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Robot-assisted intermanual transfer of handwriting skills

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ABSTRACT

We examined whether intermanual transfer of fine motor skills can be facilitated by training in a virtual environment. We focused on three types of assistance: visual – subjects could see a reference template on a computer screen – and two variants of haptic assistance. Subjects held a planar robot manipulandum and were required to write isolated cursive letters of an approximate size of 5 cm. Therefore, the task was similar to writing on a horizontal blackboard. The robot generated forces that were directed either towards the reference template (path guidance) or towards the reference trajectory (trajectory guidance). The training protocol consisted of three assisted exercise sessions on three consecutive days. Performance on the following day was tested to assess retention. After training, the improvement in trajectory shape was only significant in trajectory guidance and, to a lesser extent, visual guidance. Path guidance exhibited no significant improvement. These effects were substantially retained one day after the end of training. Similar effects were observed in shape variability. Furthermore, all training modalities caused a reduction in movement duration, but no significant differences were observed among groups. These results suggest that robot assistance may be beneficial for improving intermanual transfer, but inclusion of temporal information in the guidance strategy is essential for learning to take place.

1. Introduction

Handwriting capabilities are crucial in everyday life for achieving functional independence. The haptic experience embedded in handwriting skills also plays a constitutive role in learning and cogni-

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tive development (Hatwell, Streri, & Gentaz, 2003). Many studies have addressed the peculiar structure of handwriting movements. It has been suggested (Morasso & Mussa Ivaldi, 1982) that they can be described as sequences of rapid ballistic movements (strokes). Strokes are usually delimited by the zero crossings in the vertical velocity after rotation of the letter rotated to upright position along the vertical axis, or by local minima of absolute velocity. The velocity profile of a handwritten stroke is generally assumed to be composed of one main bell-shaped peak, followed by one or two secondary peaks (Plamondon, 1995a, 1995b).

Because of its functional relevance, handwriting performance has often been used to assess fine hand motor functions. Moreover, neurological diseases often result in an impairment of handwriting skills. Like all highly practiced and skilled motor actions, in persons with Parkinson's disease handwriting exhibits alterations in size and speed, which are only partly restored by dopamine medication (Tucha et al., 2006). Alterations in fine hand motor functions, including handwriting, have been observed in Alzheimer's disease (Schroter et al., 2003), multiple sclerosis (Longstaff & Heath, 2006), and in persons with attention deficit and hyperactivity disorder (Tucha & Lange, 2004).

Handwriting acquisition is generally difficult and slow, and young children need several years of formal training to master it properly (Bara & Gentaz, 2011). Subjects must learn the shape of the letter and the movement associated to that shape (Van Galen, 1991). It has been suggested that robots and haptic devices can be effective in facilitating the acquisition of at least some motor skills (see Reinkensmeyer and Patton (2009) for a review). Robots may mediate some form of physical interaction, which can be exploited as a task-dependent 'aid' – often referred as 'virtual fixture' (Rosenberg, 1993). In this way, users' motion is driven by robots along desired directions (guiding virtual fixtures), or motion in undesired directions or regions of the workspace may be prevented (forbidden region virtual fixtures).

Can haptic devices facilitate the acquisition of fine motor skills, in general, and of handwriting skills, in particular? The potential benefit of haptic devices has been investigated for training people in writing with non-native alphabets. Teo, Burdet, and Lim (2002) used a robotic teacher of Kanji handwriting for people with or without a previous background in Chinese, by using both forbidden region and guiding virtual fixtures. After training, naïve subjects exhibited higher accuracy and smoother movements, whereas experts only improved their movement time. In pre-school children, haptic interaction with physical models of handwritten letters may speed up handwriting acquisition (Bara & Gentaz, 2011). Using a robot to increase pen inertia and viscosity resulted in an improved handwriting quality in school-aged children (Ben-Pazi, Ishihara, Kukke, & Sanger, 2010). (Palluel-Germain, 2008) used a visuo-haptic device to train pre-school children in writing isolated cursive letters. In comparison to children trained through simple visual demonstration of the letters, those trained through haptic guidance could write more fluently, with a greater average velocity and a smaller number of velocity peaks.

Handwriting movements are typically performed with the dominant hand, and most people exhibit poor performance in writing with their non-dominant hand. Survivors of cerebrovascular accidents or amputation involving the dominant hand are forced to transfer their handwriting skills to their non-dominant hand (injury-induced hand dominance transfer, I-IHDT). This typically takes several months of training by occupational therapists (Harada, Okajima, & Takahashi, 2010), and the overall success is highly subject-dependent (Pereira, Raja, & Gangavalli, 2011; Yancosek & Mullineaux, 2011).

One recent study focused on using robots to facilitate intermanual transfer of fine motor skills (Srimathveeravalli, Gourishankar, Kumar, & Kesavadas, 2009). Subjects were trained to reproduce a variety of geometric shapes of different complexity, first with their dominant hand to establish a reference template, and then with their non-dominant hand. A robot provided haptic assistance through a variety of modalities. At the end of training, the assisted subjects outperformed non-assisted subjects in both shape error and duration.

Although drawing geometric shapes is often used with children as part of learning programs aimed at cursive handwriting skills, the individual components (strokes) of geometric shapes and those of cursive writing are peculiar in size, curvature, complexity, and in the way they are connected (Teulings et al., 1986). These aspects make writing quite distinctive in comparison to mere reproduction of complex spatial patterns, and may possibly affect the modalities of intermanual transfer.

Here we investigate whether haptic guidance could promote the intermanual transfer of writing skills. We addressed a simplified scenario: as in Palluel-Germain (2008) we focused on isolated cursive letters, but their required size was comparable to that used in writing on a blackboard. Therefore, the task mostly involved shoulder and elbow movements. Writing may be seen as a redundant task, in the sense that multiple movements satisfy the task requirements; e.g., many different trajectories may correspond to a legible ‘e’ (Latash, Danion, Scholz, Zatsiorsky, & Schöner, 2003). It is unclear how to provide assistance in these situations, but it would seem that weaker constraints might allow the trainee to fully explore (and exploit) task redundancy. With this in mind, we compared different assistance modalities to understand what scheme of assistance is more effective.

