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Effects of Biscriptuality on Graphomotor Coordination Dynamics


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De-identified data from our study are available at <https://osf.io/85c4j/>.

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Abstract

Biscriptuality is the ability to write in two different writing systems. The aim of this study was to examine the effects of biscriptuality on graphomotor coordination dynamics in right-handed adults. Thirty-four French monoscriptuals and 34 French-Arabic biscriptual participants traced series of loops in two writing directions, and in two directions of rotation. We found that biscriptuals displayed a general advantage over monoscriptuals in terms of tracing frequency, while both groups displayed a preference for the left to right direction. These results provide novel evidence on the effects of writing direction and type of expertise on graphomotor performance by showing that biscriptuality could be an asset.

Keywords: Biscriptuality, graphomotor coordination, writing, tracing frequency.

Public significance statement:

Biscriptuality - the ability to write in two different writing systems - is becoming more and more widespread. This study shows that the graphic movements of Latin-Arabic biscriptuals are faster compared to those of people who write in Latin script only. These results demonstrate for the first time that the type of writing expertise affects the control of basic graphic movements.

Effects of Biscrptuality on Graphomotor Coordination Dynamics

Handwriting is a complex fine motor skill, that requires years of practice before achieving motor expertise. This expertise is reflected through highly coordinated and rapid graphic movements. Much of what is known about graphomotor skills is based on participants in studies who only use the Latin alphabet (Van Galen et al., 1990; Athènes et al., 2004; Sallagoity et al., 2004; Danna et al., 2011). However, with the rise of globalization and international migration, an increasing number of people are becoming skilled in two scripts. This phenomenon has been termed biscrptuality. It is defined as the ability to write in two different writing systems (Usanova, 2019). Biscrptuality constitutes a different type of writing expertise.

Among the most widely used scripts worldwide, Latin-Arabic biscrptuality is of particular interest from a graphomotor point of view, because the Arabic and Latin scripts have opposite characteristics in terms of writing direction and direction of rotation: Latin is written from left to right, with most letters traced counterclockwise, while Arabic is written from right to left, with most letters traced clockwise (van Sommers, 1984; Slimane et al., 2009). Mastering two writing systems with such different characteristics could influence the way graphic movements are produced. The goal of this study was to examine whether the graphomotor performance varies with the type of writing expertise (Latin script only versus Latin and Arabic scripts).

Producing a graphic trace requires coordination of the wrist and fingers (van der Gon Denier & Thuring, 1965). This process has been termed graphomotor coordination. The oscillatory nature of graphomotor coordination has long attracted the attention of researchers (Nutt, 1917; West, 1922; Teulings & Maarse, 1984; Van Galen et al., 1990; Gangadhar et al., 2007). In his seminal model, Hollerbach (1981) described handwriting as a linear combination of oscillatory movements in the orthogonal plane. The first oscillator represents the movements of the wrist and the second represents finger movements. Various letter forms can be generated by modulating the oscillator amplitude, frequency and phase, and by adding a translation constant from left to right, as this model was developed to explain the writing behavior of Latin script users.

Following the principles of the dynamic patterns theory (Kelso, 1995), some researchers considered that graphomotor coordination could be driven by the nonlinear coupling of these oscillators (Dounskaia et al., 2000; Athènes et al., 2004; Sallagoïty et al., 2004; Danna et al., 2011). According to this approach, the oscillators interact in such a way that they reach a collective (common) state, called a graphomotor coordination pattern. The mutual dependency between the oscillators that results from the interaction is called coupling.

The collective variable of the coupled oscillators is the relative phase, e.g. the time difference between the two oscillators (Haken et al., 1985; Kay, 1988). The variations in relative phase between the two oscillators lead to the formation of elliptical shapes of varying degrees of eccentricity (Athènes et al., 2004; Sallagoïty et al., 2004).

Crucially, the RP value and its variability (RP SD) across cycles successfully explain graphomotor performance in terms of preferences for certain eccentricities because it was found that these eccentricities are produced with better accuracy and with less variability than other possible eccentricities, indicating that they correspond to an optimal coupling (Dounskaia et al., 2000; Athènes et al., 2004; Sallagoïty et al., 2004; Danna et al., 2011). Previous studies have demonstrated that the circular patterns that are produced with the best accuracy and lowest variability in expert right-handed adults correspond to ellipses of intermediate eccentricity (around 45° RP; Athènes et al., 2004; Sallagoïty et al., 2004, Danna et al., 2011). Under unconstrained conditions, participants also spontaneously produce ellipses of intermediate eccentricities when instructed to repetitively draw a circular shape at a high velocity (Dounskaia et al., 2000). These values around 45° RP are distinct from those of children, who display preferences for rounder patterns with a RP around 90° (Danna et al., 2012).

Preferences can also be evidenced through the slant of the traced patterns. Slant corresponds to the degree of orientation of the graphomotor pattern towards the left or the right (Danna et al., 2011, 2012), with values ranging from 0° (3 hrs) to 180° (9 hrs; Figure 2e). Patterns with slant values between 90° and 15° (right-slanted ellipses) tend to be the easiest to produce (most accurate and fastest; Danna et al., 2011). When the slant is not constrained experimentally, graphomotor patterns are produced with an average 64° slant by expert adults (Dounskaia et al., 2000). The lack of slant in

handwriting (values around 90°) is associated with slow (Dounskaia et al., 2000) or less mature handwriting (Phelps et al., 1985; Danna et al., 2012; Li et al., 2019).

The frequency of the oscillators represents the speed of the graphomotor patterns (Bosga-Stork et al., 2011; Sallagoity et al., 2004). This constitutes a solid indicator of preferences in graphomotor pattern tracing (Danna et al., 2012). It quantifies the pace of the movements, that is the number of patterns traced per second. It varies with the difficulty of execution: higher frequencies indicate that the participant faces less difficulty in tracing the given pattern (Danna et al., 2011). When comparing the frequency of children and adults, it was found that frequency changes from 0.5 Hz to 2 Hz (Danna et al., 2012), indicating that frequency increases with expertise.

Finally, further findings within the dynamic approach to graphomotor coordination showed that the performance is also affected by specific factors, namely the writing direction and the direction of rotation in which the ellipses are traced (Danna et al., 2011). Rightward ellipses and counterclockwise ellipses are traced with less variability and higher frequency than leftward ellipses and clockwise ellipses (Danna et al., 2011), indicating that the latter conditions are more difficult. In addition, expert adults also tend to preferentially trace rounder patterns under these more difficult conditions, suggesting that task difficulty impacts the relative phase and drives it into a state that is closer to that of children (Danna et al., 2012).

Overall, these preferences have been interpreted as resulting from biomechanical constraints inherent in the coordination between the wrist and the fingers, since the participants were right-handed (van Sommers, 1984; Dounskaia et al., 2000; Danna et al., 2011). According to this interpretation, the anatomical configuration of the effector leads to the establishment of preferred graphomotor patterns of about 45° eccentricity, slanted towards the right, produced at a frequency of about 2 Hz, and these patterns are most efficient in the left to right direction and for counterclockwise rotations. However, the studies that evidenced these preferences were conducted with monoscriptual participants who only write in the Latin script.

