Dinis Miguel Duarte Catronas

The influence of sensorimotor training in learning a novel script: A comparison between handwriting and visual learning

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Trabalho efetuado sob a orientação de:

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Para a minha família,
sem eles nada seria possível.

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Abstract

Reading and writing are relatively recent cultural acquisitions in the history of human cognition, yet they have become essential to the functioning of today's modern society. It is well accepted that simple perceptive exposure to letters is not sufficient for the emergence of a highly specialized system in the brain to the ability to read and write an alphabet. Exactly what type of experiences are key for the emergence of the system devoted to letter processing is largely unknown. Recent research on this field has suggested that learning a new alphabet with motor integration (via handwriting) is more beneficial to visual letter recognition than other forms of practice such as mere visual exposure to the characters.

In the present study we wanted to explore whether and how visual-motor integration could be beneficial in learning a new alphabet compared to purely visual learning. For this aim, adult participants were exposed to a new alphabet, an artificial script, composed of 12 pseudoletters, each of them being associated with a corresponding syllabic sound. Thirty-six adults were trained in a novel set of letters, through either “visual-only” (mere visual exposure – Visual-Only Group) or “visual-to-motor” (visual exposure plus handwriting – Visual-Motor Group) practice over a three-days Learning Phase. Participants were asked to learn the new alphabet. Behavioral and eye-tracking tasks were created to evaluate the learning curve of the two experimental groups, the ability to recognize and discriminate the new letters after training, and their reading ability.

Significant differences between groups were found across Learning Phases; the Visual-Motor Group had higher Dwell Times. First Fixation Duration and Fixation Count on the last Learning Phase compared to the first Learning Phase than the Visual-Only group when correct responses were considered. These results seem to suggest that the group with the combined training spends more time on the correct response. On the other hand, the Visual-Motor Group spent less time and had lower fixation count on distractors compared to the Visual-Only Group, suggesting that the group with the combined training (visual and motor training) is sensitive to interference of an irrelevant target.

Keywords: Reading, Writing, Visual learning, motor integration, ocular measures.

Resumo

A leitura e a escrita são invenções relativamente recentes na história da cognição humana, no entanto tornaram-se essenciais para o funcionamento da sociedade moderna atual. Apesar da aquisição da leitura e da escrita ser um fenómeno recente em termos evolutivos, o nosso cérebro reconhece letras em menos de 200ms. Esta rápida perceção do estímulo escrito deve-se à emergência de uma rede neuronal universal e altamente especializada para o reconhecimento de letras.

É consensual na literatura que a simples exposição preceptiva às letras não é suficiente para o surgimento de um sistema altamente especializado no cérebro, capacitando-o para ler e escrever um alfabeto, sendo ainda amplamente desconhecido que tipo de experiências são essenciais para surgir no ser humano um sistema dedicado ao processamento de letras. Estudos recentes sobre esta temática sugerem que aprender um novo alfabeto com integração motora (escrita manual) é mais benéfico para o reconhecimento visual de letras do que outras formas de aprendizagem, como por exemplo, a mera exposição visual às letras.

No presente estudo, pretendemos explorar se, e de que forma, a integração visuo-motora poderá ser benéfica na aprendizagem de um novo alfabeto quando comparada à aprendizagem puramente visual. Para isso, os participantes foram expostos a um novo alfabeto (*script* artificial), composto por 12 pseudoletras, cada um deles associado a um som silábico correspondente.

Neste estudo participaram 36 sujeitos aleatoriamente divididos em dois grupos experimentais: o Grupo Visual, onde toda a aprendizagem realizada do novo alfabeto se desenrolou por estimulação puramente visual e auditiva; e o Grupo Visuo-Motor, onde além da exposição visual e auditiva era acrescentado um treino de componente motora. Todos os participantes foram submetidos a uma avaliação inicial de forma a garantir

que não existiam diferenças ao nível da fluência leitora, idade de leitura e processamento específico de letras e pseudoletras. Esta avaliação permitiu, numa fase posterior, garantir que todas as diferenças entre sujeitos e grupos se deviam exclusivamente à manipulação experimental realizada e não a fatores que precedem ao estudo.

Ao longo de três sessões de treino e avaliação, os participantes foram expostos ao novo alfabeto. Foram criadas tarefas comportamentais para avaliar a aprendizagem do novo alfabeto pelos dois grupos experimentais, não só no reconhecimento das novas letras, mas também na capacidade de leitura das mesmas. À exceção da forma como o alfabeto foi aprendido, ambos os grupos experimentais realizaram as mesmas tarefas. Para realizar a análise das mesmas optámos por utilizar medidas como Tempos de Resposta (*ms*) e Número de Acertos como diferenciadoras do nível de aprendizagem entre dias e entre grupos.

