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# Stability of Coordination Patterns in Handwriting: Effects of Speed and Hand

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Previous studies have shown the existence of preferred stroke directions and shapes in handwriting. Assuming that such a two-dimensional trajectory formation process relies on the nonlinear coordination between two abstract orthogonal oscillators, a recent study (Athènes et al., in press) investigated the relative stability and the temporal accuracy of such coordination patterns in performing various ellipsoids corresponding to different phase and amplitude relationships between the oscillators. Results showed that only a small subset of the patterns was stable and accurate. The present study tested and verified the assumption that more stable coordination patterns deteriorate less under a speed constraint. In addition, differences between the dominant and nondominant hands gave insights into various effects modulating the stability and accuracy of such preferred patterns. Evidence of preferred coordination patterns and the predictability of their deterioration corroborate the existence of dynamics underlying handwriting in terms of nonlinearly coupled oscillators.

*Key Words:* dynamic pattern theory, self-organization, dynamical systems, graphonomics, drawing

Handwriting involves highly automated, individualized movements, realizing various letters that people practice extensively during their lifetime. Cursive letters consist of shapes, composed of loops and strokes, which are co-articulated to form words. The legibility of the written words improves with practice, but could also deteriorate in some adverse situations, such as when the writer has to write quickly. For the sake of handwriting recognition or of remediation of handwriting disorders, it is crucial to establish whether such distortions of the script occur in a systematic fashion. A major question is whether some features of the script remain constant under varying levels of constraint, such as writing speed, while others might be altered. Such a balance between invariant and mutable characteristics of the script mirrors the writer's struggles between a tendency toward simplification, leading to a reduced number

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of basic strokes that are easy to execute, and a tendency toward differentiation, avoiding confusion among letters that look similar (Irigoin, 1990).

An objective of motor control studies of handwriting is to identify basic features and regularities in graphic motion in various task contexts. Comparing different handwriting systems (Arabic, Chinese, Hebrew, and English, among others), van Sommers (1984) showed that strokes towards the bottom right and the bottom left (and to the right and top right, to a lesser extent) are most frequent, whereas strokes toward the top and the left are virtually nonexistent. Not only are these preferred orientations produced more accurately, but they also bias the production of other strokes toward these orientations (Meulenbroek & Thomassen, 1991). Such preferences are deemed to pertain to the coordination between finger and wrist movements at the biomechanical level (van Emmerick & Newell, 1990; Dooijes, 1983; Maarse, Schomaker, & Thomassen, 1986; Teulings, 1996), which accounts chiefly for differential complexity of the performed coordination patterns (Dounskaia, van Gemmert, & Stelmach, 2000). Moreover, at fast speed (Dounskaia et al., 2000) or without visual feedback (Meulenbroek & Thomassen, 1991), such preferred patterns become more prevalent, shaping the degradation of the production. These results corroborate the existence of preferred tendencies that influence all the graphic production, and of systematic deteriorations with increasing task constraints.

One way to understand script production is to assume that some part of the trajectory, such as ballistic strokes (Maarse & Thomassen, 1983), complete allographs (Teulings, Thomassen, & van Galen, 1983), or upstrokes pairs (Wing, 1978), constitute graphical units that are preplanned and implemented at a higher level in the control system. Another approach is to conceive of handwriting as the outcome of the combination of two oscillatory movements, one horizontal resulting from wrist motion and one vertical resulting from finger movements, with the addition of a rightward continuous translation (Hollerbach, 1981; Singer & Tishby, 1994). All the letter shapes present in cursive script can thus be segmented and implemented in terms of the relative phase, the relative amplitude, and the frequency ratio between the two orthogonal oscillators. These types of models, however, fall short of addressing two basic issues in handwriting: the co-articulation between shapes and the presence of preferred coordination tendencies that shape the production and the deterioration of the graphic script under various constraints.

An entry point into these issues is a dynamic approach to coordination (Kelso, 1995; Schöner & Kelso, 1988a), especially in reference to models of nonlinear coupled oscillators. Seminal work by Haken, Kelso, & Bunz (1985) established that the coordination of periodic multilimb movements can be captured by the dynamics of a collective variable, relative phase, derived from a system of two nonlinear coupled oscillators. In a now classical study on bimanual coordination, Kelso (1984) showed that limbs act as biological oscillators, and that their coupling leads to only two spontaneously stable coordination patterns, namely, in-phase and anti-phase. Numerous studies shown that the dynamics of relative phase governs the formation and change of behavioral patterns in many other coordination tasks, for instance, between homolateral limbs (e.g., Kelso & Jeka, 1992) or between two persons (Schmidt, Carello, & Turvey, 1990). Of particular relevance to the topic of handwriting, the formation of endpoint planar trajectories also proved to be an outcome of coordinating the periodic motion of two orthogonal components (de Guzman, Kelso, & Buchanan, 1997; Buchanan, Kelso, & Fuchs, 1996; Buchanan, Kelso, & de Guzman, 1997). A common thread in these studies is that the relative stability of the spontaneous coordination patterns determines their loss of stability and the direction of behavioral change from one pattern to another when a critical constraint, such as movement speed, is increased.