2. Materials and methods

2.1. Experimental set-up

A planar manipulandum with two degrees of freedom – PhysioAssistant (Celin srl, Follo, Italy, see (Casadio, Sanguineti, Morasso, & Arrichiello, 2006) for details) – was used to record hand positions and to generate assistive forces. Subjects sat on a chair, with their torso restrained by means of suitable holders. They grasped the handle of the manipulandum with their dominant hand. Their forearm was placed over a support, so that its movements were restricted to the horizontal plane, with no influence of gravity (see Fig. 1a). A vertical 19” LCD computer screen placed at eye level in front of the subject displayed a virtual environment resembling the top view of a notepad (with 8 cm squares), and a small red cursor (5 mm diameter) continuously displayed the position of the robot handle, which was used as the virtual ‘pen’. The software application was based on the open-source platform H3DAPI (SenseGraphics, Kipsta, Sweden).

2.2. Task

One letter was displayed (in a typed-print font) on the left side of the screen, and subjects were required to reproduce it by approximately fitting letter height into one or two notepad squares (in-line letters, and ascending/descending letters, respectively); see Fig. 1b.

The ‘pen’ (i.e., the cursor) started to leave a trace on the screen once it was placed inside a start area (displayed in green, and visible only before movement start). Writing finished when the cursor speed went below a threshold (set to 1 mm/s). At this point, a numeric score was displayed on the screen, calculated in terms of the shape ‘error’ (see Section 2.6). The same quantity was used to provide an audio feedback on performance, consisting of a voice pronouncing the written letter, whose pitch frequency was modulated by the shape error.

2.3. Assistance modalities

We tested different assistance modalities in different groups of subjects. In one subject group (control group, C), assistance was purely visual, and consisted of displaying the reference template in the background, as a gray line to trace over.

In the other subjects’ groups, in addition to visual assistance the robot generated assistive forces. In two different subject groups, we tested two variants of robot assistance. In the trajectory guidance (T) modality, a proportional-derivative motion controller attracted the subjects’ hand, $x(t)$, toward the ongoing position of the reference trajectory, $x_d(t)$:

$$F(t) = -k_P[x(t) - x_d(t)] - k_V\dot{x}(t) \tag{1}$$

Over the whole experiment, the controller parameters were set to $k_p = 1500\ \mathrm{N\,m^{-1}}$ and $k_V = 10\ \mathrm{Ns\,m^{-1}}$.

In the path guidance (P) modality, assistive force was always directed toward the closest point of the template trajectory. At every time, given the current hand position $x(t)$, and the robot closest point of the reference template x_c, if $n(t)$ is the unit vector determined by the direction $[x(t) - x_c]$, the robot generated a force according to the following expression:

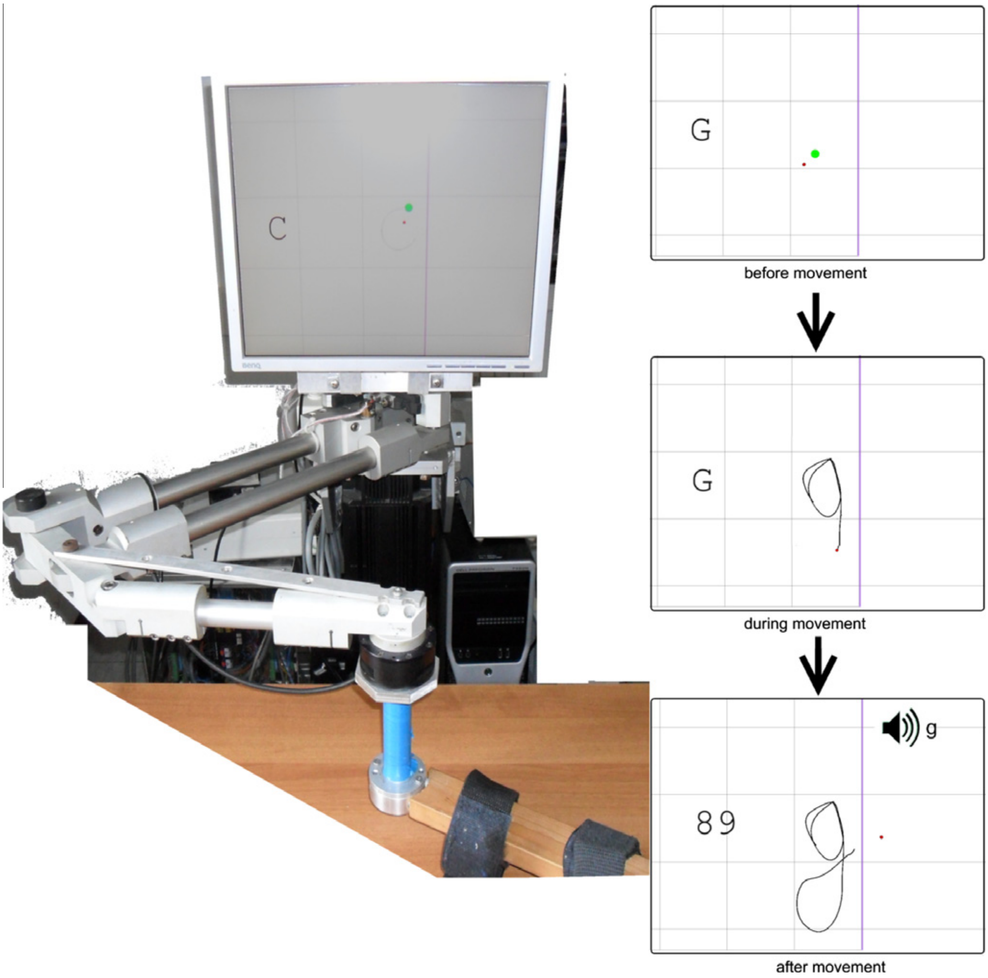

Fig. 1. Experimental setup and screenshots of the visual display during the different phases of the experiment.

$$F = -k_P(x - x_c) - k_V(n^T \cdot \dot{x}) \cdot n \tag{2}$$

To correctly identify the next closest point in case of line crossing on the reference template, we restricted the search to a time window of 0.5 s following the current closest point. Under the assumption that all the loops in the template last more than 0.5 s, this guarantees that closest points are uniquely defined.