Para além das tarefas comportamentais, utilizámos medidas fisiológicas, neste caso, medidas oculares (*Eye-Tracking*), para monitorizar o processo de aprendizagem dos participantes. Sendo uma janela de aprendizagem curta, as medidas oculares permitirão uma discriminação mais fina na avaliação dos benefícios de cada treino. Para isso foi construída uma tarefa de escolha múltipla onde após a apresentação do som correspondente a uma das novas letras aprendidas, o participante tinha de escolher uma das quatro opções de resposta enquanto os seus movimentos oculares eram monitorizados. As quatro opções eram compostas por: uma resposta correta; um distrator visual (rotação no plano de 90 ou 180 graus da opção correta); um distrator fonológico (uma letra aprendida que fosse fonologicamente similar à resposta correta) e por um distrator puro (uma letra aprendida que não se assemelhava visualmente ou fonologicamente à resposta correta). Na análise dos dados extraídos desta prova,

focámo-nos em três medidas oculares: Duração da primeira fixação (*ms*), Tempo Total da Fixação (*ms*) e Número Total de Fixações.

Foram encontradas diferenças significativas entre grupos que tendem a apoiar a nossa hipótese inicial: o grupo que realiza a aprendizagem com integração motora (Grupo Visuo-Motor) revela uma aprendizagem mais eficaz, demonstrando melhores capacidades de leitura e discriminação das novas letras aprendidas quando comparado com o Grupo Visual. Estas diferenças revelaram-se particularmente significativas na análise das medidas oculares ao longo das sessões de aprendizagem, onde o Grupo Visuo-Motor apresentou valores mais elevados de Tempo Total de Fixação e de Duração da Primeira Fixação para a resposta correta. Estes resultados levam-nos a concluir que o Grupo Visuo-Motor não só despende mais tempo e atenção no alvo (resposta correta) do que nos distratores adjacentes, como também desenvolve resistência a esses mesmos distratores, quando comparado com o Grupo Visual.

Palavras-chave: Leitura; Escrita; Treino Visual; Treino Motor; Medidas oculares

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1. Introduction

1.1. The neural subtract of reading acquisition

Literacy is a cultural invention that allowed human beings to express themselves and communicate with each other, being an essential capacity in our daily life. However, the ability to read and write is a relatively new cultural invention (with approximately 5400 years) being unlikely the existence of biologically programmed neural bases to support these skills. Paradoxically, our brain has the capacity to recognize letters in less than 200ms, thanks to a highly specialized and universal neural network for letter processing.

To explain the emergence of this specialized network, Dehaene (2005) proposed the neuronal recycling hypothesis. This hypothesis is based on three main assumptions (Dehaene & Cohen, 2007): the first argues that although in the human brain there are strong anatomical connections resulting from the evolutionary process, these connections eventually begin to form specific neural maps through learning in childhood. This learning is not a similar process in all children, since it depends, among many other factors, of the cultural environment in which the child is raised. The second assumption postulates that reading and writing skills, developed and influenced by culture, will have to find their "place" in the existing neural network. With that in mind, numerous neural circuits with a significant proximity and plasticity must provide resources to the acquisition of this new capacity. The third assumption holds that the pre-existent cortical organization is never completely lost during the learning process, being that it exerts a significant influence in the acquisition of cultural learning and in the cerebral organization that we can observe on the mature brain.

This reorganization of neural circuits frequently occurs during childhood, where humans develop a high rate of learning and skills, though it is not exclusive of earlier stages of development. The brain plasticity potential extends to adulthood, as it is possible to observe significant changes in the adult brain (see, for example, Dehaene, Morais & Kolinsky, 2015 and Dehaene *et. al.,* 2010).

A growing body of literature has examined the potential of brain plasticity even later in life, by studying subjects who, due to socioeconomic or cultural reasons, have only learned to read in adult ages (ex-illiterates). For instance, Skeide *et. al.,* (2017), using imaging techniques, concluded that with only six months of formal reading training, macroscopic changes were observed in the adult brain. Other studies also found that ex-illiterate adults show similar functional patterns of response when confronted with written letters and phrases to those of literate adults (Dehaene *et. al.*, 2010; Pegado *et. al.*, 2014). In addition, illiterate adults showed electroencephalographic markers associated with familiarization with words after a short-term reading training (Sánchez-Vincitore *et. al.,* 2018). Hence, these results support the idea that literacy acquisition leads to changes in the human brain, and that even in adulthood a specialized system for letters can emerge.

As previously mentioned, the acquisition of reading promotes a structural and functional reorganization of the existing neural networks of the brain at different levels and areas, such as the temporal and frontal cortex. However, one of the main areas that has been the focus of attention in the study of the neural specialization for letters is in the ventral visual cortex, the so-called Visual Word Form Area (VWFA) (Cohen *et. al.*, 2000).

The VFWA is located in the fusiform gyrus of the left hemisphere and is highly specialized for letter and word recognition. It is selectively activated by words and pseudowords compared to other categories (faces, objects, houses) (Dehaene *et. al.*, 2002; Dehaene & Cohen, 2007). The processing in the VWFA goes beyond generic characteristics such as font, size and location (Cohen & Dehaene, 2004). Indeed, similar patterns of activation are evoked either by the presentation of congruent size letters (e.g. "ORANGE*") vs* incongruent size letters (e.g. "oRaNgE") (Polk & Farah, 2002; Dehaene & Cohen, 2007).

To support this idea of functional specialization of the VWFA, a study conducted by James (2010), pre-literate children who practiced handwriting of letters and words compared to children who did not practiced the visuomotor training, showed stronger activation of the fusiform regions when confronted with letters *vs.* geometric shapes and false-fonts.

