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Does modifying visual feedback facilitate learning to write new pseudoletters?

Jean-François Connan^{1,2,3}, Marianne Jover¹, Alexandrine Saint-Cast⁴, & Jérémy Danna^{2,5}

¹Aix Marseille Univ, PSYCLE, Aix-en-Provence, France

²Aix Marseille Univ, CNRS, LNC, Marseille, France

³ISRP, Marseille, France

⁴ISRP, Paris, France

⁵CLLE, Université de Toulouse, CNRS, Toulouse, France

Abstract. Learning to write relies on the efficient integration of visual and proprioceptive feedback, with a transition from a control, based on the visual inspection of the written trace at the beginning of the learning process to a more predictive control, based mainly on handwriting movement, in proficient writers. The aim of this study was to test the effect of a partial deletion of the written trace, as well as the effect of supplementary visual information, on handwriting kinematics in a learning task. Twenty-four adults learned to write six new pseudoletters using their non-dominant hand on a touch screen digital tablet. Three pseudoletters were trained with modified visual feedback conditions and the other three, in the control condition, i.e. without any visual modification. Results revealed that, in the short-term, the pseudoletters learned with modified visual feedback were traced faster and more fluently than those learned in the control condition, without spatial accuracy reduction. This method seems to be efficient in adults, which is a prerequisite before testing a method with children.

Keywords: Graphonomics; Digital; Handwriting; Visual Feedback; Motor learning

1. Introduction

Handwriting is a fundamental skill that students must master to succeed in school. Digital tablets in school classrooms encourage the development of new methods to help students learn to write by hand, thanks to computer-assisted supplementary feedback (FB) (Berninger et al., 2015; Bonneton-Botté et al., 2019, 2020). The general goal of computer-assisted supplementary FB is to transmit additional information, during or after execution. The information can concern the quality of the written trace, i.e. the product of handwriting, or the quality of the movement that generates this written trace, the process of handwriting. Interestingly, the relationship between process and product is not direct in handwriting: a legible trace can be produced by a slow and jerky movement just as a fast and fluid movement can lead to an illegible trace. Thus, the quality of handwriting depends, from the writer's point of view, on the balance between a correct trace and a correct movement.

Learning to write relies on the efficient integration of visual and proprioceptive FB, with a transition from a control, based on a visual confirmation of the written trace to a control, based mainly on writing movements, in expert writers. Supplementary FB makes it possible to modify the basic mechanisms that are involved in the motor control of handwriting (for a review, see Danna & Velay, 2015), by providing additional information that a writer can access in real-time (concurrent FB), or by providing new information not naturally accessible either during or after execution (terminal FB, Sigrist et al, 2013). For example, during execution, it is possible to correct handwriting movements with haptic guidance (Bluteau et al., 2008), to provide additional auditory FB with handwriting sonification (e.g., Danna et al., 2015; Ecalle et al., 2021), or to change the digital trace on the screen in order to add customized visual information (e.g., Loup-Escande et al., 2017). After execution, it is also possible to provide additional visual FB on the product (e.g., on the shape, Bonneton-Boné et al., 2020) or on the process of handwriting (e.g., Sjøvik & Teulings, 1983). In this study, we tested the combination of the two strategies: modifying the visual perception of the handwriting by partially deleting the trace during execution and providing additional visual FB after execution.

Providing supplementary real-time visual FB in handwriting has seldom been tested because vision is already used to control the trace at the beginning of learning (Danna & Velay, 2015). Splitting visual attention may be detrimental. Furthermore, processing additional visual information requires time and leads the writer to slow down (Portier & van

Galen, 1992). Nevertheless, some strategies remain relevant, one of which is changing either the color of the trace in order to inform on the writing speed or the trace's thickness depending on the pressure exerted by the pen on the tablet. Both strategies have been tested in adults and appear to be promising (Loup-Escande et al., 2017). However, the possible overload of the visual information processing must be considered in the case of learning.

An efficient strategy for optimizing the learning or the rehabilitation of handwriting could rely on the facilitation of this transition from a *product*-based control exploiting the online visualization of the written trace to a *process*-based control drawn from the motor control of handwriting movement. To facilitate this transition, it is possible to decrease the visual perception of the written trace, totally or partially, leading the writer to focus on the ongoing movement. The total deletion of the written trace was tested a long time ago in adults who were asked to write without seeing their hand (Portier & van Galen, 1992). The authors reported a positive effect on writing speed and fluency, but the effect on the legibility of the trace has not been evaluated. More recently, Bara & Bonneton-Botté (2021) tested this method with young children who were asked to write isolated cursive letters without seeing the written trace. They confirmed a positive effect on handwriting kinematics, but the total trace deletion impacted the accuracy. This deterioration can be explained by the participants' lack of knowledge about the result.

To our knowledge, the effects of a partial deletion of the written trace have never been tested. The method proposed here was inspired by *Light Drawing* (or *Light Painting*, e.g., Hu et al., 2020), a photographic technique that consists of moving a light source while taking a long exposure photograph to “draw” with a light source in the air. The individual creating this effect only sees the light point (an LED) at the pen tip during the trial and the result of their action after tracing. During tracing, the light point becomes a luminous trace that follows the moving pen. This luminous trail results from retinal persistence, and lasts several tens of milliseconds after the disappearance of the stimulus. As a result, the length of this luminous trail depends on the velocity: the faster the movement, the longer the trail. Therefore, this technique provides real-time visual FB on both the position of the pen tip within the written trace and the movement velocity.

This technique of decreasing visual FB during execution has been transposed onto a digital tablet and was tested with adults who were learning to write pseudoletters (Connan et

al., 2021). This pilot study showed both the limits and the potential benefits of such a strategy: velocity and fluency improved during practice with the modified visual FB whilst no effect was observed on accuracy. Unfortunately, this positive effect on handwriting kinematics disappeared in the post-tests realized just after the training. The authors hypothesized that the positive effect of training with modified visual FB was not transferable to the normal writing condition, probably because of the dependence on augmented FB (Ronsse et al., 2011). The inherent cognitive load involved in the systematic augmentation of FB would prevent the processing and exploitation of intrinsic sensory FB (Wulf & Shea, 2004). One way to reduce this dependence is to reduce the frequency of the modified FB or to regularly change the supplementary visual FB. Similar strategies have already been tested and validated in the field of motor learning (e.g., Winstein & Schmidt, 1990).

The impact induced by supplementary FB on attentional focus is an important factor in determining the effectiveness of different FB frequencies (Wulf *et al.*, 2010). Another condition was added every other trial, it was based on an additional visual terminal FB on the movement fluency. This second strategy of adding supplementary FB on handwriting movement after the performance has already been tested in 11-year-old children and seems promising (Søvik & Teulings, 1983). In their study, a supplementary FB related to both movement velocity and fluency was given to the participants and the supplementary FB improved handwriting speed but no fluency. In the present study, a supplementary FB on movement fluency was added after trial execution: red dots were added over the trace wherever the movement was less fluent. These red dots corresponded to the abnormal velocity peaks determined by the Signal-to-Noise velocity peaks difference (SNv_{pd}, Danna et al., 2013). This strategy allowed the writer to see if the shape of the pseudoletter was correct and where the movement was not fluent. These static (on the product) and dynamic (on the process) aspects of handwriting have rarely been considered at the same time (Bonneton-Botté et al., 2019). We suppose that the combination of a concurrent visual FB in one trial and a supplementary terminal FB produced in a condition without manipulation in the following trial would reduce the dependence to the FB, by limiting the processing of concurrent FB information (Blandin et al., 2008). Furthermore, switching from one strategy to another, which differs in the timing of the FB - either during or after execution - may have a positive effect on motor learning (for a review, see Sigrist et al., 2013).

The aim of this study was to test the effect of a combined visual FB modification in learning to write new pseudoletters. We hypothesized that the combination of a partial deletion of the written trace during execution and a supplementary visual FB after execution every other trial, lead the writer to focus on the writing process (additive effect) without being dependent on either FB. Nevertheless, we sought to ensure that this strategy did not come at the expense of accuracy. Since we were not sure whether such a method would have a positive effect on learning to write, we conducted a study among adults, in whom a possible negative effect would have a lower impact than among children. In order to put the adults in a more difficult situation, we asked them to write unknown pseudoletters with their non-dominant hand.