Previous work (Athènes et al., in press) identified stable coordination patterns in a handwriting-like task for right-handers. Whereas several different patterns (i.e., ellipses of various eccentricities) were required by the task, only a few were spontaneously performed in a stable and precise fashion, namely, four lines and four ellipsoids of various orientations. Such preferred coordination patterns corresponded to specific and stable phase and amplitude relationships between two frequency-locked orthogonal nonlinear oscillators. They were characterized by a high accuracy with respect to the (temporal) task requirements and by a notable stability, as well as by attraction of nearby patterns. Such features are reputed hallmarks of attractors (see Schöner & Kelso, 1988b, for a theoretical treatment; Zanone & Kelso, 1992, for an empirical treatment), suggesting that there are stable states of the spontaneous coordination dynamics of handwriting. Like all periodic motion, graphic skills are thus governed by the dynamics of nonlinear coupled oscillators.

In our previous study, handwriting coordination dynamics was asserted at a spontaneous movement speed for right-handed adults who, admittedly, had a fairly extended practice culminating with expert repertoire and skills. The central question addressed in the present study is how handwriting coordination dynamics evolves in the face of different factors that could limit, degrade, or change the production of script patterns. Two such factors are scrutinized here, namely, movement speed and the usage of the left versus right hand. Our basic assumption is that faced with higher levels of constraints, writers are limited by the dynamic properties of the existing preferred coordination patterns, namely, their stability.

With respect to the effect of speed, the theoretical model stipulates that the order of destabilization of attractive states follows the inverse order of their respective stability. Accordingly, we hypothesize that the pattern that is least stable in the slowest condition of handwriting should also be the first to destabilize with increasing movement speed, and so on for the other preferred patterns. We further compare the spontaneous dynamics of the dominant (right) hand with that of the nondominant (left) hand in right-handers. Our rationale is that the coordination dynamics identified in the previous work surely pertain to an expert performance, which has accommodated for most trajectories and neuro-biomechanical constraints imposed by the task (Dooijes, 1983; Thomassen, 1992). It is then likely that the observed dynamics results from the interplay between the spontaneous dynamics specific to the writing right hand before any practice and coordination patterns acquired with practice. A similar process has been shown for learning new bimanual coordination patterns (Zanone & Kelso, 1992, 1997). Over the years, the practicing child will eventually trade dynamics that are determined mostly by the effectors properties and allow producing easy patterns with dynamics that include learned coordination patterns and permit the execution of (all) legible words. Based on the relative stability of the coordination patterns known to the right hand and on the symmetry properties between the hands, we expect both dynamics to show some similarities, but also notable differences, especially in terms of stability, because of the stabilizing effects of practice on some specific patterns.

To detect systematic alterations of the spontaneous coordination dynamics under speed constraints and to compare the right and left hand dynamics, we used a "scan" paradigm adept to identify the stable states in the dynamics of a given system (Tuller & Kelso, 1985; Yamanishi, Kawato, & Suzuki, 1980; Zanone & Kelso, 1992; see the "Task" section for details). Consistent with our previous study (Athènes et al., in press), several shapes corresponding to various relative phases and relative amplitudes between orthogonal oscillators were performed with the right (dominant) and the left (nondominant) hand at spontaneous and high movement speeds.

## Methods

### Participants

Eight right-handed adults ■ participated in the experiment on a voluntary basis. Hand dominance was assessed by a questionnaire of hand preference in various daily tasks (Dellatolas et al., 1988).■

### Apparatus

Various shapes appeared successively every 7 s at the center of a digitizing tablet ■(active surface 21 × 15 cm), which was inserted in a table of adjustable height facing the participants. This tablet sampled the $x$ and $y$ coordinates of the trajectories realized by the stylus at a frequency of 100 Hz and a spatial accuracy of .05 cm. Collected data were stored for later processing.

### Task

Participants were required to draw the shapes displayed on the tablet using an attached stylus. Two sets of 13 shapes were presented, ranging from a 2-cm-long line to a circle of 2 cm diameter and going through several ellipses of varying eccentricities. These two sets of shapes corresponded to the progressive manipulation of either the relative phase or the relative amplitude between two orthogonal oscillators, so-called relative phase and relative amplitude scanning tasks. Participants had to reproduce, without lifting the stylus, 13 shapes that appeared successively for 7 s on the tablet. The ascending and descending orders of appearance within a participant were counterbalanced across participants. The instructions were to be as accurate as possible and to maintain a constant speed during the entire scan of 13 shapes. Both relative phase and relative amplitude scanning tasks were performed in four different conditions: with the right hand (RH) and the left hand (LH), at spontaneous (S) and high (F) speed.

For the sake of simplicity, we assumed that the oscillators are orthogonal. Figure 1 depicts the mapping between the relative phase between the oscillators and the shapes displayed on the tablet during the scan of relative phase from 0° to 180° in 15° steps. Each shape corresponded to an ellipse or a stroke with an oblique orientation. The amplitude for both oscillators remained constant (2 cm). Figure 2 shows the mapping between the ratios of the two oscillators' amplitude and the shapes presented during the scanning of relative amplitude. The shapes were various ellipses and strokes with a vertical or horizontal orientation. Thirteen relative amplitudes were obtained by diminishing the amplitude of one oscillator, for example, from $A_x = 2$ cm to $A_x = 0$ cm, in six equal steps, while maintaining the amplitude of the other oscillator at its maximal value, for example, $A_y = 2$ cm. Thus, the amplitude ratio $A_y{:}A_x$ (see Figure 2) would change from 6:6 to 6:0. Note that meanwhile the relative phase was set at a constant 90°. The same procedure was carried out with the other oscillator.