Dehaene *et. al.,*2010, carried out a study using literate, ex-illiterate and illiterate adults. Various stimuli were presented repeatedly to the participants in pairs and mirror forms, such as pseudowords, faces, houses and false fonts. Event-related potentials were measured to evaluate the degree of activation of the VWFA. The authors concluded that literacy and reading ability had a major impact in early visual processing, since participants who were literate had better performance in simple and mirror discrimination and also had higher activation rate of the VWFA. This study clarifies the impact of literacy and reading abilities on the emergence of the functional specialization of the VWFA.

Neuropsychological evidence also supports this idea. For instance, Damásio and Damásio (1983) reported cases of pure alexia due to lesions in this area, that is, the inability to read although the patient has a completely normal visual acuity.

Altogether, these evidence reveal that, in the development of reading competence, literates develop a form of visual expertise for letters in the VWFA, that becomes sensitive to the orthographic properties of the subject's language and preferentially responds to letters compared to other categories (Cohen & Dehaene, 2004).

This specialization for letters and words can be detected from very ages allied with letter knowledge. In preliterate children, the VWFA already responds differently to letter-like symbols in comparison to faces or objects such as shoes (Canton, Pinel, Dehaene & Pelphrey, 2011). However, there is also a significant activation of this area – but less than for letters – when other visual stimuli are presented, such as objects or line drawings. This result is probably due to the proximity (and sometimes overlapping) of this region to the occipital lateral areas, that are associated with the recognition of static images of objects (Price & Devlin, 2003; Price *et. al.,* 2006; Ben-Shachar *et. al.,* 2006).

It is important to add that VWFA's lateralization to the left hemisphere is due to the establishment of privileged connections with linguistic areas, located in the temporal and frontal cortex. This area integrates different types of information in a network that supports reading: is sensitive to the orthographic characteristics of words (Price & Devlin, 2011) and integrates visuospatial information with information from other areas, such as the left temporal and frontal cortex, which are sensitive to phonological components of the word (Glezer *et. al.,* 2015). A neuroimaging study preformed with adult readers (Norton *et. al.,* 2015) reinforces the idea of a network established in the left hemisphere, by showing a widespread activation of visual, auditory and linguistic areas from the left hemisphere when subjects performed a reading task.

Summing up, the acquisition of written language abilities is a very recent phenomenon in human history, being unlikely to have caused evolutionary changes to the human brain (Huettig & Mishra, 2014; James & Atwood, 2009). Despite that fact, we can recognize letters in a very short time span (less than 200 ms). This recognition speed can be explained by the neuronal recycling hypothesis proposed by Dehaene

(2005), which suggest that areas in the human brain can be "recycled" to accommodate new skills, different from the ones that their initial proprieties were prepared to receive. The acquisition of literacy boosts the development of a highly specialized network to support letter processing, being a good example of this recycling process, and notably the VWFA.

The impact of literacy acquisition in the visual processing of letters and words

As mentioned before, learning to read is a gateway to culture and education, leading to profound changes in the human brain. This acquisition has a strong impact on older evolutionary systems, including the visual object recognition system in the ventral visual stream (Dehaene *et. al.*, 2010, Dehaene *et. al.*, 2010). Specifically, reading recruits ventral occipitotemporal (vOT) regions, including the VWFA in the left fusiform gyrus, which was originally dedicated to visual identification and recognition of familiar objects (Fernandes, Coelho, Lima & Castro, 2018). In other words, ventral occipitotemporal regions that were primarily devoted to object recognition are partially recycled to support literacy skills (Dehaene, *et. al.*, 2010), as explained by the neuronal recycling hypothesis (Dehaene, 2005).

In our day-to-day life, it is not uncommon to come across different views of the same object and we must know how to interpret them as being similar and not different representations. To do this, we rely on the original proprieties of the ventral occipitotemporal (vOT) regions: mirror invariance and plane rotation sensitivity (Fernandes & Kolinsky, 2013). In particular, mirror invariance processing occurs in both humans and animals (Logothetis, Pauls & Poggio, 1995, Rollenhagen & Olson, 2000), with neurons in inferotemporal areas on monkeys showing the same mirror invariance on object recognition tasks as happens in humans (Logothetis *et. al.*, 1995).

When we talk about the acquisition of literacy, we must comprise the different alphabets used worldwide, and in some of them mirror discrimination is essential (e.g. Latin alphabet) because they contain mirrored symbols (e.g. d vs b). Although the vOT comprises mirror invariance properties, we are able to correctly discriminate mirrored letters as different. This means that mirror invariance is "broken" in order to learn a script with mirrored symbols (Gibson, 1969).

Interesting results were obtained by Kolinsky *et. al.*, (2011). The authors showed that illiterates displayed more difficulty in mirrored letters discrimination tasks that included shape and size decisions than schooled literates and ex-illiterates. In contrast, ex-illiterates were as able as schooled literates to discriminate mirror images. Thus, it is the acquisition of literacy that triggers the ability to discriminate mirror images (Fernandes *et. al.*,2016). Previous studies have suggested that the key to develop mirror sensitivity relies on the specificities of the script itself, being that in the Tamil syllabary, a script with no mirrored symbols, literates displayed as poor mirror discrimination skills as illiterates (Pederson, 2003).

