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Writing in two different scripts promotes fine motor control

Alhaddad G.¹, Dione M.¹, Danna J.², Alario F.-X.¹, Honorat A.¹, Velay J.-L.¹, Gilhodes J.-C.¹, Longcamp M.¹

1 Centre de Recherche en Psychologie et Neurosciences, UMR 7077, CNRS and Aix-Marseille Université, Marseille, France

2 CLLE, Université de Toulouse, CNRS, France

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Research Transparency Statement

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. All raw data for behavior, kinematic data, and bilingualism questionnaire can be accessed through the following repository: <https://osf.io/2zft8/>.

The questionnaire data, as well as other materials such as the MATLAB analysis script for the extraction of the frequency, RP, and slant; the R statistical analysis script; as well as the handwriting data-collecting software are available, due to ethical barriers, by requesting the corresponding author under a formal data-sharing agreement. Regarding research materials, only paper-based surveys are fully accessible via the same repository, while electronic surveys and psychometric instruments are restricted due to legal barriers. Access to these materials requires requests to the corresponding author and application to external authorities. Links are provided in the repository.

The design of the present study was based on the STROBE cross-sectional statement. The procedure and the analysis plan of this study were not preregistered prior to its implementation. The authors declare that there are no conflicts of interest with respect to the authorship or the publication of this article. This work has received support from the French government under the “France 2030” investment plan managed by the French National Research Agency (reference : ANR-16-CONV000X / ANR-17-EURE-0029) and from Excellence Initiative of Aix-Marseille University - A*MIDEX (AMX-19-IET-004), as well as the Institute of Convergence ILCB (ANR-16-CONV-0002) and the Fondation pour la Recherche en Psychomotricité et Maladies de Civilisation. These funders played no role in the research.

Abstract

Biscriptuality is the ability to write in two different scripts. Achieving handwriting expertise in a single script demands years of intensive practice, and these demands are even stronger when two scripts must be mastered. Biscriptuality could thus impact the cognitive and motor skills underlying graphomotor control. Here, we aimed at establishing that biscriptuality enhances graphomotor control, and at testing whether biscriptuals have better fine motor skills and working memory performance compared to Latin monoscriptuals.

We found that biscriptuals perform better than monoscriptuals on graphomotor tasks, and on 3 types of fine motor control tasks indexing dexterity, motor timing under spatial constraints, and spontaneous motor tempo; the two groups did not significantly differ in their working memory performance. These results demonstrate that writing expertise widely impacts the organization of the motor system.

Keywords: Biscriptuality, graphomotor control, handwriting, fine motor control, working memory.

Introduction

Handwriting stands among the most complex movements within the human repertoire of motor skills, as it requires years of practice until full proficiency is reached. Expertise is reflected through highly coordinated and rapid graphic patterns (van der Gon Denier & Thuring, 1965; Hollerbach, 1981; Athènes et al., 2004; Danna et al., 2011), generated by a brain network distributed over several regions of the motor system (Paine et al., 2004; Palmis et al., 2017; Planton et al., 2013; Saarinen et al., 2020). This sophisticated coordination of the fingers and the wrist allowing the smooth tracing of shapes is termed graphomotor control.

Theoretical models assume that proficient graphomotor control lies in a continuous interaction between fine motor skills and working memory processes (Van Galen, 1990; Grossberg & Paine, 2000; Saarinen et al., 2020). The known neural organization of handwriting supports this assumption: for instance, analysis of the neural dynamics of the graphomotor network during handwriting tasks led to the identification of a pericentral and a frontoparietal subsystems that are known to implement manual motor coordination and working memory processes, respectively (Saarinen et al., 2020). Fine motor skills are a major contributor to graphomotor performance because fast and accurate formation of letter shapes can only be achieved through the proper timing and force modulations of coordinated arm, hand, and finger movements (Thomassen & Teulings, 1983; Alston & Taylor, 1987; van Galen, 1991). Fine motor abilities consistently predict handwriting performance (Tseng & Chow, 2000; Smits-Engelsman et al., 2001; Rosenblum et al., 2013) and poor handwriting is often attributed to fine motor deficits (Smits-Engelsman & Van Galen, 1997; Smits-Engelsman et al., 2001; Rosenblum et al., 2013; Piller & Torrez, 2019). Working memory allows temporarily storing information when learning and subsequently performing any sequential motor task (Maxwell et al., 2003; Nicoladis & Gagnon, 2020; Bo & Seidler, 2009; Anguera et al., 2010; Ohbayashi et al., 2003). During handwriting, a prototypical sequential motor task, the current state of the graphomotor system must be constantly updated according to the active gestural representations and to sensory feedback (Grossberg & Paine, 2000; Salas & Silvente, 2020; Seidler et al., 2012; Van Galen, 1990).

Biscriptuality is a special case of handwriting expertise where two scripts and the consequent motor patterns are mastered (Usanova, 2019; Vaid, 2022; Fabiani et al., 2023). These motor patterns can strongly differ, such as in Arabic-Latin biscriptuality where handwriting is produced in two opposite directions: Arabic involves a majority of right-to-left strokes and of clockwise rotations, while the opposite is true for Latin (Fabiani et al., 2023). From a motor control perspective, learning two scripts composed of different sets of characters bearing distinct graphomotor characteristics is especially challenging, and could have long-term impacts on graphomotor control. While empirical approaches to this question remain scarce, some data indicate that biscriptuals perform better than monoscriptuals in graphomotor tasks (Matta Abizeid et al., 2017; Alhaddad et al., 2023). These effects need to be confirmed, but they suggest that the demands brought on by learning and practicing two scripts may promote graphomotor control.

Here, biscriptuality is used within the context of two scripts requiring the use of two languages (Vaid, 2022). As such, bilingualism occurs as a confounding factor of biscriptuality. Therefore, disentangling the differential effects of bilingualism within biscriptuality is necessary. Bilingualism might affect executive functioning in general, including working memory processes (Adesope et al., 2010; van den Noort et al., 2019), although recent reviews pointed towards an absence of differences between biscriptual and monoscriptual performance on cognitive functioning, regardless of the levels of proficiency (Paap, 2022).