### Procedure

The relative phase and amplitude scanning tasks were executed with the right hand (RH) and with the left hand (LH). To account for the bilateral symmetry between hands, ellipses were performed in counterclockwise rotation with the RH and in clockwise rotation with the LH. Likewise, drawing a line tilted to the right with the RH corresponded to drawing a line tilted to the left with the LH. Six trials of approximately 100 s were performed for each condition. Participants were tested over 2 days in four separate sessions, lasting about 1 hour each. One day was devoted to the RH and the other to the LH. Half the participants began with the LH or half with the RH. There were two sessions on each day. The first session was

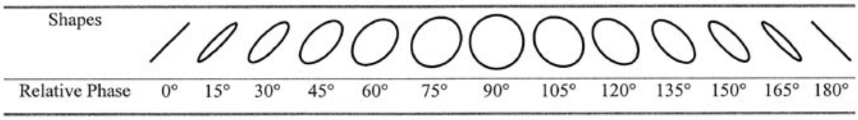

**Figure 1 Scan of relative phase. Mapping of the diagonal shapes with their expression in relative phase. The diameter of the circle is 2 cm.**

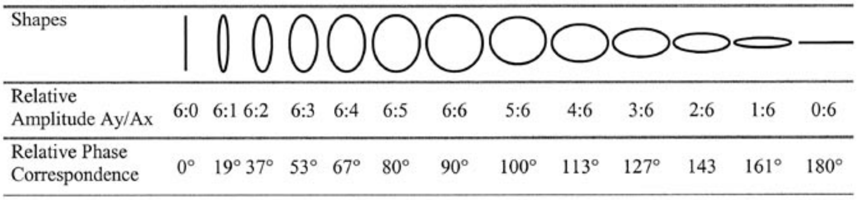

**Figure 2 Scan of relative amplitude. Mapping of the upright shapes with their expression in amplitude ratios and in relative phases. Maximal amplitude, denoted 6, corresponds to a length of 2 cm.**

devoted to the spontaneous (S) and the second to the fast (F) speed condition. At the beginning of each day, participants were required to repetitively trace a circle in the middle of the screen for 30 s. We noted the relative position of the arm (angle between the arm and the horizontal border of the tablet) and required participants to maintain this position throughout the session. Prior to the experiment, one extra trial was carried out for each task for familiarization purposes.

### Data Analysis

For both scans, we assessed performance by computing the mean and variability of actually performed relative phase (RP, in degrees) as a cycle-by-cycle estimate (see Zanone & Kelso, 1992). For analysis and comparison purposes, the amplitude scanning task was also measured in terms of relative phase, following a planar transformation that led to a 45° counterclockwise rotation of the coordinate axes (for details, see the Appendix in Athènes et al., in press). The resulting mapping of relative amplitude onto relative phase is shown in Figure 2. We then calculated the constant error (CE) corresponding to the difference between the performed and the required RP for each pattern, the absolute error (AE), the corresponding standard deviation (*SD*), and the movement frequency (F, in Hz). The CE provides a good estimation of the location of attractive states: In a plot of CE as a function of required RP, a negative slope indicates which relative phase pattern pulls nearby values, as a result of the attractive properties inherent to its stability.[1] AE yields a reliable accuracy measure, because it avoids canceling out the over- and under-estimation in the vicinity of the attractors, and *SD* provides a good measure of the stability of the performed pattern. It is important to keep in mind that following the adopted description of the task in terms of coupled oscillators, accuracy is defined here strictly in the *temporal domain*, that is, in the space of relative phase (a measure of the time delay between two periodic processes) *and not in the space domain*, that is, in terms of the discrepancy between the model and performed shapes. Of course, a substantial error in relative phase might lead to significant deformations from the required shape, but not necessarily and not in a unequivocal fashion because of the possible intervening effects of amplitude modulations.

## Results

Results for the scans of relative phase and of relative amplitude are presented in two subsections. Analyses of variance regarding the effects of Hand (2), Shape (13), and Speed (2), with repeated measures of all factors were performed on mean AE, *SD*, and F. Significant effects were further analyzed by Fischer post hoc tests with a threshold set at $p < .05$.

### Scan of Relative Phase

Although participants were required to maintain the same movement frequency all along a scan, the ANOVA revealed that all main effects were significant: Hand [$F(1, 7) = 28.24$, $p < .001$], Speed [$F(1, 7) = 119.5$, $p < .001$] and Shape [$F(12, 84) = 3.7$, $p < .0001$]. Two two-way interactions were also significant: Shape × Speed [$F(12, 84) = 5.24$, $p < .001$], Shape × Hand [$F(12, 84) = 2.13$, $p < .05$], as well as the three-way Shape × Speed × Hand interaction [$F(12, 84 = 2.9, p < .001$]. Mean frequencies were 3.15 Hz, 4.57 Hz, 2.03 Hz, and 2.88 Hz for the RHS, RHF, LHS, and LHF conditions, respectively. The first result is that the overall frequency was higher for the RH than the LH. Moreover, as instructed, participants increased the frequency in the fast speed condition for both hands ($p < .05$). Post hoc analysis revealed that all conditions were significantly different from each other, except for RHS and LHF. In all conditions, except for RHS, participants could not maintain the same frequency from the initial to the final required RP.