To account for the peculiar importance of the high-curvature points, which have been associated to the trajectory via-points (Morasso & Mussa Ivaldi, 1982), the proportional gain k_p of the controller was set to be proportional to the curvature of c_c of the reference template in the closest point:

$$k_P = k_{P0} + k_{P1}|c_c| \tag{3}$$

with k_{P0} = 1000 N/m and k_{P1} = 16.67 N m^2. Likewise, the damping effect of the derivative component of the controller was set to be dependent on the speed v_c of the reference template:

$$k_V = k_{V0} + k_{V1}|v_c| \tag{4}$$

with k_{V0} = 10 Ns/m and k_{V1} = 20 N. In both modalities, the assistive force generated by the robot was reduced across days (75% on the second day, 50% on the third day).

Both modalities of assistance follow a type of minimum intervention principle, in the sense that no force is generated if movements follow exactly the reference trajectory (T) or path (P). However, the T modality is more constraining, as it imposes not only a specific path, but also a specific timing.

2.4. Experimental protocol

Table 1 summarizes the experimental protocol. The experiment lasted a total of 4 days, in which subjects practiced the generation of five cursive letters (*a*, *c*, *e*, *g*, *l*) with different degrees of complexity (as measured by the number of strokes: *c*: 1 stroke; *e*, l: 2 strokes; *a*: 2–3 strokes; *g*: 3 strokes). The experimental protocol was organized into epochs. During each epoch, letters were presented in a fixed sequence, in increasing order of complexity (*c*, *e*, *l*, *a*, *g*), two repetitions per letter. This cycle was repeated for three times (a total of $5 \times 2 \times 3 = 30$ movements).

On the first day, in an initial phase (dominant hand baseline, DHb – 1 epoch) subjects had to reproduce the letters that appeared on the screen by using their dominant hand. The average trajectory for each letter was used as the reference template for all subsequent epochs.

Then subjects were required to reproduce letters by using their non-dominant hand, without any assistance (non-dominant hand baseline, NDb – 1 epoch). In a subsequent phase (non-dominant hand training, NDt – 6 epochs), subjects practiced with their non-dominant hand according to several modalities of assistance. Then subjects practiced again without assistance (non-dominant hand after-effect, NDa – 2 epochs).

The sequence of NDb, NDt and NDa phases (9 epochs in total) was repeated for the next two days, so that training lasted a total of three consecutive days. On the fourth day, subjects underwent a single NDa phase to assess whether learning was retained.

2.5. Subjects

A total of nineteen subjects (18 M, 1F) participated in the study. All subjects were undergraduate engineering students, with no prior history of neurological disorders, and had no serious injuries at their upper extremities in the previous six months. All subjects normally used their right hand when writing. Handedness was assessed through the Edinburgh Handedness Inventory (Oldfield, 1971) (left handed: -100, right handed: 100). All subjects were randomly assigned to one of three groups: control group (C); trajectory guidance (T); path guidance (P); see Table 2 for details.

2.6. Data and statistical analysis

Hand position was sampled at 60 Hz, and smoothed by using a 4th order Savitzky–Golay smoothing filter with a 250 ms window (equivalent cut-off frequency: $\sim$7 Hz). We used the same filter to estimate hand velocity and hand acceleration. We then identified the start and end of each trajectory as,

Table 1
Summary of the experimental protocol.

Day	Epochs	Phase	Assistance (%)
1	1	DH baseline	0
1	1	ND baseline	0
1	6	ND training	100
1	2	ND aftereffect	0
2	1	ND baseline	0
2	6	ND training	75
2	2	ND aftereffect	0
3	1	ND baseline	0
3	6	ND training	50
3	2	ND aftereffect	0
4	2	Retention (ret)	0

Table 2
Subjects.

Group	Subjects	Age (years)	Handedness Edinburgh score (−100,100)		
			Mean ± *SE*	Min	Max
Control	7	26 ± 2	79 ± 14	60	100
Trajectory	6	25 ± 1	78 ± 21	50	100
Path	6	25 ± 2	73 ± 14	50	90

respectively, the time instant when the cursor first came out of the start area, and that in which the speed went below 1 cm/s.

All letters with abnormal duration (less than 0.5 s), size (height or width less than 1 cm) or length (less than one half or more than twice that of the reference template) were considered as outliers, and were not used in the subsequent analysis.

To capture the main spatial and temporal features of each movement, for each movement we calculated a number of indicators:

Shape error, defined as the difference between each trajectory and the 'reference' template. Given two trajectories A and B (consisting respectively of m and n points each), assuming that dAB is a vector containing the distances between the trajectory B and each point in A, whereas the vector dBA contains the distances between the trajectory A and each point in B, the figural distance (FD) between A and B is defined (Conditt, Gandolfo, & Mussa-Ivaldi, 1997) as:

$$\mathrm{FD}_{AB} = 1/(m+n) \cdot \left[\sum_{i=1}^{n} d_{AB}(i) + \sum_{j=1}^{m} d_{BA}(j) \right] \tag{5}$$

We used the FD between each trajectory and the reference trajectory as a measure of shape error. The same quantity was used to provide feedback to subjects at the end of each movement (see above). Therefore, the shape error measures differences in shape, irrespective of the differences in speed.

Shape variability, defined as the standard deviation of the shape error (see above), calculated on each epoch.

Duration ratio, defined as the ratio between the duration of each movement, T, and the duration of the reference trajectory T_0.

Duration variability, defined as the standard deviation of the duration ratio (see above), calculated on each epoch.

Degree of assistance, defined as the root mean square of the force generated by the robot (subjects in the T and P groups only). This indicator reflects the degree to which the observed performance is due to robot assistance. For similar values of the shape error, smaller forces would indicate improved skills.

To assess the effect of training, we performed a four-way ANOVA, by testing the influence of letter (*c*, *e*, *l*, *a*, *g*), day (1, 2, 3), session (before and after training), and type of assistance (C, T and P). The 'session' effect was defined in terms of the changes between the NDb and the last (second) NDa epoch on each day. This analysis was performed on shape error, duration ratio and their variability.

