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Hypothesis regarding the transformation of the intended direction of movement during the production of graphic trajectories: A study of drawing movements in 8- to 12-year-old children

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ABSTRACT

Children from 8 to 12 years of age drew figure-eights and ellipses at a self-chosen tempo on a digitizing tablet. Global aspects (perimeter and average speed) and local aspects (relation between instantaneous speed and curvature) of performance were analyzed across age groups and types of figures. We tested the predictions of the transformation model, which is based on the hypothesis that changing the intended direction of movement is a time-consuming process that affects the evolution in time of the movement trajectory, and compared how well it fitted the data relative to the power law. We found that the relation between speed and curvature was typically better described by the transformation model than by the power law. However, the power law provided a better description when ellipses were drawn at a fast speed. The analyses of the parameters of the transformation model indicate that processing speed increased linearly with age. In addition, the results suggest that the effects of the spring-like properties of the arm were noticeable when ellipses were drawn at a fast speed. This study indicates that both biomechanical properties and central processes have an effect on the kinematics of continuous movements and particularly on the relation between speed and curvature. However, their relative importance varies with the type of figure and average movement speed. In conclusion, the results support the hypothesis that a time-consuming process of transformation of the intended direction of movement is operating during the production of continuous movements and that this process increases in speed between 8 to 12 years of age.

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1. Introduction

Many studies of children drawing or handwriting performance have focused on teaching techniques, as well as on the expressive and representative content of the graphic production rather than on the execution itself (Graham and Weintraub, 1996). Nonetheless, the spatial aspects and kinematics of this type of continuous movements have also been

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analyzed in several studies with children subjects (van Galen et al., 1993; Meulenbroek and van Galen, 1986, 1990; Meulenbroek et al., 1998; Mojet, 1991; Rosenblum et al., 2006; Sciaky et al., 1987; Viviani and Schneider, 1991; Wann, 1987; Wann and Jones, 1986; Zesiger et al., 1993). In this context, it is of particular interest to study (1) the relations between movement parameters and (2) how these relations change with age. The reason rests on the premise that functional relations between movement parameters reflect properties of the neural and biomechanical components engaged in controlling and producing the movement. Accordingly, changes in the characteristics of such functional relations with age can be interpreted as resulting from concomitant transformations of these components (e.g., Wade and Whiting, 1986).

1.1. *Relation between movement speed and path curvature*

A prominent example of relation between movement parameters is the dependence between movement speed and curvature of the path. It is well known that the speed of natural movements decreases as curvature increases, that is, the hand slows down when the path is more curved (Abend et al., 1982; Binet and Courtier, 1893; Flash and Hogan, 1985; Freeman, 1914; Jack, 1895; Morasso and Mussa-Ivaldi, 1982; Viviani and Terzuolo, 1982). This relation exists in spite of the fact that these two variables do not need to be dependent (i.e., one could build a robot that executes movements with speed independent of curvature or with a speed-curvature relation that is different than the one observed in humans). Therefore the functional linkage between movement speed and curvature must result from constraints within the components involved in the control and execution of the motor response.

1.2. *The power law describing the relation between speed and curvature*

An empirical description of the relation between movement speed and curvature was provided by Lacquaniti et al. (1983) using a power law which is typically expressed as:

$$V(t) = KR(t)^{1/3} \tag{1}$$

where $V(t)$ is the instantaneous movement speed, $R(t)$ is the radius of curvature and K is a constant. However, subsequent studies have shown that the value of the exponent of the power function, even though it is often close to 1/3, can deviate systematically from such a value in various experimental conditions (Flanders et al., 2006; Hicheur et al., 2005; Pollick and Ishimura, 1996; Saling and Phillips, 2005; Schaal and Sternad, 2001; Viviani and Flash, 1995; Viviani and Schneider, 1991; Wann et al., 1988). An example of systematic deviation from the 1/3 power law comes from developmental data.

1.3. *The power law in children*

Viviani and Schneider (1991) have analyzed drawings of ellipses of subjects from 5 to 12 years of age and found that the exponent of the power function increased progressively from a fairly low value for the younger subjects toward a value close to one-third for the older subjects. These results were interpreted as reflecting the development of the neuromuscular system toward an ideal mass-spring system (Viviani and Schneider, 1991). This interpretation is based on the demonstration that when the exponent of the power function is equal to one-third and the trajectory is an ellipse, the end-point trajectory can be described as the combination of two orthogonal sinusoidal oscillators of same frequency (Hollerbach, 1981; Lacquaniti et al., 1983; Soechting and Terzuolo, 1986; Viviani and Schneider, 1991). Trajectories more complex than ellipses are considered within this scheme as sequences of elliptical segments strung sequentially (Soechting and Terzuolo, 1986; Viviani and Cenzato, 1985).

1.4. *Origin of the relation between speed and curvature*

One of the fundamental questions raised by the relation between speed and curvature is why does it exist? It has been suggested that this relation originates from constraints on joints motion (Dounskaia, 2007; Schaal and Sternad, 2001). However, several studies have shown that the relation exists even without arm movement. For example, in an experiment in which subjects drew various types of figures by applying force on a 3-D isometric manipulandum (i.e., no hand displacement occurred), it was found that the curvature of the 3-D force trajectory and its speed had the same relation than during actual movements (Massey et al., 1992). These results, as well as the neurophysiological studies (Schwartz, 1994; Schwartz and Moran, 1999) and the perceptual studies mentioned below (de'Sperati and Stucchi, 1995; Levit-Binnun et al., 2006; Viviani et al., 1997; Viviani and Stucchi, 1989, 1992), reject unambiguously joints motion as the primary cause of the relation between speed and curvature.