Individual differences in the number and type of scripts practised influence how graphomotor patterns are learned (Nonaka, 2017). Do the graphomotor preferences of biscriptuals, as indexed by the

relative phase, its variability, the slant and the tracing frequency, differ from that of monoscriptuals? Will biscriptuals display the same sensitivity to writing direction and direction of rotation than monoscriptuals? Simultaneously mastering two writing systems with radically opposite characteristics could modify the coordination dynamics underlying handwriting. In fact, within the more general dynamic approach to bimanual coordination, it has been shown that learning new coordination patterns can lead to long-term qualitative and quantitative changes in coordination preferences (Schöner et al., 1992; Zanone & Kelso, 1992).

If the preferred coordination patterns are solely driven by biomechanical factors, then the extensive expertise in Latin and Arabic scripts should not have any impact on performance. Thus, right-handed monoscriptuals and biscriptuals should display the same preferences, and their performance should be equally facilitated in the left to right direction and for counterclockwise rotations. Conversely, if long-term training for non-preferred conditions impacts the dynamic system underlying graphomotor coordination, we should observe differences in the preferences of the two groups, as well as a different effect of direction and rotation for biscriptuals in comparison with monoscriptuals. To discriminate between these alternative hypotheses, we designed a study where right-handed French monoscriptual and Arabic-French biscriptual participants traced loops in two writing directions (left to right and right to left) and directions of rotation (clockwise and counterclockwise). This task corresponds to the tracing of ellipses with a superimposed translation (Hollerbach, 1981). Loop tracing has been extensively used in writing research as a valid and reliable task to assess graphomotor control (Meulenbroek et al., 1998; Marquis et al., 2007; Segal & Petrides, 2012; Kahindo et al., 2018; Senatore & Marcelli, 2019; Vaivre-Douret et al., 2021). It allows the assessment of graphomotor coordination dynamics (RP of the loops, slant, and frequency).

Method

Transparency and Openness

Program codes and statistical packages used are cited in the text and listed in the references section. As per Level 1 requirements, anonymized data sets are publicly available, and can be accessed

through the following repository <https://osf.io/85c4j/>. The questionnaire data, as well as other materials such as the MATLAB analysis script for the extraction of the frequency, RP, Slant, the R statistical analysis script as well the handwriting data collecting software are available upon request. The design of the present study was based on the STROBE cross-sectional statement. This study was not pre-registered prior to its implementation.

Participants

Thirty-five right-handed biscriptual participants and 34 right-handed age-matched monoscriptual participants volunteered for the experiment that was conducted from December 2020 to May 2021. Sample size was determined using GLIMMPSE (<https://glimmpse.samplesizeshop.org>). Previous studies on graphomotor coordination dynamics typically used repeated measures designs without any group factor. The only effect sizes available in the literature were for the main effect of orientation (Danna et al., 2011, $n = 10$ right-handed participants). We based our calculations on the smallest effect size reported, a main effect of slant on the variability of the RP (partial eta-squared = 0.68). Based on this effect, a positive correlation of $r = 0.8$ between left to right and right to left directions, an alpha of .05 and an 80% power, the required number of participants was 12. We then simulated our design with GLIMMPSE and computed the power for the Writing Direction x Group interaction assuming an effect size twice smaller for the biscriptuals. With the same parameters and the assumption of group sizes, the required overall sample size was 68.

One participant with an incomplete set of loops was excluded from the biscriptual group. The final sample size largely exceeded the sample sizes used in previous studies on graphomotor coordination dynamics (typically around ten participants per group; Dounskaia et al., 2000; Athènes et al., 2004; Danna et al., 2011, 2012). The participants filled in an online questionnaire that identified the spoken languages and written alphabets of the sample through questions that assessed the duration, amount and frequency of exposure to French and Arabic, and the manual laterality. To take part in this study, all participants had to meet the following requirements: (1) to be aged between 20 and 40 years old, (2) to demonstrate established right-handedness, (3) for biscriptual participants, to speak fluently

and write with equal proficiency French and/or Arabic, meaning that all biscriptual participants must be native Arabic speakers and writers.

None of the participants reported any relevant medical history. All participants had normal or corrected-to-normal vision and signed a written informed consent before starting the experiment, in accordance with the ethical standards set out in the Declaration of Helsinki and approved by the local Ethics Committee.

The writing habits of the two groups of participants, as well as their academic and linguistic backgrounds, are summarized in table 1.

Table 1

Sample characteristics, writing habits, academic and linguistic backgrounds of the two groups of participants.

| | MONOSCRIP TUALS | | BISCRIP TUALS | |
|---|------------------------|-----------------|----------------------|-----------------|
| | | (n = 34) | | (n = 34) |
| Age | | 26.04 | | 26.30 |
| Gender | M | 35.3% | M | 41.2% |
| | F | 64.7% | F | 58.8% |
| Level of education | BSc | 11.7% | BSc | 11.8% |
| | MSc | 35.3% | MSc | 46.3% |
| | PhD | 53% | PhD | 41.9% |
| Writing habits | | | | |
| Number of pages written in Latin script per week | < 5 | 82.4% | < 5 | 76.5% |
| | ≥ 5 | 17.6% | ≥ 5 | 23.5% |
| Number of pages written in Arabic script per week | | | < 5 | 100% |
| Typing habits | | | | |
| Number of pages typed in Latin script per week | < 5 | 44.1% | < 5 | 41.2% |
| | ≥ 5 | 55.9% | ≥ 5 | 58.8% |
| Number of pages typed in Arabic script per week | | | < 5 | 100% |
| Alphabet used when typing in Arabic | | | Latin only | 61.8% |
| | | | Latin & Arabic | 38.2% |

Spoken languages

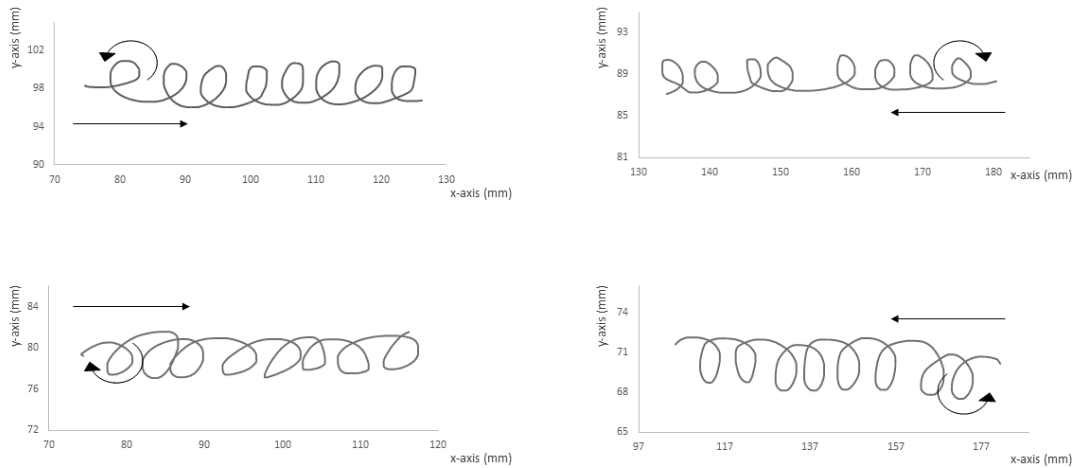
| | | | | |
|--------|---------|-------|---------|-------|
| L2 | English | 88.2% | French | 91.2% |
| | Spanish | 8.8% | English | 8.8% |
| | German | 3% | | |
| | < 4 | 6.6% | < 4 | 50% |
| L2 AOA | 4-9 | 38.2% | 4-9 | 50% |
| | ≥ 10 | 55.2% | | |

Task and Procedure

All participants completed the experiment under similar conditions. They were seated on an adjustable chair facing an appropriate height desk. The Edinburgh Handedness inventory (Oldfield, 1971) was then administered to verify each participant's handedness. Prior to starting the graphomotor task, the participants were also asked to adjust the tablet's orientation to replicate their preferred writing conditions and maximize their comfort when writing. They were then asked to trace upscaled and downscaled loops starting from left to right then right to left, from an indicated starting position following the template placed at the beginning of the line (Figure 1a). The order of the conditions was switched randomly between participants. The loops were copied in 10x1 cm rectangles from a starting point, following a rectangular frame. The number of loops to produce was not indicated in the instructions, but the participants were required to trace the model without pen lifts, at spontaneous speed. The frame was intended to give an indication of size, without constraining the size since it was explicitly mentioned to the participants that they could go over the edges or trace at a size smaller than the frame, without touching the edges.