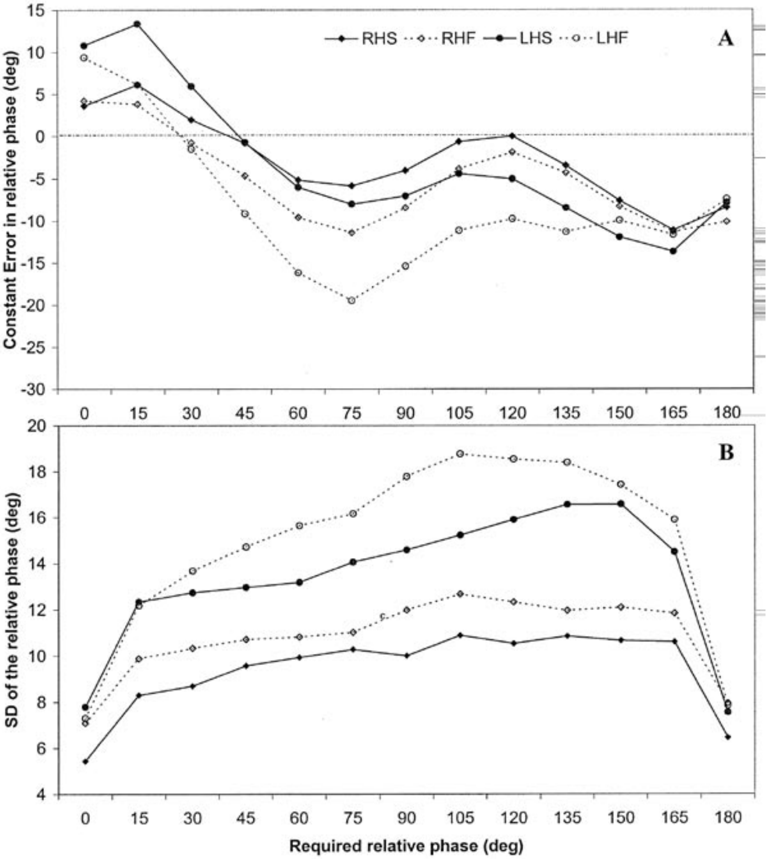

**Figure 3 Scan of relative phase. Panel A: Constant error of the produced relative phase for each task condition (RHS, RHF, LHS, and LHF), as a function of the required relative phase. Panel B: Standard deviation of the produced relative phase for each task condition, as a function of the required relative phase. In both panels, the left-hand conditions are represented by a diamond and the right hand conditions by a circle. For each hand, spontaneous and fast speed corresponds to solid and dotted line, respectively.**

Figure 3 presents the results of the scan of relative phase for each condition (RHS, RHF, LHS, and LHF) averaged over participants and trials. Figure 3A shows the mean CE of the performed RP and Figure 3B the associated *SD*, as a function of the required RP. In Figure 3A, the RHS curve (spontaneous frequency and right hand, denoted by solid diamonds) shows a good match between the performed and the required RP at 0°, 45°, and 120°, and a decrease of CE toward 180°. Moreover, there are negative slopes of the CE curve toward 45° and 120°, a clear sign of attraction. For 45°, the negatively-sloped zero-crossing means that patterns were systematically over- or under-estimated for RP values below and above 45°, respectively. For 120°, attraction is noticeable only for higher RP values, as the negatively-sloped curve does not cross the abscissa at 120°, but only "points to it'" Individual CE curves (data not shown here), however, did cross the abscissa near 120° for six of the eight participants. The results reveal attraction toward 45° and 120°, and confirm the state of the coordination dynamics reported for similar conditions in our recent study (Athènes et al., in press). Regarding the hand effect, the LHS curve (solid circles) undergoes a slight downward shift, especially for the high RP values, suggesting a slight move of the 120° attractor to a lower value (i.e., 105°), without dramatic change in the global regime, because the 45° attractor is still present. Regarding the speed effect, the RHF curve (open diamonds) reveals a negative slope with a zero-crossing shifted toward 30°, without any major change near 120° with respect to RHS. For the LHF (open circle), cumulating speed and hand effects, there is a drift of the negative slope from 45° to 30° and a lack of negative slope about 120°. This indicates that the corresponding attractor vanished altogether under such a high level of constraints.

Figure 3B presents the *SD* of the performed relative phase for each condition. In all conditions, the performed *SD* was lower when 0° and 180° patterns were required. For the LH at both speeds, there was an increase of *SD* between 75° and 165° patterns. The ANOVA showed that all main effects were significant, $F(1, 7) = 25.97, p < .0001$, $F(1, 7) = 24.43, p <. 05$, and $F(12, 84) = 70.23, p < .0001$ for the Hand, Speed, and Shape effect, respectively. The Hand × Shape interaction was also significant ($F\,(12, 84) = 6.01, p < .0001$). This suggest that irrespective of the speed, the 0° and 180° patterns were most stable and all RPs were less variable when produced by the RH as compared to the LH. Moreover, patterns between 15° and 165° increased in variability in a steeper fashion for the LH than for the RH. Post hoc analyses confirmed that, in all conditions, the 0° and 180° patterns were significantly less variable than any other patterns, while the 15°, 30°, and 45°/60° patterns were significantly more stable than the patterns between 105° and 165°.