2. Method

2.1. Participants

Twenty-four right-handed adults (mean age: 24.6 years \pm 6.32, 22 women) volunteered for the experiment. None of the participants presented any known neurological or attentional deficits, as determined by a detailed questionnaire completed prior to the experiment. They all had normal or corrected-to-normal vision. All participants signed a written informed consent before starting the experiment, in accordance with the ethical standards set out in the Declaration of Helsinki.

2.2. Task and procedure

The task consisted of learning to write six new pseudoletters with the non-dominant hand (see Fig. 1B). Participants were asked to write the pseudoletters on a touch screen digital tablet (Windows surface pro® 6: 12.3 inches; spatial resolution 267 PPI and sampling frequency 60 Hz; 4096 pressure levels) with a stylus (surface pen, HB lead). The tablet displayed the pseudoletter to be traced and below, a 4x4 cm square in which the participant reproduced it.

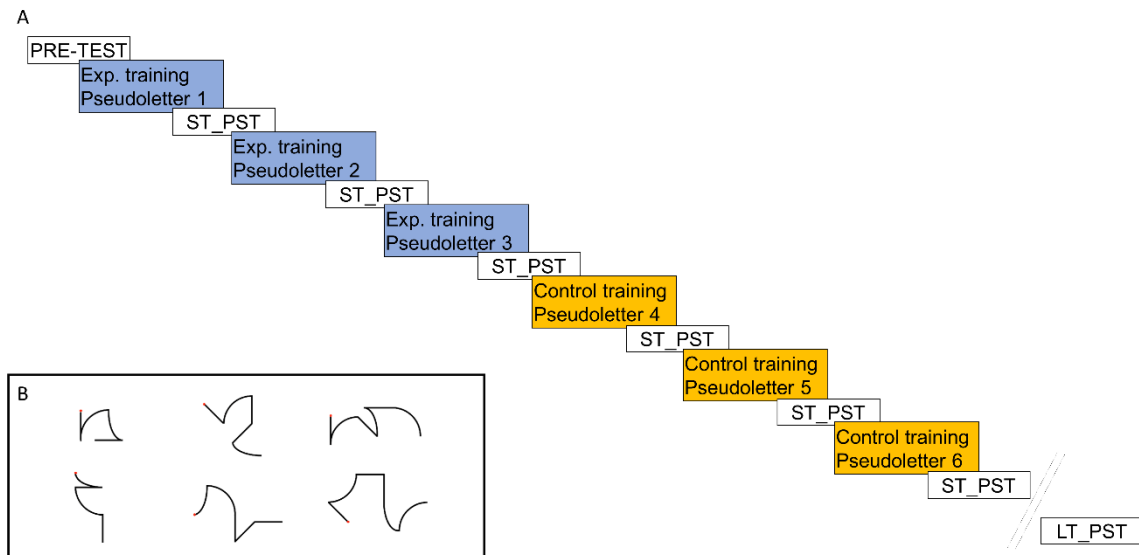


Figure 1. Description of the experimental design (A) and pseudoletters (B). The pseudoletters were created from a combination of elementary strokes, with the same strategy as conducted by Seyl et al. (2020). These pseudoletters were divided into two sets of three. Each set included a 4-stroke pseudoletter, a 5-stroke pseudoletter, and a 6-stroke pseudoletter. Each participant learned one set in the control condition (orange) and the other in the modified visual FB condition (blue). Both the condition order (between experimental and control trainings) and the pseudoletter order were counterbalanced between participants. Note: Exp. = Experimental; ST_PST = Short-Term Post-Test; LT_PST = Long-Term Post-Test.

The procedure was as follows (Fig.1 A). The experiment began with a familiarization phase with the tablet and the two types of modified visual FB. During familiarization, the participants were asked to reproduce a new pseudoletter three times without modified visual FB, three times with the real-time modification called “snake”, and three times with the delayed supplementary FB, called “enriched postponed”. This pseudoletter was not used for the learning task.

The learning task included a pre-test, six training sessions, six short-term post-tests and two long-term post-tests. In the pre-test (PRE), the participants had to reproduce six pseudoletters twice without modified visual FB (i.e. normal writing conditions, with the participant seeing their trace). During the training session (TRAINING), participants wrote one of the six pseudoletters 10 times, with or without modified visual FB according to the training condition (experimental vs. control). The training of each pseudoletter was presented in a block design so that the participant can correct himself from one trial to the next. Both the condition order

(between experimental and control trainings) and the pseudoletter order were counterbalanced between participants.

After each training session, the participant had to reproduce the trained pseudoletter twice without modified visual FB (short-term post-test -ST_PST).

The following day, two long-term post-tests (LT_PST) were performed. First, the participants had to recognize the six learned pseudoletters from a set of twenty-four pseudoletters (recognition task). Three distractors were created for each learned pseudoletter: the mirror image (mirror pseudoletter), the learned pseudoletter with a feature displaced (transformed pseudoletter) and the mirror image of the transformed pseudoletter (mirror transformed pseudoletter). The set of the 24 pseudoletters can be found in supplementary data. After this recognition task, the second long-term post-test (LT_PST), identical to the PRE and ST_PST, was performed. The presentation order of the six pseudoletters was the same between the PRE and LT_PST. In both training and test sessions, the model remained displayed during the trial.

2.3. Visual FB Modification

During the training session under the experimental condition, two visual FB modifications were applied alternately. The first was based on the partial deletion of the written trace, a real-time visual modification called “snake”. The second consisted of a supplementary terminal visual FB on movement fluency called “enriched postponed”. Both the snake and the enriched postponed FB were shown to all participants.

Snake: The black trace of the pen's movement remained displayed for a time window of 192 ms and then disappeared. This condition created a real-time animation of a *black snake* following the pen tip movement, and the length of the “snake” varied according to the velocity of the pen’s movement and disappeared completely 192 ms after the pen stopped moving. This time window was chosen empirically from a pilot experiment (Connan et al., 2021), so that the participants are able to see the last stroke of the letter they are writing. At the end of the trial, the pseudoletter produced by the participants appeared in its entirety and the model remained displayed on the screen for visual comparison. An illustration of this method is presented in supplementary video 1. This modification was used every odd-numbered trial of the training.

----- Please, insert supplementary video 1 here -----

Enriched postponed: During an enriched postponed trial, the participant wrote the pseudoletter without FB modification of the written trace. At the end of the trial, the model and the pseudoletter produced by the participant remained on the screen. Over the pseudoletter, red dots appeared wherever the movement was less fluent. These red dots corresponded to the abnormal velocity peaks determined by the Signal-to-Noise velocity peaks difference (SNv_{pd}, Danna et al., 2013). We localized these peaks on the written trace by selecting the abnormal peaks (based on the velocity filtered at 10 Hz with a low pass Butterworth filter) that were farthest in time from the normal velocity peaks (based on the velocity filtered at 5 Hz with a low pass Butterworth filter). An illustration of this method is presented in supplementary video 2. This modification was used every pair-numbered trial of the training.

----- Please, insert supplementary video 2 here -----

As can be seen in Fig. 1, three pseudoletters were trained with “snake” then “enriched postponed” (experimental condition) and three others were trained without modified visual FB (control condition).

2.4. Data analysis

Based on the position and the axial pressure of the stylus, we segmented the written signal to distinguish the tracing segments from the pen lifts. Only the written trace was analyzed through five variables, three on handwriting process and two on handwriting product:

- The mean velocity (millimeters/second) corresponds to the mean of absolute velocity from the time the stylus was first in contact with the tablet until the pseudoletter was completed;
- The mean disfluency corresponds to the number of abnormal velocity peaks computed from the SNv_{pd} method (Danna et al., 2013). These abnormal velocity peaks result from the difference between the number of velocity peaks after filtering the absolute velocity with a cutoff frequency (fc) of 10 Hz and the number of velocity peaks after filtering the tangential velocity with an fc of 5 Hz. The lower the number of peaks, the more fluent the movement;
- The mean stylus pressure (arbitrary unit – A.U. – normalized between 0 and 1) corresponds to the mean of the axial pressure of the stylus. Note that this variable has not been calibrated. As it can be different from one stylus to another or from one tablet to another, the same stylus and tablet were used here.

