Bringing Letters to Life: Handwriting with Haptic-Enabled Tangible Robots

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ABSTRACT

In this paper, we present a robotic approach to improve the teaching of handwriting using the tangible, haptic-enabled and classroom-friendly Cellulo robots. Our efforts presented here are in line with the philosophy of the Cellulo platform: we aim to create a ready-to-use tool (i.e. a set of robot-assisted activities) to be used for teaching handwriting, one that is to coexist harmoniously with traditional tools and will contribute new added values to the learning process, complementing existing teaching practices.

To maximize our potential contributions to this learning process, we focus on two promising aspects of handwriting: the visual perception and the visual-motor coordination. These two aspects enhance in particular two sides of the representation of letters in the mind of the learner: the shape of the letter (the grapheme) and the way it is drawn, namely the dynamics of the letter (the ductus).

With these two aspects in mind, we do a detailed content analysis for the process of learning the representation of letters, which leads us to discriminate the specific skills involved in letter representation. We then compare our robotic method with traditional methods as well as with the combination of the two methods, in order to discover which of these skills can benefit from the use of Cellulo.

As handwriting is taught from age 5, we conducted our experiments with 17 five-year-old children in a public school. Results show a clear potential of our robot-assisted learning activities, with a visible improvement in certain skills of handwriting, most notably in creating the ductus of the letters, discriminating a letter among others and in the average handwriting speed.

Moreover, we show that the benefit of our learning activities to the handwriting process increases when it is used after traditional learning methods. These results lead to the initial insights into how such a tangible robotic learning technology may be used to create cost-effective collaborative scenarios for the learning of handwriting.

CCS CONCEPTS

• **General and reference → Design**; *Measurement*; *Metrics*; *Evaluation*; *Performance*; • **Social and professional topics → Computing education**; • **Applied computing → Collaborative learning**; *Interactive learning environments*;

KEYWORDS

Handwriting; Tangible Robots; Interactive Learning; Child-Robot Interaction; Haptic Interfaces

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1 INTRODUCTION

Handwriting is a paramount skill to be acquired for school-aged children, as it is needed in a wide range of vital tasks such as communication, self-expression or recording ideas. It has also been shown that handwriting is a critical skill to be acquired for the educational development of students [9, 11]. Handwriting is a complex perceptual-motor skill involving visual-motor coordination abilities, motor-planning, cognitive, and perceptual abilities such as visual perception, as well as tactile and kinesthetic sensitivity [1, 28].

In order to have a complete letter representation, a child should acquire the visual perception of a letter to grasp its visual representation, called the **grapheme**, to discriminate between the graphemes of different letters [23, 36], but also should acquire visual-motor coordination skills to produce the dynamics of the letter, also called **ductus** [3]. The latter represents the "*ability to integrate the visual images of letters or shapes with the appropriate motor response*" [20, 23, 35].

To enhance the visual perception as well as the visual-motor coordination, it is shown that using more sensory information ranging from audio, visual to kinesthetic feedback is important [3, 7, 10, 15]. Because of this very reason, teachers commonly use techniques allowing children to experience various sensory information. These techniques include drawing letters in sand or semolina, touching and sensing the grapheme of letters which are craved in a piece of wood, verbally describing the letters or building the letter with play-dough [2, 6]. Examples of these techniques can be seen in Figure 1.

Visual perception and visual-motor coordination are aspects of handwriting that start to be developed early in the handwriting learning process. Children generally adopt the same motor rules as the ones they use to produce the standard geometrical forms [13] that are taught in the very early stage of school education: the circle at age 3, the cross at age 4 and the triangle around age 5½ [37]. This is one of the reasons why several research studies define handwriting readiness on the basis of the child's ability to copy several standard geometric forms [4, 5] and this is why we focus here on schoolchildren that are five or six years of age.

In this study, we aim to enhance this sensory information by using the tangible, haptic-enabled, low-cost, small-sized Cellulo robots [32]. The learner can observe a letter's grapheme drawn on a sheet of paper, like the one in Figure 2, as well as the letter's ductus, performed by the robots. Moreover, the haptic and visual capabilities of the robots are used throughout the activities to maximize the sensory information provided to the learner. We hypothesize that a training with the robot can convey the procedural knowledge of the grapheme and ductus of the letter.

On the other hand, by using multiple synchronized robots, we are able to design collaborative learning activities. Even if no general assumption can be made about the benefits of collaborative learning (because strongly dependent on the activities designed), Kreijns et al. [22] resume the positive effects that may arise with collaborative learning as "*deeper level of learning, critical thinking, shared understanding, and long term retention of the learned material*".

The remainder of this paper is organized as follows: Section 2 presents the related work on the different technologies for handwriting as learning tools. In Section 3, we describe our pedagogical goals and activity design with tangible robots followed by Section 4 which shows the detailed design of performance evaluation methods. Section 5 explains the experimental design. Section 6 highlights our findings and results and, finally, Section 7 ends the paper with a conclusion and potential future directions.

2 RELATED WORK

Adaptive Learning. Even if the final product of the handwriting process is a static trace (grapheme), the dynamics of its creation (ductus) is also of prime importance. This aspect of handwriting is hard to be taught in an optimal and adapted way at the class level as the hand movement's analysis need to be investigated for all children. Several recent studies propose to tackle this problem by using graphical tablets that allow the display of additional visual information to provide adaptive feedback and instructions to the learners [26, 38].