Figure 1

A participant's sample of the four graphomotor conditions: left to right and right to left writing directions / counterclockwise and clockwise direction of rotation.



Materials

The handwriting movements were recorded by means of a Wacom® 4 Medium tablet connected to a computer via a USB cable and its specific ballpoint pen. Participants copied and traced the pre-printed forms on paper fixed on the tablet's active area. Tracing coordinates were recorded with a handwriting data collecting software (developed within the laboratory in JAVA) that tracks the X and Y coordinates of the pen tip at 200 Hz.

Data Analysis

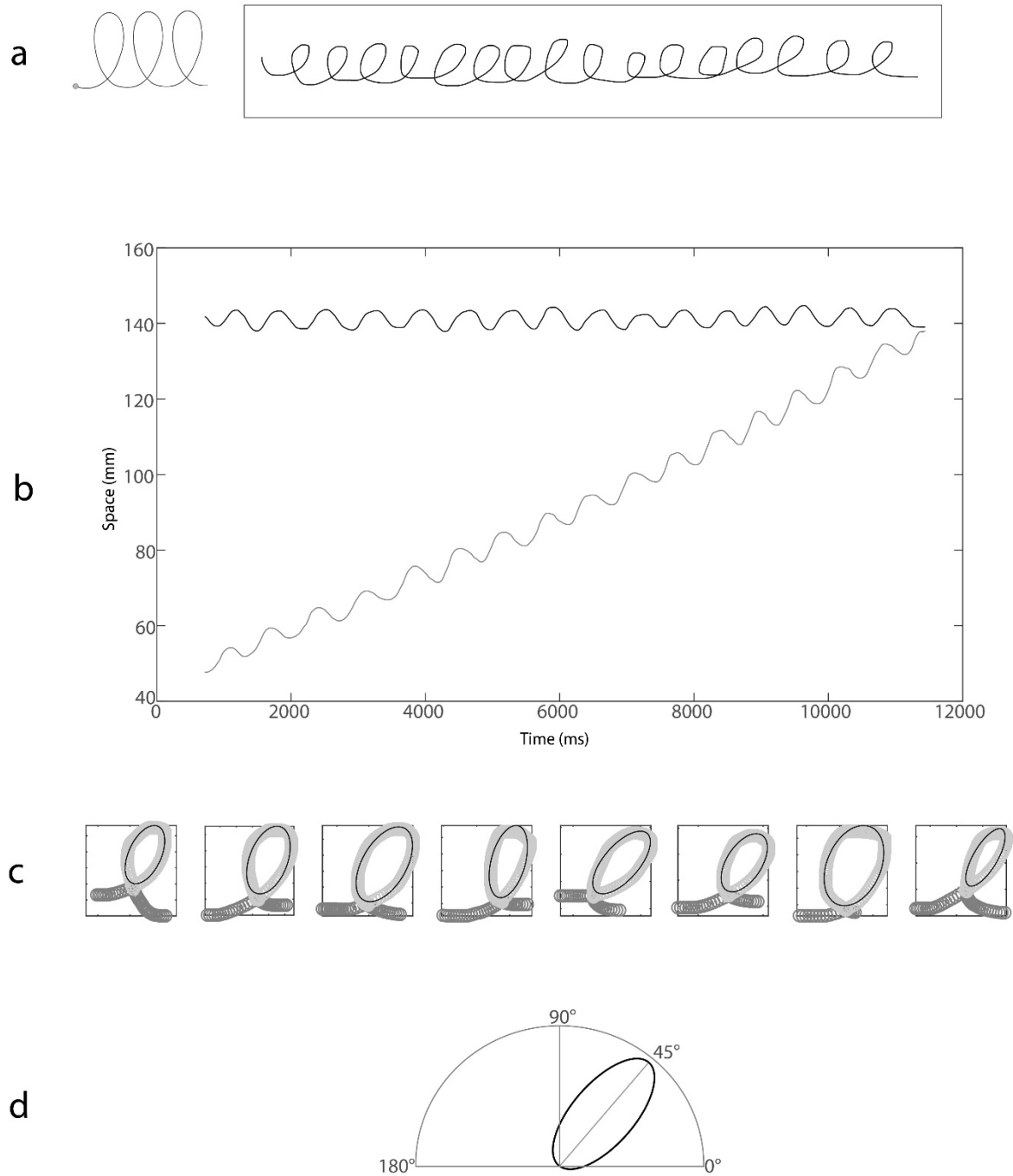
Four variables were analyzed (Figure 2). 1. The frequency corresponds to the number of loops drawn per second. 2. The mean RP. Values range between 0° (line) and 90° (circle). 3. The SD of the RP. Lower values indicate that the RP is stable across the 8 loops while higher values show variability. 4. The mean slant indicated the inclination angle of the axis of the loop relative to the baseline (Li et al., 2019), with minimum and maximum values of 0° and 180° , indicating the orientation of the main axis of the ellipse. Values between 0° and 90° indicated a rightward slant, whereas 90° to 180° values meant that the loops were slanted to the left. Circular statistics were used for this variable (Batschelet, 1981; Meulenbroek et al., 1998).

The data analysis was performed on the first eight correct¹ ellipses within each series of loops. Based on cycle-by-cycle analysis, we calculated the closest theoretical ellipse for each drawn loop using the Gander et al. (1994) transformation. This transformation extracted the RP (mean and SD) corresponding to the eccentricity of the ellipse, and its mean slant. We also calculated the frequency from the local extrema on the y-axis between two loops. Data analysis was performed following the 2 writing directions (left to right and right to left) x 2 directions of rotation (counterclockwise and clockwise) x 2 groups (monoscriptuals and biscriptuals) factorial design.

Figure 2

Loop series analysis: (a) Template (condition) of the loops to be traced and loop series traced by a participant. (b) Temporal evolution of oscillations in the x-axis (in gray) and y-axis (in black). (c) Fitting ellipses onto the first 8 correctly drawn loops to compute the RP and slant (mean and SD). (d) Example of the graphical determination of the slant in degrees on a single loop.

¹ 22 loop series out of 272 (8%) required a minimum number of dot corrections in order for the Gander et al. (1994) transformation to work, as these loops were closer to lines rather than ellipses. These changes had no effect on the outgoing data.



Statistical analysis

The data were analysed using linear mixed models (Baayen et al., 2008) via RStudio (version 1.3.1093) with the lmerTest package (Kuznetsova et al., 2017) using the following code line:

dependent variable ~ group * direction of rotation * writing direction + age + gender + amount of handwriting practice + ratio Latin Arabic writing + (1 | subject).