- The trace length (millimeters) corresponds to the total distance traveled by the stylus from the instant it was first in contact with the tablet until the pseudoletter was completed;

- The spatial error between the produced pseudoletter and a reference pseudoletter (Fig. 2 for an illustration). The reference pseudoletter corresponds to the pseudoletter copied over the template by an adult writer (who did not participate to the study) with his dominant hand and filtered with a low-pass Butterworth filter of order 4 and with a cut-off frequency of 5Hz. We developed Matlab® software that: A) normalized the produced pseudoletter (in red) and the reference pseudoletter (in blue) between 0 and 1 from the local maxima and minima of each pseudoletter on both x and y axes (to allow a superposition between them); B) interpolated them to 1000 coordinates using a cubic interpolation polynomial; C) segmented the pseudoletters by strokes based on identification of the turning points that separate the strokes; and D) computed the minimal distance between the coordinates of the two pseudoletters based on a stroke-by-stroke analysis (in green). The spatial error corresponds to the average distance between the two shapes.

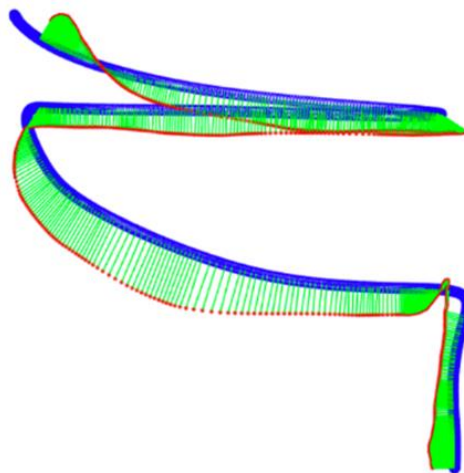


Figure 2. Illustration of spatial error (in green) between the pseudoletter produced by a participant (in red) and the reference pseudoletter (in blue).

2.5. Statistics

A total of 2304 trials were collected. The distribution of each variable was tested. Four dependent variables (Velocity, Disfluency, Length, and Spatial Error) did not satisfy Howell's (2016) criteria for kurtosis (between ± 1.3 sd) and skewness (between ± 2 sd). Thus, these variables were log-transformed. We also identified and excluded outliers for each condition using the interquartile range (IQR) method with a factor 2 of the IQR above the 75th

percentile and below the 25th percentile. In total, 50 trials (2.17%) were excluded for the statistical analysis because of recording problem or outliers.

The statistical analysis used Linear Mixed Model (LMM, GAMLj module, Galluci, 2019), which was conducted with JAMOVI® (The jamovi project, 2020; R Core Team, 2019). Omnibus tests were carried out with three "Test" conditions (PRE, ST_PST, and LT_PST) and two "FB" conditions (experimental *vs.* control) as fixed factors with repeated measures, and with the "participants" and "pseudoletters" as random factors. Concerning the training, omnibus tests were carried out with two "FB" conditions (experimental *vs.* control) and ten "Trials" (trial 1 to 10) as fixed factors with repeated measures, and with the "participants" and "pseudoletters" as random factors. All significance levels were set at $p = 0.05$. A simple-effect analysis of the FB factor with the factor "Trials" as moderator was performed when the omnibus analysis revealed a significant effect of both fixed factors. Fisher LSD post-hoc test with Bonferroni correction were applied for multiple comparisons.

Finally, the correct responses in the recognition task were summed and the results submitted to a non-parametric t-test (Wilcoxon) to determine whether the visual FB modification influences pseudoletter recognition.

3. Results

The average evolution of velocity, movement disfluency, and stylus pressure during the tests and the training are presented in figure 3. For the sake of clarity, the non-transformed values are illustrated. Statistical information about the models and full results are reported in supplementary material.

3.1. Tests

The estimated means of performance in the test phases are presented in table 1.

Table 1. Estimated means (*standard errors*) of the test phases. *Exp: Experimental; ST_PST = Short-Term Post-Test; LT_PST = Long-Term Post-Test.*

Variable	Training Condition	PRE	ST_PST	LT_PST
Velocity	Exp	14.10 (1.44)	18.58 (1.44)	16.18 (1.44)
	Control	14.43 (1.44)	17.49 (1.44)	16.72 (1.44)
Movement disfluency	Exp	11.31 (1.18)	7.93 (1.18)	9.5 (1.18)
	Control	11.02 (1.18)	9.24 (1.18)	9.52 (1.18)
Trace length	Exp	54.73 (4.80)	56.78 (4.80)	56.01 (4.80)
	Control	54.61 (4.80)	55.78 (4.80)	56.010 (4.80)
Stylus pressure	Exp	0.66 (0.02)	0.63 (0.02)	0.70 (0.02)
	Control	0.67 (0.02)	0.68 (0.02)	0.71 (0.02)
Spatial error	Exp	0.0680 (0.004)	0.0711 (0.004)	0.0696 (0.004)
	Control	0.0713 (0.004)	0.0727 (0.004)	0.0667 (0.004)

Velocity: The analysis revealed a main effect of Test on velocity ($F(2,806) = 82.72, p < 0.001$) and a FB by Test interaction ($F(2,806) = 4.39, p < 0.05$). The post hoc tests revealed a significant increase in the control ($p < 0.001$ for both comparisons) and the experimental conditions ($p < 0.001$ for both comparisons), both between the PRE and the ST_PST and between the PRE and the LT_PST. Interestingly, as can be seen in fig 3A, the velocity during ST_PST was higher for pseudoletters learned in the experimental condition than for those learned in the control condition ($p < 0.05$).

Movement disfluency: The analysis revealed a main effect of Test ($F(2,806) = 44.79, p < 0.001$) and a FB by Test interaction ($F(2,806) = 6.82, p < 0.001$). The post hoc comparisons between PRE and ST_PST revealed a significant decrease of disfluency both in the control ($p < 0.001$) and the modified ($p < 0.001$) conditions. The comparisons between PRE and LT_PST revealed a significant decrease in the experimental condition ($p < 0.001$) whereas this difference did not reach the significant threshold in the control condition ($p = 0.06$). Finally, as displayed in fig 3B, the disfluency during ST_PST was lower in the experimental condition than in the control condition ($p < 0.001$).

Trace length: The analysis revealed a main effect of Test ($F(2,806) = 3.997, p < 0.05$). The post-hoc tests showed that the trace length tends to increase between the PRE and the ST_PST ($p = 0.06$) and increases significantly between the PRE and LT_PST ($p < 0.05$). No difference was observed between the two post-tests. Finally, the analysis did not reveal a significant effect of FB, nor any interaction between FB and Test.

Stylus pressure: The analysis showed main effects of Test ($F(2,806) = 29.8, p < 0.001$) and FB ($F(1,806) = 16.5, p < 0.001$), and a significant FB*Test interaction ($F(2,156) = 4.75, p < 0.01$). As can be seen in fig 3C, the post hoc tests revealed a significant increase of pressure between the PRE and LT_PST ($p < 0.001$) both in the control and the experimental conditions ($p < 0.01$ for both comparisons). Surprisingly pseudoletters learned in the experimental condition were produced with a lower pressure than those learned in the control condition in the ST_PST ($p < 0.001$).

Spatial error: The analysis revealed a main effect of Test ($F(2,806) = 3.84, p < 0.05$). The post-hoc tests did not show any differences between the PRE and the two post-tests. A decrease of spatial error between ST_PST and LT_PST was observed ($p < 0.05$). The analysis did not reveal a significant effect of FB and interaction between factors.

3.2. Trainings

The estimated means of performance in the training phase are presented in table 2.