To directly assess the effect of haptic assistance on subjects' voluntary control, we additionally performed a four-way ANOVA (effects: letter, epoch, day and group) on the amount of assistance and the shape error during the training phase (6 epochs per day).

To assess the overall effect of training over the whole 3 days, we ran a three-way ANOVA with letter, phase (early: NDb on day 1, late: NDa on day 3) and type of assistance (C, T and P) as factors. We specifically assessed shape error, duration ratio and their variability.

In order to quantify the overall effect of the different types of assistance, we also calculated percent changes in shape error, duration ratio and their variability (over six repetitions of each letter) in NDb and NDa on day 3. On this, we ran a two-way ANOVA (with letter and group as factors).

Furthermore, to assess retention, we compared the performance at the end of day 3 (second NDa epoch) with that observed on day 4 (second NDa epoch). Finally, we used contrast analysis to assess the effect of training on the individual subjects' groups. Post-hoc analysis – Tukey's Honest Significant Difference (HSD) test – was performed wherever appropriate.

3. Results

During the whole experiment, for each subject we collected a total of 900 trajectories (=30 epochs × 30 movements per epoch). The average width of the handwritten letters was 5.07 ± 0.7 cm (average ± *SD*). The fraction of trials that were considered as outliers was 2.1 ± 1.6% (average ± *SD* over subjects).

Fig. 2 displays samples of letters, written with the non-dominant hand by one typical subject for each group, on the first baseline epoch on the first day (NDb) and on the last epoch (NDa) on the third day. The figure suggests that at the end of training, subjects were able to correctly reproduce the reference templates. Furthermore, performance improved over days, irrespective of the assistance modality.

3.1. Shape error

Fig. 3 displays the time course of the shape error (averaged over letters for each epoch) during the whole experiment. During the training epochs, all assistance modalities led to a decreased shape error.

The observation of the non-assisted epochs (NDb and NDa) suggests that only the T group exhibits a significantly improved performance, and this improvement is retained on day four. These observations are confirmed by statistical analysis. We found the shape error to decrease within (significant session effect: $F(1,16) = 39.876$, $p = .000010$) and between days (significant day effect: $F(2,32) = 35.081$, $p = .000001$). In addition, we found a significant Day × Group interaction, $F(4,32) = 9.7534$, $p = .000028$. Contrast analysis clarified that the day effect is only present in the T group ($p = .000007$). We also found a significant effect of letter, $F(4,64) = 9.5991$, $p = .000004$, which reflects the fact that more complex letters have a longer path and therefore exhibit a greater shape error.

To quantify the overall effect of training, we compared the NDb epoch on the first day with the second NDa epoch on the third day. Again, we found significant letter, $F(4,64) = 4.930$, $p = .001580$, session, $F(1,16) = 52.377$, $p = .000002$, and Session × Group effects, $F(2,16) = 8.044$, $p = .003822$. Contrast analysis confirmed the previous result – significant improvement in the T group ($p = .000007$) – and additionally revealed a smaller, but still significant session effect in the C group ($p = .011$).

In addition, we found no significant changes between the last epoch on day 3 and the first epoch on day 4, thus indicating that learning is retained one day after the end of training.

The time course of the shape error in Fig. 3 also indicates that in all three days, despite the gradual decrease of assistance, subjects with haptic assistance (both T and P groups) exhibit lower errors during the training phase. Statistical analysis revealed significant letter, $F(4,40) = 2.983$, $p = .030223$, and epoch effects, $F(5,50) = 1.120$, $p = .000001$. Post-hoc analysis confirmed that the shape error in the last three assisted epochs was lower than that observed in each the first two epochs. In other words, shape error gradually reduces during training.

3.2. Duration ratio

Fig. 4 displays the evolution of the duration ratio during the whole experiment, averaged – for each epoch – over letters.

Fig. 4 suggests that in all assistance modalities the duration ratio during test epochs (NDb, NDa) tends to decrease over days. However, the different types of assistance have very different effects. In the T group, during the training epochs the duration ratio is almost constant and close to one. In contrast, in subjects in the C and P groups, this quantity tends to be greater than in the test epochs. In other words, in the T group duration tends to be constant and equal to that of the template; subjects in the C and P groups tend to move more slowly.

Statistical analysis revealed an highly significant effect of day, $F(2,32) = 19.218$, $p = .000003$, and session, $F(1,16) = 15.129$, $p = .001302$. As regards the different assistance modalities, we found significant Day × Letter × Group, $F(16,128) = 2.1706$, $p = .008985$, and Day × Session × Letter × Group effects, $F(16,128) = 2.307$, $p = .024142$. Post-hoc analysis revealed that during the first session the