Studies with literate and illiterate adults, within the Latin alphabet, have also shown that whereas the illiterate group had the strongest performance drop in mirror discrimination tasks, the same did not occur when the task required discrimination of plane rotations, i.e. the performance drop was similar for both groups (Fernandes *et. al.*,2016). This result demonstrates that mirror image discrimination tasks are harder than plane rotation tasks, and that literacy has a stronger impact on the former. In addition, neuropsychological evidence supports the idea that mirror discrimination and plane rotation sensitivity are two different processes that run in independent neuronal pathways: there are reports of patients with mirror agnosia, i.e. with mirror discrimination impaired as a result of a parietal lesion but not plane rotation sensitivity

(Priftis, Rusconi, Umiltà, & Zorzi, 2003), and patients with orientation agnosia, i.e. the reverse behavioural pattern resulting from temporal and anterior parietal lesions (Turnbull, Beschin & Della Sala 1997).

1.2. The effect of sensorimotor training on letter processing

Learning to read implies multisensorial training on visual, auditory, and motor modalities, as well as their integration (Pegado, Nakamura, & Hannagan, 2014). Indeed, literacy includes both reading and writing, and hence, visual object recognition, language, and motor action. Most studies have thus far investigated reading and writing separately, but a growing body of research has examined the potential impact that handwriting (i.e., the motor production of symbol-forms by hand, either by copying, tracing, or writing from memory) can have in visual letter recognition (a necessary precursor of reading), at both behavioural and brain levels (Planton, Jucla, Roux, & Démonet, 2013; Vinci-Booher, Cheng & James, 2019).

A proposal found in the literature states that visual presentation of letter-strings leads to the activation of not only vOT regions, but also left dorsal premotor cortex that codes for inferred gestures in writing, the Exner's area (Nakamura *et. al.*, 2012). The authors hypothesize that the matured reading network contains a visual shape analysis system (VWFA) and a motor gesture decoding system (Exner's area), stating that this global system is a cross-cultural phenomenon. They further the existence of a fast-sensory motor loop that automatically retrieves the intended motor gestures while passingly viewing a letter.

For instance, Longcamp *et. al.*, (2008), evaluated the ability of participants to discriminate mirror images of new learned characters. This new script was learned by the subjects in one of two ways: traditional handwriting in paper *vs* computer typing.

This study showed the benefits of handwriting training in mirror discrimination tasks, since they found stronger and longer lasting facilitation in recognizing the orientation of characters that had been learned by handwriting, compared to those who learned by typing.

According to James & Engelhardt (2012), handwriting is an important aspect of reading acquisition and has a role in the emergence of the reading neural network. The authors tested pre-literate children, trough functional fMRI scanning while was asked to the children to draw, write and type various letters and shapes. The results indicated that a standard neuronal reading circuit (including the VWFA) was only activated for letters after handwriting experience.

In Longcamp, Anton, Roth, & Velay, 2003, this idea was reinforced, with participants activating the same motor areas associated with reading (premotor cortex and Exner's area) while were passively viewing letters and writing them. However, when pseudoletters were passively observed, the areas mentioned before were not activated. These results bring to light the functional associations between reading and writing mechanisms, suggesting that our reading skills can be influenced by the way we learn to write.

A growing body of literature has suggested that learning letters trough handwriting practice facilitates consolidation and subsequent recognition of these letters when compared to other forms of training such as trace and pure visual exposure (Hulmem, 1979; Naka & Naoi, 1995). James & Gauthier (2006) conducted a brain-imaging study to clarify if different ways of interacting with letters during learning lead to different patterns of cortical activation. The study was carried out with college students divided in three main groups that differ on the type of training they receive during a letter, shape and object exposure paradigm handwriting training *vs.* typewriting training vs. pure visual exposure. They observed that following handwriting training, brain areas responsible for processing known letters were also activated in the recognition of pseudo-letters. In addition, this study brings to light that a multi-modal interaction (visual, motor and auditory) with letters leads to an integrated network of different areas (fusiform gyrus, inferior frontal gyrus, ventral pre-central gyrus and dorsal pre-central gyrus) that assists the recognition and consolidation of letter learning. These areas increase their activation only after a specific motor training, i.e., the handwriting training. In another study conducted by Longcamp *et. al.,* (2005), pre-literate children were divided into two experimental groups during a three-weeks learning period: handwriting group *vs.* typing on a keyboard. In this study, the authors focused, not only on the learning and recognition of letters, but also on the timing of the learning (two evaluation moments – one after the three weeks, and the second one, one week after that), since the acquisition of motor skills is a process known by its progressive evolution, requiring several repetitions during successive training sessions (Karni, 1996). They found significant differences between the two groups, showing a clear benefit from handwriting compared to typewriting learning group. According to the authors, this benefit in the learning and recognition of letters might be explained by the fact that handwriting provides stimuli from various sources (visual, motor commands, proprioceptive feedback - notion of body and action in space), which are closely linked.

However, the benefits of a grapho-phonological training allied with handwriting training have not always been found. In a study conducted by Vinter and Chartrel (2010), pre-literate children were divided into four experimental groups of training (visual-only group, motor group, visual-motor group and control group). The authors gave the children of all experimental groups three letters and asked them to copy them to a sheet of paper. in cursive (prior to the formal learning of cursive in school). The results showed that, although the visuomotor training was in general the most effective at movement execution, the visual-only group was faster in learning the shape of the letter. However, compared to similar studies, this study used a short time learning phase (four days), and this might have affected the results.