Table 2. Estimated means (*standard errors*) of performance in the training phase. *Exp: Experimental.*

Variable	Condition	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10
Velocity	Exp	15.78 1.64	15.90 1.64	16.52 1.64	16.78 1.64	16.91 1.64	16.94 1.64	17.48 1.64	17.35 1.64	17.45 1.64	17.17 1.64
	Control	17.47 1.64	17.07 1.64	18.38 1.64	17.28 1.64	18.53 1.64	18.27 1.64	19.36 1.64	19.04 1.64	20.14 1.64	18.77 1.64
Movement disfluency	Exp	8.79 1.19	8.68 1.19	7.92 1.19	8.42 1.19	7.66 1.19	7.82 1.19	7.30 1.19	7.87 1.19	7.07 1.19	8.40 1.19
	Control	10.62 1.19	10.01 1.19	9.81 1.19	9.51 1.19	9.15 1.19	9.23 1.19	8.99 1.19	9.03 1.19	8.25 1.19	8.68 1.19
Trace length	Exp	57.74 5.21	54.82 5.21	57.09 5.21	54.44 5.21	56.83 5.21	56.14 5.21	57.60 5.21	56.53 5.21	59.55 5.21	56.66 5.21
	Control	56.79 5.21	56.28 5.21	55.65 5.21	56.49 5.21	56.30 5.21	55.82 5.21	56.93 5.21	57.19 5.21	56.50 5.21	56.09 5.21
Stylus pressure	Exp	0.66 0.02	0.66 0.02	0.63 0.02	0.64 0.02	0.64 0.02	0.65 0.02	0.66 0.02	0.66 0.02	0.65 0.02	0.66 0.02

	Control	0.68 0.02	0.69 0.02	0.68 0.02	0.67 0.02	0.68 0.02	0.69 0.02	0.68 0.02	0.65 0.02	0.66 0.02	0.67 0.02
Spatial error	Exp	0.067 0.004	0.071 0.004	0.074 0.004	0.069 0.004	0.077 0.004	0.068 0.004	0.073 0.004	0.069 0.004	0.078 0.004	0.072 0.004
	Control	0.070 0.004	0.067 0.004	0.068 0.004	0.068 0.004	0.071 0.004	0.073 0.004	0.068 0.004	0.074 0.004	0.072 0.004	0.072 0.004

Velocity: The analysis revealed main effects of Trial ($F(9,1362) = 7.08, p < 0.001$) and FB ($F(1,1362) = 116.94, p < 0.001$) on velocity. The FB by Trial interaction tended to be significant ($F(9,1362) = 1.76, p = 0.07$). The simple effects analysis of FB (with Bonferroni's corrections) with the Trial factor as a moderator revealed that the shapes trained in the experimental condition were written faster than the shapes learned in the control condition for the trials 1, 3, and 5 to 10 (see figure 3A for more details).

Movement disfluency: The analysis revealed main effects of Trial ($F(9,1362) = 5.082, p < 0.001$) and FB ($F(1,1302) = 47.093, p < 0.001$) on movement disfluency. It decreased significantly for the trials 6 to 10 compared to the first trial. Furthermore, the pseudoletters trained in the experimental condition were written more fluently than those trained in the control condition. The analysis did not reveal any interaction between the factors.

Trace length: The analysis showed a main effect of Trial on trace length ($F(9,1362) = 2.03, p < 0.05$). The post-hoc comparisons between the trials did not reveal any significant differences after Bonferroni's corrections.

Stylus pressure: The analysis revealed a main effect of FB ($F(1,1362) = 32.68, p < 0.001$) with a decrease in stylus pressure in the experimental condition as compared to the control condition ($p < 0.001$).

Spatial error: We observed a main effect of FB on spatial error ($F(1,1362) = 4.27, p < 0.05$). The spatial error was higher in the experimental condition than in the control condition ($p < 0.05$).

3.3. Recognition task

No significant difference was revealed between the pseudoletters learned with or without the modified visual FB in this task ($p = 0.51$).

4. Discussion

This study aimed to evaluate the effect of a visual FB modification, combining both a partial deletion of the written trace during execution and a supplementary visual FB after execution, in a graphomotor learning task. The results revealed positive effects in favor of this mixed visual modification during the training phase, which remained significant at the short-term post-test. The participants traced the pseudoletters faster, more fluently and with a lower pen pressure, while remaining accurate, when trained in the modified visual FB compared to when trained in the control condition.

4.1. Benefits of reduced visual FB while writing

In one of two trials, the partial deletion of the trace changed the online visuospatial processing: it decreased the amount of spatial information about the written trace and increased the amount of information about writing speed (the faster the pen, the longer the visible trace) during execution. More precisely, the writers had access to visual information about the hand and the position of the pen on the screen, but not about the complete pseudoletter. This condition prevented them from focusing on the produced shape and its online comparison with the visual model to be traced. The decrease in online adjustments related to the absence of visual back and forth verification between the model to be reproduced and the production seems to increase the movement speed and fluency. This accords with studies that have modified the availability of the written trace and reported that a reduction in visual FB increased mean velocity and movement fluency (Bara & Bonneton-Boté, 2021; Chartrel & Vinter, 2006). The authors suggested that processing the visual information of the emerging trace interrupts movement fluency due to movement discretization (Van Mier, 2006). This stroke-by-stroke production permits a visual confirmation of whether the produced trace is correct and a readjustment of the trajectory if necessary. Surprisingly, this effect was apparent from the first trial, probably because the partial deletion of the trace strongly changes the online control of the movement. A similar effect has already been observed in a study in which a supplementary real-time auditory FB on writing speed was given to adult writers learning new letters (Danna et al., 2015).

It is well established that skilled handwriting is monitored by two modes of control: a predictive feedforward control that needs an internal model of action (Wolpert et al., 1995, 2011), sometimes referred to as motor program (van Galen et al., 1991), and a reactive control

where visual and somatosensory FB is used to update the ongoing movement (for a review, see Palmis et al., 2017). Writing without seeing the trace would also place greater emphasis on the use of somatosensory FB or on a more predictive control of action. This hypothesis is in line with Van Doorn and Keuss (1992) who observed an increase of latency in the case of writing without being able to see the hand and stylus. This increase of latency resulted from the additional processing of information prior to the action, i.e. a pro-active strategy. We assume that such a strategy promotes a better encoding of the pseudoletter motor information. Unfortunately, focusing on the process of handwriting is detrimental to accuracy during the training phase. Similar results have also been reported by Bara & Bonneton-Botté (2021) in the case of a total trace deletion with children, as well as by Chartrel & Vinter (2008) in the case of instruction to write faster to young children. Deferring the visual perception of the shape of the pseudoletter to the end of the trial in order to lead the writer to focus on the trace quality after execution did not compensate for this lack of accuracy (Connan et al., 2021). This observation led us to reduce the frequency of this visual modification to alternate trials, in order to add supplementary visual FB after execution without modifying the trace while writing.

4.2. Interest of increasing visual FB on handwriting process after execution

In every other trial, the real-time visual control did not change during execution and the writer had access to supplementary visual FB on movement fluency after execution. This strategy was inspired by the study conducted by Søvik and Teulings (1983) who reported a positive effect on handwriting speed by adding supplementary visual FB, without diminishing writing accuracy or size. In their protocol, the participants were informed about both movement speed and fluency but they did not improve in movement fluency. In the present study, we thus focused on movement fluency, since other trials with the partial deletion of the trace already provide more information on writing velocity.

Contrary to Søvik and Teulings (1983) who applied a global fluency score, we provided a fine index of movement fluency showing where the movement was not fluent in the pseudoletters. Consequently, the writer had access to both the product, namely the shape of the produced pseudoletter, and to the process, namely where the movement had lacked fluency on this pseudoletter. Our results revealed positive effects on movement fluency but with a higher spatial error in this experimental condition compared to the control condition. We hypothesize that adding two pieces of visual information concomitantly, one on the

process and one the product, interfered with the ability to process information about the spatial accuracy of the product. Fortunately, this adverse effect disappeared in the post-test, contrary to the positive effect on movement speed and fluency, which remained in the short-term post-test.