Figure 4 presents mean AE for each condition as a function of the required RP. The ANOVA indicated that the Hand, Speed, and Shape main effects were significant [$F(1, 7) = 5.94, p < .05$; $F(1, 7) = 6.33, p < .05$ and $F(12, 84) = 3.7, p < .0001$, respectively]. The Shape × Hand [$F(12, 84) = 2.13, p < .05$] and Shape × Speed [$F(12, 84) = 6.89, p < .001$] interactions were significant, as well as the three-way Shape × Speed × Hand interaction [$F(12, 84 = 2.9, p < .001$]. These results indicate that the RH is more accurate than the LH and that accuracy deteriorates with higher speed. Moreover, for the RH, post hoc analyses revealed that the 0°, 30°/45°, (and 15° for RHF) and the 105°/120°/135° patterns were more accurate than the other patterns, and that AE decreased from the 165° to 180° pattern. Except for the LHF condition, accuracy was higher at about 0°, 45°, and 120°, and, to a lesser extent, at 180°, as compared to their neighbors. For LHF, the lowest error was reached at 30°, while 120° was comparable to its neighbors.

To sum up, the scan of relative phase for the right hand at spontaneous speed (RHS), our "baseline" condition, reveals attraction to four patterns, 0°, 45°, 120°, and 180°, a finding in accordance with our previous study (Athènes et al., in press). Performing at high speed (RHF and LHF) and with the left hand (LHS and LHF) entails an overall decrease in accuracy and stability. In particular, the 120° preferred pattern experiences a vanishing of the negative slope and a dramatic increase in variability for the LHF "toughest" condition, while the 0°, 45°, and 180° patterns remained least variable and most accurate. This suggests that the attractor close to 120°, the least stable initially, completely destabilizes with increasing constraints.

### Scan of Relative Amplitude

Regarding the movement frequency, mean frequencies were 3.18 Hz, 4.62 Hz, 2.07 Hz, and 3.29 Hz for the RHS, RHF, LHS, and LHF conditions, respectively. An ANOVA revealed that all main effects were significant: Hand [$F(1, 7) = 28.5$, $p < .001$], Speed [$F(1, 7) = 126.5$, $p < .0001$] and Shape [$F(12, 84) = 29.2$, $p < .0001$]. The Shape × Hand interaction was significant [$F(12, 84) = 3.28$, $p < .0001$]. Frequency was lower at spontaneous (2.6 Hz) than at fast speed (3.95 Hz) and was lower with the left hand (2.7 Hz) than with the right hand (3.9 Hz).

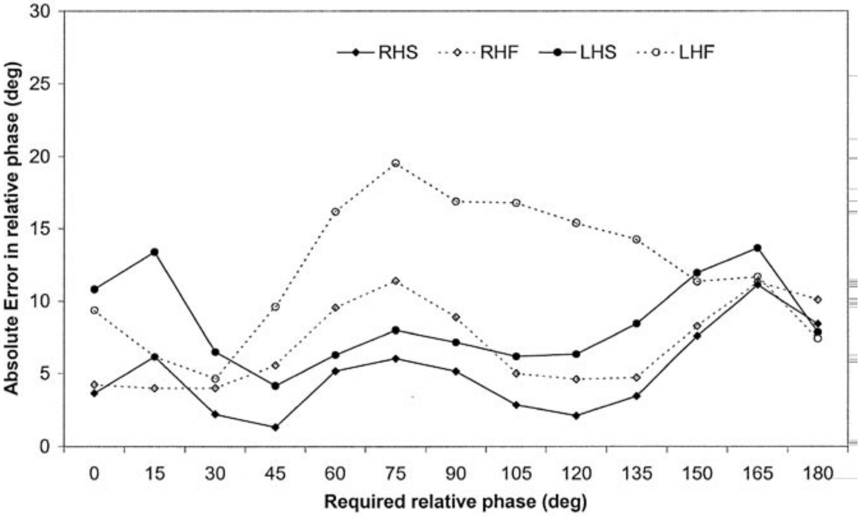

**Figure 4 Scan of relative phase: Mean absolute error of produced relative phase for each task condition (RHS, RHF, LHS, and LHF), as a function of the required relative phase.**

Figure 5 shows the results of the relative amplitude scan for each condition (RHS, RHF, LHS, and LHF), averaged over participants and trials. Figure 5A displays the CE of the performed RP and Figure 5B the corresponding *SD*, as a function of the required RP for each condition. The RHS curve in Figure 5A (solid diamond) reveals a minimal error between the performed and required RP at 0°, 53°, and 113°, and a decrease of CE toward 180°. The slope of the CE curve is negative near 53° and 113° associated with a zero-crossing near 53°, but the curve does not