Controversial results found in the literature regarding the effects of motor experience in reading may be explained by the duration of the learning phases, given that the acquisition of motor skills seems to be consolidated in two phases: first, there is an initial acquisition resulting from a single training session (reduced maintenance, from a few minutes to hours); in a second phase, there is a slower and gradual consolidation that results from several sessions, which can extend over weeks of practice (Ungerleider, Doyon, & Karni 2002)

Summing up, there is evidence that handwriting experience when learning letters (either from a new script in adults or from the alphabet in children) enhances visual letter recognition more than other forms of training (such as mere visual exposure, typing, tracing), and increases activation in the left fusiform gyrus, a region pivotal for orthographic processing in the visual cortex).

However, the study conducted by Vinter & Chartrel (2010), brings to light the shor-term benefits of a visual-only training, showing a spick of letter form learning in the first session of the experiment.

1.3. Goals and Hypothesis

The main goal of this study is twofold: i) to test the hypothesis that visual letter recognition and learning is accelerated by training in the motor representations of letters through handwriting, beyond visual perceptual training; ii) to investigate how exactly this occurs. Our original proposal is that handwriting practice during learning assists perceptual learning of fine contrasts discrimination: discrimination of mirror letters and the ability to achieve distinct phoneme-grapheme mappings; both pivotal in early reading acquisition.

To do so, we will use an artificial learning paradigm in which participants will learn the association between novel pseudoletters and corresponding sounds, either in visual-only contexts (mere visual exposure, with no motor action) or visual-motor context, allied with handwriting. The Learning Phase will occur across three consecutive days, followed by reading in the new alphabet. To examine learning benefits due to training we used a four-alternative forced choice letter identification task (with three distractors: mirror-reversed image; phonologically similar; and a totally different letter from the same script) at pre- and post-training while the participants' eye-movements were recorded. During the task forced choice task both behavioural (accuracy) and oculomotor data (First Fixation Duration (*ms*), Total Fixation Time (*ms*), Dwell Time (*ms*) and Fixation Count) will be recorded. The use of eye-tracking is an added value of this project, as it will allow to collect for the first time fine-grained physiological measures with a high temporal resolution such as total fixation duration, number of fixations and duration of first fixation.

First, we expect to replicate in literate young adults the results from previous studies (e.g., Longcamp, *et. al.*,2005; Longcamp, *et. al.*,2008), where the participants preforming handwriting training will show significantly better learning and visual recognition of the newly learned letters than participants preforming a more passive learning (mere visual exposure). We also predict more overt attention (e.g., greater proportion of fixations, longer gaze time) will occur to the critical letter than to the competitors as a function of training, expressed by difference scores close to zero at

Day 1 and a bias of looks towards the target letter over competitors after training (Day 3), and especially in the Visual-Motor group. This would suggest that motor experience with letters through handwriting leads to fine tuning of visual/phonological representations.

2. Methods

2.1. Participants

Thirty-six Portuguese college students (M_{age} ± [std] = 21.9 ± 3.5 yrs; $M_{education}$± [std] = 14.7 ± 2.2 yrs) participated voluntarily in our study after informed consent was obtained (Attachment B). We established as inclusion criteria the following: (1) Being a native Portuguese speaker; (2) Education level equal or above college level; (3) No known history of neurodevelopmental disorders, nor of reading and/or writing impairments; (4) Normal or corrected vision. All participants answered a brief questionnaire that probed all these conditions were fulfilled (Attachment A). In addition, in order to ensure that the participants did not have reading problems, all were screened with two reading tests: the Reading Age Test - TIL, testing the ability to decode and comprehend 36 sentences in one-minute (Fernandes *et. al.*, 2017), and the 3DM word reading test (Reis *et. al.*, 2010) to assess reading fluency, containing three lists of high- and low-frequency words and pseudowords (75 items per list) and a time limit of 30 second per list. None of the participants scored below 13 (corresponding to the 15th percentile) on the TIL test (based on Portuguese norms for college students, Fernandes *et. al.*, 2017).

The participants were randomly assigned to two experimental groups that differed only in the type of training they received at the learning phase, a *visual-motor group* and a *visual-only group* (described below).

2.2. Material and Procedure

In this study, two groups of adults received grapho-phonological training during three consecutive days in a novel syllabic script (see Figure 1) either in a visual-only context (no motor actions involved) or in a visual-motor context (allied with symbol handwriting). The learning phase consisted of training procedures (Day1 to Day 3), followed by behavioral testing to assess the benefits of training over time.