4.3. Benefits of a mixed strategy

Motor learning is relatively specific to the conditions in which the practice occurs (Proteau et al 1987). Consequently, providing supplementary FB during the training phase improves performance, but its removal during a post-test may result in performance deterioration. This phenomenon, known as the “guidance hypothesis of FB information”, suggests that the learners become dependent on supplementary FB, possibly at the expense of relying on their own intrinsic sources of sensory information to support performance under control conditions, i.e. without supplementary FB (e.g., Schmidt, Young, Swinnen, & Shapiro, 1989). It has been shown that this dependency phenomenon is modality-dependent, and particularly important in the visual modality (Ronsse et al., 2011). In the present study, both strategies of visual FB modification led the writer to focus on the process of writing, but at different times. We assumed that the alternation between the two types of visual FB, either during or after the performance, would reduce this dependency phenomenon, as Winstein & Schmidt (1990) have already shown in the field of motor learning. In particular, this would allow the writer not to develop too much expertise in the particular condition where the trace disappears (snake condition), for which the effects to normal writing conditions were not observed by Connan et al. (2021).

Looking in more detail at the performance between the two modified FB conditions during the training phase, we observed a sawtooth progression, with a difference of both velocity and fluency between the control and the snake conditions manifesting more rapidly (as early as the 1st trial) than between the control and the enriched postponed FB conditions (from the 6th trial). This sawtooth progression may be explained by an instantaneous effect of the snake condition that changes the online visual control of handwriting. This effect is not so immediate for the following trial in the enriched postponed condition because the supplementary FB appears once the participant has completed the movement. This terminal FB allows the writer to adapt the movement to the next trial, which corresponds to the snake condition. Nevertheless, we suppose that the alternation of conditions remains important because it limits the negative effects of the snake condition on spatial accuracy in the training phase only (Connan et al., 2021).

4.4. A surprising effect of visual FB modification on pen pressure

All studies that have investigated a reduction of the visual FB while writing, whether from a total suppression of visual information (eyes closed, Chartrel & Vinter, 2006; van Doorn & Keuss, 1992), from a suppression of hand and trace information (Chartrel & Vinter, 2006; Guilbert et al., 2018), or from a total suppression of the trace (Bara & Bonneton-Botté, 2021), have the common point of leading the writers to press down with greater force on the pen and/or write larger letters. The common interpretation was a compensation for the absence of visual information by maximizing proprioceptive FB to guide the movements (van Doorn, 1992). Surprisingly, our results revealed that the pseudoletters learned in the modified visual FB condition were produced with less pressure than those trained in the control condition. We hypothesize that this reduction resulted from the partial trace deletion (snake condition). Indeed, when the trace is not visible, the writers cannot be sure that the pen is in contact with the tablet, especially when writing on a smooth tablet surface that minimizes proprioceptive information (Guilbert et al., 2018). Therefore, they would press harder to increase the level of confidence related to this important information. In our condition, the ‘snake’ following the pen tip movement is sufficient to visually inform whether the pen is making contact or not. Therefore, increasing the pressure would no longer be useful. If this hypothesis explains why writers do not press with greater force, it does not explain why they press with lesser. Going back to the proprioceptive compensation hypothesis, we can also assume that the visual FB modification that informs about movement speed (i.e., that length varied according to velocity) provided kinesthetic information that overrides the somatosensory channel.

4.5. Study limitations and implications

First of all, in the long term, the specific benefits of the visual modification were not maintained, with an overall positive effect of the training independent of condition. It is possible that the number of trials per pseudoletter ($n = 10$) was not sufficient to obtain long term effects. The second limit of the study is related to the tool used for modifying the written trace in real-time, i.e. the use of a digital tablet. Their friction coefficient is much lower than that of a sheet of paper, which induces a decrease in proprioceptive FB during tracing and changes in handwriting performance (Gerth et al., 2016; Guilbert et al., 2018). The addition of a transparent textured surface should be considered, especially in children who press down with greater force.

4.6. Conclusion

This study suggests that the mixed strategy facilitates the learning process at the kinematic level (speed and disfluency) without affecting spatial accuracy. In conclusion, this method seems promising, at least in proficient adults who learn new graphic patterns with their non-dominant hand. It will be important to ensure that such suppression of FB does not come at the expense of trace quality in children for whom visual FB is crucial, until the letter's shape representation is complete. The next step is thus to test this method of visual FB modification in a similar learning task, with more trials, in typical developing children, before validating it in a rehabilitation protocol for children with dysgraphia.

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Supplementary materials to “Does modifying visual feedback facilitate learning to write new pseudoletters?”

1. Tests

1.1. Velocity

Model

Info	
Estimate	Linear mixed model fit by REML
Call	log velocity ~ 1 + TEST + FB + TEST:FB+(1 Participants)+(1 Pseudoletters)
AIC	-1501.1682
BIC	-1415.9819
LogLikel.	738.2913
R-squared Marginal	0.0486
R-squared Conditional	0.7697
Converged	yes
Optimizer	bobyqa

Fixed Effect Omnibus tests

	F	Num df	Den df	p
TEST	82.72	2	806	< .001
FB	2.54	1	806	0.112
TEST * FB	4.39	2	806	0.013

Note. Satterthwaite method for degrees of freedom

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	4.16947	0.03471	4.10144	4.2375	27.1	120.132	< .001
TEST1	PRE-TEST - LT PST	-0.06391	0.00771	- 0.07903	-0.0488	806.0	-8.286	< .001
TEST2	ST PST - LT PST	0.03410	0.00769	0.01903	0.0492	806.0	4.435	< .001
FB1	EXPERIMENTAL - CONTROL	0.01003	0.00630	- 0.00232	0.0224	806.0	1.592	0.112
TEST1 * FB1	PRE-TEST - LT PST * EXPERIMENTAL - CONTROL	0.00564	0.01543	- 0.02460	0.0359	806.0	0.365	0.715

Model

Info	
TEST2 * FB1	ST PST - LT PST * EXPERIMENTAL - CONTROL
	0.04208 0.01538 0.01194 0.0722 806.0 2.736 0.006

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.1587	0.02518	0.7516
Pseudoletters	(Intercept)	0.0296	8.74e-4	0.0951
Residual		0.0912	0.00832	

Note. Number of Obs: 840, groups: Participants 24, Pseudoletters 6

1.2. Movement disfluency

Model

Info	
Estimate	Linear mixed model fit by REML
Call	log disfluency ~ 1 + TEST + FB + TEST:FB+(1 Participants)+(1 Pseudoletters)
AIC	-238.0858
BIC	-161.5241
LogLikel.	111.0624
R-squared Marginal	0.0450
R-squared Conditional	0.6404
Converged	yes
Optimizer	bobyqa

Fixed Effect Omnibus tests

	F	Num df	Den df	p
TES T	44.79	2	806	< .001
FB	1.59	1	806	0.208
TES T * FB	6.82	2	806	0.001

Note. Satterthwaite method for degrees of freedom

Model**Info****Fixed Effects Parameter Estimates**

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	0.8897	0.0578	0.775	1.0025	25.6	15.403	<.001
TEST 1	PRE-TEST - LT PST	0.0802	0.0165	0.048	0.112	80.0	4.857	<.001
TEST 2	ST PST - LT PST	-0.0765	0.0165	-0.087	0.0044	80.0	-4.647	<.001
FB1	EXPERIMENTAL - CONTROL	-0.0170	0.0135	-0.044	0.0094	80.0	-1.259	0.208
TEST 1 * FB1	PRE-TEST - LT PST * EXPERIMENTAL - CONTROL	0.0269	0.0330	0.037	0.0156	80.0	0.814	0.416
TEST 2 * FB1	ST PST - LT PST * EXPERIMENTAL - CONTROL	-0.0896	0.0329	-0.154	0.0251	80.0	-2.723	0.007

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.2403	0.05775	0.603
Pseudoletters	(Intercept)	0.0729	0.00531	0.122
Residual		0.1952	0.03809	

Note. Number of Obs: 840, groups: Participants 24, Pseudoletters 6

1.3. Trace length

Model

Info	
Estimate	Linear mixed model fit by REML
Call	log trace length ~ 1 + TEST + FB + TEST:FB+(1 Participants)+(1 Pseudoletters)
AIC	-2446.40930
BIC	-2355.61750
LogLikel.	1208.10906
R-squared Marginal	0.00219
R-squared Conditional	0.81748
Converged	yes
Optimizer	bobyqa