It has been suggested also that the spring-like properties of muscles could explain the relation between speed and curvature in movement as well as in isometric conditions (Gribble and Ostry, 1996). On the basis of a modeling study it was shown that the low-pass filtering properties of muscles cause speed and curvature to co-vary, even if the central control signal defines a trajectory at a constant speed (Gribble and Ostry, 1996). In other words this latter study indicates that peripheral smoothing factors can be at the origin of the relation between speed and curvature. In contrast, other studies have assumed that the smoothing constraints are of central origin and that they apply to the motor signal itself (Harris and Wolpert, 1998; Todorov and Jordan, 1998; Viviani and Flash, 1995). All of these studies have shown that smoothness constraints on movement trajectories, whether these constraints are assumed to be central or peripheral, result in a relation between speed and curvature that is equal or similar to the one described by Eq. (1) (Gribble and Ostry, 1996; Harris and Wolpert, 1998; Todorov and Jordan, 1998; Viviani and Flash, 1995).

The most direct evidence of the presence of central constraints at the origin of the relation between speed and curvature was provided by studies in which the activity of motor cortical neurons was recorded while monkeys traced figures with their hand (Schwartz, 1994; Schwartz and Moran, 1999). In these studies, the neural representation of the hand trajectory was visualized using the neuronal population vector calculated in time (Georgopoulos et al., 1983). It was found that the relation between speed and curvature existed at the level of the neural representation of the trajectory (Schwartz, 1994; Schwartz and Moran, 1999). In other words, these results indicate that the relation between speed and curvature is present already at the planning stage before the execution of the movement.

Other studies have provided evidence that this relation extends beyond the limits of arm-related motor trajectories. For example, it was found that the relation between speed and curvature applies also to pursuit eye movements (de'Sperati and Viviani, 1997) and to locomotion (Hicheur et al., 2005), which are systems that have different biomechanical properties and engage different neural networks than arm movements. In addition, this relation affects also the perception of visual (de'Sperati and Stucchi, 1995; Levit-Binnun et al., 2006; Viviani and Stucchi, 1989, 1992) and kinesthetic stimuli (Viviani et al., 1997). For example, Viviani and Stucchi (1989) have shown that the perception of the shape of an ellipse traced by a moving dot is affected by the relation between speed and curvature of the dot trajectory. In particular, the shape was perceived as distorted when the relation between speed and curvature was not conforming to that of human movements.

This ensemble of studies has shown that the relation between speed and curvature is present across different motor and perceptual contexts, which hints to the existence of a unifying general principle. One possibility is that this relation arises from constraints determined by the neural dynamics of neurons engaged in coding spatio-temporal aspects of behavior (Levit-Binnun et al., 2006; Pellizzer and Georgopoulos, 1993). Neurons in many motor-related and perceptual-related brain areas have similar properties: they are directionally tuned (e.g., Battaglia-Mayer et al., 2003; Born and Bradley, 2005; Hsiao et al., 2002) and their interactions are determined partly by their directional properties (Georgopoulos et al., 1993; Maynard et al., 1999). These properties have non-trivial effects on the dynamics of neuronal networks (Erlhagen and Schöner, 2002). In other words, the manifestations of the relation between speed and curvature across different contexts could result from the similar properties of the neurons engaged in coding the different behavioral parameters.

In conclusion, many studies indicate that central processes are involved in the generation of the functional relation between speed and curvature. However, this does not preclude biomechanical constraints, such as muscle properties, to be involved as well in shaping this relation.

1.5. *Transformation of the intended direction of movement*

It has been suggested that the central processing constraint at the origin of the relation between speed and curvature is that the transformation of the intended direction of movement is a time-consuming process (Pellizzer, 1997). This hypothesis was inspired by the results of behavioral and neurophysiological experiments on visuo-manual mental rotation (Bhat and Sanes, 1998; Georgopoulos and Massey, 1987; Georgopoulos et al., 1989; Lurito et al., 1991; Pellizzer and Georgopoulos, 1993; Wise et al., 1995). In these experiments, subjects were instructed to make a pointing movement at an instructed angle from the direction of a visual stimulus. It was found that the response time increased as the angle between the direction of the visual stimulus and the direction of the motor response increased (Bhat and Sanes, 1998; Georgopoulos and Massey, 1987; Pellizzer and Georgopoulos, 1993). These results suggest that the representation of the intended direction of movement changed progressively and rotated from the direction of the stimulus toward the direction of movement.

A direct support for the mental rotation hypothesis (Shepard and Cooper, 1982) was obtained by analyzing the activity of a population of motor cortical neurons while monkeys performed a task in which they had to move a handle at 90 degrees counterclockwise from the direction of a visual stimulus (Georgopoulos et al., 1989; Lurito et al., 1991). The results showed that during the response time the neuronal population vector, which reveals the directional coding of the population of neurons, pointed initially in the direction of the visual stimulus and rotated passing through intermediate directions toward the direction of the upcoming movement. In summary, these studies indicate that the spatial operation required by the visuo-manual mental rotation task is realized by a time-consuming process of transformation of the directional signal, and that the time spent by the process is a linear function of the angle of transformation.

1.6. *Transformation of the intended direction of movement during drawing and handwriting*

The results discussed above have implications for handwriting and drawing movements. Indeed in these cases, the direction of the ongoing movement is continuously changing which requires a continuous update of the neural representation of movement direction (Fig. 1A). If a time-consuming process of transformation of the intended direction of movement is operating during the production of a continuous trajectory, it will have consequences on the execution of the trajectory. That is, the kinematics of the movement will be necessarily affected by the path of the trajectory.

