used their arm while in a second condition they used a large pointer (1 m) to point at visual targets in 3D space. Again the accuracy of these movements was not affected by the transformation from large arm movements to small wrist movements (to control the pointer) using the same visual targets.

The observation of large intersubject differences when kinematic parameters are measured for reaching movements has led to the proposal that movement parameters should be studied individually for every subject before valid conclusions may be drawn (Holly 1997). Although a significant subject effect was observed, the two-way interaction terms for each of the factors that we manipulated was not significant in almost all cases except for the interaction of target distance and subject for the time to maximum speed. Thus our data indicate that, although a strong intersubject variability was present, this variability was more of a general gain factor and did not interact with target size, distance or direction for any of the kinematic parameters that we measured.

Finally the use of a strict definition of the movement end point resulted in a large reduction of the original data set (by 516 movements). This reduction did not affect the contribution of each subject to the data set (see Table 1). We repeated the ANOVA analysis using a more relaxed criterion for the definition of movement end point (resulting in the exclusion of only 54 trials from the original data set). The results in all cases were the same as with the smaller data set. Actually the use of a more relaxed criterion produced a more significant effect in almost all cases. We kept though the strict criterion for defining our data set because we believe that a strict definition of movement end point is crucial for the validation of our findings.

Main effects of target distance, size and direction

The time to movement completion was not affected by target direction but was significantly affected by target distance and target size. Thus the original observation of the speed-accuracy trade-off by Fitts can be extended to movements in different directions in space (Georgopoulos et al. 1981; Hermann and Soechting 1997). It still remains an open question whether the change in movement origin affects the speed-accuracy trade-off.

We observed that subjects very often used one and in some cases two smaller speed peaks to accurately bring the cursor inside the peripheral target. As movements became more accurate the number of times that a second speed peak appeared increased as well. It has been shown that the existence of these small peaks depends on the visual feedback. If the visual feedback is eliminated they disappear (Chua and Elliott 1993, 1997). These observations support then the hypothesis of a basic dichotomy in movement between the initial part or the transport phase and the final part of accurate pointing or grasping (Woodworth 1899; Soechting 1984).

Target direction had a significant effect on the initial movement time. A similar effect was shown in previous studies (Gordon et al. 1994b; Ghez et al. 1994) where movements were performed with no visual feedback and the accuracy of the movement was measured. In these studies only one peak was present on the speed record and the variation of movement time with direction was much larger (about 30% of total movement time) than in our results (only 7 ms on average between the two axes, horizontal and vertical). These differences can be explained by the different task requirements. Specifically in our study the subject had to point accurately at a target and had continuous feedback of the movement. Subjects made many errors in our task (23.7%) before being able to perform the task correctly. In the studies of Gordon et al. (1994b) and Ghez et al. (1994), the accuracy of the movement was allowed to vary and was measured. The subjects were not instructed to produce movements of a specific accuracy in a specific time window. Furthermore the subjects could not use visual feedback to correct their movements at the end point. In our task the effects of direction on movement time were seen only on the first component of the speed record. These effects of direction can be attributed to the different maximum acceleration observed at the beginning of the movement for different directions. The acceleration was larger on a horizontal axis and smaller on the vertical axis that was closer to the axis of maximum limb inertia (Hogan 1985). Thus initial inertial anisotropy could be a factor in the explanation of the differences in maximum acceleration that we observed for different directions of movement (Gordon et al. 1994b; Ghez et al. 1994). It is interesting that in our study where subjects used visual feedback to correct their movements this correction did not affect the magnitude of initial acceleration that remained different for different directions. The subjects used the maximum deceleration to compensate for the effect of maximum

acceleration. They also used the time to maximum speed for compensation although to a lesser degree than the compensation with deceleration. Thus, they allowed the initial force to act for a shorter period of time when moving in the horizontal axis and the resulting maximum speed occurred earlier. The magnitude of the speed remained larger for this axis, indicating that compensation was not complete at that point. The compensation was almost complete after the deceleration phase at the time at the initial movement time. The number of errors where the subject did not reach the target in time was larger for movements on the horizontal axis. One explanation for this difference could be that the compensation for the larger initial acceleration in this axis was larger than optimal (larger deceleration, sooner in time) in these cases. Another explanation could be that subjects made more directional errors on this axis. We observed though that the direction of the movements varied by a very small amount after the first two to three movements in a particular direction and the subjects in the great majority of movements followed a straight trajectory to the peripheral target.