Fixed Effect Omnibus tests

	F	Num df	Den df	p
TEST	3.997	2	806	0.019
FB	1.099	1	806	0.295
TEST * FB	0.482	2	806	0.618

Note. Satterthwaite method for degrees of freedom

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	4.73012	0.03665	4.65829	4.80195	7.07	129.0679	< .001
TEST1	PRE-TEST - LT PST	0.01116	0.00438	0.01974	0.00258	806.01	-2.5502	0.011
TEST2	ST PST - LT PST	8.91e-4	0.00436	0.00944	0.00766	805.99	-0.2041	0.838
FB1	EXPERIMENTAL - CONTROL	0.00375	0.00357	0.00326	0.01075	806.01	1.0483	0.295
TEST1 * FB1	PRE-TEST - LT PST * EXPERIMENTAL - CONTROL	5.98e-4	0.00875	0.01656	0.01775	806.00	0.0684	0.946

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
TEST2 * FB1	ST PST - LT PST * EXPERIMENTA L - CONTROL	0.00772	0.00873	- 0.00938	0.02482	805.99	0.8846	0.377

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.0723	0.00523	0.661
Pseudoletters	(Intercept)	0.0820	0.00673	0.715
Residual		0.0518	0.00268	

1.4. Stylus pressure

Note. Number of Obs: 840, groups: Participants 24, Pseudoletters 6

Model

Info	
Estimate	Linear mixed model fit by REML
Call	Pressure ~ 1 + TEST + FB + TEST:FB+(1 Participants)+(1 Pseudoletters)
AIC	-1740.7444
BIC	-1653.3048
LogLikel.	856.9527
R-squared Marginal	0.0379
R-squared Conditional	0.6297
Converged	yes
Optimizer	bobyqa

Fixed Effect Omnibus tests

	F	Num df	Den df	p
TEST	29.80	2	806	< .001
FB	16.50	1	806	< .001
TEST * FB	4.75	2	806	0.009

Note. Satterthwaite method for degrees of freedom

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	0.67431	0.02164	0.6319	0.71672	26.3	31.161	< .00
TEST1	PRE-TEST - LT PST	0.04072	0.00677	-0.0540	-0.02746	806.1	-6.017	< .00
TEST2	ST PST - LT PST	0.04847	0.00675	-0.0617	-0.03524	806.0	-7.184	< .00
FB1	EXPERIMENTAL - CONTROL	0.02245	0.00553	-0.0333	-0.01161	806.1	-4.062	< .00
TEST1 * FB1	PRE-TEST - LT PST * EXPERIMENTAL - CONTROL	0.00980	0.01353	-0.0167	0.03632	806.1	0.724	0.46
TEST2 * FB1	ST PST - LT PST * EXPERIMENTAL - CONTROL	0.03026	0.01349	-0.0567	-0.00381	806.0	-2.242	0.02

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.0998	0.00996	0.6086
Pseudoletters	(Intercept)	0.0165	2.74e-4	0.0410
Residual		0.0800	0.00640	

Note. Number of Obs: 840, groups: Participants 24, Pseudoletters 6

1.5. Spatial error

Model

Info	
Estimate	Linear mixed model fit by REML
Call	log spatial error ~ 1 + TEST + FB + TEST:FB+(1 Participants)+(1 Pseudoletters)
AIC	-712.95150
BIC	-631.80190
LogLikel.	346.20125
R-squared Marginal	0.00884
R-squared Conditional	0.17558
Converged	yes
Optimizer	bobyqa

Fixed Effect Omnibus tests

	F	Num df	Den df	p
TEST	3.84322	2	806	0.022
FB	0.00136	1	806	0.971
TEST * FB	0.63560	2	806	0.530

Note. Satterthwaite method for degrees of freedom

Fixed Effects Parameter Estimates

Name s	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	1.1873	0.0205	1.227 48	1.147 0	9.76	57.861 7	< .001
TEST1	PRE-TEST - LT PST	0.0177	0.0129	0.007 52	0.042 9	806.0 6	1.3756	0.169
TEST2	ST PST - LT PST	0.0356	0.0128	0.010 42	0.060 7	805.8 7	2.7724	0.006
FB1	EXPERIMENTAL - CONTROL	3.88e- 4	0.0105	0.020 98	0.020 2	806.1 1	0.0369	0.971
TEST1 * FB1	PRE-TEST - LT PST * EXPERIMENTAL - CONTROL	0.0254	0.0257	0.075 86	0.025 0	806.0 0	0.9881	0.323

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
TEST2 * FB1	ST PST - LT PST * EXPERIME NTAL - CONTROL	-0.0247	0.0257	-0.07496	0.0256	805.88	-0.9616	0.33

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.0556	0.00310	0.1179
Pseudoletters	(Intercept)	0.0398	0.00159	0.0641
Residual		0.1522	0.02315	

Note. Number of Obs: 840 , groups: Participants 24, Pseudoletters 6

2. Trainings

2.1. Velocity

Model

Info	
Estimate	Linear mixed model fit by REML
Call	log velocity ~ 1 + TRIAL + FB + TRIAL:FB+(1 Participants)+(1 Pseudoletters)
AIC	-3125.3747
BIC	-2858.2430
LogLikel.	1512.5038
R-squared Marginal	0.0224
R-squared Conditional	0.8387
Converged	yes
Optimizer	bobyqa

Fixed Effect Omnibus tests

	F	Num df	Den df	p
TRIAL	7.09	9	1361	< .001
FB	117.01	1	1361	< .001
TRIAL * FB	1.77	9	1361	0.070

Note. Satterthwaite method for degrees of freedom

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	4.20636	0.03610	4.13561	4.27711	27.2	116.521	< .001
TRIAL1	2 - 1	0.00274	0.00892	0.02023	0.01475	1361.0	-0.307	0.759
TRIAL2	3 - 1	0.02129	0.00899	0.00368	0.03890	1361.0	2.369	0.018
TRIAL3	4 - 1	0.00928	0.00897	0.00830	0.02686	1361.0	1.034	0.301
TRIAL4	5 - 1	0.02626	0.00895	0.00871	0.04381	1361.0	2.933	0.003
TRIAL5	6 - 1	0.02079	0.00895	0.00324	0.03834	1361.0	2.321	0.020
TRIAL6	7 - 1	0.04175	0.00899	0.02414	0.05936	1361.0	4.646	< .001
TRIAL7	8 - 1	0.03229	0.00895	0.01474	0.04984	1361.0	3.606	< .001
TRIAL8	9 - 1	0.04893	0.00895	0.03137	0.06648	1361.0	5.464	< .001
TRIAL9	10 - 1	0.02826	0.00902	0.01058	0.04594	1361.0	3.133	0.002
FB1	EXPERIMENTAL - CONTROL	0.04317	0.00399	0.03535	0.05100	1361.0	10.817	< .001
TRIAL1 * FB1	2 - 1 * EXPERIMENTAL - CONTROL	-0.0225	0.01785	-0.0574	0.01246	1361.0	-1.262	0.207
TRIAL2 * FB1	3 - 1 * EXPERIMENTAL - CONTROL	0.00290	0.01797	-0.0323	0.03813	1361.0	0.162	0.872
TRIAL3 * FB1	4 - 1 * EXPERIMENTAL - CONTROL	-0.0409	0.01794	-0.0761	-0.0058	1361.0	-2.285	0.022
TRIAL4 * FB1	5 - 1 * EXPERIMENTAL - CONTROL	-0.0036	0.01791	-0.0387	0.03145	1361.0	-0.204	0.839
TRIAL5 * FB1	6 - 1 * EXPERIMENTAL - CONTROL	-0.0086	0.01791	-0.0437	0.02648	1361.0	-0.482	0.630

