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RESEARCH ARTICLE

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Drawing under visuomotor incongruence

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Abstract Six human subjects were asked to draw ellipses presented on a screen by moving a manipulandum that controlled the position of a cursor. Six visual templates were used, which comprised three different ellipses displayed either horizontally or vertically; the ratio between the major and minor axes was 2, 4, or 5. For each visual template, the gains were set such that the movement trajectories required to trace the template with the cursor corresponded to one of six ellipses. Thus these movement ellipses were horizontal or vertical with a ratio between major and minor axes of 2, 4, or 5. All 36 combinations of six visual ellipses and six required movement ellipses were used. Therefore, in some conditions the required movement ellipse had a different orientation (with respect to the major axis) than the visual template. These conditions were called *orientation incongruent*, whereas, when the orientation of the required movement ellipse matched the orientation of the visual template, the conditions were called *orientation congruent*. Similarly, *eccentricity incongruent* referred to conditions where the eccentricities of the visual ellipse and the required movement ellipse were different, as opposed to *eccentricity congruent*. The main results were as follows: (a) The perimeter of the traced ellipse always tended to be larger than that of the visual template. In addition, it was significantly larger in the orientation incongruent conditions than in the orientation congruent conditions. Nevertheless, the perimeter of the traced figure increased with the template in both orientation congruent and incongruent conditions. (b) The shape of the traced figure varied appropriately with the visual template, but differed significantly between the orientation congruent and incongruent conditions. It was closer to the one of the template in the orientation congruent than in the incongruent conditions. Finally, (c) the instantaneous speed was significantly correlated with curvature but more tightly so in the orientation congruent than in the orientation incongruent conditions. The parameters defining the relation between speed and curvature were affected by the required movement ellipse, but not by the particular visuomotor condition. These results showed that although spatial motor performance was affected by changes in the correspondence between visual and movement coordinates, the relation between the speed and curvature of the movement trajectory was stable despite drastic changes in this correspondence.

Key words Hand movement · Visuomotor coordination

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Introduction

The relation between speed and curvature of drawing and handwriting trajectories is an important principle of organization of voluntary movements. Specifically, it has consistently been shown that the drawing motion of the hand slows down when the path is more curved (e.g., Binet and Courtier 1893; Viviani and Terzuolo 1982; Pellizzer 1997). It was suggested that this relation arises from central processing constraints of the motor system (Massey et al. 1992). One of the arguments in favor of this hypothesis is that the activity of motor cortical neurons is related to the movement velocity vector, and that the coupling between speed and curvature is observable at the level of the motor cortical representation of the movement trajectory (Schwartz 1994).

We suggested that the central constraint underlying the relation between speed and curvature is the time-consuming process of transforming the intended direction of movement (Pellizzer 1997). In particular, the results from visuomotor mental rotation studies indicate that the duration of the transformation increases with the size of the angle (Georgopoulos and Massey 1987; Pellizzer and Georgopoulos 1993; Georgopoulos et al. 1989; Lurito et al. 1991).

Considering these results within the context of a continuous movement led to the following formulation of the relation between speed and curvature:

$$V(t) = \frac{V_{TR}\,\omega}{\omega + V_{TR}\,C(t)} \tag{1}$$

where $V(t)$ and $C(t)$ are the instantaneous speed and curvature, respectively; whereas V_{TR} and ω are constant parameters that represent the velocity of translation, and the angular velocity of transformation of the intended direction of movement, respectively (Pellizzer 1997). We found that such a formulation describes well the data of subjects drawing different types of figures (Pellizzer 1997).

The question addressed here concerns the robustness of the relation between speed and curvature. We sought to perturb the concordance between visual and movement spaces by changing the gain settings relating the position of a cursor and the position of a two-dimensional manipulandum. We tested the effect of changing the concordance between visual and movement spaces on drawing movements, and in particular the effect on the traced path (perimeter and shape) in visual space and the relation between speed and curvature in movement space after a short period of adaptation.

Materials and methods

Subjects

Six healthy young adult human subjects (two women and four men) participated in this experiment. Four of them were naive about the purpose of the experiment. All the subjects were right handed and performed the task with their preferred hand. The experimental protocol was approved by the Institutional Review Board.