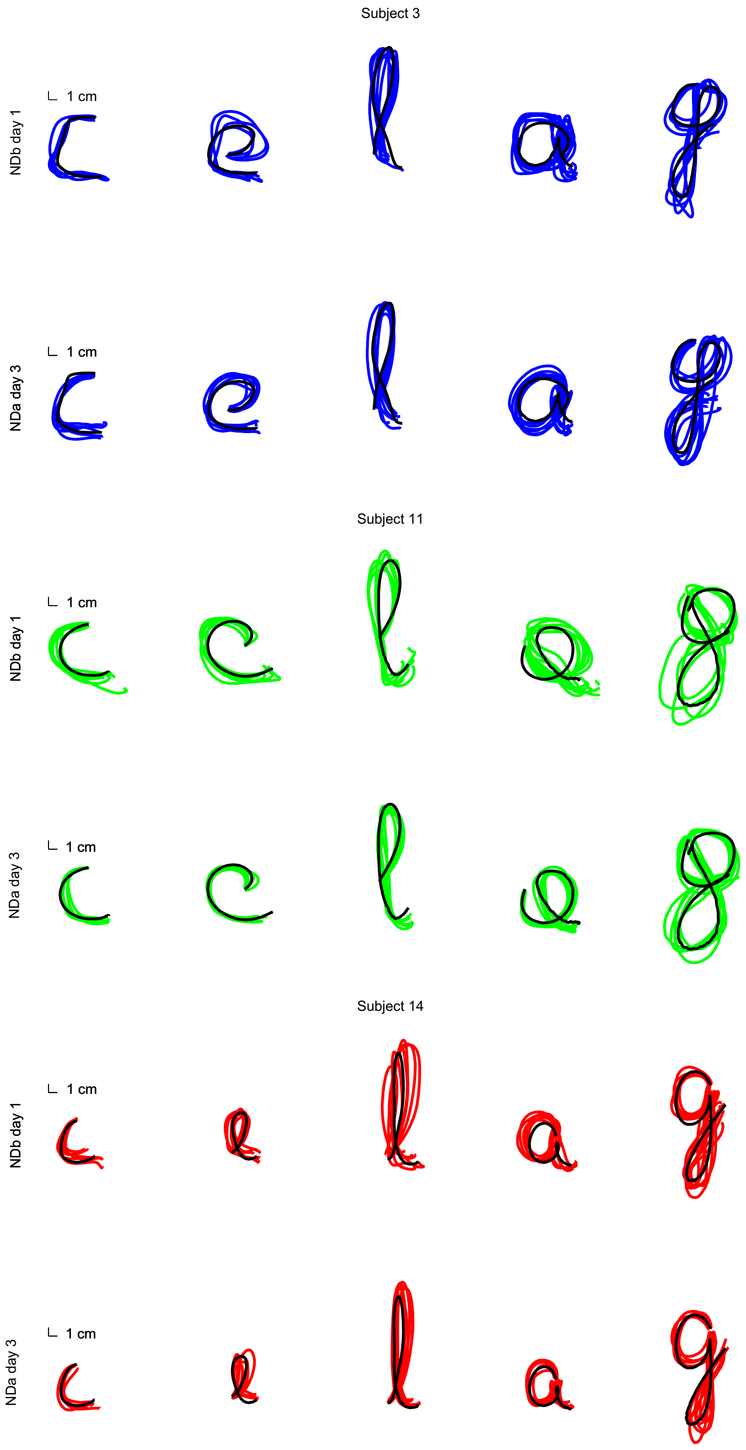

Fig. 2. Letters written with the non-dominant (ND) hand by one typical subject within each group, before and after training. The black trace is the reference template written with the dominant hand, which subjects were required to reproduce.

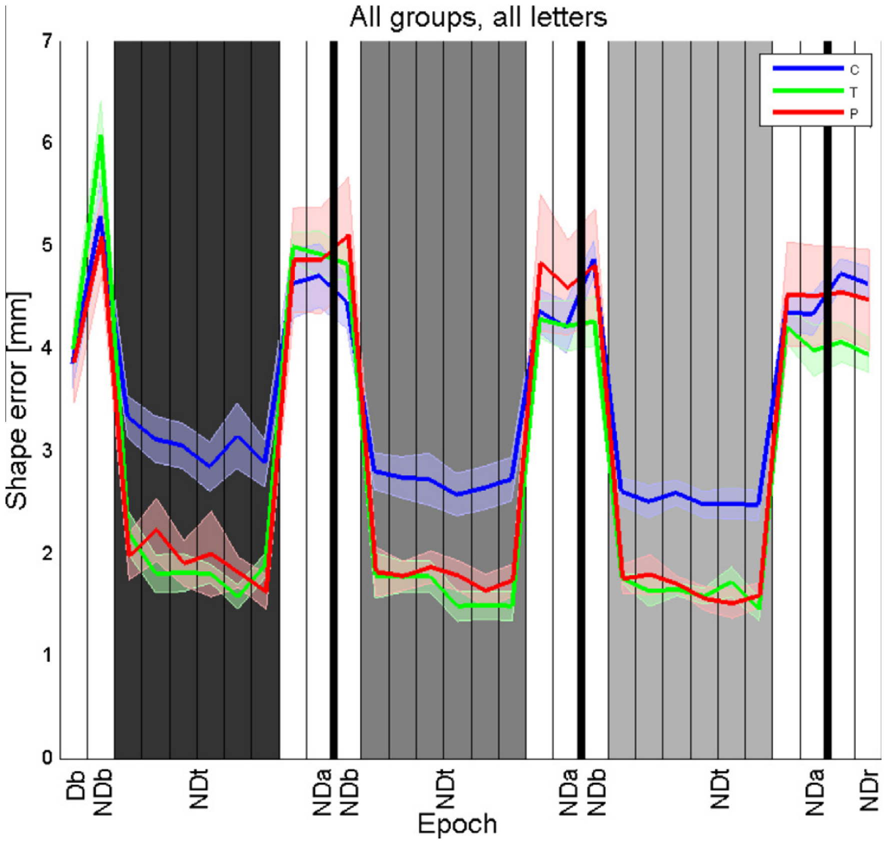

Fig. 3. Temporal evolution (average ±*SE*) of the shape error, during unassisted and training epochs (white and gray background, respectively) for the Control (C), Trajectory (T) and Path (P) groups. Gray level indicates the magnitude of haptic assistance.

duration ratio reduced in four letters out of five (*c*, *l*, *a*, *g*), in the C group alone. In contrast, during the second session the duration ratio reduced in T subjects for letter '*c*', and (for P subjects) for letter '*l*'.

As regards the overall effect of training, we found a significant decrease in the duration ratio from the NDb epoch on the first day and the second NDa epoch on the third day (phase effect: $F(1, 16) = 40.111$, $p = .000010$). However, statistical analysis did not reveal significant group differences.

As before, we observed no significant differences between the third and the fourth day, i.e., the effect of training was retained on day four.

3.3. Shape variability

Shape variability gradually decreased during both training and test phases, in all assistance modalities. More specifically, we found significant session, $F(1, 16) = 21.752$, $p = .000259$, and day effects, $F(2, 32) = 13.418$, $p = .000059$. We also found a significant letter effect, $F(4, 64) = 16.969$, $p < .000001$, – again, this reflects the fact that variability increases with letter complexity. This effect remained, $F(4, 64) = 11.616$, $p < .000001$, when looking at the overall effect of training, by comparing NDb on the first day with the last NDa epoch on the third day. In this latter comparison, a significant phase effect, $F(1, 16) = 39.4045$, $p = .000011$, confirmed the effectiveness of training in reducing shape variability. We also found a significant Phase × Group effect, $F(2, 16) = 6.844$, $p = .007116$, and contrast analysis revealed that shape variability was significantly decreased by training for T ($p = .000007$) and P group ($p = .042549$).