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
TRIAL6 * FB1	7 - 1 * EXPERIMENTAL - CONTROL	0.00493	0.01797	-0.0302	0.04016	1361.0	0.275	0.784
TRIAL7 * FB1	8 - 1 * EXPERIMENTAL - CONTROL	-0.0104	0.01791	-0.0455	0.02465	1361.0	-0.584	0.560
TRIAL8 * FB1	9 - 1 * EXPERIMENTAL - CONTROL	0.02151	0.01791	-0.0136	0.05661	1361.0	1.201	0.230
TRIAL9 * FB1	10 - 1 * EXPERIMENTAL - CONTROL	-0.0083	0.01804	-0.0436	0.02705	1361.0	-0.461	0.645

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.1656	0.02743	0.830
Pseudoletters	(Intercept)	0.0306	9.38e-4	0.143
Residual		0.0749	0.00561	

Note. Number of Obs: 1409, groups: Participants 24, Pseudoletters 6

2.2. Movement disfluency

Model

Info	
Estimate	Linear mixed model fit by REML
Call	log disfluency ~ 1 + TRIAL + FB + TRIAL:FB+(1 Participants)+(1 Pseudoletters)
AIC	-446.3423
BIC	-216.7866
LogLikel.	191.7756
R-squared Marginal	0.0225
R-squared Conditional	0.6749
Converged	yes
Optimizer	bobyqa

Model**Info****Fixed Effect Omnibus tests**

	F	Num df	Den df	p
TRIAL	5.104	9	1361	< .001
FB	47.310	1	1361	< .001
TRIAL * FB	0.492	9	1361	0.881

Note. Satterthwaite method for degrees of freedom

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	0.82719	0.0639	0.7020	0.95243	25.6	12.9453	< .001
TRIAL1	2 - 1	-0.0198	0.0233	-0.065	0.02573	1361.0	-0.8544	0.393
TRIAL2	3 - 1	-0.0503	0.0234	-0.096	-0.0043	1361.0	-2.1469	0.032
TRIAL3	4 - 1	-0.0496	0.0234	-0.095	-0.0037	1361.0	-2.1195	0.034
TRIAL4	5 - 1	-0.0578	0.0234	-0.103	-0.0121	1361.0	-2.4779	0.013
TRIAL5	6 - 1	-0.0791	0.0234	-0.124	-0.0333	1361.0	-3.3882	< .001
TRIAL6	7 - 1	-0.0973	0.0234	-0.143	-0.0514	1361.0	-4.1538	< .001
TRIAL7	8 - 1	-0.0819	0.0234	-0.127	-0.0361	1361.0	-3.5096	< .001
TRIAL8	9 - 1	-0.1254	0.0234	-0.171	-0.0796	1361.0	-5.3708	< .001
TRIAL9	10 - 1	-0.0877	0.0235	-0.133	-0.0416	1361.0	-3.7297	< .001
FB1	EXPERIMENTAL - CONTROL	-0.0716	0.0104	-0.092	-0.0512	1361.0	-6.8782	< .001
TRIAL1 * FB1	2 - 1 * EXPERIMENTAL - CONTROL	-0.0035	0.0466	-0.094	0.08766	1361.0	-0.0771	0.939
TRIAL2 * FB1	3 - 1 * EXPERIMENTAL - CONTROL	0.0259	0.0469	-0.065	0.11787	1361.0	0.5541	0.580
TRIAL3 * FB1	4 - 1 * EXPERIMENTAL - CONTROL	0.02059	0.0468	-0.071	0.11231	1361.0	0.4399	0.660
TRIAL4 * FB1	5 - 1 * EXPERIMENTAL - CONTROL	0.03511	0.0467	-0.056	0.12666	1361.0	0.7515	0.452

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
TRIAL5 * FB1	6 - 1 * EXPERIMENTAL - CONTROL	0.01175	0.0467	-0.079	0.10333	1361.0	0.2514	0.802
TRIAL6 * FB1	7 - 1 * EXPERIMENTAL - CONTROL	0.02535	0.0469	-0.066	0.11725	1361.0	0.5407	0.589
TRIAL7 * FB1	8 - 1 * EXPERIMENTAL - CONTROL	0.02366	0.0467	-0.067	0.11524	1361.0	0.5064	0.613
TRIAL8 * FB1	9 - 1 * EXPERIMENTAL - CONTROL	-0.0019	0.0467	-0.093	0.08965	1361.0	-0.0412	0.967
TRIAL9 * FB1	10 - 1 * EXPERIMENTAL - CONTROL	0.07529	0.0471	-0.017	0.16754	1361.0	1.5996	0.110

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.2639	0.06964	0.646
Pseudoletters	(Intercept)	0.0832	0.00693	0.154
Residual		0.1953	0.03814	

Note. Number of Obs: 1409, groups: Participants 24, Pseudoletters 6

2.3. Trace length

Model

Info	
Estimate	Linear mixed model fit by REML
Call	log trace length ~ 1 + TRIAL + FB + TRIAL:FB+(1 Participants)+(1 Pseudoletters)
AIC	-4298.47730
BIC	-4015.64850
LogLikel.	2091.20653
R-squared Marginal	0.00386
R-squared Conditional	0.84231
Converged	yes

Model

Info	
Optimizer	bobyqa

Fixed Effect Omnibus tests

	F	Num df	Den df	p
TRIAL	2.032	9	1361	0.033
FB	0.443	1	1361	0.506
TRIAL * FB	1.733	9	1361	0.077

Note. Satterthwaite method for degrees of freedom

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	4.73643	0.03860	4.66077	4.81209	6.89	122.6979	< .001
TRIAL1	2 - 1	-0.0137	0.00589	-0.0253	-0.0022	1361.00	-2.3355	0.020
TRIAL2	3 - 1	-0.0073	0.00593	-0.0189	0.00429	1361.01	-1.2365	0.216
TRIAL3	4 - 1	-0.0162	0.00592	-0.0278	-0.0046	1361.01	-2.7452	0.006
TRIAL4	5 - 1	-0.0082	0.00591	-0.0198	0.00329	1361.00	-1.4030	0.161
TRIAL5	6 - 1	-0.0128	0.00591	-0.0244	-0.0013	1361.00	-2.1798	0.029
TRIAL6	7 - 1	-0.0030	0.00593	-0.0146	0.00859	1361.01	-0.5124	0.608
TRIAL7	8 - 1	-0.0056	0.00591	-0.0172	0.00596	1361.00	-0.9516	0.341
TRIAL8	9 - 1	0.00145	0.00591	-0.0101	0.01304	1361.01	0.2454	0.806
TRIAL9	10 - 1	-0.0109	0.00595	-0.0226	6.86e-4	1361.01	-1.8448	0.065
FB1	EXPERIMENTAL - CONTROL	0.00175	0.00263	-0.0034	0.00692	1361.01	0.6657	0.506
TRIAL1 * FB1	2 - 1 * EXPERIMENTAL - CONTROL	-0.0154	0.01178	-0.0385	0.00763	1361.00	-1.3124	0.190
TRIAL2 * FB1	3 - 1 * EXPERIMENTAL - CONTROL	0.00380	0.01186	-0.0194	0.02706	1361.01	0.3205	0.749
TRIAL3 * FB1	4 - 1 * EXPERIMENTAL - CONTROL	-0.0229	0.01184	-0.0461	2.68e-4	1361.01	-1.9374	0.053
TRIAL4 * FB1	5 - 1 * EXPERIMENTAL - CONTROL	-0.0027	0.01182	-0.0259	0.02039	1361.00	-0.2353	0.814

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
TRIAL5 * FB1	6 - 1 * EXPERIMENTAL - CONTROL	-0.0016	0.01182	-0.0248	0.02154	1361.01	-0.1379	0.890
TRIAL6 * FB1	7 - 1 * EXPERIMENTAL - CONTROL	3.71e-4	0.01186	-0.0228	0.02363	1361.01	0.0312	0.975
TRIAL7 * FB1	8 - 1 * EXPERIMENTAL - CONTROL	-0.0122	0.01182	-0.0354	0.01090	1361.01	-1.0381	0.299
TRIAL8 * FB1	9 - 1 * EXPERIMENTAL - CONTROL	0.01631	0.01182	-0.0068	0.03948	1361.01	1.3797	0.168
TRIAL9 * FB1	10 - 1 * EXPERIMENTAL - CONTROL	-0.0027	0.01191	-0.0261	0.02056	1361.01	-0.2334	0.816