Apparatus

The experimental apparatus consisted of a manipulandum and a video monitor onto which templates and a position feedback cursor were displayed. The manipulandum was a vertical handle which the subjects grasped with the hand pronated. The vertical rod was 18 cm long and was mounted on two angle shaft encoders that measured its angular deviation from the vertical in two orthogonal $\langle X, Y \rangle$ directions. The movement of the hand was made in a horizontal plane with the X direction as a frontal axis relative to the subject, and the Y direction as a midsagittal axis. The nominal accuracy of the angle measured was 0.09 deg. The position of the feedback cursor on the monitor reflected the position of the manipulandum, which was sampled every 10 ms. At each moment in time, only the visual template and the present position of the cursor were visible, whereas the trace of the path of the cursor was not displayed. The display was located in front of the subject and was updated at a frequency of 60 Hz. The gain settings between the $\langle X, Y \rangle$ coordinates of the manipulandum and the corresponding coordinates of the cursor were varied from trial to trial; therefore, a given position of the manipulandum did not always produce the same position of the cursor. The acquisition of the data and the display of the templates and feedback cursor were controlled through the appropriate interfaces using a personal computer.

Visual templates and gain settings

Six visual templates were used, which were three ellipses of different eccentricity displayed either horizontally or vertically. The ratio between the major and minor axes of the ellipse was 2, 4, or 5 (Fig. 1A). The major axis of the template ellipses was 75.0 mm long, and the minor axis was 37.5, 18.75, or 15.0 mm, corresponding to the ratios above. Their respective perimeters were 18.2, 16.1, and 15.8 cm.

For each visual template, the gains were set such that the movement trajectories required to trace the template with the cursor corresponded to one of six ellipses (Fig. 1A). The required movement ellipse was either horizontal or vertical with a ratio between major and minor axes of 2, 4, or 5. The major axis was 29.2 mm, and the minor axis was 14.6, 7.3, or 5.8 mm. The respective perimeter of the required movement ellipses was 7.1, 6.3, or 6.1 cm. All 36 combinations of six visual ellipses and six required movement ellipses were used. Therefore, in some conditions the required movement ellipse had a different orientation than the visual template. These conditions were called *orientation incongruent;* in contrast, when the orientation of the required movement ellipse matched the orientation of the visual template, the conditions were called *orientation congruent.* The orientation of the ellipse was defined by the direction of the major axis. A different type of congruence/incongruence was defined by the eccentricity of the visual and movement ellipses. When the eccentricities of the visual and required movement ellipse were identical the conditions were called *eccentricity congruent,* whereas when their eccentricities were different the conditions were called *eccentricity incongruent.* This means that only when the aspect ratio in movement and visual space was equal was the condition congruent in orientation and eccentricity. In all the other cases the condition was incongruent in orientation, eccentricity, or both.

Behavioral task

The manipulandum was in front of the subjects and in the midsagittal plane, so that the subject's upper arm was along the trunk and the forearm was approximately horizontal. Subjects grasped the handle of the manipulandum with an unrestrained pronated hand and traced the shape of the visual templates with the feedback cursor at a self-chosen rhythm. They were instructed to make a continuous rhythmic movement in duplicating the visual template. The recording of the data started after the subject attained a stable rhythm, which usually occurred after a few seconds. A trial could be repeated if for any reason the subject was dissatisfied with the performance. The data acquisition time for each trial was 10 s, and the experimental session ended after about 60 min. Some subjects did not perform in all the conditions.

Data analysis

The subjects usually traced several cycles of the ellipse during the 10 s of data acquisition. A cycle was defined between two odd zero-crossings of the coordinate with major displacement. For exam-