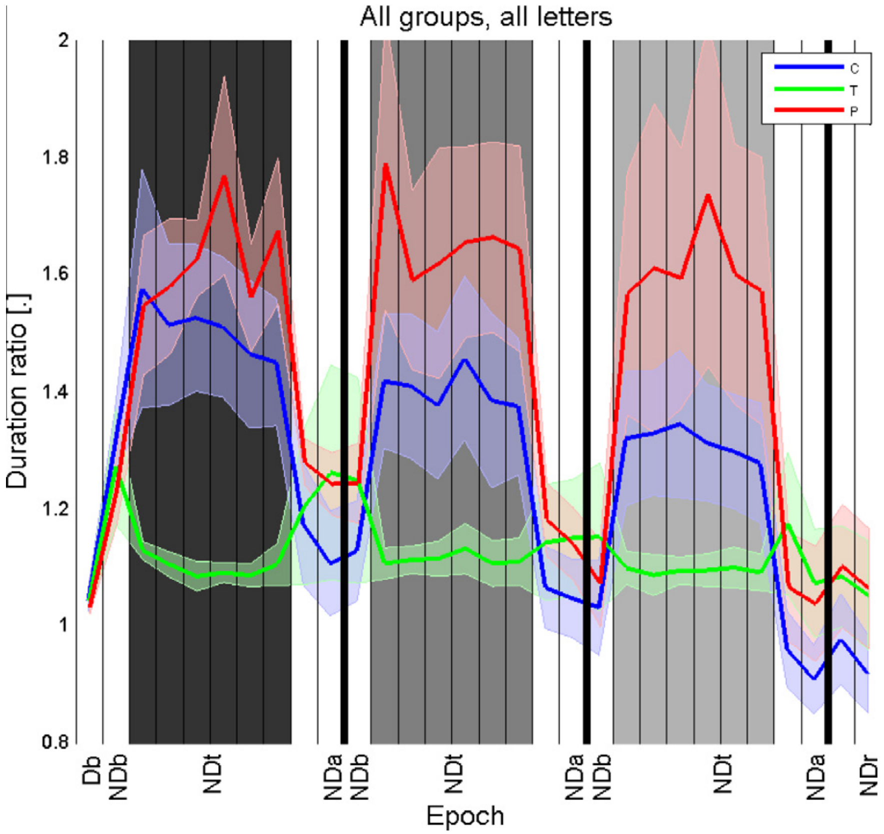

Fig. 4. Temporal evolution (average ± *SE*) of the duration ratio, during unassisted and training epochs (white and gray background, respectively) for the Control (C), Trajectory (T) and Path (P) groups. Gray level indicates the magnitude of haptic assistance.

3.4. Duration variability

Like shape error variability, duration ratio variability gradually decreased during both training and test phases, in all assistance modalities. More specifically, we found significant session, $F(1, 16) = 22.103$, $p = .00024$, and day effects, $F(2, 32) = 13.274$, $p = .000063$. We also found a significant letter effect, $F(4, 64) = 7.040$, $p = .000092$, – again, this reflects the fact that variability increases with letter complexity. As regards group differences, we also found a Phase × Group effect, $F(2, 16) = 4.285$, $p = .032341$, for which contrast analysis revealed that the variability only decreased after training with visual assistance ($p = .000079$). The latter effect remained, $F(4, 64) = 3.272$, $p = .016701$, when looking at the overall effect of training, by comparing NDb on the first day with the last NDa epoch on the third day. In this latter comparison, a significant phase effect, $F(1, 16) = 35.124$, $p = .000021$, confirmed the effectiveness of training in reducing variability. In this case, we found no significant group effects. Finally, like the other indicators, the observed effects were retained on day four.

3.5. Percent changes

To test whether haptic guidance led to advantages in term of consistency of performance, we looked at the intra-individual percent change in mean (over letter) value of mean and standard deviations (over the six repetition of each letter) of shape error and duration ratio, from the NDb epoch on the first day to the last NDa epoch of the third day.

Fig. 5 shows that trajectory guidance is the most effective in reducing both shape error (5a) and shape variability (5b). We found a significant group effect, $F(2, 16) = 6.736$, $p = .007546$, for the percent change of shape error. Contrast analysis revealed that the reduction of shape error was greater for subjects in the T group than in the C group ($p = .011907$), and than in the P group ($p = .003204$). In quantitative terms, this corresponds to percent changes of, respectively, 34%, 13% and 8% – however, only the changes in T and C are significant.

We found similar group differences in shape error variability; see Fig. 5b, $F(1, 16) = 11.932$, $p = .003264$. The T modality is significantly more effective than C ($p = .03264$) and P ($p = .016849$) – the percent changes are, respectively, 40%, 5%, and −4%, but only the changes in T are significant. As regards movement duration, all assistive modalities resulted in a decreased duration ratio (Fig. 5c), with C having the greatest effect. Duration ratio variability was also reduced by training (Fig. 5d) in all subject groups, but we found no significant between-groups differences.

3.6. Force magnitude

Fig. 6 displays the root mean square value of the force generated by the robot during the training phase of each day, for subjects in the T and P (assisted) groups.