In this study, we reasoned that if biscriptuality does provide a graphomotor advantage, it is possible that one or both subsystems underlying graphomotor control have been optimized in biscriptuals in comparison with their monoscriptual counterparts. We conducted a series of behavioral tests that aimed at establishing that biscriptuality enhances graphomotor control (Alhaddad et al., 2023; Matta Abizeid et al., 2017), and at assessing whether biscriptuality promotes fine motor skills, or working memory, or both. Graphomotor control was quantified with a loop tracing task and a standardized text copying task (Albaret & Soppelsa, 2012). Loop tracing has been extensively used in writing research as a valid and reliable task to assess graphomotor control (Lopez & Vaivre-Douret, 2023; Meulenbroek et al., 1998; Senatore & Marcelli, 2019; Vaivre-Douret et al., 2021). Beyond its universal feature, a thrust of such a simple task is that it can be assessed with few variables, on the basis of an oscillatory conceptualization of the formation of the written trace (Hollerbach, 1981). Here, we focused on the spontaneous frequency and relative phase between the two orthogonal oscillators x and y of the writing plane. In line with the dynamical systems framework (Kelso, 1995), the basic assumption is the existence of motor preferences in the graphomotor coordination dynamics, which that can be indexed by these variables (Athènes et al., 2004; Alhaddad et al., 2023; figure 1). Concerning the text copying task, indexes of speed and quality were compared between mono- and biscriptuals. Fine motor control was split into dexterity, timing under spatial constraints, and spontaneous motor tempo. All three aspects are central to perform handwriting movements (Gangadhar et al., 2007; Nutt, 1917; Rosenbaum, 2009). Dexterity refers to the precise, intentional and flexible action of manual muscle groups whose repertoire can be widened through training; it is typically measured by fine object manipulation tests. Here it was indexed using a peg placement task (Gonzalez et al., 2017). Timing control under spatial constraints can be either implicit or explicit depending on the task demands (Dione & Delevoeye-Turrell, 2015; Huys et al., 2008; Robertson et al., 1999; Zelaznik et al., 2002). Implicit timing is thought to emerge from the spatial constraints, while explicit timing is assumed to rely on internal clock mechanisms. The spatial tapping task developed by Dione et al. (2015), offers the unique opportunity to index the variations in the spatial error under timing control, hence reflecting both the spatial precision of the motor apparatus and its timing performance. Spontaneous motor tempo, a feature of various types of coordinated actions (e.g. walking, hammering, clapping hands, etc; Fraise, 1982), is typically measured with finger tapping tasks (Hervé et al., 2005; Kellor et al., 1971; Mathiowetz et al., 1985). Here we adapted the spatial tapping task (Dione & Delevoeye-Turrell, 2015) into a spontaneous motor tempo assessment. Finally, working memory processes were indexed using a 2-back task indexing information update (Kessels et al., 2000) and a Span task indexing spatial working memory (Zimmermann & Fimm, 2002). This task setting enabled us to probe the graphomotor system, and evaluate the functioning of its underlying building blocks, in Latin monoscriptuals and Arabic-Latin biscriptuals.

One additional aspect to consider is that biscriptuals use two scripts to write two languages (Vaid, 2022). As such, bilingualism occurs as a confounding factor of biscriptuality. Bilingualism might affect executive functioning in general, including working memory processes (Adesope et al., 2010; van den Noort et al., 2019). However, recent reviews pointed towards an absence of differences between bilingual and monolingual performance on cognitive functioning, regardless of the levels of proficiency (Paap, 2022). Given the lack of consensus on the issue, we measured the level of bilingualism of the participants to account for its potential effect on the graphomotor variables.

Methods

Participants

Anonymized data can be openly accessed via this repository: <https://osf.io/2zft8/>. Additional data and scripts are accessible upon request. No part of the study procedures or analysis plans was preregistered prior to the research being conducted. We report how we determined our sample size, all data

exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study

Participant characteristics, such as writing habits, academic and linguistic backgrounds, are summarised in Table 1. Thirty-three Arabic-Latin biculturals and 33 matched Latin monoculturals participated in the experiment between July and November 2022. Sample size was established with GLIMMPSE (<https://glimmpse.samplesizeshop.org>). Our calculations were based on the Alhaddad et al., (2023) study which used a linear regression mixed model with a group factor and compared 34 participants per group. We aimed at replicating the group effect with an alpha of .01 and 80% power. With the same parameters and group size assumptions as in the princeps study, the necessary overall sample size was estimated to be N=32. Our final sample size included 66 participants. This number is considerably larger than the group sizes in other prior studies of graphomotor coordination dynamics, typically consisting of just around 10 participants per group (e.g., Dounskaia et al., 2000; Athènes et al., 2004; Danna et al., 2011, 2012).

Subjects, aged between 20 and 40, showed established right-handedness (scores between 50 and 100 at the Edinburgh handedness inventory (Oldfield, 1971)). None of the participants reported any relevant medical history. All participants provided written informed consent before the experiment and received financial compensation for their participation. A French ethics committee approved this study (RIPH2G: 22.00610.000116).

All participants were born and raised in their native country. Monoculturals were thus native French speakers (L1). Biculturals were born and lived in an Arabic-speaking country before expatriation, with Arabic being their dominant language (L1) and script despite the simultaneous exposition to French and to the Latin alphabet. As a consequence, Bicultural participants spoke and wrote fluently in French and Arabic with equal proficiency.

The two groups were also matched as a function of several demographic characteristics such as socio-economic status (SES), educational level, or cultural background, because these factors are known modulators of linguistic and cognitive functions (Ursache et al., 2015; Xu et al., 2020; Paap, 2022). These factors were thus controlled by matching groups.