The assumptions that (1) transforming the direction of movement is a time-consuming process, and (2) that the time spent for the transformation is a linear function of the angle, lead to the following formulation of the relation between speed and curvature (c.f., Appendix):

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

where $C(t)$ is the instantaneous curvature [note that $C(t) = 1/R(t)$], and V_{TR} and ω are two constant parameters. V_{TR} is the speed of translation, which is equal to the speed of the movement in straight parts of the path, whereas ω is the angular velocity of rotation of the intended direction of movement. Therefore, ω estimates the speed of the transformation of the representation of movement direction. We will refer to this model as the *transformation model*. Although Eq. (2) is obviously different from the power law [Eq. (1)], both functions are qualitatively similar in describing the inverse relation between speed and curvature. Nevertheless, it was found that the transformation model described the relation between speed and curvature as well or better than the power law (Pellizzer, 1997). An important point to consider is that the

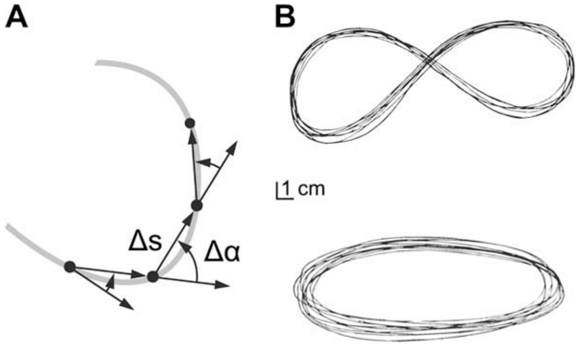

Fig. 1 – (A) The execution of drawing and handwriting movements requires steering the end-point along the desired path. For illustration convenience, we consider the movement path as a sequence of straight segments Δs of equal length. Realistically, these segments should be considered infinitely small (i.e., δs). The angle $\Delta\alpha$ between the segments varies depending on the local curvature. In this context, the time needed to change the intended direction of movement increases as $\Delta\alpha$ increases, which has the consequence of slowing the ongoing movement. In other words, the hypothesis of the transformation model is that the time-consuming transformation of the intended direction of movement affects the time-course of execution of the movement in a predictable way (Eq. (2); Appendix). (B) Templates used to instruct subjects about the type of figure to draw.

transformation model is a biologically inspired model, which was derived from the results of independent behavioral and neurophysiological studies, whereas the power law was determined empirically.

The question addressed in this study is how the parameters of the transformation model (i.e., V_{TR} and ω) change with age. From the results of previous studies (Sciaky et al., 1987; Viviani and Schneider, 1991) we can expect to observe a modification of the relation between speed and curvature with age. In the context of the transformation model, we can interpret this modification in relation with spatio-motor processes that control the production of the motor trajectory. A change in V_{TR} indicates a change in linear speed, whereas a change of ω indicates a change in the speed of transformation of the intended direction of movement. We have studied drawing movements of children from 8 to 12 years of age to examine how these parameters change with age. The subjects were asked to draw figure-eights and ellipses at a self-chosen tempo. We analyzed the data using the transformation model and compared the results with those obtained using the power law.

2. Materials and methods

2.1. Subjects

Sixty 8 to 12-year-old children attending public schools in Geneva (Switzerland) participated in the study. 12 subjects (6 girls and 6 boys) were selected in each of five age groups. The mean age and age range (years, months) in each age group were the following: 8-year-old: 7, 10 (7, 8–8, 2), 9-year-old: 9, 1 (8, 9–9, 7), 10-year-old: 10, 0 (9, 9–10, 5), 11-year-old: 11, 1 (10, 9–11, 5) and 12-year-old: 12, 0 (11, 10–12, 4). All subjects were right-handed according to Bryden (1977) laterality questionnaire (all laterality scores $\geq .7$) and had normal or corrected-to-normal vision. The authorizations for the experiment were obtained from the Department of Education, the school administrators and the parents.

2.2. Apparatus

The drawing movements were recorded on a digitizing tablet (ZedPen+, T.D.S./Numonics, Blackburn, England) using a ball-point pen attached to it through a flexible cable. The coordinates of position of the pen on the tablet were recorded at a frequency of 200 Hz and the data were stored on-line on a personal computer. The nominal spatial accuracy was .25 mm.

2.3. Procedure

The subjects were tested individually in a quiet room of the school. They were seated in front of the digitizing tablet, which was lying on a table. The instructions were to draw repetitively at a self-chosen tempo a figure similar to the sample figure presented before each trial. The subjects were shown the sample then, after it had been removed from their view, they had to reproduce it. They were not asked to copy exactly the figure, but rather to execute a continuous movement that reproduced the same type of figure and approximately the same size.

The figure sample presented to the subject was either a figure-eight or an ellipse (Fig. 1B). We used samples that were repetitively hand-drawn figures, rather than geometric templates to emphasize that the figure should be repetitively drawn and that it was not required that it be excessively accurate. The mean size of the sample figures was the following: mean length = 10.5 cm and mean height = 3.5 cm. The subjects had to draw the figure within a horizontal rectangular window of 20 cm × 10 cm cut in a cardboard that was lying on top of the surface of the digitizing tablet.

Data were recorded during 5 sec ($N = 1000$ $\langle x,y \rangle$ coordinates) per trial. The recording started a few seconds after the movement reached a stable rhythm. There were 5 consecutive trials per figure. A few practice trials were performed before the actual recordings.

2.4. Data processing

The time series of the $\langle x,y \rangle$ coordinates of position were low-pass filtered and differentiated in the frequency domain using a regularization procedure (Andersen and Bloomfield, 1974) to obtain velocity and acceleration data. The regularization procedure determined the optimal Wiener filter for each case on the basis of the periodogram of the data. The time series of curvature C(t) was estimated using the vector formula:

$$C(t) = \frac{|\mathbf{V}(t) \times \mathbf{A}(t)|}{|\mathbf{V}(t)|^3}, \tag{3}$$

where $\mathbf{V}(t)$ is the velocity vector and $\mathbf{A}(t)$ is the acceleration vector.