In Fig. 3 we have shown that the shape error remained approximately within the same range (2 mm) during these phases for both groups. However, subjects in the T group experienced greater values of force, with a gradual reduction across days. In contrast, subjects in the P group experienced forces that were approximately constant across days. A significant group effect, $F(1, 7) = 31.635$,

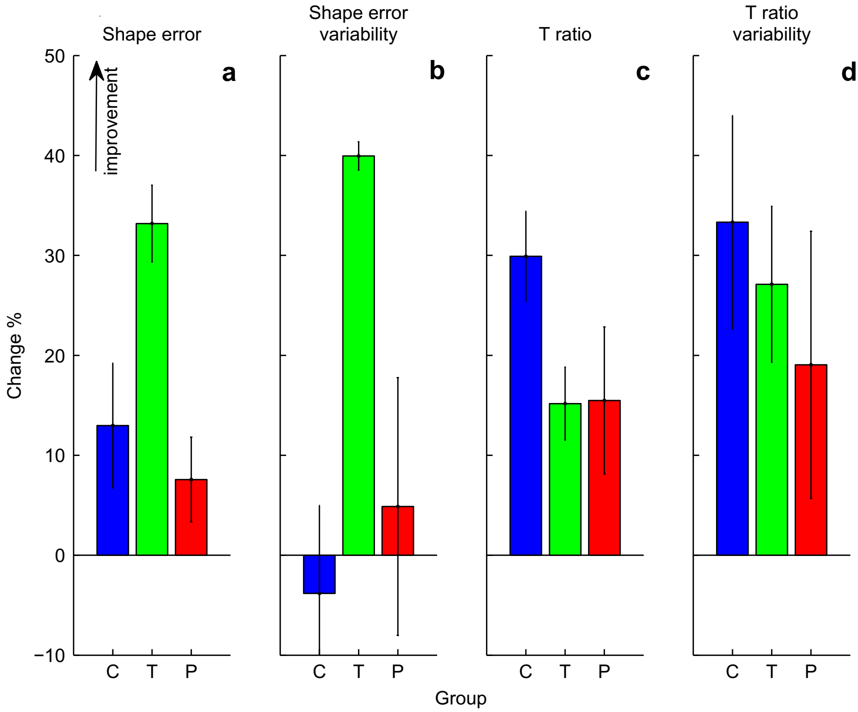

Fig. 5. Percent changes of shape error and duration ratio and their respective variability from NDb on day 1 to NDa on day 3, for the Control (C, blue), Trajectory (T, green) and Path (P, red) groups. Positive change denotes improvement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

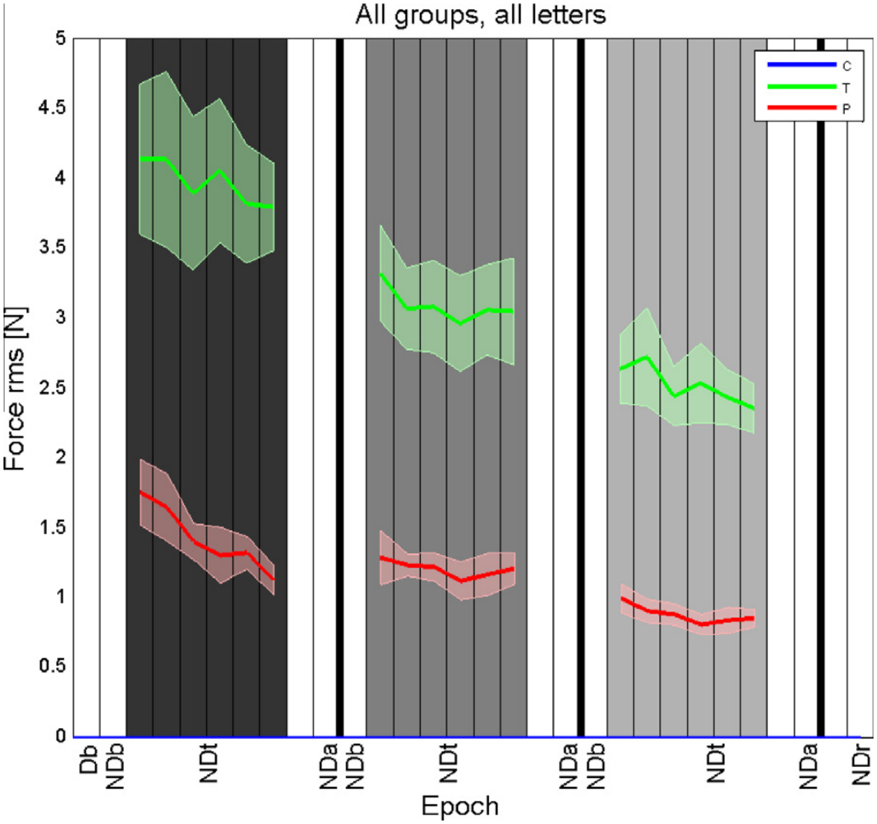

Fig. 6. Amount of assistive force provided by the robot (root mean square value), during unassisted and training epochs (white and gray background, respectively) for the Trajectory (T) and Path (P) groups. Gray level indicates the magnitude of haptic assistance. Assistive force is not present in the Control (C) group.

$p = .000795$) confirmed that the T group received a greater amount of assistance. This is no surprise, as subjects in the T group, in addition to being kept on the right path (like those in the P group), were also constrained to move at a target speed. Therefore, in the T group assistance has an additional component in the direction of the movement.

As in the shape error, we found an epoch effect, $F(5, 35) = 3.116$, $p = .019796$. The reduction of assistance was further confirmed by significant day, $F(2, 14) = 20.388$, $p = .000071$, and Day × Group, $F(2, 14) = 5.904$, $p = .013827$, effects.

4. Discussion

4.1. Haptic guidance facilitates intermanual transfer of cursive writing

The aim of this study was to investigate whether haptic guidance could facilitate the intermanual transfer of cursive writing skills. To this purpose, subjects were required to reproduce samples of their own (dominant hand) handwriting, by using their non-dominant hand. The training protocol consisted of three 1-h sessions in consecutive days, plus one additional test on day four to assess retention. We tested different modalities of assistance: (i) purely visual – subjects could see a trace of the target handwritten pattern; (ii) haptic guidance toward the reference trajectory (trajectory guidance); and

(iii) haptic guidance toward the reference path (path guidance). At the end of each session, we tested subjects' performance in free hand conditions, in which neither haptic nor visual assistance were present.

During training, all three assistance modalities resulted in a gradual reduction of the shape difference between handwritten letters and the corresponding reference templates; see Fig. 3. A similar reduction was observed in the timing – see Fig. 4 – with the exclusion of the trajectory guidance modality in which time is explicitly regulated by assistance. Likewise, in all modalities letters gradually became more reproducible (lower shape variability and lower duration variability) see Fig. 5.