In their study, Lee et al. [26] show that personalized information and feedback given to each learner in the classroom appears to be very valuable as it contributes to the knowledge acquisition more than class-level feedback.

Another example of such system is proposed by Yamasaki et al. [38]. In it, the authors developed a software analyzing various features of handwritten Japanese letters such as the "*stroke order, writing speed, letter speed, and allocation of sub-patterns*" to then give specific instructions to the learners on what to be corrected and how to improve. Commercially available solutions such as Kaligo[1] or Letterschool[2] are also using this principle.

Benefits of haptic sensory information. Even if these systems are low-cost and accessible solutions for handwriting improvement, they do not provide kinesthetic real-time feedback which is shown to be a paramount sensory information needed during the process of handwriting [24, 25]. That is why, several recent studies are using a haptically active training program to teach handwriting.

In [3], the authors compared a visual-haptic to a visual-only program to teach letter recognition of five letters to 21

[1]https://www.cahier-kaligo.com/
[2]http://www.letterschool.org/

Figure 1: Example of devices used to teach visual perception and visual-motor coordination of letters. Left: the letters are formed using play-dough. Middle: the child draws the letter in a sandbox. Our system on the right: Haptic assistive force applied when the user is out of the letters' grapheme. The LED on the robot also provide real-time feedback.

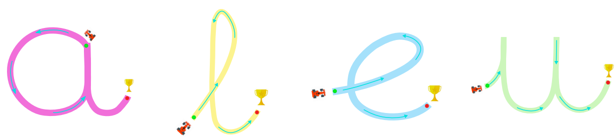

Figure 2: Letter maps with direction cues.

first-grade children. Results show that visual-haptic information is more efficient than visual-only information because it improves both perceptual and visual-motor skills.

Haptic devices. Since these studies use passive tangible methods, the haptic information supports the learning of letters' grapheme only. The letters' ductus remains not easily perceivable by the learner.

A recent and original approach proposed as a solution to this problem uses haptic-enabled devices providing force feedback to guide the user's hand while dynamically creating the letter [33]. The authors use visual-haptic feedback to teach handwriting to kindergarten children. A device named "*Telemaque*" presenting a force-feedback programmable pen allowing to provide a letter model "*not only static (the shape) but also dynamics (rules of motor production)*". This device was used to enhance the visual-motor perception of the letters targeted. This study focused on six cursive letters (a,b,f,i,l,s) and significant improvement of the handwriting's legibility (measured via the average velocity, the number of velocity peaks and the number of breaks during the production) for all trained letters was measured after the visual-haptic training compared to the control group.

Garcia-Hernandez et al. [12] proposed a tele-operated haptic training method for motor skill acquisition. A master helped an apprentice by describing a desired path (a letter) using a robot end-effector which was followed by the learner with the haptic device. The idea behind this application is that the master does not strictly control the position or velocity of the learner device which "*avoids learner dependence on the master*". Results show a faster and better learner motor control than the one obtained when only using visual information.

Robotic approaches. Previous studies investigate how a robot can be used as a peer learner in the domain of education and in particularly for the teaching of handwriting. This is the case in the co-Writer project [16, 18, 19, 27] where an original approach to teach handwriting to children facing difficulties is used. The child becomes the teacher of the robot needing help to better write. The idea behind this approach leans on the "protege effect" [8] which state that children are more engaged in the task when they are responsible of someone (in this case a NAO robot).

Our Proposal. Even though these devices seem to bring very promising results, a clear drawback that remains is that their very high cost makes them unaffordable for most schools. Also, to the best of our knowledge, there is currently no haptic system providing collaborative handwriting activities for classrooms.

In this study, we aim to regroup the benefits of all the examples detailed above with the capabilities proposed by the Cellulo robot [32]. More explicitly, the haptic, audio and visual capabilities of the robots allow us to provide a real-time multi-sensory information feedback during the handwriting task at the individual learner level.

Our robots are low-cost, palm-sized tangible mobile robots, capable of holonomic motion, haptic feedback (see [31] for details) and absolute 3DOF global localization while on the printed paper sheets. 6 capacitive touch buttons individually illuminated with full RGB colors on the top surface provides simple visual output and touch input. The locomotion system was designed to withstand intensive use expected in a classroom; it contains measures to increase the lifetime of the components and is passively backdrivable to a degree (see [30] for details). Each robot can self-localize with sub-mm accuracy at about 93Hz framerate while on the printed microdot pattern via a downward-facing camera found underneath the robots (see [17] for details). This design further allows the robots to recover instantly from kidnapping when returned to paper, and thus be used as active tangible items. Each robot is connected to the consumer-grade tablet through Bluetooth 2.1 serial ports and acts as a peripheral, reporting all events (e.g. pose changed) and receiving commands (e.g. track pose goal) to/from the tablet. A cross-platform QtQuick application runs on the tablet to coordinate the robots and run the logic of the activity.

3 PEDAGOGICAL DESIGN

A letter representation is defined by the letter's grapheme (visual representation), ductus (the direction its writing should follow between start and end points) and phoneme (its pronunciation).