The sample size, all data exclusions, all inclusion and exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

Assessment of bilingual practice: LEAP-Q

The Language Experience and Proficiency Questionnaire (LEAP-Q, Marian et al., 2007) is a validated tool for collecting self-reported proficiency and experience data from bilingual and multilingual speakers, providing a comprehensive description of their bilingualism level. It's primarily used to categorize individuals as early/simultaneous or late/sequential bilinguals and to document differences in their skills between their first (L1) and second (L2) language usages in daily life (speaking and reading). We computed variables that consisted of the subjective proficiency levels in the L1 and L2, as well as the years the participants were immersed in L1 and L2.

Assessment of handwriting practice

In addition, a questionnaire on handwriting practice was administered to participants through an online survey. This questionnaire assessed the writing habits (handwriting, typing) of the participants in Arabic and French, and gathered the number of pages written per week in each language.

Table 1. Sample characteristics, writing habits, academic and linguistic backgrounds of the two groups of participants. * = Significant differences (Mann-Whitney U test) (L2 = Second Language; AOA = Age Of Acquisition)

	MONOSCRIP TUALS (n = 33)	BISCRIP TUALS (n = 33)
Age	23 (range: 18 - 36)	23 (range: 17 - 31)
Gender		
Male	48.84%	45.45%
Female	51.51%	54.54%
Level of education		
BSc	54.54%	36.36%
MSc	42.42%	48.48%
PhD	3.03%	15.15%
Writing habits		
Number of pages written in Latin script per week		
<5	42.42%	45.45%
≥5	57.57%	54.54%
Number of pages written in Arabic script per week		
<5		90.90%
≥5		9.09%
Typing habits		
Number of pages typed in Latin script per week		
<5	24.24%	27.27%
≥5	75.75%	78.78%
Number of pages typed in Arabic script per week		
<5		100%
≥5		
Alphabet used when typing in Arabic		
Arabic only		12.12%
Latin only		60.60%
Latin and Arabic		27.27%
Spoken languages		
L2		
English	100%	

French		100%
L2 AOA	*	
<4	0%	84.84%
4-9	51.51%	15.15%
≥ 10	48.84%	0%
Number of years in France		
<5		87.87%
≥5		12.12%
L2 proficiency (subjective score)	*	
	6.33 (range: 3.33 - 9)	8.30 (range: 6.33-10)
<4	12.12%	0%
4 - 7	57.57%	9.09%
≥7	30.30%	90.90%
Subjective assessment of financial situation		
Financially insecure	12.12%	6.06%
Somewhat financially secure	48.48%	60.60%
Financially secure	39.39%	33.33%
L1 proficiency (subjective score)		
<4		
4 - 7	15.15%	9.09%
≥7	84.84%	90.90%

Procedure

Task order was randomized into four different sequences, starting with either working memory, fine motor control, writing tasks, or questionnaire completion.

Tasks

Handwriting

Loop tracing task

The loop tracing task was performed on a graphic tablet (Wacom 4 Pro Large) connected to a computer via a USB cable and its paired ballpoint pen. Participants traced the pre-printed forms on paper affixed to the tablet's active area. Tracing coordinates were recorded using handwriting analysis software (Gilhodes et al., 2023), which measures the x and y coordinates of the pen tip at 200 Hz. The loop tracing tasks replicates the task presented in Alhaddad et al. (2023)..Participants were instructed to trace upscaled or downscaled loops, starting from left to right or from right to left, from an indicated

starting position following the template placed at the beginning of the line. The order of these 4 conditions was randomized among 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 participants were required to trace the loop series at spontaneous speed without pen lifts. The frame was intended to give an indication of size, without constraining it 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 edge.

Four variables were analysed (see Alhaddad et al., 2023 for a reference): 1) the tracing frequency (number of loops drawn per second); 2) the mean relative phases (RP) with values ranging between 0° (line) and 90° (circle); 3) the SD of the RP (lower values indicate that the RP is stable across the loops, higher values show variability); 4) the mean slant (inclination angle of the axis of the loop relative to the baseline) with values between 0° and 90° indicated a rightward slant, and values from 90° to 180° values indicating a leftward slant.

Text copying task

The Concise Assessment Scale for Adolescent's Handwriting (BHK-Ado) is a standardized tool used to evaluate handwriting in adolescents (Albaret & Soppelsa, 2012); it was used here with adults given the lack of adapted tests (Palmis et al., 2021). Participants are instructed to copy a French text for five minutes in their typical handwriting style on a blank sheet of A4 paper. The handwriting quality (legibility) measure is a sum of nine features reflecting handwriting legibility (stability of words and letters, height of letters).

The total degradation score ranges from 0 to 45, with higher scores indicating more errors and a lower legibility. The second measure, speed, was determined by totalling the number of letters written within 5 minutes.

Fine motor control

Purdue Pegboard Test

The Purdue Pegboard is a test of fine motor control that measures the dexterous coordination of the hands and fingertips (Gonzalez et al., 2017). Participants are asked to place as many pins as possible in 30s with their right hand in the right row, then with the left hand in the left row, and finally using both hands in both rows simultaneously.

A score combining the performance on these 3 tasks is computed (overall number of pins placed; Peg placement score). The second part of the task requires the use of both hands to assemble pins, washers and collars to form a given structure as quickly as possible in one minute. An assembly score is used for this task (total number of elements used in the structure, assembly score), and reflected fine motor praxis.

Spatial tapping task

This task requires participants to synchronize visuo-motor pointing actions with a metronome towards six black targets that are displayed on a touch screen (Dione & Delevoeye-Turrell, 2015). The targets were placed around a virtual circle of 100 mm radius. Participants touched each target sequentially, starting from the bottom right, moving counterclockwise using the right index finger, synchronized to regular auditory tones (metronome). Nine trials were conducted, with tempi presented in the same order for all participants, starting from slow (1100 ms intervals) to fast (300 ms intervals) tempi. Performance was indexed by time asynchronies, that were calculated as the difference in time between

the onset of a tap and the start of the nearest auditory tone and by endpoint distributions of pointing actions fitted with spatial ellipses whose surface measured spatial error, as well as the spatial accuracy (mean area of spatial ellipses in mm², computed from the distribution of the taps at each target location).