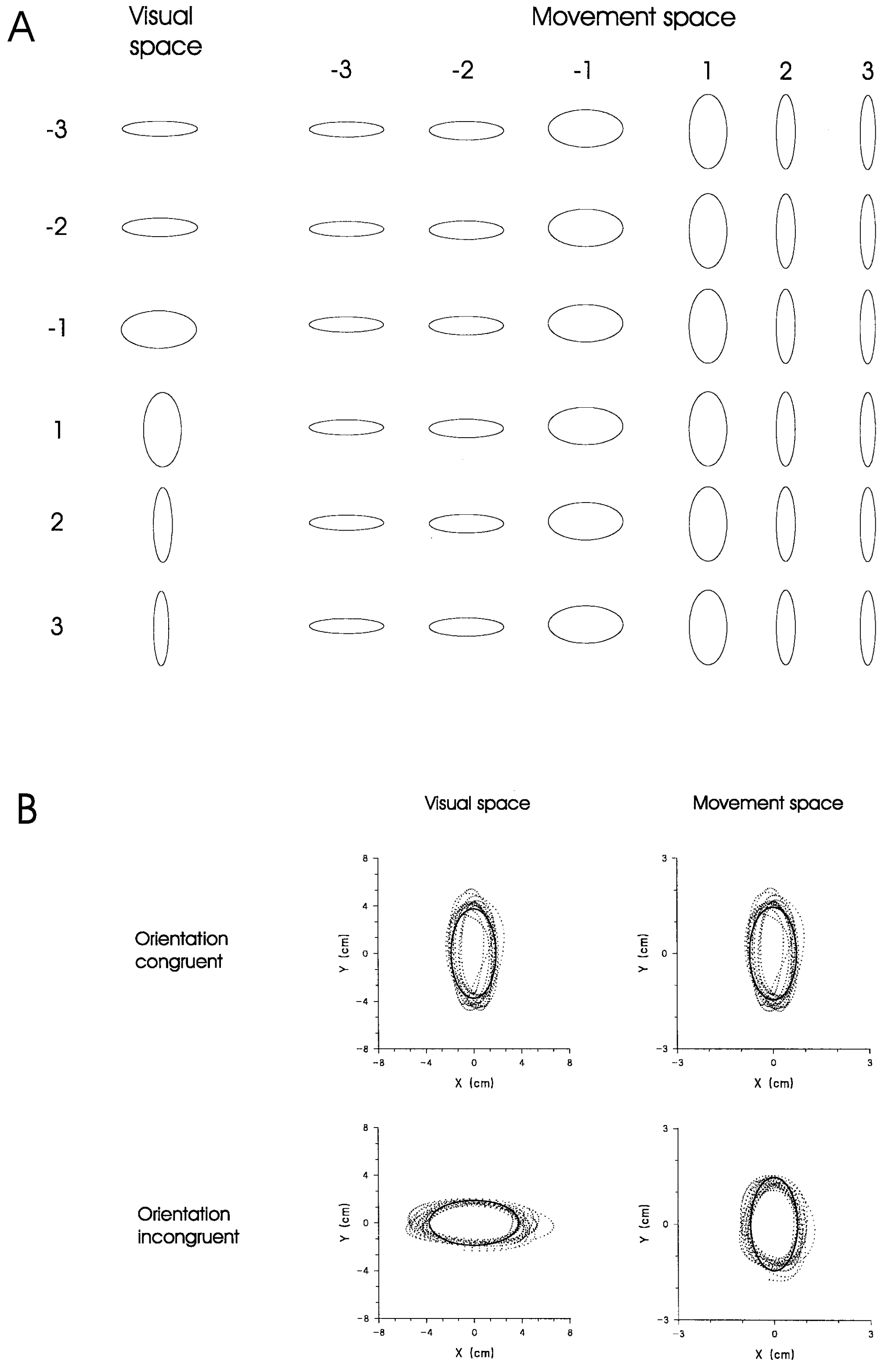

Fig. 1 **A** *In the left column* are drawn the visual ellipses that were presented as templates on a monitor to the subjects. *The other columns* show the movement ellipse that the subjects had to execute with a manipulandum in order to draw the corresponding visual ellipse. **B** Examples of drawings of a subject in an orientation congruent and an orientation incongruent trial. *In the left column* are presented the trajectories of the feedback cursor on the monitor. *In the right column* are presented the corresponding trajectories of the manipulandum. *The data at the top* are from the orientation congruent trial; *those at the bottom* are from the orientation incongruent trial