The primary aim of this study is to support the teaching of a letter's grapheme and ductus in classrooms by enhancing the visual perception as well as the visual-motor coordination of participating children.

As can be seen in Figure 3, we aim that the children recall the grapheme and ductus when they hear the phoneme of the letter, and that they recall the ductus when they see the grapheme. It is important to notice that we excluded the fine-motor aspect of handwriting as it is totally different than the visual perception and visual-motor coordination aspects that we are interested in. In other words, we aim that the child enhances their representation of letters (grapheme and ductus) but not the way they produce these letters on paper. The link from the letter's phoneme to its corresponding grapheme is also excluded from this study as it is more related to learning how to read, which is not a part of our design goals.

Using this, we define the following sub-goals:

1. **Remember Grapheme**: Memorizing the letter's physical representation (Free recall and Recognition).
2. **Remember Ductus**: Memorizing the letter's drawing pattern (Imitation).
3. **Remember the link from Phoneme to Ductus and Grapheme**: Memorizing the link between the letter's pronunciation (phoneme) and the corresponding grapheme and ductus.

In order to help the children to create these multi-modal mental representations (represented by the arrows in red in Figure 3), we proposed several learning activities described in section 3.

Activity Design

Before defining our activities, we discussed with pre-school teachers how we can position Cellulo in handwriting activities. We decided to use three features of the robot, namely haptic information, autonomous motion and synchronized behaviour of multiple robots. Haptic features allow each child to receive individual instant feedback, and autonomous motion makes the robot reproduce the ductus, whereas synchronization helps designing collaborative team activities.

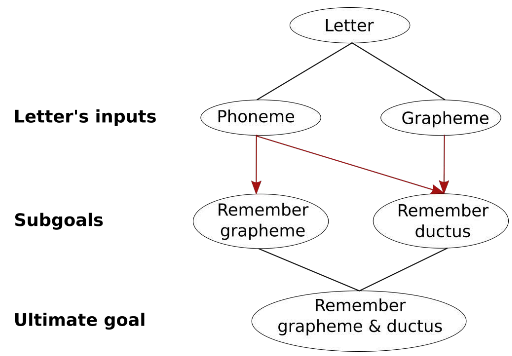

Figure 3: Content Analysis Graph: The letter's inputs are in the second level, and they are provided to achieve the subgoals at the third level. The ultimate goal is at the fourth level.

In order to avoid the split attention effect and an excessive cognitive load for the schoolchildren, we started with passive activities where the child does not move the robot then continue with active learning activities where the child moves the robot and gets haptic, LED-based and sound feedback. This follows classroom activity design: first, learning through lessons (passive learning) and then practising through exercises (active learning).

We selected the letters that will be taught in the targeted school to be aligned with their current curriculum. The teachers decided on the following letters: '*a,l,e,u*'. These letters will be **the only ones** targeted during all the teaching sessions run during this study.

During a learning session, 2 or 3 children sits together in front of three maps of a letter. They first watch repeatedly (3 to 4 times) how the robots move to draw the letter's grapheme on the maps, with the correct ductus. Then, they hold their robots slightly with the hand with which they usually write, and feel how the robots write 3 to 4 times. Afterwards, they actively drive the robot on top of the map 3 to 5 times. Then the maps are changed and these 3 activities are done for the next letter. After finishing all 4 letters, the children finally move on to the team activity. Each activity is explained in detail in the following subsections.

Activiy 1: Watch the Robot to Learn a Letter's Grapheme and Ductus. In this activity, we aim that the child learns the letter's ductus by watching the robot moving on a map with the grapheme of that letter drawn on top. Arrows on the map show the letter's ductus, as in Figure 2. The robot performs the ductus that should be done while writing the letter. Its LEDs turn red when the robot starts writing, and turn green when it finishes. The lights are informative of the writing process, and the movement of the robot provides a new way to represent the ductus of the letter. In addition, the letter's phoneme is generated at the beginning and the

Figure 4: Feeling the robot activity with 3 children. All robots move simultaneously while each child holds their robot in order to feel the ductus of the letter.

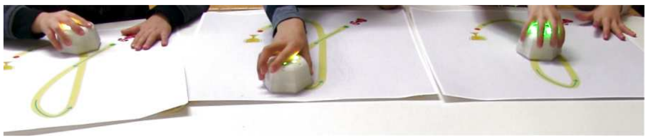

Figure 5: Driving the robot activity with 3 children. Each child drives their own robot with real-time haptic feedback when the robot is out of the letter's path.

end of the writing process, to strengthen the link with the corresponding grapheme.

Activity 2: Feel the Robot to Learn Letter's Grapheme and Ductus. While the child is only watching the robot in the first activity, we add another representation of the letter's ductus in this one by asking the child to put their hand on the robot as it draws the letter. The child does not actively move the robot, but only follows its automated motion in a passive way as can be seen in Figure 4. This passive handheld activity is a prelude for the following activities where the child takes on a more active role.