Spontaneous motor tempo task

For the purpose of the current study, we adapted the spatial tapping task (Dione & Delevoye-Turrell, 2015) to index the spontaneous motor tempo in the context of spatially constrained movements. Participants were instructed to stand in front of the screen, tap each target in sequence using their right index finger with a closed fist, starting from the bottom targets at a spontaneous pace. Two directional paths were explored: clockwise and counterclockwise, aiming at reproducing some of the directional properties of the loop tracing task. Endpoint distributions were analyzed both in time and space, providing us with the means to evaluate the motor speed-accuracy trade-off, i.e. whether an advantage in time occurs or not at the expense of the spatial accuracy or vice versa, compared to classic non spatial spontaneous rhythmic task. We computed the spontaneous motor tempo (median inter-response intervals, IRI, which consists of the time intervals between the each of the of successive taps) and the spatial accuracy.

Working Memory

2-back task with digits

This task assesses the ability to control the flow and update of information in working memory (Zimmermann & Fimm, 2002). The test was implemented from the third and most challenging working memory condition of the Test of Attentional Performance battery (Zimmermann & Fimm, 2002). Participants were presented with a series of numbers on a computer monitor and asked to quickly press a response key to indicate whether each number matches the number that occurred two positions before it (n-2 preceding number). The two performance parameters are number of omissions and median reaction times.

Corsi block tapping test

Corsi block testing is used to evaluate immediate non-verbal working memory particularly in its visuospatial aspects (Kessels et al., 2000). It involves the replication of a sequence of pointing movements on different cubes placed on a board displayed by the examiner. Participants are asked to reproduce this sequence either in the same order it was presented or in reverse order. The difficulty of the task is progressively increased by adding more blocks to the sequence, starting with 2 until 9 blocks. The goal is to determine the maximum number of blocks that a subject can recall without making an error. The score given is the rank of the last correctly reproduced sequence in the normal order and in the backwards condition. The higher the score, the better the memory span.

Data Analysis

The handwriting, working memory and fine motor control data were analyzed using linear regression mixed effects models (Baayen et al., 2008) via RStudio (Version 1.3.1093) with the packages lmerTest (Kuznetsova et al., 2017) and lme4 (Bates et al., 2015) packages.

The following code line was used for the loop tracing task:

dependent variable ~ group * directionOfRotation* writingDirection + age + gender + amountOfHandwritingPractice +(1|subject).

The dependent variables of the models were the mean RP, RP standard deviation, mean slant, and frequency. Writing direction, direction of rotation, group (monoscriptual or biscriptual), and the interaction between group, were defined as predictors.

Linear models were used for the analysis of the handwriting task, the working memory and the fine motor control tasks with the following code line: dependent variable~group+age+gender. The models also included the age and gender as controls variables because they are known to have an effect on handwriting performance (Albaret et al., 2013). The total amount of weekly handwriting practice was also included as control for handwriting variables. Random effects of participants were included in the model for each variable; group, direction of rotation and writing direction were dummy coded. Two-way interactions between the writing direction and rotation direction were not further tested for contrasts.

When an interaction between group and another factor was 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)).

We also ran complementary analyses accounting for bilingual practice of the participants to control for this possible confound, with the following line codes:

dependent variable ~ Bilingualism levels (YearsImmersionL2; ProficiencyL2) + age + gender +(1|subject).

Results

All significant effects are reported in Table 2 and represented in Figure 2.

Graphomotor control: loop-tracing task

Mean Tracing Frequency

Biscriptuals produced the loops at a higher frequency than monoscriptuals ($\beta = 0.33$, $t = 2.07$, $p = .042$; biscriptuals = 2.14 Hz, monoscriptuals = 1.79 Hz). Additionally, frequency was higher for counterclockwise than clockwise loops ($\beta = 0.08$, $t = 2.37$, $p = .018$; counterclockwise = 2.01 Hz, clockwise = 1.92 Hz). The mean tracing frequency was also higher for the left-to-right than for the right-to-left direction ($\beta = -0.22$, $t = -5.93$, $p < .001$; left to right = 2.08 Hz, right to left = 1.86 Hz), in both monoscriptuals ($\beta = 0.29$, $t = 5.69$, $p < .001$) and biscriptuals ($\beta = 0.14$, $t = 2.69$, $p = .038$).

Mean Relative Phase

The loops were produced with higher mean relative phase (RP) for right-to-left than left-to right directions ($\beta = 6.31$, $t = 5.95$, $p < .001$; left to right = 49.7°, right to left = 56°) (Fig. 2a). None of the group, direction of rotation, or interaction factors reached significance.

Standard Deviation of the RP

Biscriptuals produced more stable loops than monoscriptuals ($\beta = -0.44$, $t = -3.11$, $p = .002$; biscriptuals = 6.62°, monoscriptuals = 8.06°). The RP was more variable in the right-to-left than in the left-to-right direction ($\beta = 0.31$, $t = 2.79$, $p = .005$; left to right = 6.88°, right to left = 7.80°) (Fig. 2a). Neither of the direction of rotation factors, nor the interactions reached significance.

Slant

For the mean slant, none of the main effects nor interactions reached significance.

Graphomotor control: text copying task

Handwriting speed

Biscriptuals copied the text at a higher speed compared to monoscriptuals ($\beta = 45.84$, $t = 2.36$, $p = .021$; biscriptuals = 1.97 characters per second, monoscriptuals = 1.81 characters per second). The control variable of gender indicated significant differences, females had higher handwriting speed ($\beta = -49.61$, $t = -2.54$, $p = .013$; males = 1.80 characters per second, females = 1.97 characters per second) (Fig. 2b).