The mean RP, RP SD, mean slant, and frequency were entered into the models as dependent variables. Writing direction, direction of rotation, group (monoscriptual or biscriptual) and the interaction between group, writing direction and direction of rotation were defined as predictors. The models also included the age and gender variables as controls, as they are known to have an effect on handwriting performance (Albaret et al., 2013). Writing habits, that is the total amount of weekly handwriting practice (total number of pages written by hand) and the ratio of weekly handwriting practice between Latin and Arabic alphabets were also included as controls.

The ratio was calculated according to the following formula: (number of pages written in Latin alphabet – number of pages written in Arabic alphabet) / (number of pages written in Latin alphabet + number of pages written in Arabic alphabet), so that the ratio was 1 for Latin-only practice, -1 for Arabic-only practice and 0 for equal Latin and Arabic practice. On average the ratio was 0 for the biscriptual group.

Random effects of participants were included in the model for each variable. For 3 out of the 4 variables, the models would not converge when random slopes were included; for the sake of consistency, they were not included in any model.

When interactions between group and another factor were significant, pairwise contrasts were tested with the emmeans package (Searle et al., 1980) using the following code line: emmeans (mixed_effect_model, list (pairwise ~ group * dependent variable)). Two-way interactions between the writing direction and rotation direction were not further tested for contrasts.

Results

All mixed-model effects are reported in Table 1 and significant effects represented in Figure 3.

Mean Frequency

Biscriptuals produced the loops at a higher frequency than monoscriptuals ($\beta = -0.81$, $t = -2.85$, $p < .006$; biscriptuals = 2.41, monoscriptuals = 1.89). Additionally, frequency was higher for counterclockwise than clockwise loops ($\beta = -0.12$, $t = -3.42$, $p < .001$; counterclockwise = 2.21, clockwise = 2.09), and higher for the left to right than for the right to left direction ($\beta = -0.26$, $t = -7.57$, $p < .001$; left to right = 2.28, right to left = 2.02). A significant group by writing direction interaction was also observed ($\beta = -0.17$, $t = -2.49$, $p = .013$; biscriptuals left to right = 2.59, biscriptuals right to left = 2.24, monoscriptuals left to right = 1.98, monoscriptuals right to left = 1.80). Further contrast analysis revealed significant differences when comparing biscriptuals and monoscriptuals in the left to right writing direction ($\beta = -0.90$, $t = -3.14$, $p = .012$), as well as significant differences between left to right and right to left directions with larger estimates in biscriptuals ($\beta = -0.35$, $t = 7.12$, $p < .001$) than in monoscriptuals ($\beta = 0.18$, $t = 3.59$, $p = .002$) and significant differences between biscriptuals in the left to right direction and monoscriptuals in the right to left direction ($\beta = 1.08$, $t = 3.74$, $p = .001$). The interaction between group and direction of rotation did not reach significance.

Mean Relative Phase (RP)

For the mean RP, the loops were produced with larger eccentricity for counterclockwise than clockwise rotations ($\beta = 3.21$, $t = 2.88$, $p = .004$; counterclockwise = 54.11, clockwise = 50.89) and with larger eccentricity for right to left than left-to right directions ($\beta = 6.49$, $t = 5.82$, $p < .001$; left to right = 49.26, right to left = 55.74). Neither the group factor nor the interactions reached significance.

SD of the Relative Phase

For the RP SD, the RP was more variable in the right to left than in the left to right direction ($\beta = 1.21$, $t = 3.58$, $p < .001$; left to right = 7.17, right to left = 8.37). Neither the group, direction of rotation factors nor the interactions reached significance.

Slant

For the mean slant, the interaction between group and direction of rotation was significant ($\beta = 7.75$, $t = 2.30$, $p = .022$; biscriptuals clockwise = 79.89, biscriptuals counterclockwise = 83.15, monoscriptuals clockwise = 86.09, monoscriptuals counterclockwise = 81.65). Contrast analysis yielded no significant differences between groups and direction of rotation. Neither the main effects nor the interaction between group and writing direction reached significance.

Table 1

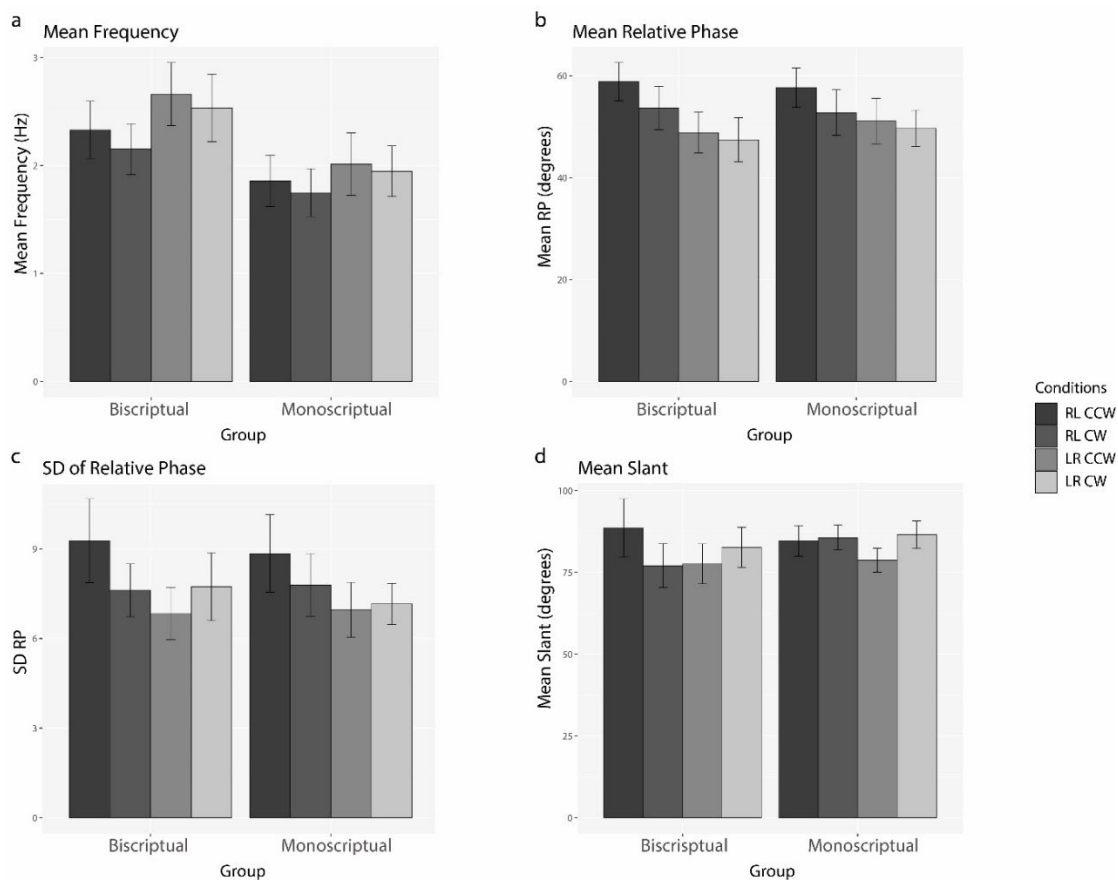
Results of the mixed effects models on the frequency, RP and slant of loops in biscriptual and monoscriptual participants. Fixed effects of interest are outlined in bold.