Activity 3: Drive the Robot by Memorizing the Ductus of the Letter. In this activity, the child is more active as it is him/her that needs to drive the robot in order to produce the ductus of the letter. The grapheme of the letter is drawn on a map as can be seen in Figure 1, Right). As can be seen in Figure 5 each child moves with their own speed since the robot is in passively drivable mode. The robot provides assistive haptic feedback by moving the child's hand towards the expected path if the child moves away from it. At the same time, the robot's LEDs turn green when the correct path is followed, and turn red otherwise. These two feedback elements condition the child to recognize errors, and they serve as extrinsic motivation for drawing correctly. Since this activity is done with group of 2 to 3 children, it is observed as a race in between them. They tried to finish their path as precise and as fast as possible to win and engaged with the activity.

Team Activity: Guess the Letter Grapheme by Watching Ductus. In this team activity, children form groups of three where they take turns at drawing a letter with a Cellulo robot. Each time, the other two children have to guess which letter is being drawn. In a group, the three children sit next to each other, with the writer on the left separated from

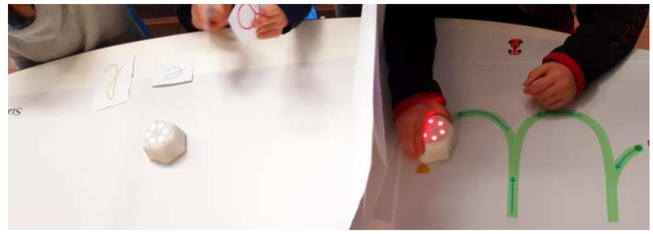

Figure 6: Team activity. One child draws a letter with the red colored robot on the right side, and the white colored robot on the left imitates this motion. Then two kids on the left side guess which letter is drawn.

the other two by a physical barrier, in order to ensure that they cannot see each other. The writer has one robot, and the other two children have one robot each that reproduces whatever movement the first robot performs. An illustration of this activity can be seen in Figure 6.

In the beginning of the activity, the writer is shown (privately) the map of the letter that indicates only the grapheme, which they then have to draw with their robot. The other two children watch their robot reproduce the letter drawn on their empty map. Then, they have to choose the correct letter from their graphemes.

4 PERFORMANCE EVALUATION

In order to explore the added value of our system to the handwriting learning process, we want to assess the visual perception (representation of the letter's grapheme) and the visual-motor coordination (representation of the letter's ductus) aspects of the learners in detail. In other words, we want to assess the quality of the letter representation in the child's mind in terms of ductus and grapheme. In all the performance evaluation tests described below, the same 8 letters are investigated. These letters include the 4 letters (e,l,a,u) that are taught during every teaching session (with traditional methods and with robots) and 4 others not targeted during these sessions (y, m, n, o). These last 4 are added here to see if learning transfer occurs during our teaching session.

As described in Section 3, three different sub-skills are investigated.

From Phoneme to Grapheme-Ductus

In this test, we want to assess if the child remembers both the grapheme and the ductus of the letters. To do so, we created a software (see Figure 7) that works in the following way: the child hears the phoneme of a letter (upon pressing button #1) and is asked to draw the grapheme on a graphic tablet (Wacom Cintiq Pro) with a pen. As the link between the grapheme and the phoneme of the letter might not yet be fully operational, we offer the child the possibility to see the model of the letter (only the grapheme and not the ductus) during a short period (one second, upon pressing button

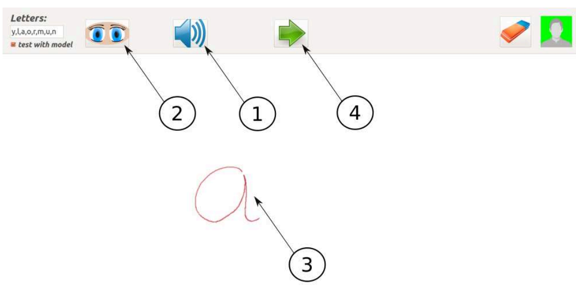

Figure 7: Software created to assess the link between the phoneme of the letter and its associated grapheme-ductus. With button #1, the child hears the phoneme of the letter. With button #2, the child has access to the model of the letter (grapheme only) during 1 second. #3 is the grapheme drawn by the child. Once finished, button #4 is used to save the data.

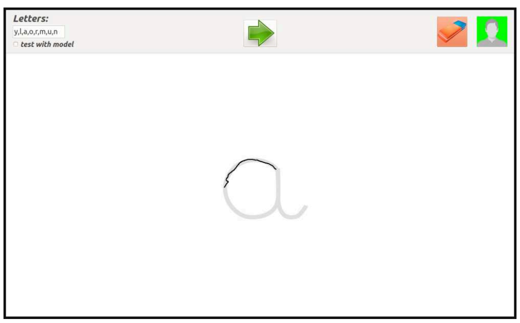

Figure 8: Software created to assess the link between the grapheme of the letter and its associated ductus. The model of the letter is presented on the screen, the child simply draws the letter on top of the model.

#2). As the child might want to have access to the model even though they have the representation of the letter in their mind (just to make sure they is writing correctly or to ameliorate the letter), we ensured throughout the test that they can press the button only if they have not memorized the grapheme of the letter at all.

The use of the graphic tablet allows us to save various data concerning the child's handwriting: the x and y coordinates of the pen were recorded as well as the pressure and the pen tilt for every time frame at a sampling rate of 200Hz.