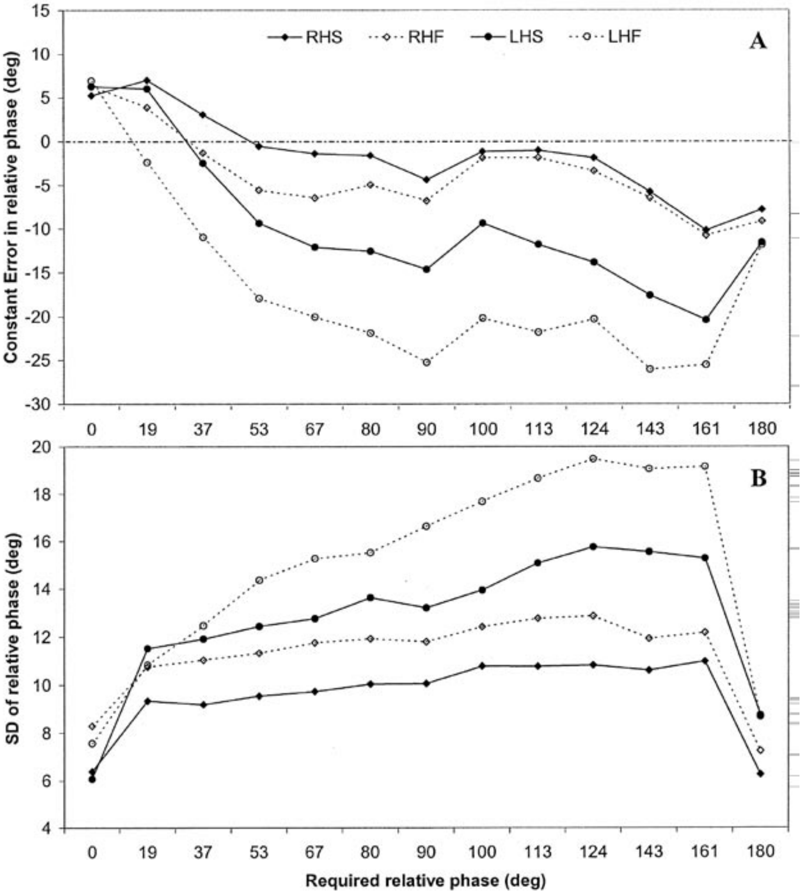

**Figure 5 Scan of relative amplitude. Panel A: Constant error of produced relative phase for each task condition (RHS, RHF, LHS, and LHF) as a function of the required relative phase. Panel B: Standard deviation of the produced relative phase for each task condition, as a function of the required relative phase. In both panels, the left-hand conditions are represented by a diamond and the right hand conditions by a circle. For each hand, spontaneous and fast speed corresponds to solid and dotted line, respectively.**

cross the abscissa near 113°. The individual CE curves, however, exhibited a zero-crossing at 53° for all participants and near 113° for five of the eight participants. Again, such features of attraction toward 53° and 113° confirmed the coordination dynamics tendencies reported in our previous study. Regarding hand effect, the LHS curve (solid circle) showed a negative slope with a zero-crossing about the 37° pattern, and a shift of the negative slope at 113° to a lower value (80°), as compared to the RHS. Regarding speed, the dotted curves indicated a drift of the negative slope about 53°/37° to lower values for both hands. Moreover, although the negative slope to 113° exists in both speed conditions for the RH, such an attraction vanished for the LH at high speed. These results are substantially in line with the scan of relative phase (see Figure 3), especially with respect to the loss of attraction for the 113° pattern in the LHF condition.

Figure 5B presents the *SD* of the performed RP for each condition. In all conditions, *SD* was minimal when the required patterns were 0° and 180°. There was an increase of *SD* from RHF, LHS, and LHF conditions, as compared to RHS. Moreover, this increase in *SD* appears steeper from 90° to 161°, especially with the LH. An ANOVA revealed significant main effects of Hand [$F(1, 7) = 53.32$, $p < .0001$], Speed [$F(1, 7) = 23.4$, $p < .01$], and Shape [$F(12, 84) = 36.87$, $p < .0001$]. The interactions Shape × Hand [$F(12, 84) = 6.73$, $p < .0001$] and Shape × Speed [$F(12, 84) = 4.05$, $p < .01$] were significant, as well as the three-way interaction Shape × Hand × Speed [$F(12, 84) = 3.61$, $p < .05$]. These results indicate that beyond an overall increase of variability under high speed for both hands, there was an additional increase in variability for patterns in the vicinity of 113° in the LHF condition. Post hoc analyses confirmed that for all conditions, except for LHF, the 0° and 180° patterns were significantly less variable than the others, while the patterns between 19° and 67° were significantly more stable than those between 105° and 161°. For the LHF, the 0°, 19°, and 180° patterns were the most stable. Beyond slight numeric differences, the results of the relative amplitude scan are identical to those of the relative phase scan (see Figures 3B and 4B).