| | MEAN RP | | | | RP SD | | | |
|--|-----------|-----------|----------|----------|------------|-----------|----------|----------|
| | <i>B</i> | <i>SE</i> | <i>t</i> | <i>p</i> | <i>B</i> | <i>SE</i> | <i>t</i> | <i>p</i> |
| (Intercept) | 55.52 | 7.77 | 7.13 | 0.000*** | 7.11 | 1.66 | 4.26 | 0.000*** |
| Group | -0.98 | 3.77 | -0.26 | 0.795 | 0.43 | 0.81 | 0.53 | 0.591 |
| Direction of rotation | 3.21 | 1.11 | 2.88 | 0.004** | 0.40 | 0.33 | 1.20 | 0.229 |
| Writing direction | 6.48 | 1.11 | 5.82 | 0.000*** | 1.20 | 0.33 | 3.58 | 0.000* |
| Group*Direction of rotation | 0.10 | 2.22 | 0.046 | 0.963 | -0.05 | 0.67 | -0.07 | 0.937 |
| Group*Writing direction | 3.28 | 2.22 | 1.473 | 0.142 | -0.09 | 0.67 | -0.17 | 0.889 |
| Direction of rotation*Writing direction | 3.59 | 2.22 | 1.61 | 0.108 | 1.90 | 0.67 | 2.82 | 0.005** |
| Group*Direction of rotation*Writing direction | 0.20 | 4.45 | 0.04 | 0.963 | 1.31 | 1.34 | 0.97 | 0.330 |
| Weekly amount of writing practice | 0.22 | 0.29 | 0.77 | 0.441 | 0.04 | 0.06 | 0.65 | 0.516 |
| Ratio AR/LAT practice | 0.28 | 2.97 | 0.09 | 0.924 | 0.39 | 0.64 | 0.62 | 0.537 |
| Age | -0.13 | 0.27 | -0.47 | 0.638 | 0.01 | 0.05 | 0.13 | 0.860 |
| Gender | -1.64 | 2.22 | -0.73 | 0.463 | 0.07 | 0.47 | 0.14 | 0.881 |
| | FREQUENCY | | | | MEAN SLANT | | | |
| | <i>B</i> | <i>SE</i> | <i>t</i> | <i>p</i> | <i>B</i> | <i>SE</i> | <i>t</i> | <i>p</i> |
| (Intercept) | 2.43 | 0.63 | 3.86 | 0.000*** | 83.79 | 9.24 | 9.06 | 0.000*** |
| Group | 0.81 | 0.28 | 2.85 | 0.005** | -7.39 | 4.51 | -1.63 | 0.106 |
| Direction of rotation | 0.12 | 0.03 | 3.42 | 0.000*** | -0.61 | 1.68 | -0.36 | 0.714 |
| Writing direction | -0.26 | 0.03 | -7.57 | 0.000*** | 2.60 | 1.68 | 1.55 | 0.122 |

| | | | | | | | | |
|--|-------|------|-------|--------|-------|------|-------|----------|
| Group*Direction of rotation | 0.06 | 0.07 | 0.87 | 0.384 | 7.74 | 3.36 | 2.30 | 0.022* |
| Group*Writing direction | -0.17 | 0.07 | -2.49 | 0.013* | 0.14 | 3.36 | 0.04 | 0.965 |
| Direction of rotation*Writing direction | 0.04 | 0.07 | 0.60 | 0.544 | 11.71 | 3.36 | 3.48 | 0.000*** |
| Group*Direction of rotation*Writing direction | 0.01 | 0.14 | 0.08 | 0.932 | 9.80 | 6.72 | 1.45 | 0.146 |
| Weekly amount of writing practice | 0.00 | 0.02 | 0.146 | 0.884 | -0.44 | 0.34 | -1.28 | 0.202 |
| Ratio AR/LAT practice | 0.30 | 0.22 | 1.38 | 0.170 | -7.04 | 3.56 | -1.97 | 0.052 |
| Age | -0.16 | 0.02 | -0.74 | 0.457 | 0.26 | 0.32 | 0.82 | 0.415 |
| Gender | -0.02 | 0.18 | -0.16 | 0.868 | -7.50 | 2.64 | -2.84 | 0.006** |

Figure 3

Effects of writing direction (RL: right to left; LR: left to right) and direction of rotation (CW: clockwise; CCW: counterclockwise) on the frequency, RP and slant of loops in biscriptual and monoscriptual participants.



Discussion

The aim of this study was to determine whether graphomotor coordination dynamics vary as a function of the type of writing expertise (Latin script only versus Latin and Arabic scripts). We found that the graphomotor patterns of both monoscriptual and biscriptual participants were influenced by writing direction and direction of rotation, indicating the presence of similar directional preferences in both groups. This argues in favor of the biomechanical hypothesis. However, our results also showed that biscriptuals display significantly higher tracing frequencies than monoscriptuals. We also evidenced a stronger effect of writing direction on the tracing frequency in biscriptuals than in monoscriptuals, and an interaction between group and direction of rotation on the slant of the produced loops. Overall, these effects indicate that the graphomotor coordination dynamics are affected by the type of script expertise.

Biscriptuality, a possible asset for graphomotor coordination?

Oscillatory behaviors have been the subject of numerous studies, as they are inherent to tasks such as walking and speaking, where individuals display repetitive sequences (Murray et al., 1964; Loehr & Palmer, 2011; Ruspantini et al., 2012; Morillon et al., 2019; Poeppel & Assaneo, 2020). Expertise has been shown to influence the frequency of production of hand movements, particularly in musicians compared to non-musicians (Drake et al., 2000). Similar to these observations, our results suggest that expertise in two writing systems with very different graphomotor constraints could lead to modifications in the spontaneous pace of hand movements during loop tracing.

Higher frequencies show that biscriptuals display an advantage in spontaneous tracing compared to monoscriptuals. In handwriting research, less demanding conditions typically yield the highest frequencies, while more demanding handwriting tasks are performed at lower frequencies (Saarinen et al., 2020). It should be noted that this increase in frequency does not occur along with a degradation of the performance for the other variables, as would happen if the differences were driven by a speed-accuracy tradeoff (MacKay, 1982; Gatouillat et al., 2017; Dui et al., 2019). This result constitutes one of the first experimental indications of graphomotor effects of the type of script expertise. It confirms psychometric observations made on groups of children showing that biscriptuals were faster in writing tests than monoscriptuals (Matta Abizeid et al., 2017). These results were

interpreted as a consequence of intensive simultaneous training in two different scripts. From this perspective, biscriptuality seems to constitute an asset for graphomotor control. It remains to be tested whether this graphomotor advantage transfers to actual handwriting tasks or impacts the cognitive processes associated with handwriting such as spelling or text composition (Graham et al., 1997).

Changes in oscillatory behaviors with expertise have been explained by improved motor control abilities (Drake et al., 2000). The higher spontaneous tracing frequency could thus be explained by a more efficient ~~neuromotor~~ motor control of handwriting in biscriptuals compared to monoscriptuals. Future investigations including measures of manual motor control skills could confirm this assumption.

The impact of writing direction and direction of rotation on graphomotor coordination dynamics

For all participants, the indexes of graphomotor coordination dynamics were closer to the preferential values when the loops were traced in the left to right direction. This indicates that the task was easier to complete in this condition (Danna et al., 2011). Surprisingly, this effect was present in both groups. This finding is in agreement with the results of indicates that this general preferential writing direction is rather related to the biomechanical constraints inherent in the right-handedness of the participants (van Sommers, 1984; Athènes et al., 2004; Danna et al., 2011) independently of the scripts practised (van Sommers, 1984). Handedness is an established factor influencing orientation preferences (Dreman, 1974; van Sommers, 1984; Meulenbroek & Van Galen, 1989; Meulenbroek & Thomassen, 1992). In addition, movements directed away from the body are performed faster than movements directed towards the body, so outward movements from left to right are easier for right-handers (van Sommers, 1984, 1991; Vaid, 1998; Vaid & Meuter, 2017). Finally, graphomotor coordination may also be affected by the medium used for writing. In that perspective, one hypothesis is that the right to left direction originally emerged from material constraints of carving (Sirat, 1988). This direction may be less optimal than the left to right direction in terms of biomechanics when writing with a pen.