Our subjects compensated for the initial differences in acceleration but they did not effectively change their initial force production to eliminate these differences. The largest compensation occurred at the time of maximum deceleration at approximately 170 ms from movement onset. This is enough time for compensation effects to take place (Prablanc and Martin 1992). The neural mechanism of this ongoing control of the kinematic variables is still unknown. One hypothesis involves a proprioceptive feedback control at the level of the spinal cord and another involves the specification of a time-varying equilibrium position of the arm instead of the actual kinematic trajectory (Bizzi et al. 1992). It is possible that an efference copy of the motor command is compared with the actual motor outcome and is used to shape the motor command in a series of movements through a learning mechanism. A model based on a cerebrocerebellar circuit (Houk and Wise 1995) uses this efference copy of a cortical motor output and feedback from the periphery to shape a number of possible modifications in the trajectory and kinematics of the movement to match the specific task requirements. This learning circuit could be used to modify all kinematic parameters and it seems that it is especially sensitive to the speed of the movement (as the Purkinje cells, which are a crucial part of the model, are related to the speed of the ongoing movement). In a recent study, patients with cerebellar ataxia performed reaching movements in 3D space (Day et al. 1998). Their movements were slower and their maximum speeds were smaller than those of healthy subjects. In addition their handpath variability was larger even in the presence of visual feedback. Interestingly, when visual feedback was provided, subjects with ataxia had a smaller constant error and spatial variability but their movements were prolonged and a different type of directional error appeared at the final phase of the movement. The authors point to the significant role of the cer-

ebellum in programming the movement trajectory and especially in incorporating visual and proprioceptive information on flight to correct the movement spatial error. It would be interesting to examine kinematic variables such as maximum speed and acceleration in a task similar to the one used in this study for these patients to test the cerebellar involvement in shaping the velocity profile of the movement.

Interactions of the effects of target distance, size and direction

Another finding of this study was the lack of interactions among the manipulated target size, distance and direction for almost all of the movement parameters measured. It has been shown previously that the direction and distance of the movement affect in different ways the accuracy of the movement when no feedback for accuracy is required (Gordon et al. 1994b). Furthermore when the time provided for isometric force initiation or movement initiation is limited, the distance and directional errors show that direction is specified independently from distance (Favilla et al. 1989). We provide further evidence that direction and distance do not interact and that their effects are independent on all movement parameters measured even when visual feedback is used for movement completion and the accuracy requirements are varied. Furthermore, no other interaction was observed between accuracy and distance and accuracy and directional effects. A difference in the neural circuits responsible for the specification of distance, direction and accuracy could account for these data. There is evidence that different neural structures respond to the manipulation of specific movement parameters. Thus, the primary motor cortex (area 4) is very sensitive to the directional characteristics of movement and less so to the distance of the movement (Georgopoulos 1991). The cerebellum is implicated for the specification of movement accuracy during the final phase of the movement (Thach et al. 1992).

In conclusion, this study demonstrated that the use of two different definitions for movement time resulted in a different effect of target direction on the speed-accuracy trade-off. Thus, although direction did not affect the total movement time that included the final corrections while approaching the target, it did have a significant effect on the initial movement time until the first zero crossing of the speed record. Such a measurement of movement time would be the appropriate one to use if the accuracy of the movement was not predefined and/or visual feedback was not provided. Thus, the generality of Fitts' law for different movement directions depends on the definition of movement time and is not very informative regarding the complex problem of movement control. This control seems to arise online as soon as the movement starts and probably results in an online modification of movement speed to match the specific accuracy requirements. Sensory feedback information might be used to shape the feedforward control of the movement by a learning neu-

ral network. The use of very small pointing movements as studied here offers the opportunity to investigate aspects of motor control in subjects with neurological problems.

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