Figure 6 presents the mean AE for all conditions as a function of the required RP. An ANOVA revealed significant main effects of Hand [$F(1, 7) = 8.37$, $p < .05$), Speed [$F(1, 7) = 6.53$, $p < .05$] and Shape [$F(12, 84) = 4.08$, $p < .0001$]. The two-way interactions Hand × Shape [$F(12, 84) = 3.2$, $p < .0001$] and Shape × Speed were significant [$F(12, 84) = 5.4$, $p < .05$]. The Shape effect reflects an overall higher accuracy at about 0°, 37°, 113°, and 180° with respect to their neighbors, while the interactions indicate that using the left hand and performing at high speed led to a cumulative decrease in accuracy for patterns in the vicinity of 100°.

To sum up, in accord with our previous findings, the 0°, 37°, 113°, and 180° patterns exhibited a low (temporal) error, small variability, or a negative slope, indicating attraction toward these values in the least strenuous condition (RHS). At fast speed and with the LH, there was a larger increase of *SD* for 113° than for other preferred patterns accompanied by the lack of the negative slope. In agreement with our findings pertaining to the scan of relative phase, the attractive state at about 120°, the least stable spontaneously, destabilizes when performed at high speed and with the left hand.

## Discussion

In light of a recent work by Athènes et al. (in press) reporting the presence of spontaneous dynamics in handwriting, this study aimed to demonstrate how these dynamics are modified when the graphic task is performed at high speed and with the nondominant hand, and to show empirically that these modifications could be predicted by the relative stability of the preferred coordination patterns or attractors. First, the present results corroborate the findings of the above study showing attraction to four stable coordination patterns for the right hand at spontaneous speed. In spite of individual differences, these preferred coordination patterns corresponded to specific and comparable relative phases (roughly at 0°, 45°, 120°, and 180°) for the relative phase and relative amplitude scans.[3] As with other multistable systems, these dynamics define differential (temporal) accuracy, stability, and frequency for the attractive coordination patterns. Moreover, these very dynamic specificities of the patterns allow the formulation of robust and verifiable predictions about their degradation in unfavorable situations.

A major result follows from the comparison between the dominant and the nondominant hand dynamics. As expected, the least stable pattern for the right hand (at about 120°) exhibited for the left hand lower stability at spontaneous speed and was no longer a preferred pattern at high speed. This suggests that the left-hand dynamics might be seen as determining only three stable patterns (i.e., 0°, 45°, and 180°), which correspond to the most stable patterns exhibited by the right hand. Admittedly, with respect to speed and accuracy, for instance, asymmetries between the hands have been linked to several factors, such as hemispheric differences and functional specialization of the hands (for a review, see Elliot & Roy, 1996). ■

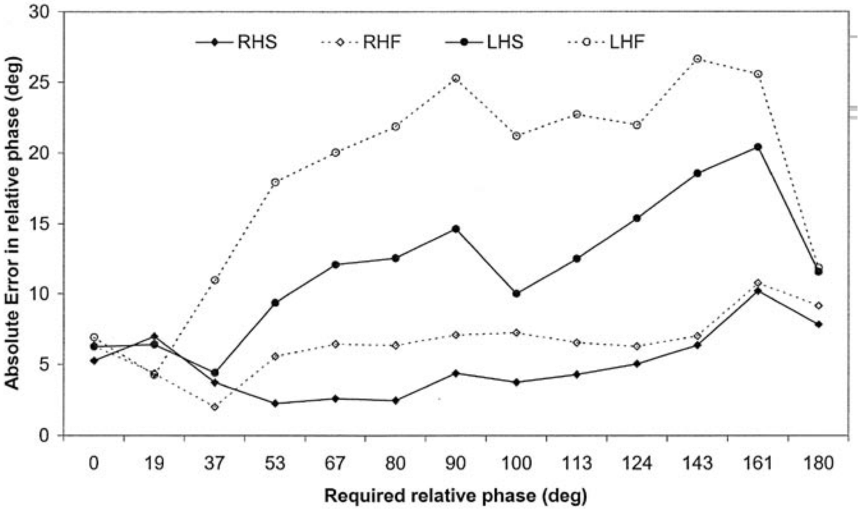

**Figure 6 Scan of relative amplitude: Mean absolute error of produced relative phase for each task condition (RHS, RHF, LHS, and LHF) as a function of the required relative phase.**

Concerning the attractor layout per se, however, a seductive hypothesis is that the tristable dynamics of the left hand are determined essentially by the neurobiomechanical properties of the effector (the finger-wrist system), whereas the quadristable dynamics of the right hand represents the handwriting dynamics that result after the effector dynamics have been modified by many years of practice, in a broad sense. Practice could induce the hand dynamics to be reorganized as a consequence of the different constraints that are imposed on the action (direction, legibility, speed, slant), thereby contributing to the flexibility and adaptability of handwriting. Thus, the current state of coordination dynamics for the right dominant hand might be viewed as the result of the interplay of handwriting practice and the effectors spontaneous dynamics. Some shapes of the script could correspond to preferred coordination patterns (e.g., 0°, 45°, and 180°), leading to cooperation between the required pattern and the spontaneous dynamics. In contrast, other shapes could not conform to the existing spontaneous dynamics, thereby giving rise to a competition regime. Such a view has two consequences (Schöner & Kelso, 1988b). First, competition entails enhanced destabilization of the produced pattern, leading to a high level of variability and discrepancy, whereas cooperation leads to its stabilization, with low variability and error, so that the "quality" of handwriting is affected by the actual dynamical regime. Second, to reduce the cost associated with a competition regime, in particular attentional (e.g., Temprado, Monno, Zanone, & Kelso, 2002), a low-cost cooperation regime could be achieved with learning, which integrates a new coordination pattern into the existing dynamics (Schöner, Zanone, & Kelso, 1992). Thus, learning might stabilize new relative phase patterns (e.g., 120°) into existing handwriting dynamics, through a process similar to that reported for learning bimanual coordination patterns (Zanone & Kelso, 1997; Kelso & Zanone, 2002; Kostrubiec & Zanone, 2002) and other tasks (Fink, Foo, Jirsa, & Kelso, 2000; Jirsa, Fink, & Kelso, 2000).