The directional preference common to both groups could also have other origins: for instance, it could illustrate the influence of the biscriptuals' bilingual education context where Latin script is prioritized (Bacha & Bahous, 2011). The directional preferences of biscriptual participants could result from the more frequent use of Latin script during learning. Furthermore, the loop tracing task might have favored left to right direction for all participants, as the 'l' and 'e' letters in cursive Latin are composed of counterclockwise loops traced from left to right (Edelman & Flash, 1987), whereas very few complete loops exist in the Arabic alphabet.

Aside from this general directional preference, we also found that the effect of writing direction on tracing frequency was stronger for biscriptuals than for monoscriptuals. Biscriptual participants were living in France, and were therefore less exposed to Arabic script. Prolonged exposure to a graphic system has a direct impact on directional preferences (Goodnow et al., 1973; Padakannaya et al., 2002; Suitner et al., 2017). It is therefore possible that the greater directional preferences of biscriptual participants in terms of tracing frequency are due to a more frequent use of Latin than Arabic script in this group. More generally, it is also possible that biscriptuality enhances the effect of biomechanical constraints on graphomotor coordination dynamics.

RP values were approximately of 50-55°, which differs from the typical value of preferential coordination patterns of 45° RP reported in previous studies (Athènes et al., 2004; Sallagoïty et al., 2004; Danna et al., 2011; Zanone & Athènes, 2013). This difference could be explained by the addition of the arm translation in our task, as effects of directional preferences were investigated without this arm translation in previous studies (Dounskaia et al., 2000; Danna et al., 2011).

Finally, counterclockwise rotations were traced with higher frequencies than clockwise rotations for all participants. This confirms previous findings (Danna et al., 2011). However, the effect is more difficult to interpret as it is coupled with an increase in RP, indicating higher task difficulty (Danna et al., 2011). This result could be explained by conflicts between biomechanical preferences for clockwise rotations and writing habits where counterclockwise rotations are dominant (Goodnow et al., 1973; Meulenbroek et al., 1993). In addition, a specific effect was found in which clockwise loops were more slanted for biscriptuals than for monoscriptuals, indicating a greater preference for clockwise rotations in the former group, consistent with the more common clockwise rotations in

Arabic (van Sommers, 1984). This effect is consistent with the hypothesis that the coordination dynamics underlying handwriting is different for participants trained in both scripts compared to monoscriptuals. However, it should be confirmed in future studies specifically focused on the effect of writing expertise in Arabic on writing slant, as the direct contrasts between conditions did not yield significance.

Concluding remarks

There are some limitations in this study. First, the absence of standardized handwriting tests in both languages of interest for adults did not allow for the assessment of the participants' handwriting abilities. As a way to compensate for this lack, sample selection guaranteed homogeneity by recruiting native biscriptuals and monoscriptuals with similar academic backgrounds. Second, each of the loop series were only traced once. Although fewer trials might have affected the results, we chose to analyze the tracing patterns of the participants when faced with a new task without prior familiarization or training.

Constraints on the generality of our findings also apply. The effects of biscriptuality could be specific to the pair of scripts chosen, given that Latin and Arabic display opposite graphomotor features and might lead to a greater effect of training on coordination dynamics than pairs displaying similar features (Latin-Cyrillic, etc.). In addition, since we recruited biscriptual participants in France, a concession had to be made on the amount of Arabic writing and more generally, the amount of exposure to Arabic. This specific Arabic-Latin biscriptual group might not be fully representative of all Arabic-Latin biscriptuals, as cultural and academic practices related to handwriting greatly vary from one Arab country to another.

In conclusion, these differences in graphomotor coordination dynamics between monoscriptuals and biscriptuals open new perspectives in handwriting research. For instance, since variations of graphomotor coordination dynamics with writing expertise are largely unexplored, interesting perspectives arise from the study of other types of biscriptuality, where scripts are written from left to right. Our results also show that directional progression is an important factor to account

for when studying graphomotor coordination, even though it has been relatively overlooked in handwriting research. The loop tracing task is interesting when comparing different script writers, as using this orthographically and semantically neutral task makes it possible to solely focus on handwriting movements associated with the different writing directions and directions of rotations. Finally, investigating the neural activation underlying graphomotor coordination (Pei et al., 2021) is an important perspective to understand the possible changes in the relationship between brain activity and writing with the type of expertise.

References

- Albaret, J.-M., Kaiser, M.-L., & Soppelsa, R. (2013). *Troubles de l'écriture chez l'enfant : Des modèles à l'intervention*. De Boeck-Solal.
- André, G., Kostrubiec, V., Buisson, J.-C., Albaret, J.-M., & Zanone, P.-G. (2014). A parsimonious oscillatory model of handwriting. *Biological Cybernetics*, *108*(3), 321-336.
<https://doi.org/10.1007/s00422-014-0600-z>
- Athènes, S., Sallagoïty, I., Zanone, P.-G., & Albaret, J.-M. (2004). Evaluating the coordination dynamics of handwriting. *Human Movement Science*, *23*(5), 621-641.
<https://doi.org/10.1016/j.humov.2004.10.004>
- Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*(4), 390-412.
<https://doi.org/10.1016/j.jml.2007.12.005>
- Bacha, N. N., & Bahous, R. (2011). Foreign Language Education in Lebanon : A Context of Cultural and Curricular Complexities. *Journal of Language Teaching and Research*, *2*(6), 1320-1328.
<https://doi.org/10.4304/jltr.2.6.1320-1328>
- Batschelet, E. (1981). *Circular statistics in biology*. Academic Press.
- Bosga-Stork, I. M., Bosga, J., & Meulenbroek, R. G. J. (2011). Intentional control and biomechanical exploitation in preparatory handwriting. *Human Movement Science*, *30*(4), 687-697.
<https://doi.org/10.1016/j.humov.2010.06.007>