Handwriting quality

The handwriting of biscriptuals was also of better quality than that of the monoscriptuals ($\beta = -1.22$, $t = -2.01$, $p = .048$; biscriptuals legibility score = 5.82, monoscriptuals legibility score = 7.09; a higher score corresponds to more degraded handwriting). Among the variables controlled, we also found an effect of gender, females displaying higher handwriting quality than males ($\beta = 1.60$, $t = 2.62$, $p = .010$; males = 7.32, females = 5.69) (Fig. 2b).

Fine motor control skills

Dexterity scores

Peg placement score: biscriptuals placed more pegs than their monoscriptuals counterparts ($\beta = 6.39$, $t = 4.76$, $p < .001$; biscriptuals = 49.2, monoscriptuals = 48.2). Females also placed more pegs than males ($\beta = -2.82$, $t = -2.09$, $p = .040$; males = 44.4, females = 47.5) (Fig. 2c).

Assembly score: For the assembly score of the pegboard task, group factors did not reach significance.

Spatial Tapping Task

Tempo condition had an effect on asynchronies ($\beta = -0.05$, $t = -3.97$, $p < .000$; 1200 = -33.38 ms, 1100 = -49.15 ms, 1000 = -86.70 ms, 900 = -77.11 ms, 800 = -85.45 ms, 700 = -67.42 ms, 600 = -60.44 ms, 500 = -35.40 ms, 400 = -1.77 ms, 300 = 19.82 ms). Neither the group nor interactions had a significant effect.

Biscriptuals had smaller spatial errors than monoscriptuals ($\beta = 54.27$, $t = 3.26$, $p = .001$; biscriptuals = 89.66 mm², monoscriptuals = 104.39 mm²). A condition effect was also significant ($\beta = -0.16$, $t = -14.38$, $p < .000$; 1200 = 44.48 mm², 1100 = 47.47 mm², 1000 = 53.09 mm², 900 = 58.89 mm², 800 = 68.95 mm², 700 = 73.21 mm², 600 = 88.24 mm², 500 = 103.22 mm², 400 = 155.88 mm², 300 = 277.99 mm²). Finally, a group by condition interaction effect was significant ($\beta = -0.05$, $t = -3.23$, $p = .001$). Further contrast analysis indicated that biscriptuals produced smaller spatial errors than monoscriptuals on the fastest condition ($\beta = -80.52$, $t = -5.35$, $p < .000$; biscriptuals = 237.09 mm², monoscriptuals = 317.61 mm²) (Fig. 2d).

Spontaneous motor tempo

There was a significant interaction effect between the direction of rotation and the group on the inter-response-intervals of the spontaneous tapping task ($\beta = -77.19$, $t = -4.00$, $p < .001$; biscriptuals counterclockwise rotation = 561 ms, biscriptuals clockwise rotation = 582 ms, monoscriptuals counterclockwise rotation = 610 ms, monoscriptuals clockwise rotation = 556 ms). Further contrast

analysis revealed that monoscriptuals were affected by the direction of rotation ($\beta = 56.75$, $t = 4.12$, $p < .001$), while biscriptuals were not (Fig. 2d). The main effects of group and direction of rotation did not reach significance.

Concerning the spatial accuracy, neither the group, direction of rotation factors, nor interactions reached significance.

Working memory

Neither of the Corsi block tapping scores nor 2-back tasks indexes reached significance.

Effect of bilingualism on graphomotor control

Knowing the possible effect of bilingualism on cognitive processes (Adesope et al., 2010), we checked whether the graphomotor performance of the two groups of participants was affected by L2 proficiency and L2 exposition. This analysis was limited to the graphomotor variables that differed significantly between groups (mean frequency, PR SD, handwriting legibility and speed). We ran a separate analysis for each group because the distribution of the bilingualism variables was necessarily different in the 2 groups.

Within the biscriptual group, L2 proficiency and the number of years of immersion in L2 impacted the handwriting legibility scores ($\beta = 1.23$, $t = 2.76$, $p = .015$ and $\beta = 3.80$, $t = 4.43$, $p < .001$, respectively). L2 proficiency and years of immersion in L2 had no significant effect on the remaining handwriting and graphomotor variables in biscriptuals and had no effect on any of the graphomotor variables in monoscriptuals.

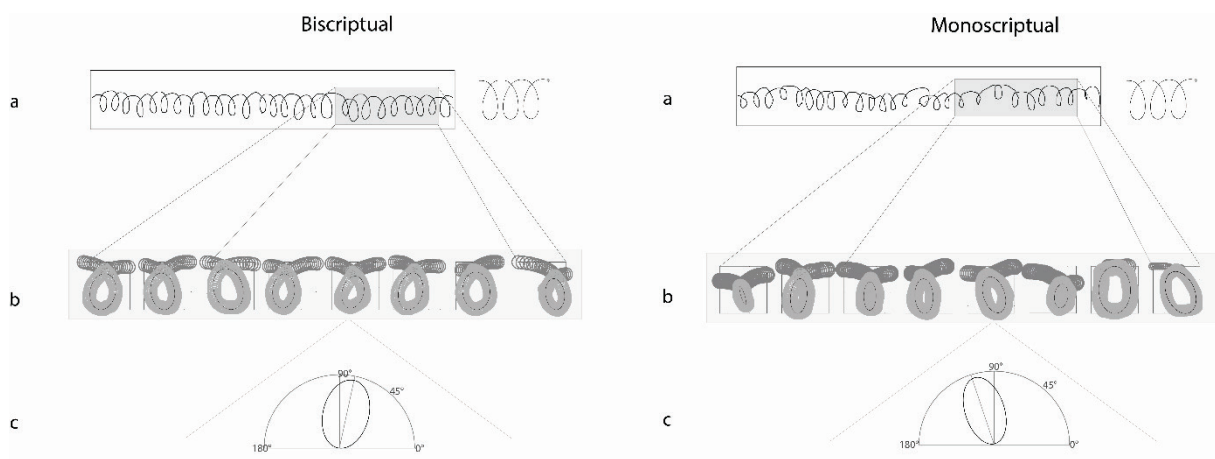


Figure 1. Example of a loop series analysis in a biscriptual and monoscriptual participant. Panel a: Template (condition) of the loops to be traced and loop series traced by a participant. Panel b: Fitting ellipses onto the first eight correctly drawn loops to compute the relative phase (RP, mean and sd) and the slant. Panel c: Example of the graphical determination of the slant in degrees on a single loop.