Our results related to speed manipulation support our main hypothesis: When participants had to perform the same patterns at a higher speed, systematic deterioration was observed. For both relative phase and relative amplitude scans, the order of degradation of the preferred coordination patterns followed the order of their respective stability. Beyond an overall increase in variability and imprecision for fast movements, the most stable and accurate patterns remained the most stable and accurate in the high-speed condition. As expected, the least stable pattern in the least demanding condition (i.e., 120° and 113° for the relative phase and amplitude scans, respectively) destabilized first and foremost, losing their attractive strength, as well as their temporal accuracy and stability. Another indicator of destabilization is the downward shift of the curves of constant error observed with the addition of adverse factors, which could result from an increase in the asymmetry between the oscillators, along the line of theoretical work on bimanual coordination (Fuchs, Jirsa, Haken, & Kelso, 1996). Our findings might thus inform the rules governing degradation in handwriting with increasing constraints. In cursive handwriting, an increase in writing speed should also lead to a decrease in accuracy, the magnitude being different for each letter. For instance, some letters corresponding to a combination of less stable patterns should be more variable than others combining more stable patterns. Moreover, it is likely that the often-observed changes in the formation of some letters at high speed (e.g., “n” looks like “u”) are a result of the writer resorting to combinations of most stable patterns to comply with increasing constraints.

## Conclusion

A main contribution of the present study is the extension of the framework of dynamic pattern theory to a richer coordination system, handwriting, which spontaneously exhibits more than two preferred coordination patterns. We have shown that dynamic principles based on stability and loss of stability govern the orderly formation and change of handwriting patterns as a function of various task requirements. At this stage, however, further investigations are needed to strengthen the link between our results and the action of writing per se. One possibility might be a novel definition of a behavioral unit of writing: a unit is a segment of trace that corresponds to a specific and stable value of relative phase, namely, about 0°, 45°, 120°, or 180°. Different letters (e.g., “e” and “l”) might then pertain to the same unit, because they share the same relative phase pattern. By contrast, a single letter (e.g., “g”) could involve several units because of the different phase relationships performed. Moreover, in a dynamic framework, pattern stability determines the switching among coordination patterns (Kelso, Scholz & Schöner, 1988; Scholz & Kelso, 1990; Carson, Goodman, Kelso, & Elliott, 1994). Thus, transition phenomena, with their expected manifestations, so-called critical phenomena, could govern the co-articulation between coordination patterns that underlie cursive handwriting. Therefore, the formation of graphic patterns, their co-articulation, and their degradation in response to various task contexts might eventually be described by the evolution of a single collective variable, a prerequisite to a comprehensive model of handwriting.

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## Notes

[1] In an ideal and most frequent case, the negative slope of the CE curve crosses the abscissa, thereby signaling what the (locally) attractive (hence, stable) pattern is, namely, about the very RP value where the crossing occurs. In the other cases, even though there is, in fact, no zero-crossing of the CE curve, a negative slope is still an unambiguous sign of attraction. A negative slope of the CE curve in the positive values indicates that the overestimation of the required value decreases systematically as the latter approaches a given value: the attractor. This means that irrespective of the task requirement, performance remains somewhat stationary at a larger value, close to the attractor. Conversely, a negatively sloped CE in the negative values (as in Figures 2 and 5) indicates that the underestimation of the required RP increases systematically as the latter departs from a given value. Irrespective of the task requirement, performance remains about the same smaller value, near the attractor. In both cases, practically, such a stable, attractive pattern is the RP value at which the negative slope would cross the abscissa, were it "long enough" to do so.

[2] That similarity of the attractor layout across scans (relative phase versus relative amplitude) points to the abstract nature of the dynamics, because they remain basically invariant through the 45° rotation imposed by the task (see Figures 1 and 2). Yet, such a rotation must entail a notable change in the actual implementation of the endeffector components. Such independence of the coordination dynamics from the effectors, a property already reported in Kelso & Zanone (2002), might be the origin of the well-known motor equivalence characterizing handwriting (Merton, 1972).■

[3] Although their low variability qualifies them as being stable states, the 0° and 180° patterns were not characterized by a negative slope, the key signature of attraction. As amply reported and discussed in our previous study (Athènes et al., in press) as well as in others (e.g., Zanone & Kelso, 1992), this phenomenon, theoretically coined as "enhanced contrast" (Tuller, Case, Ding, & Kelso, 1994), is a well-formed nonlinear transition between existing attractors, in which the system "escapes" the stable state which was set initially with the slightest change in the task parameters.