- Danna, J., Athènes, S., & Zanone, P.-G. (2011). Coordination dynamics of elliptic shape drawing : Effects of orientation and eccentricity. *Human Movement Science*, 30(4), 698-710.
<https://doi.org/10.1016/j.humov.2010.08.019>
- Danna, J., Enderli, F., Athènes, S., & Zanone, P.-G. (2012). Motor coordination dynamics underlying graphic motion in 7- to 11-year-old children. *Journal of Experimental Child Psychology*, 111(1), 37-51. <https://doi.org/10.1016/j.jecp.2011.07.005>
- Dounskaia, N., Van Gemmert, A. W. A., & Stelmach, G. E. (2000a). Interjoint coordination during handwriting-like movements. *Experimental Brain Research*, 135(1), 127-140.
<https://doi.org/10.1007/s002210000495>
- Dounskaia, N., Van Gemmert, A. W. A., & Stelmach, G. E. (2000b). Interjoint coordination during handwriting-like movements. *Experimental Brain Research*, 135(1), 127-140.
<https://doi.org/10.1007/s002210000495>
- Drake, C., Jones, M. R., & Baruch, C. (2000). The development of rhythmic attending in auditory sequences : Attunement, referent period, focal attending. *Cognition*, 77(3), 251-288.
[https://doi.org/10.1016/S0010-0277\(00\)00106-2](https://doi.org/10.1016/S0010-0277(00)00106-2)
- Dreman, S. B. (1974). Directionality Trends as a Function of Handedness and of Reading and Writing Habits. *The American Journal of Psychology*, 87(1/2), 247. <https://doi.org/10.2307/1422018>
- Dui, L. G., Lunardini, F., & Ferrante, S. (2019). A Tablet-based Application to Study the Speed-Accuracy Tradeoff in Handwriting throughout Lifespan. *2019 E-Health and Bioengineering Conference (EHB)*, 1-4. <https://doi.org/10.1109/EHB47216.2019.8969869>
- Edelman, S., & Flash, T. (1987). A model of handwriting. *Biological Cybernetics*, 57(1), 25-36.
<https://doi.org/10.1007/BF00318713>
- Gander, W., Golub, G. H., & Strebel, R. (1994). Least-squares fitting of circles and ellipses. *BIT*, 34(4), 558-578. <https://doi.org/10.1007/BF01934268>
- Gangadhar, G., Joseph, D., & Chakravarthy, V. S. (2007). An oscillatory neuromotor model of handwriting generation. *International Journal of Document Analysis and Recognition (IJDAR)*, 10(2), 69-84. <https://doi.org/10.1007/s10032-007-0046-0>

- Gatouillat, A., Dumortier, A., Perera, S., Badr, Y., Gehin, C., & Sejdić, E. (2017). Analysis of the pen pressure and grip force signal during basic drawing tasks : The timing and speed changes impact drawing characteristics. *Computers in Biology and Medicine*, *87*, 124-131. <https://doi.org/10.1016/j.combiomed.2017.05.020>
- Goodnow, J., Friedman, S. L., Bernbaum, M., & Lehman, E. B. (1973). Direction and Sequence in Copying : The Effect of Learning to Write in English and Hebrew. *Journal of Cross-Cultural Psychology*, *4*(3), 263-282. <https://doi.org/10.1177/002202217300400301>
- Graham, S., Berninger, V. W., Abbott, R. D., Abbott, S. P., & Whitaker, D. (1997). Role of mechanics in composing of elementary school students : A new methodological approach. *Journal of Educational Psychology*, *89*(1), 170-182. <https://doi.org/10.1037/0022-0663.89.1.170>
- Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, *51*(5), 347-356. <https://doi.org/10.1007/BF00336922>
- Hollerbach, J. M. (1981). An oscillation theory of handwriting. *Biological Cybernetics*, *39*(2), 139-156. <https://doi.org/10.1007/BF00336740>
- Kahindo, C., El-Yacoubi, M. A., Garcia-Salicetti, S., Rigaud, A.-S., & Cristancho-Lacroix, V. (2018). Characterizing Early-Stage Alzheimer Through Spatiotemporal Dynamics of Handwriting. *IEEE Signal Processing Letters*, *25*(8), 1136-1140. <https://doi.org/10.1109/LSP.2018.2794500>
- Kay, B. A. (1988). The dimensionality of movement trajectories and the degrees of freedom problem : A tutorial. *Human Movement Science*, *7*(2), 343-364. [https://doi.org/10.1016/0167-9457\(88\)90016-4](https://doi.org/10.1016/0167-9457(88)90016-4)
- Kelso, J. A. S. (1995). *Dynamic patterns : The self-organization of brain and behavior*. The MIT Press.
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). **lmerTest** Package : Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, *82*(13). <https://doi.org/10.18637/jss.v082.i13>
- Li, M. M. Q., Leung, H., Li, T. M. H., & Li-Tsang, C. W. P. (2019). Measuring the tilt and slant of Chinese handwriting in primary school students : A computerized approach. *PLOS ONE*, *14*(11), e0223485. <https://doi.org/10.1371/journal.pone.0223485>

- Loehr, J. D., & Palmer, C. (2011). Temporal Coordination between Performing Musicians. *Quarterly Journal of Experimental Psychology*, *64*(11), 2153-2167.
<https://doi.org/10.1080/17470218.2011.603427>
- MacKay, D. G. (1982). The problems of flexibility, fluency, and speed–accuracy trade-off in skilled behavior. *Psychological Review*, *89*(5), 483-506. <https://doi.org/10.1037/0033-295X.89.5.483>
- Marquis, R., Taroni, F., Bozza, S., & Schmittbuhl, M. (2007). Size influence on shape of handwritten characters loops. *Forensic Science International*, *172*(1), 10-16.
<https://doi.org/10.1016/j.forsciint.2006.11.005>
- Matta Abizeid, C., Tabsh Nakib, A., Younès Harb, C., Ghantous Faddoul, S., & Albaret, J.-M. (2017). Handwriting in Lebanese bigraphic children : Standardization of the BHK Scale. *Journal of Occupational Therapy, Schools, & Early Intervention*, *10*(4), 420-435.
<https://doi.org/10.1080/19411243.2017.1335260>
- Meulenbroek, R. G. J., & Thomassen, A. J. W. M. (1992). Effects of handedness and arm position on stroke-direction preferences in drawing. *Psychological Research*, *54*(3), 194-201.
<https://doi.org/10.1007/BF00922099>
- Meulenbroek, R. G. J., Thomassen, A. J. W. M., van Lieshout, P. H. H. M., & Swinnen, S. P. (1998). The stability of pen–joint and interjoint coordination in loop writing. *Acta Psychologica*, *100*(1), 55-70. [https://doi.org/10.1016/S0001-6918\(98\)00025-0](https://doi.org/10.1016/S0001-6918(98)00025-0)
- Meulenbroek, R. G. J., & Van Galen, G. P. (1989). Variations in cursive handwriting performance as a function of handedness, hand posture, and gender. *Journal of Human Movement Studies*, *16*, 239-254.
- Meulenbroek, R. G. J., Vinter, A., & Mounoud, P. (1993). Development of the start-rotation principle in circle production. *British Journal of Developmental Psychology*, *11*(3), 307-320.
<https://doi.org/10.1111/j.2044-835X.1993.tb00605.x>
- Morillon, B., Arnal, L. H., Schroeder, C. E., & Keitel, A. (2019). Prominence of delta oscillatory rhythms in the motor cortex and their relevance for auditory and speech perception. *Neuroscience & Biobehavioral Reviews*, *107*, 136-142.
<https://doi.org/10.1016/j.neubiorev.2019.09.012>