ple, for a horizontal ellipse, the first cycle started when the *X*-coordinate crossed zero (i.e., the center of the display in the horizontal dimension) the first time and ended when it crossed zero the third time, that is, when the path was again at the approximate same location of the cycle as for the first zero-crossing. For each complete cycle, the following variables were measured: perimeter, length of major and minor axes, period, and average speed. The so-called perimeter of a cycle corresponded to the length of the path traced between the beginning and end of the cycle. The lengths of the major and minor axes were measured between the crossings of the path on the *X*- and *Y*-axes within each cycle. For example, for a horizontal ellipse, the major axis was determined by the length between two successive crossings of the path on the *X*-axis, whereas the minor axis was calculated between the crossings on the *Y*-axis. The accuracy of the reproduction of the visual template was assessed by analyzing the perimeter and shape of the trajectory traced by the cursor. The shape of the figure drawn on the display was evaluated using the ratio between its major and minor axes.

Statistical tests on these measures of performance were done using mixed models analyses of variance and linear regression analyses (Snedecor and Cochran 1989). The factors tested in the analyses of variance were: orientation of the visually displayed ellipse (factor *OV*, two levels); eccentricity of the visual ellipses (factor *EV*, three levels); orientation of the required movement ellipse (factor *OM*, two levels); and eccentricity of the required movement ellipses (factor *EM*, three levels). The factor subject was treated as the random factor of the mixed model (Snedecor and Cochran 1989). The analyses of variance were performed using the General Linear Model procedure (SPSS Inc., Chicago, IL), which can handle unbalanced data. In some cases, variables were log-transformed ($\log_{10}$) to correct for positive skewness. Also, Fisher's *z*-transformation was applied to the Pearson correlation coefficient before any analysis on correlations (Snedecor and Cochran 1989). Effects were considered significant at a level of $P<0.01$.

Results

Figure 1B shows two examples of trials from one subject: in one trial (first row) the orientations of the ellipses (as defined by their major axis) in visual and movement spaces were congruent, and in another trial (bottom row) the orientations were incongruent. In the two trials plotted the required movement ellipse was the same but the visual templates were different. In the orientation congruent trial, the ellipses in both the movement space and the visual space were oriented vertically. Instead in the orientation incongruent trial, the ellipse in movement space was vertically oriented, and the ellipse in visual space was horizontally oriented. In the left column of Fig. 1B are plotted the trajectories of the feedback cursor in visual space, and in the right column the movement trajectories that the subject produced with the manipulandum. It can be seen that the figure traced in visual space in the orientation incongruent case tended to be more eccentric than the one in the orientation congruent case. In this example, and in general, no apparent change of performance was observed from the beginning to the end of the 10-s duration of the trial.