Global aspects of the drawing movements were characterized by calculating the perimeter and the average speed for each cycle in each trial. A cycle was defined as the trajectory occurring between the time the y coordinate crossed the zero value at one of the horizontal extrema of the figure and the time it crossed it again on the same side of the figure. For 3.5% of the trials, a complete cycle was not available using this definition therefore the global parameters were estimated by computing them on half a cycle and doubling the value obtained.

For all trials, the fit of the transformation model was evaluated using a non-linear least-squares regression procedure between the log-transformed observed and predicted speed:

$$\log(V(t)) = \log\left(\frac{V_{TR}\omega}{\omega + V_{TR}C(t)}\right). \tag{4}$$

The logarithmic transformation was used to attenuate the effect of non-homogeneity of variance (Snedecor and Cochran, 1989). The non-linear regression procedure used the modified Levenberg–Marquardt algorithm (Draper and Smith, 1981) and was implemented using the DRNLIN routine from the IMSL Fortran 90 MP Library (version 3.0, Visual Numerics, Houston, TX). The quality of the fit was assessed using Pearson's correlation coefficient, r (Snedecor and Cochran, 1989). The initial values of the parameters V_{TR} and ω used in the non-linear regression procedure were obtained from the following linear least-squares regression:

$$\frac{1}{V(t)} = \frac{1}{V_{TR}} + \frac{C(t)}{\omega}. \tag{5}$$

We have also tested how the power law fitted the data by following the procedure used by Viviani and Schneider (1991); see also Wann, (1989) in which the exponent of the power law, β, was considered a free parameter:

$$V(t) = KR(t)^{\beta}. \tag{6}$$

In addition, as proposed by Viviani and Stucchi (1992), $R(t)$ was replaced with $R^*(t)$ to circumvent the numerical difficulty associated with points of inflection (i.e., when $R(t) = \infty$; note that the transformation model does not have difficulty with points of inflection). Accordingly $R^*(t)$ was defined as:

$$R^*(t) = \frac{R(t)}{1 + \alpha R(t)}, \tag{7}$$

with $\alpha = .05$. Finally, the fit of the power law was evaluated by computing the least-squares regression of the following linearized equation:

$$\log(V(t)) = \log(K) + \beta \log(R^*(t)). \tag{8}$$

2.5. Statistical analyses

The data were analyzed using standard statistical procedures that included analyses of variance (ANOVA) for repeated measures (Snedecor and Cochran, 1989). The ANOVA model consisted of the between-subjects factor age group (5 levels: 8, 9, 10, 11 and 12 years), the within-subjects factor figure-type (2 levels: figure-eight and ellipse) and their interaction. Effects with a probability $p < .05$ were considered statistically significant. All ANOVAs were performed using the GLM procedure from SPSS (release 14.0, SPSS Inc., Chicago, Il).

3. Results

Examples of figure-eights and ellipses drawn by an 8-year-old subject are presented in Fig. 2. The drawings are represented in the left panels, the time series of speed and curvature are plotted in the middle panels, and the corresponding relations between speed and curvature are shown in the right panels. Both examples show that speed decreased when curvature increased. In addition, it can be noticed that speed was generally greater for the ellipse than for the figure-eight, and that the range of curvature was broader for the figure-eight than for the ellipse. The gray line in the scattergrams of speed versus curvature corresponds to the best fit of the transformation model.

3.1. Perimeter

The average perimeter per type of figure and age group is plotted in Fig. 3 (top). The perimeter of the drawn figures did not change significantly with age [$F(4,55) = .884$, $p = .480$]. In addition, the perimeter of the ellipse was not significantly different from the perimeter of the figure-eight [$F(1,55) = 2.039$, $p = .159$], even though this was not expressly controlled in the experiment. Finally, the interaction age group × figure-type was not significant either [$F(4,55) = .383$, $p = .820$]. The average perimeter [±Standard Error of the Mean (SEM)] of the drawings was 19.2 ± .5 cm ($N = 60$ subjects).

3.2. Average speed

Average speed is plotted for each type of figure and age group in Fig. 3 (bottom). The analysis of average speed showed a significant effect of age [$F(4,55) = 2.820$, $p = .034$], of type of figure [$F(1,55) = 102.579$, $p < .001$] and of their interaction [$F(4,55) = 2.597$, $p = .046$]. The two main effects were the consequence of the increase of average speed with age and the generally greater average speed for the ellipse than for the figure-eight. The interaction between age and type of figure resulted from the widening of the difference in average speed for the ellipse and the figure-eight with age. This interaction is illustrated by the difference of the slopes of the linear regressions between average speed and age plotted in Fig. 3 (bottom). The equations of the linear regressions were average speed $= 2.28 + .737$ age ($R^2 = .800$, $N = 5$ means) for the figure-eight and average speed $= -3.61 + 1.870$ age ($R^2 = .933$, $N = 5$ means) for the ellipse.

3.3. Relation between speed and curvature

First, we analyzed the relation between speed and curvature using the transformation model to determine its adequacy to describe the data. Second, we did the analyses using the power law to check whether the data were compatible with those obtained by Viviani and Schneider (1991), and compared the adequacy of the two models to describe the data.