From Grapheme to Ductus

This test evaluates the grapheme-ductus link: in the application, the letters' graphemes are displayed on the tablet's screen (see Figure 8), and the child is expected to draw the letter directly on top of the model. The specific path between the start and end points of the letter is assessed during this test. The quality of the final grapheme is not taken into account since we do not focus on fine motor skills in this study.

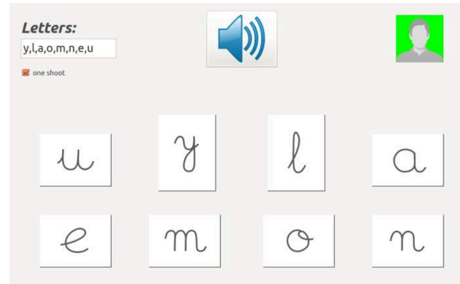

Figure 9: Software created to assess the link between the phoneme of the letter and the associated grapheme.

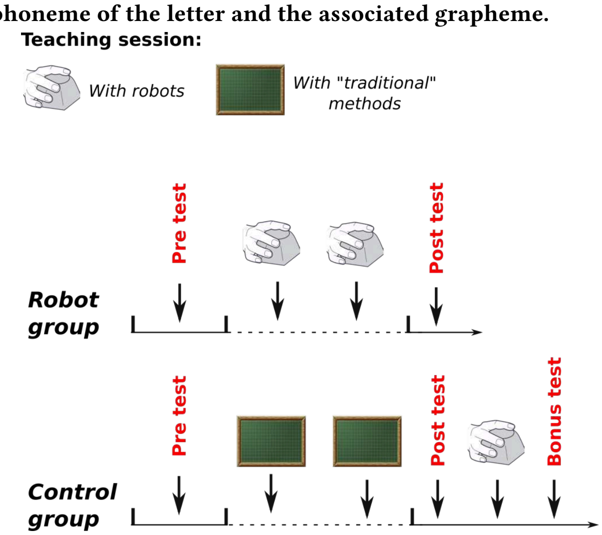

Figure 10: The schedule of the experiment.

From Phoneme to Grapheme

The goal of this test is to evaluate the visual perception which helps the child to find the right grapheme after hearing the phoneme of a letter among other letters. Concretely, the child has to press a button to hear the phoneme of a letter and find the associated grapheme among a choice of 8 letters (u, y, l, a, e, m and o) as can be seen in Figure 9.

5 EXPERIMENTAL DESIGN

As the main goal of this paper is to explore if the use of haptic-enabled robots could have a positive impact in learning the representation of letters (grapheme and ductus), we take the impact of traditional teaching methods (such as the ones presented in [2, 6]) as a baseline to our method.

We separated all participating children into two groups where the pre-test performance is similar within groups. The first group, named **"robot group"**, used the robots during their teaching sessions while the other one, named **"control group"**, learned with traditional methods. The robot group was composed of 4 males and 5 females (mean age 5.36 years old) while the control group was composed of 3 males and 5 females (mean age 5.24 years old).

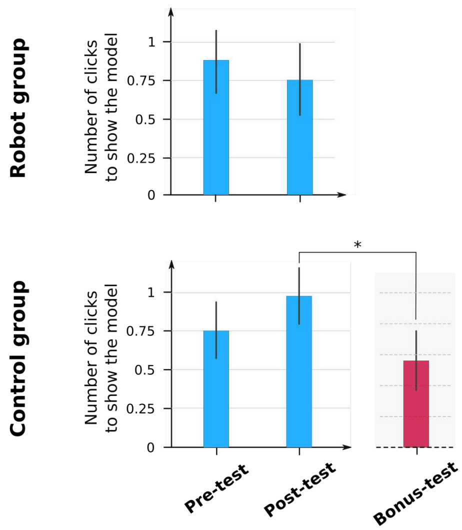

Figure 11: Number of clicks to see the letter's grapheme averaged for the letters taught during the test without model (see Subsection 4). Significant different number of clicks was observed between the bonus-test and the post-test of the control group ($W(36) = 0.0$, $p = 0.0421$)

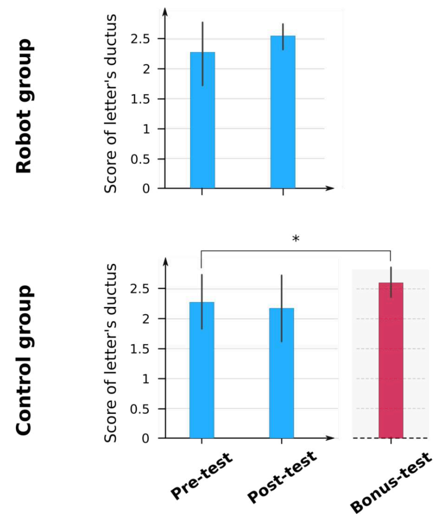

Figure 12: Ductus performance of children in the test without model (see Subsection 4). Significant progress in the ductus score was observed between the bonus-test and the pre-test of the control group ($W(36) = 1.0$, $p = 0.039$)

Figure 10 displays the schedule of the experiment for the two groups. We can see that between the **Pre-test** and the **Post-test**, two teaching sessions with the robots were given to the robot group while two teaching sessions with traditional methods were given to the control group. The session duration for the two groups were controlled to be the same (2 x 40 minutes), and the same four letters (e,l,u,a) were taught during these. A comparison between the results of the Pre-test and the Post-test of both groups would allow us to compare the two teaching methods and give us an insight on the possible value that our robots can add to a typical classroom curriculum.