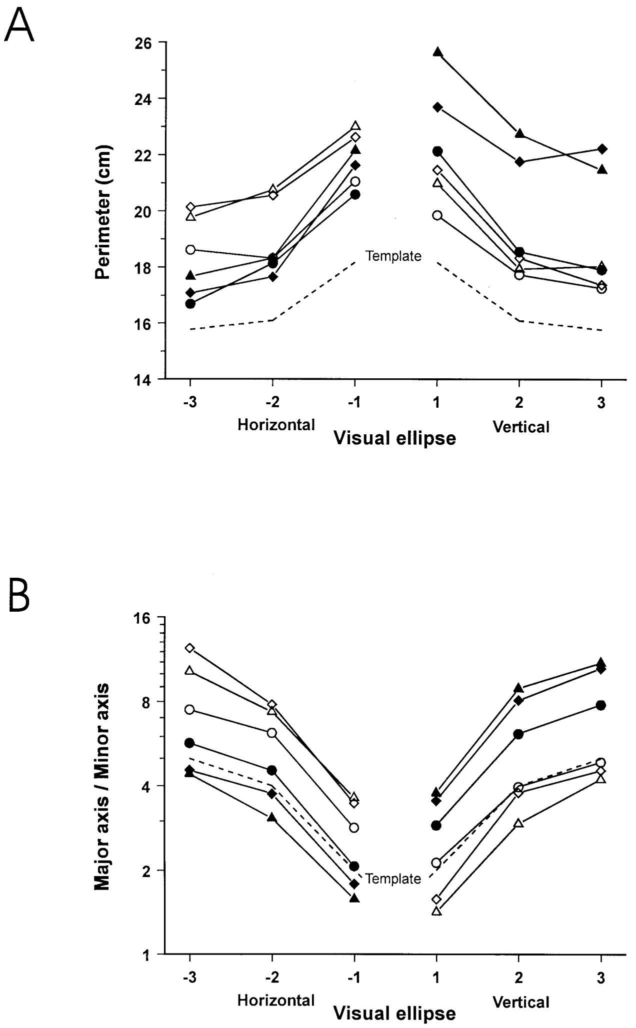

Fig. 2 **A** Plot of the perimeter of the ellipse traced on the monitor versus the visual template. **B** Plot of the ratio between major and minor axes of the drawn ellipse in log scale versus the visual template. *The numbers on the abscissa* refer to the numbers used in the left column of Fig. 1A. *The filled symbols* correspond to the horizontal required movement ellipses, whereas the *open symbols* correspond to the vertical required movement ellipses. *The circular, diamond-shaped, and triangular symbols* represent the least eccentric, middle, and most eccentric movement ellipses, respectively

Perimeter

The perimeter considered for the analyses was measured on the ellipse produced in visual space since this is what the subjects had to reproduce. First of all, the perimeter of the traced visual ellipse tended always to be larger than the one of the visual template (Fig. 2A). Regarding the analysis of variance, it should be noted that, if the subject had reproduced the template perfectly, only the factor of the eccentricity of the ellipse in visual space (*EV*) would be significant, whereas the other factors would not. The analysis indicated indeed a strong effect of the eccentricity in visual space on the perimeter (*EV: F*-test, $P<0.0005$). Subjects appropriately varied the perimeter of the ellipse they traced relative to the visual template. However, the analysis also indicated additional significant effects: the orientation of the visual ellipse (*OV: F*-test, $P=0.001$), the eccentricity of the required movement ellipse (*EM: F*-test, $P<0.0005$), the interaction between the orientation of the visual and movement ellipses (*OV×OM: F*-test, $P<0.0005$), and the interaction between the eccentricity of the movement ellipse and the orientations in visual and movement spaces (*OV×OM×EM: F*-test, $P=0.001$). As seen in Fig. 2A, these effects indicate that the perimeter was larger in the orientation incongruent conditions than in the orientation congruent ones, and this was mostly true when the required movement ellipses were the most eccentric.

Shape

The ratio of major axis versus minor axis was log-transformed before doing the analysis of variance. As can be seen in Fig. 2B, the eccentricity of the ellipse traced in visual space changed appropriately with the eccentricity of the visual template (*EV: F*-test, P<0.0005). In addition, the following significant effects were obtained: the orientation of the required movement ellipse (*OM: F*-test, P=0.007); the eccentricity of the movement ellipse (*EM: F*-test, P=0.001); the interaction between the orientation of the visual ellipse and the required movement ellipse ($OV \times OM$: *F*-test, P<0.0005); and the interaction between the eccentricity of the movement ellipse and the orientations in visual and movement spaces ($OV \times OM \times EM$: *F*-test, P<0.0005). As can be seen in Fig. 2B, the figure traced in visual space was significantly more eccentric in the orientation incongruent than in the orientation congruent condition (see also Fig. 1B). The shape of the traced ellipse was closer to the one of the template in the orientation congruent than in the orientation incongruent condition. In addition, in the orientation incongruent condition the traced ellipse was more eccentric when the required movement ellipse was also more eccentric, whereas the reverse occurred in the orientation congruent condition.

Period

The average period for drawing a cycle of an ellipse was 1.18 s (SD=0.63) and did not change significantly across the experimental conditions. The results from all conditions are plotted in Fig. 3A.

Average speed

The average speed was log-transformed for the analysis. The speed of the movement was affected by the eccentricity of the required movement ellipse (*EM: F*-test, P<0.0005). The average speed decreased as the eccentricity of the required movement ellipse increased (Fig. 3B). In addition, the analysis indicated the presence of significant effects of the orientation of the required movement ellipse (*OM: F*-test, P<0.0005) and of the interaction between the orientation of the visual and movement ellipse ($OM \times OV$: *F*-test, P=0.003). As can be seen in Fig. 3B, the average speed of movement was generally higher in the orientation congruent than in the orientation incongruent condition.