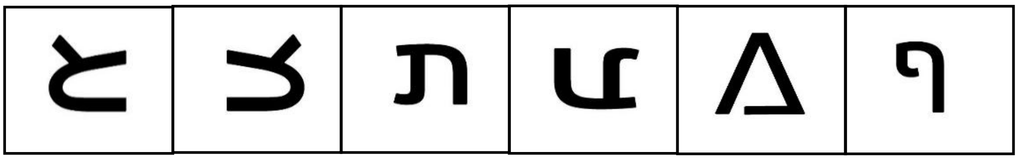

Figure 1. Example of stimuli presented in the learning phase

Participants trained and learned a new alphabet over three consecutive days (Table 1 describes the sequence of the tasks over the three days). The learning phase consisted of training tests between the first and last Learning Phases (Day 1 and Day 3), followed by behavioural testing in order to evaluate the learning effectiveness and the benefits of training over time. In the first and last Learning Phase (Day 1 and Day 3) the participants were also tested in a visual recognition task during eye-movements recording, in order to examine whether and how training influenced visual and phonetic discrimination of the new symbols.

2.2.1. Behavioural trademark of letter-like processing

Prior to the Learning Phase (Day 1), participants were asked to perform a behavioral task that was designed to assess the perceptual strategies that were used to recognize letters and non-letters (analytical or global/gestalt): Navon Task. For this task, we used real letters of the Latin alphabet and the same pseudoletters that were part of the new script learned in the Learning Phases. Both types of stimuli had the same visual complexity and only differed in the arrangement of their strokes. In the Learning Phase

(Day 3), this task was applied again, aiming to examine whether after training the new learned pseudoletters had acquired a "letter" status, and hence are processed using (letter-like) analytic strategies. This task is next described.

Navon Task

We used the well-known Navon paradigm (Navon, 1977) to examine the global precedence effect for letters and pseudoletters. In this task, two types of compound, hierarchical stimuli were used: a large letter/pseudo-letter (called "global") composed of a number of small letter/pseudoletters (called "local"). We created 24 stimuli, considering the size of the stimulus image in the retina, similar to the previous study by Lachmann *et. al.,* (2014). The global stimulus size corresponded to an approximate visual angle of 6.5° x 5.5° and the local stimulus to an angle of 0.5° (i.e, close to the optimal functional visual field for whole-word reading and for fluent reading of individual letters, respectively).

Each participant performed a total of four blocks, which differed according to the nature of the stimulus (letters versus pseudoletters) and the level to which they should attend (global versus local). In the global attention condition, participants were instructed to identify the global stimulus while ignoring the local elements; in the local attention condition, they were asked to respond to the identity of the local elements and to ignore the global shape.

The sequence of events was as follow. At the beginning of each block, the participant was instructed as to which level he/she was required to attend (global or local level). Then, a target (pseudo)letter was displayed for 500 ms, followed by four compound letters, one at a time, that remain visible on the screen until the participant responds. For each compound letter, the subject had to decide as quickly and correctly as possible whether the target (pseudo)letter was presented or not at the previously indicated level (global or local), by pressing one of the two predefined keyboard buttons (keys 1 and 9, corresponding to yes and no answers, respectively).

In this study, all compound stimuli were incongruent, meaning that the global letter always differed from the local letter. Three types of trials were presented based on the study by Poirel, Pineau, & Mellet, 2008: in 50% of the trials the target stimulus was present ("present" trials), in 25% of the trials the target stimulus was absent ("absent" trials) and in 25% of the trials the target stimuli was present but at an irrelevant level ("irrelevant" trials; see Figure 2). Each of the 12 letters and pseudoletters was repeated three times in non-consecutive order, resulting in a total of 72 stimuli throughout the entire task (36 Pseudoletters and 36 Letters). The order of presentation of the blocks was counterbalanced between subjects and experimental group.

Considering this explanation, our goal was to evaluate if pseudoletters would be processed as letters at the end of the Learning Phases. If so, our major hypothesis is a reduction in the effect of global precedence (ie, faster processing of the global level and stronger interference due to incongruency with the local-level target responses) for pseudo-letters in the end of the Learning Phases, similar to what happens in real letters (Lachmann *et. al.,* 2014).

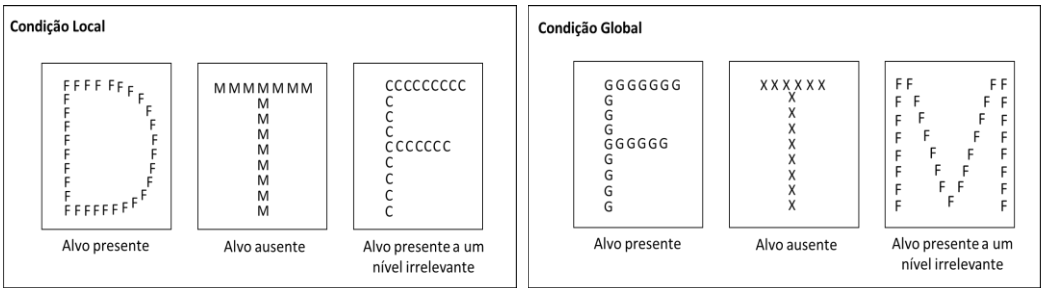

Figure 1. Illustration of the hierarchical stimuli presented in the Navon Task

2.2.2. Training Phase

Participants were randomly assigned to two experimental groups, which differed in the type of grapho-phonological training performed: (1) *visual-only* training included passive visual exposure to the graphic forms of the new symbols, with no motor actions involved; and (2) *visual-motor* training relied on learning new symbols through handwriting. It was indicated to both groups that they would be exposed to a new alphabet that they would have to learn. For each group, two different training contexts were created, leading to a diversification in the learning process: Training I and Training II. The graphic form of 12 novel symbols (pseudoletters) were visually presented along with their phonological counterpart (auditorily presented), by using a computer and the E-Prime software. We ensured that the exposure time to each of the new pseudoletters was identical in both groups over the three Learning Phases; hence, any differences between groups is unlikely due to differences in familiarity with the stimuli.