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.0735	0.00541	0.689
Pseudoletters	(Intercept)	0.0871	0.00758	0.756
Residual		0.0494	0.00244	

Note. Number of Obs: 1409, groups: Participants 24, Pseudoletters 6

2.4. Stylus pressure

Model

Info	
Estimate	Linear mixed model fit by REML
Call	Pressure ~ 1 + TRIAL + FB + TRIAL:FB+(1 Participants)+(1 Pseudoletters)
AIC	-2963.7126
BIC	-2698.2434
LogLikel.	1432.5040
R-squared Marginal	0.0125
R-squared Conditional	0.6396
Converged	yes
Optimizer	bobyqa

Fixed Effect Omnibus tests

	F	Num df	Den df	p
TRIAL	0.676	9	1361	0.731
FB	32.999	1	1361	< .001
TRIAL * FB	1.095	9	1361	0.363

Note. Satterthwaite method for degrees of freedom

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	0.66302	0.02213	0.6196	0.70639	25.0	29.9612	< .001
TRIAL1	2 - 1	0.00128	0.00957	-0.017	0.02003	1361.1	0.1342	0.893
TRIAL2	3 - 1	-0.0114	0.00963	-0.030	0.00748	1361.1	-1.1836	0.237
TRIAL3	4 - 1	-0.0112	0.00962	-0.030	0.00764	1361.1	-1.1657	0.244
TRIAL4	5 - 1	-0.0080	0.00960	-0.026	0.01081	1361.1	-0.8340	0.404
TRIAL5	6 - 1	2.59e-4	0.00960	-0.018	0.01907	1361.1	0.0270	0.979
TRIAL6	7 - 1	-0.0020	0.00963	-0.020	0.01682	1361.1	-0.2138	0.831
TRIAL7	8 - 1	-0.0120	0.00960	-0.030	0.00681	1361.0	-1.2503	0.211
TRIAL8	9 - 1	-0.0119	0.00960	-0.030	0.00687	1361.1	-1.2447	0.213
TRIAL9	10 - 1	-0.0045	0.00967	-0.023	0.01438	1361.1	-0.4732	0.636
FB1	EXPERIMENTAL - CONTROL	-0.0245	0.00428	-0.033	-0.0161	1361.1	-5.7444	< .001
TRIAL1 * FB1	2 - 1 * EXPERIMENTAL - CONTROL	-0.0062	0.01913	-0.043	0.03128	1361.0	-0.3250	0.745
TRIAL2 * FB1	3 - 1 * EXPERIMENTAL - CONTROL	-0.0223	0.01927	-0.060	0.01543	1361.0	-1.1589	0.247
TRIAL3 * FB1	4 - 1 * EXPERIMENTAL - CONTROL	-0.0129	0.01923	-0.050	0.02472	1361.1	-0.6746	0.500
TRIAL4 * FB1	5 - 1 * EXPERIMENTAL - CONTROL	-0.0109	0.01920	-0.048	0.02666	1361.0	-0.5711	0.568
TRIAL5 * FB1	6 - 1 * EXPERIMENTAL - CONTROL	-0.0153	0.01920	-0.053	0.02224	1361.1	-0.8015	0.423
TRIAL6 * FB1	7 - 1 * EXPERIMENTAL - CONTROL	0.00384	0.01927	-0.033	0.04161	1361.0	0.1994	0.842

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
TRIAL7 * FB1	8 - 1 * EXPERIMENTAL - CONTROL	0.02555	0.01920	-0.012	0.06318	1361.1	1.3306	0.184
TRIAL8 * FB1	9 - 1 * EXPERIMENTAL - CONTROL	0.00865	0.01920	-0.029	0.04628	1361.1	0.4506	0.652
TRIAL9 * FB1	10 - 1 * EXPERIMENTAL - CONTROL	0.00689	0.01934	-0.031	0.04480	1361.1	0.3561	0.722

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.1052	0.01106	0.6320
Pseudoletters	(Intercept)	0.0121	1.45e-4	0.0220
Residual		0.0803	0.00644	

Note. Number of Obs: 1409, groups: Participants 24, Pseudoletters 6

2.5. Spatial error

Model

Info	
Estimate	Linear mixed model fit by REML
Call	log spatial error ~ 1 + TRIAL + FB + TRIAL:FB+(1 Participants)+(1 Pseudoletters)
AIC	-1225.0453
BIC	-983.5591
LogLikel.	575.1619
R-squared Marginal	0.0133
R-squared Conditional	0.2140
Converged	yes
Optimizer	bobyqa

Fixed Effect Omnibus tests

	F	Num df	Den df	p
TRIAL	1.10	9	1361	0.358
FB	4.20	1	1361	0.041
TRIAL * FB	1.08	9	1361	0.375

Note. Satterthwaite method for degrees of freedom

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
(Intercept)	(Intercept)	-1.1787	0.02149	-1.2208	-1.136	11.9	-54.8	< .001
TRIAL1	2 - 1	0.00415	0.01802	-0.0311	0.0395	1361.1	0.230	0.818
TRIAL2	3 - 1	0.00786	0.01815	-0.0277	0.0434	1361.1	0.433	0.665
TRIAL3	4 - 1	-0.0040	0.01811	-0.0395	0.0315	1361.1	-0.22	0.823
TRIAL4	5 - 1	0.03063	0.01808	-0.0048	0.0661	1361.1	1.694	0.090
TRIAL5	6 - 1	0.00884	0.01808	-0.0266	0.0443	1361.1	0.489	0.625
TRIAL6	7 - 1	0.00670	0.01815	-0.0288	0.0423	1361.1	0.369	0.712
TRIAL7	8 - 1	0.01432	0.01808	-0.0211	0.0498	1361.1	0.792	0.428
TRIAL8	9 - 1	0.03713	0.01808	0.00169	0.0726	1361.1	2.053	0.040
TRIAL9	10 - 1	0.02254	0.01821	-0.0131	0.0582	1361.1	1.238	0.216
FB1	EXPERIMENTAL - CONTROL	0.01652	0.00806	7.26e-4	0.0323	1361.1	2.050	0.041
TRIAL1 * FB1	2 - 1 * EXPERIMENTAL - CONTROL	0.03310	0.03604	-0.0375	0.1037	1361.1	0.919	0.358
TRIAL2 * FB1	3 - 1 * EXPERIMENTAL - CONTROL	0.05117	0.03629	-0.0199	0.1223	1361.1	1.410	0.159
TRIAL3 * FB1	4 - 1 * EXPERIMENTAL - CONTROL	0.01046	0.03623	-0.0605	0.0815	1361.1	0.289	0.773
TRIAL4 * FB1	5 - 1 * EXPERIMENTAL - CONTROL	0.04658	0.03616	-0.0242	0.1175	1361.1	1.288	0.198
TRIAL5 * FB1	6 - 1 * EXPERIMENTAL - CONTROL	-0.0190	0.03617	-0.0899	0.0518	1361.2	-0.52	0.599
TRIAL6 * FB1	7 - 1 * EXPERIMENTAL - CONTROL	0.04993	0.03629	-0.0212	0.1211	1361.2	1.376	0.169
TRIAL7 * FB1	8 - 1 * EXPERIMENTAL - CONTROL	-0.0116	0.03617	-0.0825	0.0593	1361.2	-0.32	0.748

Fixed Effects Parameter Estimates

Names	Effect	Estimate	SE	95% Confidence Interval		df	t	p
				Lower	Upper			
TRIAL8 * FB1	9 - 1 * EXPERIMENTAL - CONTROL	0.04446	0.03616	-0.0264	0.1153	1361.1	1.229	0.219
TRIAL9 * FB1	10 - 1 * EXPERIMENTAL - CONTROL	0.02345	0.03643	-0.0479	0.0949	1361.2	0.644	0.520

Random Components

Groups	Name	SD	Variance	ICC
Participants	(Intercept)	0.0649	0.00422	0.1557
Pseudoletters	(Intercept)	0.0402	0.00162	0.0661
Residual		0.1512	0.02286	

Note. Number of Obs: 1409, groups: Participants 24, Pseudoletters 6