3.3.1. Transformation model

The average correlation coefficient for the fit of the transformation model [Eq. (4)] computed over all trials using Fisher z-transformation (Snedecor and Cochran, 1989) was $R = .787$

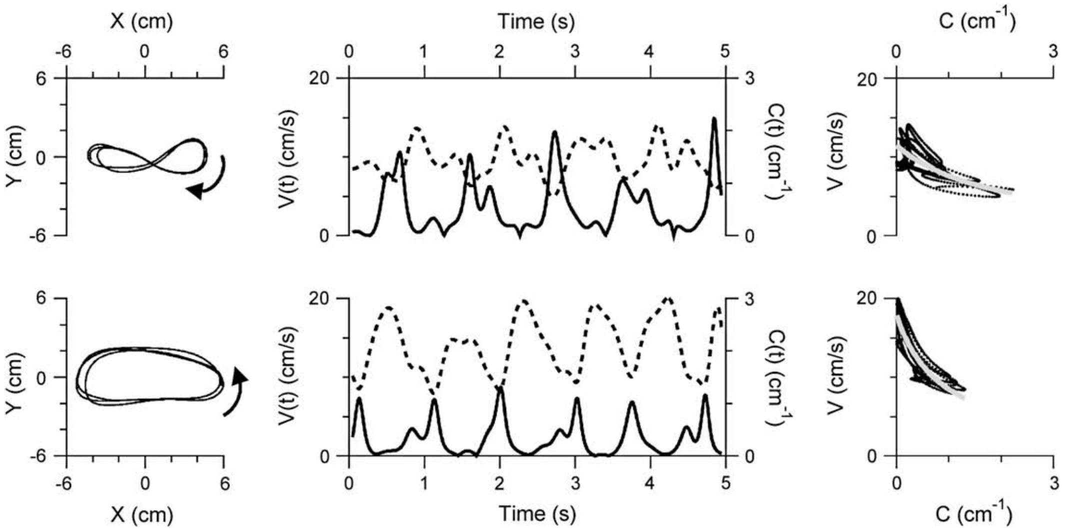

Fig. 2 – Example of a figure-eight and an ellipse drawn by an 8-year-old subject. On the left side are reproduced the figures drawn by the subject; in the middle speed (continuous line) and curvature (dashed line) are plotted against time; whereas on the right side are shown the scattergrams of speed versus curvature. The heavy gray lines in the scattergrams shows the transformation model fitted to the data.

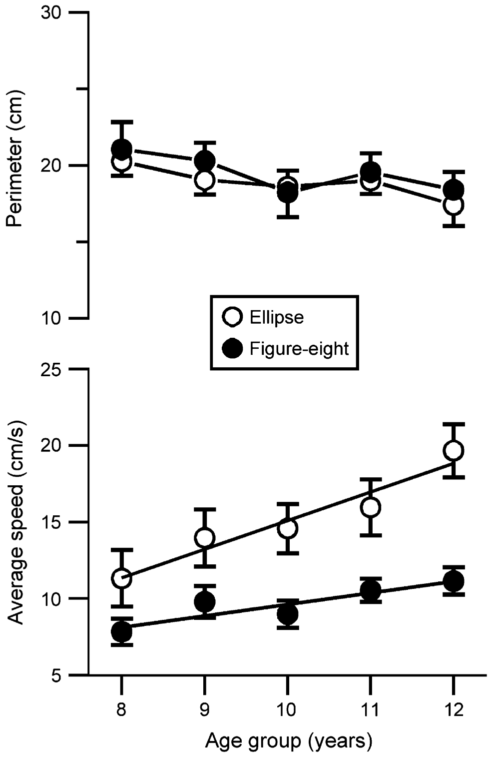

Fig. 3 – Average perimeter (top) and average speed (bottom) per age group and type of figure. The filled symbols correspond to the figure-eight condition, whereas the open symbols correspond to the ellipse condition. The linear regressions of average speed against age for the figure-eight and the ellipse conditions are plotted as straight lines in the bottom plot. Error bars represent the standard errors of the mean ($N = 12$ subjects per average).

(95% confidence interval: .774–.799, $N = 600$ trials). This result indicates that the transformation model provided a good fit of the data. The analyses of the parameters V_{TR} and ω obtained from the non-linear regressions in each trial gave the following results.

Average V_{TR} ($\pm$ SEM across subjects, $N = 12$) for the ellipse and figure-eight is plotted against age group in Fig. 4 (top). The analysis showed significant effects of age [$F(4, 55) = 3.279$, $p = .018$] of type of figure [$F(1, 55) = 106.823$, $p < .001$] and of the interaction between age and type of figure [$F(4, 55) = 3.273$, $p = .018$]. The effects were similar to those for average speed. The value of V_{TR} was greater for the drawing of the ellipse than for the figure-eight, and it increased with age at a higher rate for the ellipse than for the figure-eight. The linear regressions between V_{TR} and age were $V_{TR} = 1.9 + .99$ age ($R^2 = .785$, $N = 5$) for the figure-eight and $V_{TR} = \text{-}8.0 + 2.82$ age ($R^2 = .896$, $N = 5$) for the ellipse.

Average ω ($\pm$SEM across subjects, $N = 12$) is plotted for each type of figure and age group in Fig. 4 (bottom). The analysis indicated significant effects of age [$F(4, 55) = 3.496$, $p = .013$] and type of figure [$F(1, 55) = 25.134$, $p < .001$], but not of the interaction age group × figure-type [$F(4, 55) = .209$, $p = .932$]. The value of ω was higher for the figure-eight than for the ellipse and it increased with age. The absence of significant interaction indicates that the lines depicting the increase of ω with age for the two types of figure were not significantly different than parallel lines. The linear regressions on the means between ω and age were $\omega = 3.5 + 2.30$ age ($R^2 = .874$, $N = 5$) for the figure-eight and $\omega = -2.0 + 2.25$ age ($R^2 = .848$, $N = 5$) for the ellipse. The significance of these results will be addressed in Section 4.