Table 2. Significant results in the Mixed-Effects Models implemented on Handwriting and fine motor control variables

	β	t	p
Frequency (loop tracing)			
Group	0.33	2.07	.042
Direction of rotation	0.08	2.37	.018
Writing direction	-0.22	-5.93	.000
Group X Writing direction	0.15	2.12	.035
RP Mean (loop tracing)			
Writing direction	6.31	5.95	.000
RP SD (loop tracing)			
Group	-0.44	-3.11	.002
Writing direction	0.31	2.79	.005
Handwriting Speed (text copying)			
Group	45.84	2.36	.021
Gender	-49.61	-2.54	.013
Handwriting Quality (text copying)			
Group	-1.22	-2.01	.048
Gender	1.60	2.62	.010
L2 Proficiency - Biscrptuals	1.23	2.76	.015
Years of Immersion L2 - Biscrptuals	3.80	4.43	.001
Dexterity (peg placement score)			
Group	6.39	4.76	.000
Gender	-2.82	-2.09	.040
Spontaneous Motor Tempo			
Group X Direction of rotation	-77.19	-4.00	.000
Spatial Tapping Task			
Group	54.27	3.26	.001
Condition	-0.16	-14.38	.000
Group X Condition	-0.05	-3.23	.001

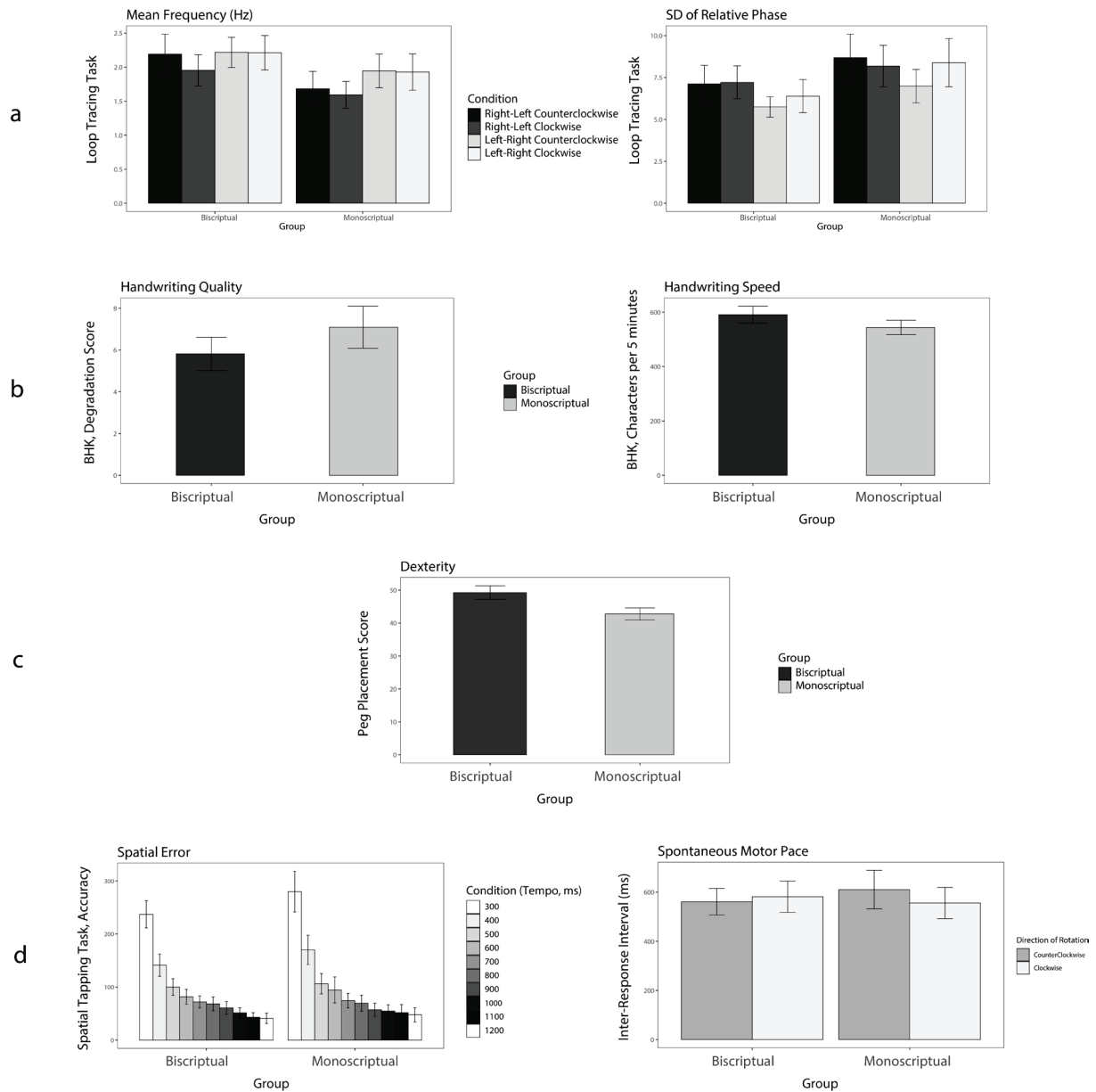


Figure 2. Significant group effects and interactions. (a) Effects of group (biscriptuals, monoscriptuals), tracing direction (Left-Right and Right-left) on the Mean frequency and the SD of relative phase during loop tracing. (b) Significant effects of group on the legibility and the speed of handwriting. (c) Significant effect of group and condition on dexterity. (d) Significant main effects and interactions between of group and condition on the spatial tapping task and interaction effects of group and direction of rotation on spontaneous tempo. Error bars represent 95% confidence intervals.