- Murray, M. P., Drought, A. B., & Kory, R. C. (1964). Walking Patterns of Normal Men: *The Journal of Bone & Joint Surgery*, 46(2), 335-360. <https://doi.org/10.2106/00004623-196446020-00009>
- Nonaka, T. (2017). Cultural entrainment of motor skill development : Learning to write *hiragana* in Japanese primary school. *Dev Psychobiol*, 59(6), 749-766. <https://doi.org/10.1002/dev.21536>
- Nutt, H. W. (1917). Rhythm in Handwriting. *The Elementary School Journal*, 17(6), 432-445. JSTOR.
- Oldfield, R. C. (1971). The assessment and analysis of handedness : The Edinburgh inventory. *Neuropsychologia*, 9(1), 97-113. [https://doi.org/10.1016/0028-3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4)
- Padakannaya, P., Devi, M. L., Zaveria, B., Chengappa, S. K., & Vaid, J. (2002). Directional scanning effect and strength of reading habit in picture naming and recall. *Brain and Cognition*, 48(2-3), 484-490.
- Pei, L., Longcamp, M., Leung, F. K.-S., & Ouyang, G. (2021). Temporally resolved neural dynamics underlying handwriting. *NeuroImage*, 244, 118578. <https://doi.org/10.1016/j.neuroimage.2021.118578>
- Phelps, J., Stempel, L., & Speck, G. (1985). The Children's Handwriting Scale : A New Diagnostic Tool. *The Journal of Educational Research*, 79(1), 46-50. <https://doi.org/10.1080/00220671.1985.10885646>
- Poeppel, D., & Assaneo, M. F. (2020). Speech rhythms and their neural foundations. *Nat Rev Neurosci*, 21(6), 322-334. <https://doi.org/10.1038/s41583-020-0304-4>
- Ruspantini, I., Saarinen, T., Belardinelli, P., Jalava, A., Parviainen, T., Kujala, J., & Salmelin, R. (2012). Corticomuscular Coherence Is Tuned to the Spontaneous Rhythmicity of Speech at 2-3 Hz. *Journal of Neuroscience*, 32(11), 3786-3790. <https://doi.org/10.1523/JNEUROSCI.3191-11.2012>
- Saarinen, T., Kujala, J., Laaksonen, H., Jalava, A., & Salmelin, R. (2020). Task-Modulated Corticocortical Synchrony in the Cognitive-Motor Network Supporting Handwriting. *Cerebral Cortex*, 30(3), 1871-1886. <https://doi.org/10.1093/cercor/bhz210>
- Sallagoity, I., Athènes, S., Zanone, P.-G., & Albaret, J.-M. (2004a). Stability of Coordination Patterns in Handwriting : Effects of Speed and Hand. *Motor Control*, 8(4), 405-421. <https://doi.org/10.1123/mcj.8.4.405>

- Sallagoïty, I., Athènes, S., Zanone, P.-G., & Albaret, J.-M. (2004b). Stability of Coordination Patterns in Handwriting : Effects of Speed and Hand. *Motor Control*, 8(4), 405-421.
<https://doi.org/10.1123/mcj.8.4.405>
- Schöner, G., Zanone, P. G., & Kelso, J. A. S. (1992). Learning as Change of Coordination Dynamics : Theory and Experiment. *Journal of Motor Behavior*, 24(1), 29-48.
<https://doi.org/10.1080/00222895.1992.9941599>
- Searle, S. R., Speed, F. M., & Milliken, G. A. (1980). Population Marginal Means in the Linear Model : An Alternative to Least Squares Means. *The American Statistician*, 34(4), 216-221.
<https://doi.org/10.1080/00031305.1980.10483031>
- Segal, E., & Petrides, M. (2012). The anterior superior parietal lobule and its interactions with language and motor areas during writing : Role of the anterior SPL in writing. *European Journal of Neuroscience*, 35(2), 309-322. <https://doi.org/10.1111/j.1460-9568.2011.07937.x>
- Senatore, R., & Marcelli, A. (2019). A paradigm for emulating the early learning stage of handwriting : Performance comparison between healthy controls and Parkinson's disease patients in drawing loop shapes. *Human Movement Science*, 65, 89-101.
<https://doi.org/10.1016/j.humov.2018.04.007>
- Sirat, C. (1988). The Material Conditions of the Lateralization of the Ductus. In D. de Kerckhove & C. J. Lumsden (Éds.), *The Alphabet and the Brain : The Lateralization of Writing* (p. 173-201). Springer. https://doi.org/10.1007/978-3-662-01093-8_11
- Slimane, F., Ingold, R., Kanoun, S., Alimi, A. M., & Hennebert, J. (2009). A New Arabic Printed Text Image Database and Evaluation Protocols. *2009 10th International Conference on Document Analysis and Recognition*, 946-950. <https://doi.org/10.1109/ICDAR.2009.155>
- Suitner, C., Maass, A., Bettinsoli, M. L., Carraro, L., & Kumar, S. (2017). Left-handers' struggle in a rightward wor(l)d : The relation between horizontal spatial bias and effort in directed movements. *Laterality: Asymmetries of Body, Brain and Cognition*, 22(1), 60-89.
<https://doi.org/10.1080/1357650X.2015.1118112>
- Teulings, H.-L., & Maarse, F. J. (1984). Digital recording and processing of handwriting movements. *Human Movement Science*, 3(1-2), 193-217. [https://doi.org/10.1016/0167-9457\(84\)90011-3](https://doi.org/10.1016/0167-9457(84)90011-3)

- Usanova, I. (2019). *Biscriptuality : Writing skills among German-Russian adolescents* (Vol. 8). John Benjamins Publishing Company. <https://doi.org/10.1075/hslld.8>
- Vaid, J. (1998). Cultural vs biomechanical influences on a graphic production task. *Brain and Cognition*, 37(1), 75-78.
- Vaid, J., & Meuter, R. F. I. (2017). Languages without borders : Reframing the study of the bilingual mental lexicon. In M. Libben, M. Goral, & G. Libben (Éds.), *Bilingual Processing and Acquisition* (Vol. 6, p. 7-26). John Benjamins Publishing Company. <https://doi.org/10.1075/bpa.6.01vai>
- Vaivre-Douret, L., Lopez, C., Dutruel, A., & Vaivre, S. (2021). Phenotyping features in the genesis of pre-scriptural gestures in children to assess handwriting developmental levels. *Scientific Reports*, 11(1), 731. <https://doi.org/10.1038/s41598-020-79315-w>
- van der Gon Denier, J. J., & Thuring, J. Ph. (1965). The guiding of human writing movements. *Kybernetik*, 2(4), 145-148. <https://doi.org/10.1007/BF00272310>
- Van Galen, G. P., Van Doorn, R. R., & Schomaker, L. R. (1990). Effects of motor programming on the power spectral density function of finger and wrist movements. *Journal of Experimental Psychology: Human Perception and Performance*, 16(4), 755-765. <https://doi.org/10.1037/0096-1523.16.4.755>
- van Sommers, P. (1984a). *Drawing and Cognition : Descriptive and Experimental Studies of Graphic Production Processes* (1^{re} éd.). Cambridge University Press. <https://doi.org/10.1017/CBO9780511897672>
- van Sommers, P. (1984b). *Drawing and Cognition : Descriptive and Experimental Studies of Graphic Production Processes* (1^{re} éd.). Cambridge University Press. <https://doi.org/10.1017/CBO9780511897672>
- van Sommers, P. (1991). Where writing starts : The analysis of action applied to the historical development of writing. In *Development of graphic skills : Research perspectives and educational implications*. (p. 3-38). Academic Press.
- West, P. V. (1922). The Relation of Rhythm to the Handwriting Movement. *Journal of Educational Psychology*, 13(7), 438-444. <https://doi.org/10.1037/h0072569>

Zanone, P. G., & Kelso, J. A. (1992). Evolution of behavioral attractors with learning :

Nonequilibrium phase transitions. *Journal of Experimental Psychology: Human Perception and Performance*, 18(2), 403-421. <https://doi.org/10.1037/0096-1523.18.2.403>

Zanone, P.-G., & Athènes, S. (2013). Switching among graphic patterns is governed by oscillatory coordination dynamics : Implications for understanding handwriting. *Frontiers in Psychology*, 4. <https://doi.org/10.3389/fpsyg.2013.00662>