3.3.2. *Power law*

As expected, the power law provided also a good fit to the relation between speed and curvature. The average correlation coefficient calculated using Fisher z-transformation (Snedecor and Cochran, 1989) was $R = .729$ (95% confidence

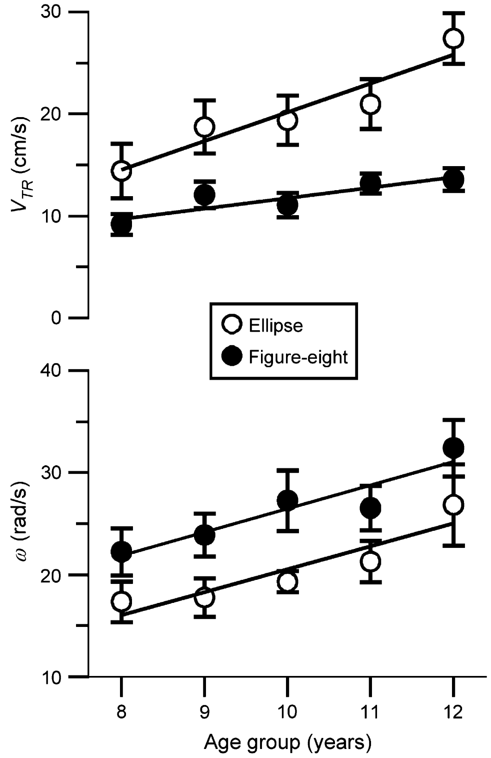

Fig. 4 – Average parameters V_{TR} (top) and ω (bottom) of the transformation model [Eq. (2)] per age group and type of figure. Conventions are as for Fig. 3.

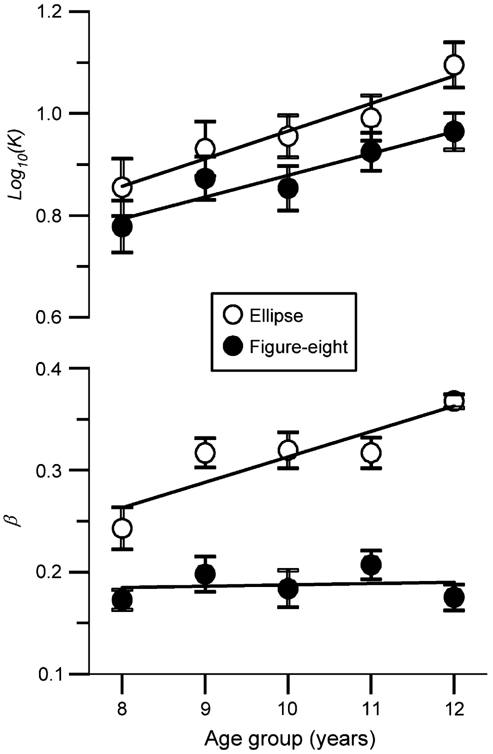

Fig. 5 – Average parameters $\log_{10}(K)$ (top) and β (bottom) of the power law [Eq. (6)] per age group and type of figure. Conventions are as for Fig. 3.

interval: .708–.749). Nevertheless, the correlation coefficient for the power law was smaller than the one obtained with the transformation model in 423/600 (70.5%) trials, which indicates that the transformation model fitted the data better in most cases ($\chi^2(1) = 100.86, p < .001$). We investigated what was different about the 29.5% trials that the power law provided a better fit. We found that almost all of them (167/177 = 94.4%) were drawings of ellipses. In addition, the average speed for these 167 trials was significantly greater than for the other trials [$t(598) = 12.783, p < .001$]. We will address in Section 4 the question of why the power law fits better fast drawing of ellipses.

The analyses of the parameters of the power function gave the following results. Average log(K) (±SEM across subjects, $N = 12$) for the ellipse and figure-eight is plotted against age group in Fig. 5 (top). The parameter log(K) was affected by the factor age group [$F(4,55) = 3.296$, $p = .017$] and figure-type [$F(1,55) = 49.370$, $p < .001$], but not by their interaction [$F(4,55) = 1.129$, $p = .354$]. The value of log(K) increased with age and was greater for the ellipse than for the figure-eight. The increase of log(K) with age was similar to the one described by Viviani and Schneider (1991).

Average β (±SEM across subjects, $N = 12$) for the ellipse and figure-eight is plotted against age group in Fig. 5 (bottom). The analysis of the exponent β of the power law showed significant effects of age group [$F(4,55) = 4.616$, $p = .003$], of figure-type [$F(1,55) = 205.736$, $p < .001$] and of their interaction [$F(4,55) = 5.204$, $p = .001$]. The value of the exponent of the power function estimated from drawings of the ellipse increased from .243 ± .020 ($N = 12$) at 8 years of age to .368 ± .007 ($N = 12$) at 12 years of age, whereas the value for the drawings of the figure-eight did not change much across age: .188 ± .007 ($N = 60$ subjects). Accordingly, post-hoc analyses indicated that the value of β changed significantly with age only for the ellipse but not for the figure-eight. The results for the ellipse show an increase of β with age that is similar to the increase found by Viviani and Schneider (1991). However, these results show also that the developmental trend of β was limited to the ellipse condition and did not generalize to the figure-eight condition.

4. Discussion

Children from 8 to 12 years of age were instructed to draw figure-eights and ellipses on a digitizing tablet. The task had little constraints given that the subjects could choose the tempo of drawing and did not have to copy exactly the sample figures. The main constraints of the tasks were that the instructed figure had to be traced within a 20 × 10 cm window and the movement had to be continuous. We have analyzed the perimeter and the average speed of the drawings, as well as the relation between instantaneous movement speed and curvature across age groups and figure types.

4.1. *Global drawing characteristics*

We found that the perimeter of the drawings did not change significantly across age groups whereas the average speed of execution increased appreciably from 8 to 12 years of age. These results are consistent with those obtained in other type of tasks such as, for example, pointing movements, that show a general increase of movement speed with age (Connolly et al., 1968; Hay, 1981; Pellizzer and Hauert, 1996; Schellekens et al., 1984; Sugden, 1980; Viviani and Zanone, 1988). This suggests that the visuo-manual system becomes more efficient between 8 and 12 years of age and could reflect an increase in the rate of the information processed to generate the movement as well as a better control of the arm biomechanics. In addition, whereas the perimeter of the two figures did not differ significantly, the average speed to execute them did. In fact, subjects drew ellipses at a higher average speed than they drew figure-eights and average speed increased more with age for the ellipse than for the figure-eight. This result is consistent with the notion that the figure-eight is a more complex shape to draw than the ellipse and that therefore it requires more control during its execution.