These effects transferred only partially to test (free hand) conditions. In fact, transfer was only significant in trajectory guidance and, to a lesser extent, visual guidance. Subjects undergoing trajectory guidance exhibited an average 34% decrease in the shape error; more than twice that observed in visual guidance subjects (13%). Subjects in the path guidance group did not show statistically significant changes. These effects were substantially retained one day after the end of training. Furthermore, only trajectory guidance resulted in a significant decrease of shape variability.

Furthermore, all training modalities led to a gradual decrease of both movement duration and its variability, in both cases with no significant group differences.

In summary, trajectory guidance reduces shape error and shape variability much more than visual guidance, but provides no additional benefit on duration and its variability. Nevertheless, the benefit on shape error is remarkable, as it would allow to greatly reduce the time needed for achieving intermanual transfer of cursive writing.[1]

4.2. Temporal information seems essential for learning

Our results indicate that trajectory guidance outperforms visual guidance in intermanual transfer. Path guidance leads to no transfer, or even has a detrimental effect.

The poor performance of path guidance (even worse than simple visual demonstration) is somewhat surprising, as this assistance modality leads to movements that are less constrained and would enable the exploration of multiple 'solutions', all equally acceptable in terms of the task (only the overall shape matters for, e.g., legibility). In this respect, trajectory guidance is more restrictive, in that it specifies both shape and timing.

Nevertheless, the inclusion of temporal information in the guidance strategy seems essential for intermanual transfer. This is consistent with the observation that learning to copy cursive handwriting in children is faster if children are shown a dynamic rather than a static model of the letter to copy (Wright & Wright, 1980).

4.3. Handwriting transfer and the dynamic dominance theory

A possible explanation of why timing information is necessary for haptic guidance to be beneficial may be suggested by looking at what has to be learned in intermanual transfer. According to the dynamic dominance hypothesis (Wang & Sainburg, 2007), dominant and non-dominant hands exhibit different functional specializations. The dominant hand specializes in dynamic control (Bagesteiro & Sainburg, 2002), whereas the non-dominant hand is better at load stabilization (Bagesteiro & Sainburg, 2003).

The dynamic dominance theory predicts that inter-manual transfer of handwriting skills would require to improve the ability of the non-dominant hand to deal with body dynamics. This has often been associated to the feed-forward modality of control. The lack of improvement through visual assistance alone is consistent with the notion that proprioception, but not vision, is essential in adapting to novel dynamic environments (Vercher, Sares, Blouin, Bourdin, & Gauthier, 2003) – again a scenario in which feed-forward control is believed to be implicated.

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[1] The only female subject (in the control group) was consistent with the outcomes of the rest of the sample.

Path guidance relies on proprioception too, but is based on spatial errors. As such, it may lead subjects to rely on their ability to make ongoing corrections, i.e., the feedback component of control. This may have adverse effects on the feed-forward control modality. In contrast, the fine-tuning of feed-forward control may be facilitated by trajectory guidance.

In conclusion, inter-manual transfer of handwriting skills may relate more to training an internal model of body dynamics than to practicing specific movements. And, a form of assistance that provides timing information could be more effective in improving the control of arm dynamics.

More in general, our results can be related to the general problem of whether robots can facilitate the acquisition of a novel motor skill. The issue is currently a matter of debate; see Reinkensmeyer and Patton (2009) for a review. Several studies have suggested that robots provide no benefit because they profoundly alter the task. For instance, Liu, Cramer, and Reinkensmeyer (2006) demonstrated no advantage of haptic guidance over visual guidance in learning a spatial task (to follow a three-dimensional path).

Heuer and Rapp (2011) reported a detrimental effect of haptic guidance (provided in a variety of ways) in adaptation to visuomotor rotations.

In contrast, Feygin, Keehner, and Tendick (2002) found that haptic (trajectory) guidance is more effective than visual guidance at learning the temporal aspects of a complex trajectory. Furthermore, (Forsyth & MacLean, 2006) observed a benefit for a dynamic form of haptic guidance in learning to control a virtual vehicle along a path. In a similar task, Marchal Crespo and Reinkensmeyer (2008) and Marchal-Crespo, McHughen, Cramer, and Reinkensmeyer (2010) reported both short-term and long-term benefits of haptic guidance. Furthermore, Luttgen and Heuer (2011) reported a benefit from robot guidance in learning to follow a specific velocity profile while drawing circles.

Overall, these results suggest that robots can be beneficial in tasks that have an inherent dynamic component (e.g., learning the dynamic behavior of a tool, or a vehicle, or a specific timing) while they provide no benefit if the task is purely spatial (e.g., reaching or keeping close to a target).

Based on the dynamic dominance theory explanation, intermanual transfer has such a dynamic component. Therefore, our results are consistent with the above findings and identify a novel possible area of application of robot guidance.

4.4. Study limitations and future developments

One major limitation of this study is that the required movements are very different from actual handwriting, which raises the question of whether our results tell us anything specific about handwriting skills. First, our experiment focuses on arm movements, whereas actual handwriting movements mostly involve the hand and the wrist, and the degree of intermanual transfer has been reported to depend on the muscle groups involved – better transfer for motor skills involving proximal muscle groups (Thut et al., 1996).

Second, subjects used a power grasp on the robot manipulandum instead of dynamic tripod grasp which is typical of writing with a pen. This may have reduced the need for multi-finger coordination, which is a requirement of handwriting (Dooijes, 1983). Third, although there is evidence of end-effector independence in handwriting, when writing relatively large letters their shapes are altered (Marquis, Taroni, Bozza, & Schmittbuhl, 2007), and the need for position accuracy is also reduced.

On the other hand, in the present task the inertia involved (arm, robot) is much greater than that found in pen-based handwriting (hand, pen). And, a greater inertia can make dynamics control – and intermanual transfer of a complex skill – more challenging and difficult to achieve.

In conclusion, our intermanual transfer scenario has important differences with respect to the handwriting case. Therefore, the functional significance of our results will need to be confirmed in future handwriting experiments that specifically focus on hand and wrist movements. Also, further experiments will be needed to assess retention and generalization to other characters and to different sizes and orientations.

Nevertheless, the significant reductions of error observed in the trajectory guidance group with respect to controls suggest that robot-assisted haptic devices that incorporate a dynamical model of handwriting movements may play a role in intermanual transfer protocols.

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