Relation between speed and curvature

The relation between speed and curvature of the movement trajectory as defined by Eq. 1 was analyzed by computing the linear regression of the following linearized equation:

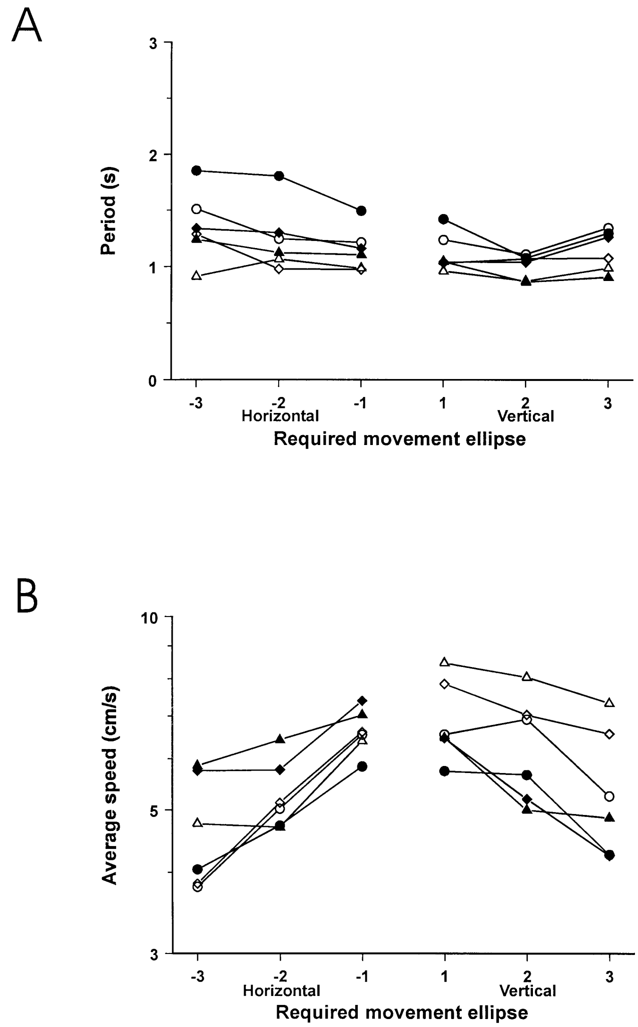

Fig. 3 **A** Plot of the period to accomplish a cycle of the figures drawn versus the required movement ellipse. **B** Plot of average speed of the movement in log scale versus the required movement ellipse. *The numbers on the abscissa* refer to the number used at the top of Fig. 1A. *The filled symbols* correspond to the horizontal visual ellipses, whereas *the open symbols* correspond to the vertical visual ellipses. *The circular, diamond-shaped, and triangular symbols* represent the least eccentric, middle, and most eccentric visual ellipses, respectively

$$\frac{1}{V(t)} = \frac{1}{V_{TR}} + \frac{C(t)}{\omega} \qquad (2)$$

In these analyses, if the visuomotor discordance had no effect, the factors related to the visual ellipse (i.e., *OV* and *EV*) should not be significant. Fisher's *z*-transformation was used before analyzing the correlation coefficient r (Snedecor and Cochran 1989). The correlation coefficient was generally higher in the orientation congruent than in the orientation incongruent condition (Fig. 4A; $OM \times OV$: *F*-test, P=0.009).

As far as the parameters of Eq. 2 are concerned, we found the following. The log-transformed intercept $1/V_{TR}$ increased with increasing eccentricity of the movement ellipse (Fig. 4B; *EM: F*-test, P<0.0005), and was generally higher for the horizontal movement ellipses than for