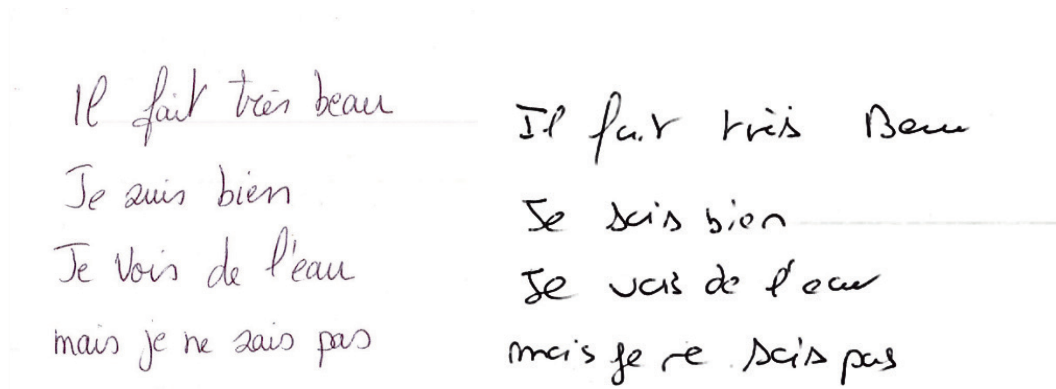


Figure 3. Excerpts of the BHK test of a biscriptual participant with high legibility (left) and a monoscriptual participant with lower handwriting legibility (right). Common indicators of handwriting legibility include letter/character size, slant/orientation, letter formation, spatial organisation, alignment, spatial consistency/uniformity of or variation/error in a writer's production.

Discussion

The graphomotor performance, fine motor skills, and working memory performance were compared in Latin monoscriptuals and Latin-Arabic biscriptuals. We established that biscriptuality promotes proficient graphomotor control. We also evidenced effects of biscriptuality on the three tasks used to measure fine motor control performance. These results show that writing expertise widely impacts the organization of the motor system. Conversely, we did not find an effect of biscriptuality on working memory performance.

A first major finding is the superior performance of biscriptuals in the 2 graphomotor tasks. We did replicate the results of Alhaddad et al. (2023), in which Arabic-Latin biscriptuals traced loops at a higher frequency than Latin monoscriptuals, with a different sample that met the same inclusion criteria. Furthermore, group differences observed in the SD of relative phase in the present study indicate that biscriptuals not only trace loops with higher frequency, but also in a more stable manner. In the text copying task, the handwriting of biscriptuals was also faster and more legible than that of monoscriptuals (figure 3), consistent with cursory observations in children (Matta Abizeid et al., 2017). Note that these results argue against a speed-quality trade-off effect (Barnett et al., 2009), as both features are improved in biscriptuals. The biscriptual advantage on graphomotor control thus stands as a reliable and robust phenomenon.

Results of the fine motor control tasks support the assumption that biscriptuals have optimized the control of their hands. We found that biscriptuals have better dexterity and better spatial accuracy when performing spatial tapping, compared to monoscriptuals. Moreover, biscriptuals were less affected than monoscriptuals by the direction of rotation during the spontaneous tapping task, suggesting that biscriptuality is also associated with changes in the spontaneous rhythmic control of motor actions. These results provide one of the first empirical demonstrations of an effect of writing practice on generic manual motor tasks.

Handwriting expertise is the result of a challenging motor learning process requiring the coupling of the thumb and index fingers with the wrist (Hollerbach, 1981; Rosenbaum, 2009). It is part of a class of dexterous movements that do not belong to the innate motor repertoire because they involve moving individual fingers whilst other remain still (Furuya et al., 2011; Häger-Ross & Schieber, 2000; Schieber & Santello, 2004; Sobinov & Bensmaia, 2021). There are numerous examples of how the acquisition of these new manual motor skills modifies the neural circuits involved in motor control

both at a functional and at a structural level (music, juggling; (Draganski et al., 2004; Schlaug, 2001), tools or chopstick use (Sawamura et al., 2019)). It is likely that the same type of neuroplasticity occurs in the case of handwriting acquisition. Previous studies do suggest that specific variations in writing expertise can be associated to neural changes in motor control networks (Cannonieri et al., 2007; Grabowska et al., 2012; Klöppel et al., 2007) and in motor performance (Llamas-Velasco et al., 2023; Sülzenbrück et al., 2010, 2011). However, these variations in expertise remain very specific (typing expertise, converted left-handedness, Parkinson's disease). Here we show that a naturally occurring individual variation in the type of handwriting expertise among typical young adults has a reliable effect on several indexes of fine motor control.

The pegboard task involves both the implementation of muscular synergies to reach and grasp the pegs, and the integration of tactile, proprioceptive and visual signals through the pyramidal tract and cortical motor and parietal regions (Sobinov & Bensmaia, 2021). In biscriptuals, this system operates faster, either because the control of the joints, the sensory integration, or both are more efficient. Future studies could uncover the fine-grained aspects of dexterity that are affected by biscriptual handwriting practice.

In the spatial tapping task, biscriptuals displayed an advantage in spatial precision in the fastest tempo condition. Previous work has shown that spatial accuracy in the fast tempo conditions may stem from efficient emergent timing (Dione & Delevoye-Turrell, 2015). In emergent timing, the temporal features of movements are adjusted dynamically while the spatial trajectory is explicitly coded (Robertson et al., 1999; Zelaznik et al., 2002). This allows for real-time adaptation to changes in movement speed or task demand rather than on a timing that is explicitly coded. Biscriptuality is thus associated with an improved control of movement trajectories while maintaining synchronization under high temporal demands.