Training I

This training consisted of five blocks, where each new pseudoletter was visually presented two consecutive times, associated with its respective sound, making a total of 120 exposures per Learning Phase. The design of the training task, number of repetitions, and exposure time to the stimuli were similar in the two training groups.

Visual-Motor Group

Participants were first exposed to a dynamic demonstration of the written form of the pseudoletter (i.e. how to write the pseudoletter) for 250 ms; after this demonstration, they were asked to copy the pseudoletter on a sheet of paper, with a time limit of 5000 ms. This procedure was repeated for the same pseudoletter two consecutive times. In each trial sequence, the corresponding letter-sound association was also displayed, once during the dynamic demonstration and again during the copy period. The following instruction was given to the participants:

"Now you will see each letter of the new alphabet. You will also hear the corresponding sound. For each new letter, you will see a demonstration of how to write the letter. Make sure to reproduce your written form correctly."

Visual-Only Group

In the Visual-only group, participants performed a more passive training, as they were instructed only to pay attention at the presented stimulus and its corresponding sound and to try to memorize both the letter form and sound. The following instruction was given to the participants:

"For each new letter, you will learn its shape and also the corresponding sound. You will see and hear each of these letters four consecutive times. You must pay attention, fixating the stimulus that is being presented, in order to memorize each letter - form and sound."

Training II

After Training I, participants were asked to perform Training II (Attachment E). This training included a production task in both groups, that is, a reproduction by memory of the pseudoletters that they had just learned, written (in the visual-motor group) or oral (in the visual-only group). Each of the 12 pseudoletters repeated two non-consecutive times per block x 5 blocks (total = 10 repetitions for each stimulus). The amount of exposure, sequence and repetition of the stimuli were similar in both groups; they only differed in the type of response that was asked (verbal or verbal/motor).

Visual-Motor Group

Each learned pseudoletter was displayed on the screen for 2000 ms, one at a time, and the participants were asked to say aloud the corresponding sound and then, after the model has erased, to write its graphic representation. The maximum time to execute both tasks was 4000 ms. Following the participant's response, feedback was provided in order to avoid a self-reinforcement of wrong associations. Participants responses were written on a sheet of paper, and the number of hits, errors and omissions were subsequently noted.

Visual-Only Group

The graphical representation of each new learned pseudo-letter was presented visually. Participants were asked to say aloud the sound associated with the visual stimulus.

Learning gains from training

Two tasks were used to assess learning gains in reading and visual and phonetic discrimination due to training. These are described below. The results of the production task (Training II) performed on the last Learning Phase (Day 3) confirmed that training in both groups was indeed effective in helping participants to learn the new script. The percentage of hits was greater than 98% in both groups.

2.2.3. Reading Tasks

This study included two reading tasks with the new script: Reading Task I (performed on day 1 and day 2) and Reading Task II (performed on day 3). By using these tasks, we intended to evaluate the impact of training on decoding ability, in other words, to test whether the participants could apply the acquired knowledge about letter-sound associations to decode words. By manipulating the word length, we also intended to examine whether training leads to the emergence of classic phenomena in reading development as the subject becomes a fluent reader (i.e., a reduction of the effect of length). Our major hypothesis regarding this task is a reduction of the length effect across Learning Phases, with participants in the Visual-Motor Group showing better improvement.

Reading I: This task included two lists with pseudo letters and pseudo-words (12 items in each list), composed of one, two and three syllables, written with the new script (Attachment F). The lists were blocked (see Figure 3).

The stimuli were presented individually on a computer screen and remained on the screen until the participant responded or the time limit of 6000 ms. The participant was instructed to read aloud each syllable or (pseudo)word, and to press the "SPACE" key immediately after that. Feedback of the correct answer was provided. The accuracy data was recorded.

Figure 2. Reading I task. Example of a trial with one, two and three syllable-words.

Reading II: The procedure used in this task was similar to the Reading Task I, but this task only included and one list of pseudowords and the participants did not receive feedback. Thus, this task included 12 new pseudo-words (i.e. not previously seen) (Attachment G). Accuracy and reading speed were also recorded.

2.2.4. Visual Symbol Recognition Task

A four-alternative forced choice letter identification task was designed to evaluate the learning curve over time and specifically the effect of training on visual and phonetic discrimination of the learned symbols. Thus, this task was performed on the first and last Learning Phases.

In this task, one of the learned syllables was presented over headphones, and at the same time four pseudoletters were presented on the screen (see Figure 4): the target stimulus (correct answer); a visual distractor, that can be a mirror-image of the target letter or a plane-rotation, being either vertically or horizontally oriented at 90º or 180º; a phonological distractor; and a totally different letter from the same script. The four stimuli were presented in the centre of the screen, being equidistant from each other, both vertically and horizontally. The participant was instructed to choose which letter corresponds to the syllable.