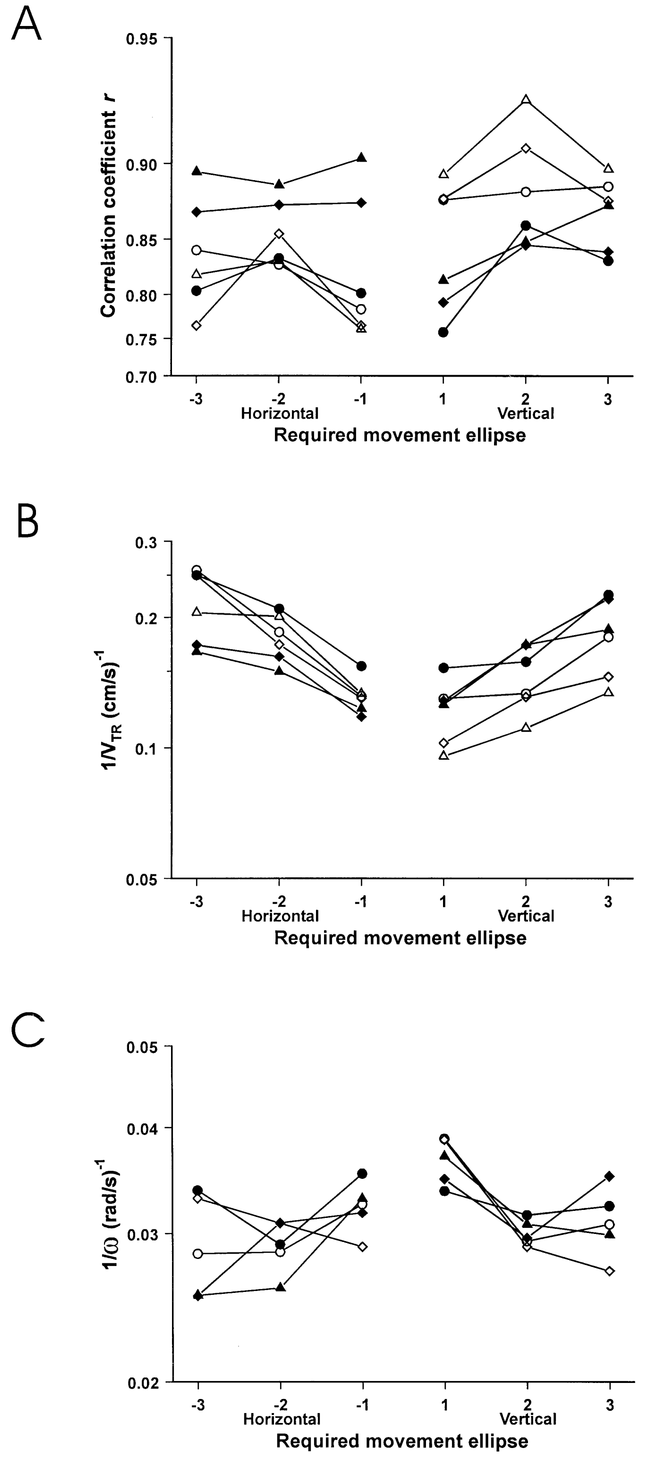

Fig. 4A–C Plot of the correlation coefficient and parameters of Eq. 2 describing the relation between instantaneous speed and curvature. **A** Plot of the correlation coefficient in Fisher's *z*-transformation scale versus the required movement ellipse. **B** Plot of the intercept ($1/V_{TR}$) in log scale against the movement ellipse. **C** Plot of the slope ($1/\omega$) in log scale against the movement ellipse. Conventions are as in Fig. 3

the vertical movement ellipses (*OM: F*-test, $P<0.0005$). The log-transformed slope $1/\omega$ (Fig. 4C) decreased significantly as the eccentricity of the movement ellipse increased (*EM: F*-test, $P=0.008$).

Discussion

In this study we tested the effects of visuomotor discordance on the performance of subjects drawing ellipses. In particular we were interested in the effect of the visuomotor perturbation produced by changing the visuomotor gains. In this experiment we did not manipulate and therefore we did not address questions related to other types of visuomotor discordances, such as the fact that the plane of the movement of the manipulandum and the plane of the visual display were not the same, nor the fact that the absolute size of the required movement ellipse and of the visual template were different. Subjects were asked to draw with a visual feedback cursor over a visual template seen on a monitor in front of them. The position of the cursor was controlled by the subject with a manipulandum. However, the gain settings were manipulated such that the movement ellipse to be executed in order to trace over the visual template was either homologous or not with the visual ellipse seen on the screen. The subjects were able to adapt to the visuomotor condition in a few seconds, as far as the orientation of the traced ellipse and the template were concerned. It has also been reported in studies of reaching movements that adaptation to a change in gain is generally easier than to other transformations (Pine et al. 1996).