4.2. *Transforming the direction of movement*

An obvious important aspect of information that needs to be processed during drawing and handwriting movements concerns the spatial aspects of the figure to be drawn. Different shapes are obtained by steering the movement and appropriately changing direction during its execution. On the basis of the results found in visuo-manual mental rotation studies (Georgopoulos and Massey, 1987; Georgopoulos et al., 1989; Lurito et al., 1991; Pellizzer and Georgopoulos, 1993), we made the hypothesis that changing the intended direction of movement is a time-consuming process which affects the kinematics of the ongoing movement, and that the time spent by the process is a linear function of the angle of transformation. This hypothesis led to Eq. (2) which describes the relation between instantaneous speed and curvature (Pellizzer, 1997; c.f., Appendix). We found that the transformation model described well the data of all age groups, which therefore provide support for the proposed hypothesis.

The description of the relation between speed and curvature using the power law was generally not as good as using the transformation model. In addition, we found that the results for the ellipse condition using the power law were compatible with those obtained by Viviani and Schneider (1991). In this condition the value of the exponent of the power function increased with age to reach a value close to 1/3 at 12 years of age. Therefore these results indicate that the data obtained in the present experiment were consistent with those obtained by Viviani and Schneider (1991). However, the change of value of the exponent did not generalize to the condition of the figure-eight, which indicates that this is not a general descriptive principle.

The adequacy of the transformation model to describe the relation between speed and curvature does not mean that other constraints were not involved in producing this functional relation, but they suggest that the process of transformation of the intended direction of movement played an important role. Other factors such as, for example, the musculo-skeletal properties of the arm play also a role in shaping the kinematics of the movement (Gordon et al., 1994a; Gribble and Ostry, 1996; Meulenbroek et al., 1998).

4.3. *Spring-like properties of the arm*

The neuromuscular system of the multi-joint arm has spring-like properties (Hogan, 1985; Mussa-Ivaldi et al., 1985). These properties are dynamically adjusted during movement (Bennett et al., 1992; Frolov et al., 2006) and adapted to changing conditions of interaction with the environment (Gomi and Osu, 1998). In particular, it has been shown that the effects of the spring-like properties of the arm on the kinematics of cyclic movements become more evident at faster movement speeds than at slower speeds. Indeed, the kinematics of alternating pointing movements get closer to sinusoidal oscillations resembling those of an ideal mass-spring system when movements are performed at higher speed (Buchanan et al., 2003; Guiard, 1993). At higher speed the kinetic energy built during the movement is transformed into potential energy that is used to execute the subsequent movement rather than being dissipated (Guiard, 1993; Hogan, 1985). In agreement with these results we found that the data from ellipses drawn at higher speed fitted the power law better than the other productions. This is because the power law with an exponent of 1/3 is equivalent to assuming that the movement is generated by two coupled harmonic oscillators (Gribble and Ostry, 1996; Lacquaniti et al., 1983). Therefore, the data suggest that the spring-like properties of the arm played a more prominent role when ellipses were drawn at high speed than in any other cases. At low speed the frictional forces are large relative to the inertial forces, which reduce the contribution of the spring-like properties of the arm in shaping the kinematics of the movement. In addition, the shape of the ellipse makes it more suitable to allow the exploitation of the elastic properties of the arm than the one of the figure-eight. This is because the kinetic energy built when drawing a segment along the principal axis can be used to draw the following segment which goes in the opposite direction after the turn at the highest point of curvature (Guiard, 1993; Desbiez et al., 1996; Meulenbroek and Thomassen, 1993). In contrast, for the figure-eight the straightest segments of the figure cross at an angle, and follow each other only after a longer curve than that for the ellipse. This means that the elastic properties of the arm are less likely to be exploitable for the figure-eight than for the ellipse (Desbiez et al., 1996; Meulenbroek and Thomassen, 1993).

Even when models of the arm that include non-linear components are used to simulate drawing of ellipses, the time-course of the $\langle x,y \rangle$ coordinates of the end-point closely resemble sinusoids and a power law with an exponent close to 1/3 fits well the simulated data (Gribble and Ostry, 1996; Wann et al., 1988). This implies that ellipses are not well suited to distinguish between different models of the relation between speed and curvature, because generally the predictions are not very different (Hicheur et al., 2005; Pellizzer, 1997; Viviani and Flash, 1995). In contrast, the use of more complex figures gives a better opportunity for discriminating among models. Using the figure-eight we found that the transformation model provided a better fit of the data than the power law. Whereas the data from the ellipses showed that the transformation model was less well supported when the movement was executed at high speed, which is when the elastic properties of the arm presumably played a greater role in the kinematics of the movement. Similar results were found with adult subjects where it was shown that the 1/3 power law fitted the data better when ellipses were drawn at a faster speed than at a slower speed (Wann et al., 1988).

These results suggest that the factors shaping the movement kinematics such as the process of transformation of the intended direction of movement and the elastic properties of the arm are both present, but their relative weight can vary in relation to constraints defined by the path of the movement and its average speed. This emphasizes the notion that the transformation model concerns mostly the planned trajectory rather than the motor output itself. The spring-like properties of the arm intervene in shaping the actual movement trajectory, but a discernible effect on the relation between speed and curvature seemed to appear only as the speed of the movement increases. Subjects tended to produce ellipses at a faster speed than figure-eights as a consequence the visco-elastic properties of the arm were more important for the ellipses than for the figure-eight. These conclusions bring the prospect of integrating the central constraints and the effect of the spring-like properties of the arm within a single model. Such a model would vary the weight to these two components depending on factors such as average speed.