Finally, in order to have a first insight on what the combined effect of the two teaching methods could be, another teaching session with the robots was given to the control group followed by another post-test called **Bonus-test**.

6 RESULTS

In order to assess the test results of within-subject studies, we used the Wilcoxon signed rank test since our data is not normally distributed. In order to assess the results of the between-subject studies, we used the Mann-Whitney U test.

The majority of the graphs only present the results concerning the **4 letters taught** during the teaching sessions (u,l,a,e) and omit the results concerning the 4 letters not taught. This is done for reason of clarity as no significant results could be observed for these last 4 letters in these cases.

From Phoneme to Grapheme-Ductus

As described in Section 5, in this test, we first asked the child to write the letter by only providing an audio input. The child has access to a button to let him/her see the model of the letter for 1 second. Our assumption was that the teaching sessions would help the child to store the letters grapheme in their mind and their need to click on the button would then decrease. Figure 11 shows the mean number of clicks for the letters taught for of all children. Concerning the robot group, even if there is no significant difference between the pre-test and the post-test, there seems to be a slight decrease in the number of clicks to see the letter model. In future work, it would be interesting to run the same test with a bigger sample of subject to see if this tendency can be confirmed.

For the control group, no significant results were found between the pre-test and the post-test. However, there is a significant decrease in the number of clicks between the post-test and the bonus-test (Wilcoxon signed rank test: $W(36) = 0.0$, $p = 0.0421$). It might be an added value of the robotic teaching session together with traditional one, but it may also be a consequence of getting three sessions of learning. In order to test this, it would be interesting to investigate in future work the impact of 3 teaching sessions to be able to compare it with this result.

The second important aspect we focused on during this test is the letter's ductus produced. To do so, we asked 4 experts to grade every child's letter's ductus between 0 (for totally wrong ductus) and 3 (perfect ductus with proper start and end points and directions). Figure 12 shows the mean grade of the 4 letters taught during the teaching sessions for

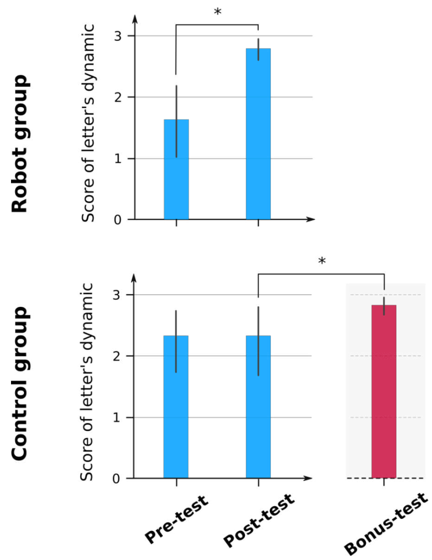

Figure 13: Ductus performance of children in the test with model (see Subsection 4). Statistically significant progress in the letters' ductus score was observed between the post-test and the pre-test of the robot group ($W(36) = 0.0, p = 0.0117$) as well as between the bonus-test and post-test of the control group ($W(32) = 1.0, p = 0.0274$)

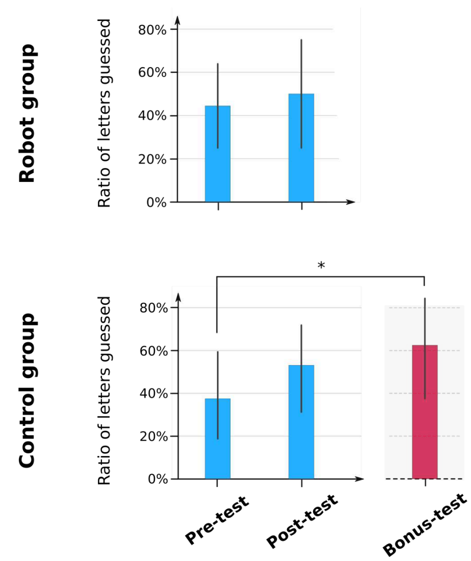

Figure 14: Results concerning the link between the letter's phoneme and its associated grapheme (see Subsection 4). The y-axis indicates the ratio of letters guessed at the first attempt. Statistically significant progress concerning the ratio of letters guessed was observed between the bonus-test and the pre-test of the control group ($W(32) = 0, p = 0.039$)

both groups and each session. In order to measure the inter-rater reliability, a Kappa test was performed and we found a medium agreement level ($K = 0.62$) [29]. Results of the robot group show a slight increase but no statistically significant improvement in the letter's ductus after the two teaching sessions with the robots. For the control group, we can see in the right part of Figure 12 that there is no statistically significant progress after the two teaching sessions with traditional methods. However, when the two teaching sessions with traditional methods were followed by one teaching session with the robots, a statistically significant improvement in the ductus of the letter can be observed ($W(36) = 1.0$, $p = 0.039$). We find this result promising as it may imply that combined teaching methods where the learning activities with the robots are introduced after the traditional learning activities can be an efficient way of teaching the letter's ductus. To confirm this hypothesis, it would be interesting to compare the progress emerging after 3 teaching sessions with traditional methods, with the progress emerging from 3 teaching sessions with traditional methods together with robots, similar to the one done here.