In the spontaneous motor tempo, monoscriptuals were sensitive to the circular direction of movement, while biscriptuals were not. Both groups were equally accurate at a spatial level, indicating that the effect cannot be explained by a speed-accuracy trade-off. The spontaneous motor tempo in rhythmic tasks is quite universal as it classically emerges as inter-response intervals of around 600 ms (Delevoye-Turrell et al., 2014; Hammerschmidt et al., 2021), as obtained in the present study. Despite universality, it is affected by the development and impairment of motor skills with age (Monier & Droit-Volet, 2019; Hammerschmidt et al., 2021) and by expertise (Loehr & Palmer, 2011). As such, it can be viewed as a general index of the natural timing dynamics of the motor apparatus (Shaffer, 1982; Sakai et al., 2004). The results obtained thus raise the fascinating possibility that script writing expertise impacts the neural delays for controlling the spontaneous timing of rotational movements using the hand apparatus. To our knowledge, it is the first time that the spontaneous tempo is shown to be affected by motor expertise.

Overall, our findings demonstrate that in biscriptuals, the simultaneous and decade long training in two distinct scripts shapes the organization of the neural circuits driving manual actions, leading to long term effects on fine motor control. But which features of the biscriptual writing experience could promote proficient graphomotor control and fine motor skills? Although the present study did not aim at investigating this question, two prominent characteristics of biscriptual training and practice can be considered: the amount of training during the initial phases of acquisition (because two scripts must be mastered, a larger amount of training is required), and the variability in the practiced graphomotor patterns. Reinforcement learning theories emphasize the importance of action exploration for skill acquisition. They consider variability in motor output during motor learning as a means of exploring motor space, leading to an optimal skill level (Dhawale et al., 2017; Tumer & Brainard, 2007; Wu et al.,

2014). Because biscriptuals get trained to two different sets of characters bearing varied graphomotor features, they could benefit from this variability to optimize their manual motor control. The specific type of biscriptuality that we focused on here could maximize this variability: the specific graphomotor features of the Arabic script contrast massively with the features of the Latin script in terms of direction, rotation and number of pen-lifts (Fabiani et al., 2023; Salameh-Matar et al., 2022; Taha et al., 2013).

Contrary to fine motor control, the results showed no significant group difference in working memory measures. Writing in two different scripts does not seem to enhance working memory abilities in biscriptuals. Researchers have shown that that bilingual language behaviour might become more automatic and less dependent on working memory with practice (Green & Abutalebi, 2013; Lehtonen et al., 2023; Pliatsikas, 2020). Similarly, the extent to which working memory is engaged in biscriptual practice would diminish over time (Lehtonen et al., 2023). Moreover, working memory is often considered as domain-general (Li et al., 2014). It is not solely mobilized through reading and writing experiences, but also in most cognitive and sensorimotor daily activities.

Some authors consider that the effects of biscriptuality can combine with the effects of bilingualism (Coderre & van Heuven, 2014) on working memory. It was thus important to verify that the effects of biscriptuality were not driven by the participants' level of bilingualism. In biscriptuals, bilingualism measures had a significant negative effect on the legibility scores of the text copying test without affecting the speed. The more proficient and immersed in French, their second language, the worse the legibility in handwriting in French. These results are surprising given that biscriptuals that are more proficient in their second language (French) seem to have less legible Latin handwriting. This effect could be related to processing the semantic contents of the text to be copied, that could interfere with the writing process. Comparable effects have previously been reported in children (Caravolas et al., 2020; Salameh-Matar et al., 2022). Although bilingual practice could thus affect some aspects of handwriting in biscriptuals, the direction of the effect argues against a contribution of bilingualism to the biscriptual advantage.

Gender had also a significant effect on handwriting speed and legibility as well as on the performance at the Pegboard task. This finding is consistent with previous studies that reported reliable sex differences in handwriting and dexterity performance, where females consistently outperform males (Cordeiro et al., 2018; Junaid & Fellowes, 2006; Nicholson & Kimura, 1996; Reilly et al., 2019; Reynolds et al., 2015; Ruff & Parker, 1993). This difference could be explained by the fact that starting a young age, girls acquire fine motor control more rapidly than boys (Albaret et al., 2013). It could also be explained by differences between males and females in the neural recruitment during handwriting (Yang et al., 2020). Gender effects did not interact with biscriptuality.

There are some limitations to this study. The absence of effects on the working memory task could be due to an incompatible task selection (Miyake et al., 2000). Furthermore, we based our selection of the fine motor control measures on Fleishman's (1972) taxonomy of motor skills, however, other tasks could have been relevant. Further studies would gain to expand the visual-motor integration evaluation, a good predictor of handwriting legibility (Tseng & Murray, 1994).

Although we directly tested for the effects of the level of proficiency and immersion in the second language in the two groups, it remains that most biscriptuals learned their second language (L2) before age 4 while all monoscriptuals learned their L2 after age 4. Early bilinguals, who acquire both languages simultaneously from a young age, might demonstrate higher performance in tasks requiring executive functions compared to late bilinguals, who learn a second language after their first language is well-established (Luk et al., 2011). This advantage is thought to arise from the continuous practice of managing two linguistic systems from an early age, which strengthens executive control processes

(Kalia et al., 2014). However, differences have mainly been reported in terms of language proficiency (Luk et al., 2011) and in neural organisation of language processing (Cargnelutti et al., 2019; Hull & Vaid, 2007; Mechelli et al., 2004). Despite these observations, the modulatory effect of the age of acquisition on cognitive outcomes remains uncertain (Grundy & Timmer, 2017), as several other studies showed no differences (Paap, 2019, 2022). This factor should be considered in future studies on biscriptuality.

Constraints on the generalizability of our findings also apply. As specified in Alhaddad et al. (2023) study, the observed effects could be specific to the practice of the Latin and Arabic alphabets. Other pairs of scripts, either similar (Latin-Cyrillic) or dissimilar (Latin-Chinese) may affect the motor system differently. Moreover, the biscriptual group comprised only expatriated participants who were more exposed to Latin than Arabic, which might not be fully representative of all Arabic-Latin biscriptuals.

To conclude, this study opens new perspectives in expert handwriting research. Biscriptuality provides a unique opportunity to advance our knowledge on the computational and neural organization of handwriting. Our results demonstrate that writing expertise widely impacts the organization of the motor system.

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