4.4. *Changes of the parameters of the transformation model with age*

Concerning the change of the parameters of the transformation model with age, we found the following. The rate of transformation of the intended direction of movement ω increased with age and was greater for the figure-eight than for the ellipse. On the other hand, the parameter V_{TR} was greater for the ellipse than for the figure-eight and it increased with age at a higher rate for the ellipse than for the figure-eight. First, these results suggest that the two parameters of the model are independent and account for different aspects of the performance. This is analogous to the relative independence between specification of extent and direction in discrete aiming movement, which has been demonstrated in behavioral (Favilla et al., 1990; Gordon et al., 1994b) and neurophysiological studies (Fu et al., 1993). Second, the effect of age and type of figure on V_{TR} was essentially the same as the effect on average speed, which indicates that V_{TR} reflects mainly the average speed at which a subject chooses to draw the figure. This result indicates that the capacity of the subjects to execute faster movements increased with age. However, since the subjects were not asked to draw the figures at the fastest speed we can surmise that the physical ability required for movement execution was not necessarily a limiting factor here, rather it was the speed at which a drawing movement can be executed comfortably that was limiting.

The increase of ω with age reflects the general increase in processing speed during childhood (Hale, 1990; Kail, 1986). In particular, it indicates that the speed of transformation of the intended direction of movement increased linearly between 8 and 12 years of age. The slope of the increase of ω with age was the same for the two types of figures, however we found that ω was systematically greater for the figure-eight than for the ellipse. This effect might be related to the greater amount of rotation required for producing a figure-eight than an ellipse. The increase in rotation speed with an increase in amount of rotation could reflect a compensation mechanism similar to the increase in movement speed with increase in movement amplitude. The differential effect of figure-type on ω needs to be addressed specifically in a different experiment.

4.5. *Continuous and discrete change of the intended direction of movement*

In the introduction we made the hypothesis that the coupling between speed and curvature results from the time-consuming process of changing the intended direction of movement, which was based on visuo-manual mental rotation studies. These studies indicate that the duration of transformation of the intended direction of movement increases linearly with the angle of transformation. However, it has also been shown that in the appropriate conditions the intended direction of movement could change in a switch-like fashion from one direction to another. In a context-recall task, we found that the activity of neurons recorded in the primary motor cortex changed abruptly reflecting first one direction and then another without passing through intermediate values (Pellizzer et al., 1995). Furthermore, in a series of experiments, Ghez and colleagues (Ghez et al., 1997) have shown that force and movement direction was specified either continuously or discretely from a default direction depending on whether targets were narrowly or widely separated from the default direction, respectively. These results suggest that under the appropriate conditions the intended direction of movement during drawing movements may be changed in a discrete way, which would have the consequence of breaking the relation between speed and curvature. Such conditions may occur if two adjacent directions of a figure are widely different and separated by a singularity in the shape such as a cusp (e.g., cursive letter ‘‘i’’).

5. Conclusions

The data obtained with subjects from 8 to 12 years of age drawing ellipses and figure-eight supported the transformation model. In this respect, this extends the results obtained with adult subjects (Pellizzer, 1997). The transformation model is based on the assumption that transforming the intended direction of movement is a time-consuming process, which affects the unfolding of the movement trajectory. The results support the hypothesis that the process of transformation of the intended direction of movement increases in speed between 8 to 12 years of age. The effects of the spring-like properties of the arm were noticeable when ellipses were drawn at high speed. These results indicate that both peripheral properties and central processes have an effect on the kinematics of continuous movements and particularly on the relation between speed and curvature. However, their relative importance varies depending on the figure and average movement speed.

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Appendix

We will assume that two independent time-consuming processes can explain how continuous drawing and handwriting movements unfold in time. In other words, the time Δt to trace a segment Δs of the path (Fig. 1A) is the sum of two components, Δt_{ROT} and Δt_{TR}:

$$\Delta t = \Delta t_{ROT} + \Delta t_{TR} \tag{A.1}$$

where Δt_{ROT} corresponds to the time needed to rotate the intended direction of movement by an angle $\Delta\alpha$ and Δt_{TR} represents the time of translation along the segment Δs. These two time components are defined as:

$$\Delta t_{ROT} = \frac{|\Delta\alpha|}{\omega} \tag{A.2}$$

and

$$\Delta t_{TR} = \frac{|\Delta s|}{V_{TR}} \tag{A.3}$$

where ω is the speed of rotation of the intended direction of movement and V_{TR} is the speed of translation. By definition, movement speed V at any point of the trajectory is:

$$V = \frac{|\Delta s|}{\Delta t}, \tag{A.4}$$

which, by using the assumption (A.1), gives:

$$V = \frac{|\Delta s|}{\Delta t_{ROT} + \Delta t_{TR}}, \tag{A.5}$$

Substituting (A.2) and (A.3) in (A.5), we have:

$$V = \frac{|\Delta s|}{\frac{|\Delta\alpha|}{\omega} + \frac{|\Delta s|}{V_{TR}}}. \tag{A.6}$$

Using the definition of curvature:

$$C = \left|\frac{\Delta\alpha}{\Delta s}\right| \tag{A.7}$$

in (A.6) we obtain:

$$V = \frac{1}{\frac{C}{\omega} + \frac{1}{V_{TR}}} \tag{A.8}$$

which can be rearranged as:

$$V = \frac{V_{TR}\omega}{\omega + V_{TR}C}. \tag{A.9}$$

Now, assuming that V_{TR} *and* ω are constant within a movement trajectory, then the instantaneous speed $V(t)$ relates to the local curvature $C(t)$ as:

$$V(t) = \frac{V_{TR}\omega}{\omega + V_{TR}C(t)}. \tag{A.10}$$

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