From Grapheme to Ductus

In order to assess the quality of the child's ductus representation of the letters we used the same expert-based grading method as previously described. The results presented in Figure 13 show the mean score of the children's letters' ductus while writing on top of the letter's models (grapheme). Here, the child needs to remember the ductus but not necessarily the grapheme of the letter.

Concerning the robot group, we can see a statistically significant improvement in the ductus representation of the letters after the two teaching session with the robots (between pre-test and post-test: $W(36) = 0.0, p = 0.0117$). On the other hand, there is no statistically significant improvement after the two sessions (between pre-test and post-test) with traditional teaching methods while statistically significant improvement was found after the last session with the help of robots (between the post-test and the bonus-test) ($W(32) = 1.0, p = 0.0274$).

We used a Mann-Whitney U test with independant samples reporting the letters' learning gain between the post-test and the pre-test of the two population to extract statistically significant differences between the learning gains of the two groups ($U(32) = 291.5, p = 0.0031$).

The results presented here show that robots can bring additional value in a typical classroom environment as we can see progress when robots are used together with traditional teaching methods. Similarly, we see progress when only robots are used, but not when only traditional methods are used; this may also be interpreted as a result of a possible ceiling effect present in the pre-test of the control group, making it difficult for them to gain learning from only traditional methods.

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From Phoneme to Grapheme

In this test, we only consider the first attempt of the children while guessing the letter as we observed that if the child does not discriminate the grapheme of the expected letter among others, they will often randomly select a letter until finding the right answer. Figure 14 presents the results of this test, where the vertical axis represents the ratio of letters guessed at the first trial (100 % means 4 letters are correctly guessed by the child at the first selection) while the horizontal axis represents the test index.

Concerning both groups, no statistically significant improvement was found neither after the 2 teaching sessions with the robots, nor after the 2 teaching sessions with traditional methods (between pre-test and post-test), even though an increasing trend can be observed. However, when the two teaching methods were taken together (between the pre-test and the bonus-test in the control group, 2 traditional sessions and one robot session), a statistically significant improvement can be seen with respect to the pre-test ($W(32) = 0$, $p = 0.039$) which may indicate that using the robot together with the traditional teaching methods improves the visual perception skill and discrimination of the letters. Another hypothesis would be that the results were not statistically significant after two sessions (both with the robots and with traditional methods) only because not enough time was spent to teach this concept, and adding one teaching session (with robots or with traditional methods) would make the progress statistically significant. In order to get more clarity on these hypotheses, it would be promising to do another study with more teaching sessions. Indeed, we would be able to see if statistically significant progress emerges when comparing three teaching sessions with the robots and three teaching sessions with traditional methods. We would then be able to see if it is really the combination of the two teaching methods that brings an added value.

Additional analysis

Even if the primary goal of this experiment was to focus on enhancing the quality of the letter representation in the learner's mind, it is also interesting to explore if the use of our haptic approach involving robots affects other skills of handwriting; more specifically, whether it affects the fine motor skills.

Even if it is difficult to extract a handwriting feature linked with the quality of the motor control skill of the writer, previous research suggests that the average handwriting speed as well as the overall letter legibility can be correlated with the handwriting fluency and in particular the fine motor skill controlling the handwriting production [14, 21].

Average handwriting speed. Figure 15 shows the evolution of the average handwriting speed for the control group and the robot group. We can see a statistically significant increase of this measure ($W(36) = 25.0$, $p = 0.0261$) for the robot group at the end of the two teaching sessions (between session the pre-test and the post-test). It is also interesting to notice that the average speed is increased for the letters not taught during the learning session ($W(36) = 26.0$, $p = 0.0299$).

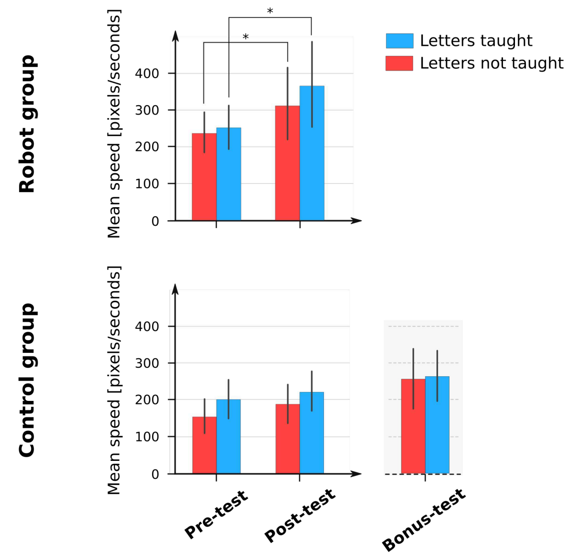

Figure 15: The average handwriting speed extracted from the test with model (see section 4). Statistically significant progress concerning the mean handwriting speed was observed between the post-test and the pre-test of the robot group for the letters taught ($W(36) = 25.0$, $p = 0.0261$) and for the letters not taught ($W(36) = 26.0$, $p = 0.0299$)

A plausible explanation for the child's progress in the letters not taught could be that the learner might transfer their learning when working on the fluidity of their gesture for a particular letter to another letter, as any letter is a composition of well-known shapes and strokes that are possibly shared across all letters of the alphabet [34].