The analyses of the traced figure on the screen indicated that overall the task was performed adequately. Despite the fact that the perimeter of the traced ellipses was in general greater in the orientation incongruent conditions than in the orientation congruent conditions, it always changed in correspondence with the perimeter of the template. However, despite an overall agreement of the performance with the template, the perimeter of the visual trajectory was also affected by the eccentricity of the movement trajectory to be executed, but only in the orientation incongruent conditions. In particular, in the two conditions with gain settings that produced the greatest difference between the visual and the movement ellipses (i.e., the most eccentric required movement ellipses in orientation incongruent conditions), the perimeter of the traced visual ellipse was larger than in all the other conditions. This indicates that in the orientation incongruent condition, the adaptation between visual and movement coordinates was not completely achieved, as opposed to the orientation congruent condition. The eccentricity congruence/incongruence did not affect the perimeter or any of the results, which indicates that within the limits tested the discordance in eccentricity was less perturbing than the discordance in orientation.

Another measure of the accuracy of the figure traced on the screen was the ratio between major and minor axes, which gives an indication of the shape (i.e., eccentricity) of the ellipse produced. The shape of the ellipse traced on the screen was significantly different between the orientation congruent and orientation incongruent conditions. In the orientation congruent conditions the shape was closer to the shape of the template, whereas in the orientation incongruent conditions it was more eccentric. In concordance with the results obtained with the measure of the perimeter, this indicates that the visuomotor adaptation was less well achieved when the orientations of the visual and movement ellipses were incongruent. In both conditions, the shape of the ellipse traced on the screen tended to deviate more from the shape of the template as the required movement ellipse was more eccentric. Nevertheless, in all conditions the eccentricity of the traced ellipses varied pari passu with the template, which indicates that the subjects were able to adapt their performance to the requirements of the task.

Regarding the timing and kinematics of the performance, we found that the time to achieve a cycle did not change significantly across conditions. On the other hand, the average speed of the movement decreased as the eccentricity of the required movement ellipse increased. In addition, movements were faster in the orientation congruent than in the orientation incongruent condition. These results are in addition to the previous ones that indicated a better visuomotor adaptation in the orientation congruent conditions than in the orientation incongruent ones.

Concerning the relation between instantaneous speed and curvature, we found that the correlation coefficient was quite high in both conditions, but was higher in the orientation congruent than in the orientation incongruent conditions. In line with the results showing a better adaptation in the orientation congruent conditions, this latter result may be caused by the presence of more movement corrections in the orientation incongruent conditions, which would add variability to the relation between speed and curvature. In addition, we found that the parameters V_{TR} and ω were affected by the movement ellipse. V_{TR} was affected by the orientation of the movement ellipse, whereas both parameters, V_{TR} and ω, changed in relation to the eccentricity of the required movement ellipse. The visual ellipse did not have a significant main effect or interaction effect on the parameters V_{TR} and ω that describe the local relation between speed and curvature (see Eqs. 1, 2).

Therefore, although the parameters of perimeter and shape were affected by the dissociation between visual and movement coordinates, the parameters concerning the relation between speed and curvature were not. In other words, whereas the specification of the path was altered by the gain settings, in particular, in the orientation incongruent conditions, the processing constraints responsible for the emergence of the relation between speed and curvature were unaffected. These results suggest that the specification of the path occurs at an earlier stage during the visuomotor transformation, whereas the processing constraints underlying the relation between speed and curvature occur at a later stage. This means that the specification of the path needs by definition the coordination of visual and movement coordinates, and was indeed affected by the gain settings that altered such a coordination. The effects occurred because the adaptation to the actual setting was not complete, particularly in the orientation incongruent conditions. The hypothesis is that the process of specification of the path leads to the representation of the upcoming direction of movement by neuronal populations that have an executive function, such as in the motor cortex. In contrast, the ongoing transformation of the intended direction of movement was performed upon such a neuronal representation of the intended direction of response, and therefore was unaffected by the specific visuomotor coordination.

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