Concerning the control group, we did not find any significant improvement in the mean handwriting speed after the two sessions with traditional teaching methods. However, even if no statistically significant difference was found after the last teaching session (with the robots), we can still observe an increasing tendency with respect to the pre-test. The reason may be that only one teaching session with the robots was performed and the progress did not appear to be statistically significant. Additional analysis will need to be performed to be able to confirm this result.

Again, a Mann-Whitney U test was run to test if difference between the learning gain of the two groups (between the post-test and the pre-test) could be extracted. This test reported marginally significant difference between the learning gain of the two groups ($U(32) = 2390.0$, $p = 0.0518$).

This result gives us reason to believe that the use of haptic-enabled robot could be an added value compared to more traditional methods to teach this aspect of handwriting.

Average legibility. In order to assess the letters' legibility, the same grading method as the one described in Subsection 6 was used. Concerning the robot group, marginally significant progress is observed for the handwriting legibility of the letters taught ($W(36) = 10.5, p = 0.091$) but not for the letters not taught. For the control group, no difference could be observed after the two teaching sessions with the traditional methods. After the last teaching session with the robots (between the post-test and the bonus-test), a clear tendency can be observed both for the letters taught and the letters not taught with marginally significant results ($W(36) = 5.0$, $p = 0.067$).

As for the mean handwriting speed, these results give us reason to believe that our robots may bring an added value when incorporated in a typical school environment. Again, more work will be needed to confirm this hypothesis and especially a comparison with results coming from 3 teaching sessions with traditional methods.

However, we believe that the haptic assistive feedback approach allowed by the use of the robot is responsible of the results (improvement in the handwriting legibility and speed) observed here and presents a possible betterment compared to traditional methods. This assumption appears to be in line with the literature interested in the contribution of haptic on learning [7, 33].

7 CONCLUSION AND FUTURE WORK

The objective of this paper was to show that incorporating a haptic sensory modality through tangible robots can be used for the learning of ductus and grapheme representation of the letters (visual perception and visual-motor coordination). Experiments were conducted with 17 five-year-old children split into two learning groups. These groups were created in order to explore the potential benefit of teaching sessions involving the robots compared to teaching sessions run with more traditional methods. In these experiments, several teaching sessions were distributed across 8 days where we measured both long term and short term learning gain. Furthermore, analysis was done to inspect if these two teaching methods (with the robots and with traditional methods) can be combined together.

The tests evaluating the performance were carefully designed in order to extract the child's knowledge in specific aspects of their letter representation (phoneme-graphme, phoneme-ductus and grapheme-ductus link) that we aimed to enhance. The fact that we focused on these specific aspects of handwriting and applied the aforementioned tests to probe the effectiveness of the robotic approach we proposed constitutes the main contribution of this paper.

Despite the limited number of trials, a considerable improvement concerning the letter representation was observed. The tests showed that the use of a haptic device allows the children to enhance their representation of the ductus of the letters in a fast and effective way (link between grapheme and ductus). The combination of the two teaching methods may also bring significant improvement in the visual perception of the letters (link between phoneme and grapheme) as well as significant improvement in the ductus representation of letters (link from phoneme to grapheme-ductus). However, we don't claim that a similar performance cannot be obtained using only traditional methods. We rather observe that using robots can be at least as effective as traditional methods to teach the concepts presented in this study. We feel that the use of robots after traditional methods helps to cross ceilings/barriers that are encountered by some children and could help overcome stagnation for them. More research will be performed in the future to investigate the assumption raised here.

In addition, significant results were observed concerning the fine motor skills of the learners. Progress in the mean handwriting speed as well as in the letter legibility were observed when the learner used the robot-enhanced activities. These results were observed to transfer from the letters taught to the ones not taught, which we believe originates from the common strokes shared across letters in the latin alphabet.

A limitation comes from the small number of subjects (17 children) involved in our experiment. It would be therefore interesting to confirm the results extracted through this study, as well as possibly confirm others that were not clearly significant, with a larger sample of students. Another of our future aims is to broaden our target group with children who are in need of special education, e.g dysgraphic and dyslexic children, as robots are known to work particularly well for learners with special needs.

Another limitation is linked with the design of our experiment. Since we could not run the bonus test with both groups, the control and the robot groups differ in their number of learning sessions and the modality of learning (different teaching methods). This prevents us to clearly decipher which factor caused the difference in learning rates. Future work will be done in order to more deeply interpret the causes leading to the progress shown through this study.

Finally, the introduction of these kinds of robots in the classroom can typically lead to a novelty effect resulting of an increase of engagement from the children which might result in bias. It is certainly interesting to run additional experiments on a long term study to test this effect, which is among our top priority future work.

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9 SELECTION AND PARTICIPATION OF CHILDREN

As explained in the introduction, we focused in this study on the visual perception as well as the visual-motor coordination that are two aspects of handwriting that need to be developed early in the handwriting learning process. That is why we targeted in this study children from kindergarten (5.2 years old in average at the moment of this study). We obtained the consent of the 17 children from the kindergarten of this school as well as the one of their legal responsible. All experiments and tests were carried out in a special classroom put at our disposal under the control of one of the school's teacher.

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