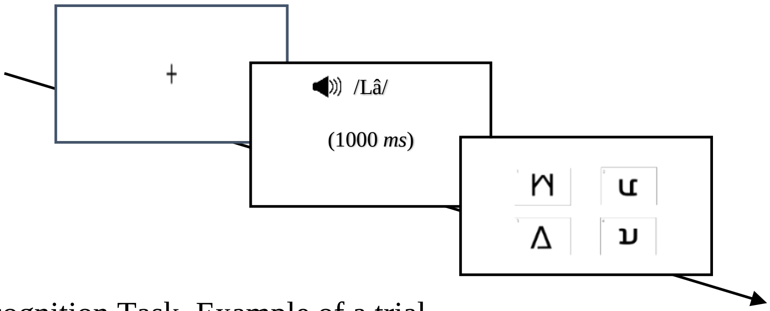

Figure 3. Recognition Task. Example of a trial.

The task included 52 trials in total. In half of the trials the correct answer was displayed and in the other half was absent from the four options presented. To clarify this procedure, in half of the trials of the experiment, we had target trials, i.e. trials were the correct pseudoletters was part of the four options given to the participant. In the other half of the trials we had filler trials, i.e. trials were none of the four options given to the participant was correct, being that in replacement of the correct response was another pseudoletter of the new script with no relation with the correct one. The test included four training trials so that participants became familiar with what was intended.

The sequence of events was as follows: first, a fixing cross (+) appeared during 500 ms, then a blank screen for 1000 ms, during which the target sound was reproduced; immediately after, the four alternative responses were visually displayed for 5000 ms. The subject had to choose the correct answer by pressing the corresponding button (numbered 1 to 4), or in case the sound did not correspond to any of the forms presented, type answer 0.

During this task we collected two types of behavioural data for each participant: accuracy and oculomotor measures. To record eye-movements, we used the SMI hi-speed eye-tracking system at a frequency of 1250 Hz. A double calibration of the eye-tracker was first performed to certify that participant's ocular data were being recorded correctly. In both cases, a maximum deviation of 0.5º from the standard validation measure (0.0º) was allowed to continue the experiment. From this moment on, the subjects were instructed not to move their heads during the experiment (to ensure calibration stability) and to avoid blinking.

3. Results

To ensure that training in both groups was indeed effective in helping participants to learn the new script, we first computed the accuracy results for the Production task (Training II) performed on the last Learning Phase (Day 3). Two participants (one from each experimental group) had extremely low scores (more than 3SD below the participants 'mean), indicating very low learning achievement, and were therefore excluded from the study. After excluding these participants, the percentage of hits on the Production task was greater than 98% in both groups.

3.1 Pre-training

An initial analysis was performed to ensure that i) the two groups did not differ in their reading level, and ii) prior to training, both groups recognized the pseudoletters from the new script by using a distinctive processing mode as that used for real letters of the alphabet (confirming that as expected pseudoletters are not yet automatized) iii) regarding the Navon task, we were able to replicate the classic Global Precedence Effect described in the literature, thereby confirming the suitability of this paradigm for our purpose (i.e., to be used as a behavioral trade mark of letter-like processing for the newly trained pseudoletters after training, meaning the prevalence of analytic processing strategies after automatization).

As expected, we found no group differences in reading fluency ($M_{\text{Visual-Motor Group}} \pm$ [std] = 1.79 ± .16 words/sec; $M_{\text{Visual-only group}} \pm$ [std] = 1.84 ± .23 words/sec; p = 0.432) and reading comprehension ($M_{\text{Visual-Motor Group}} \pm$ [std] = 17.67 ± 3.03 hits =; $M_{\text{Visual-only group}} \pm$ [std] = 17.28 ± 3.68 hits; p = 0.338), thereby indicating that both groups had a similar reading level.

Concerning the Navon Task, since all participants performed with a high rate of accuracy (>90% of hits across all conditions), our analysis focuses on RTs. We performed a Repeated Measures ANOVA on Day 1, with Level (Global *vs*. Local), Type of Stimulus (Letters *vs.* Pseudoletters), and the Trial type (Absent *vs.* Irrelevant) as within-subjects factors, and Group (Visual-Motor Group *vs.* Visual-only group) as a between-subjects factor.

We found a main effect of Level, with faster responses for global than for local level targets, $F(1,32) = 8.06$, $p = .008$, $n^2 = .201$. We also observed a robust main effect of Stimulus, $F(1,32) = 11.44$, $p = .002$, $n^2 = .263$, and Trial type, $F(1,32) = 41.08$, $p < .000$, $n^2 = 0.562$. Participants had faster response times for letters in comparison to pseudoletters and were also faster in responding to absent than to irrelevant trials.

The interaction Level x Trial Type was also reliable, $F(1,32) = 8.70$, $p = .006$, $n^2 = 0.214$, and importantly, also the three-way interaction between Level x Stimulus x Trial, $F(1,32) = 8.50$, $p = .006$, $n^2 = 0.210$. Post hoc analyses (Tukey HSD test) indicated that for letters, there was a trial effect (i.e., higher RTs in irrelevant trials compared to absent trials) both at the global (p = .017) and local level (p =.005). While for pseudoletters, the effect of trial was restricted to the local level condition (p <.001;

for the global condition, p =.916). Moreover, the results also revealed that for the local condition, the magnitude of the interference, due to the presence of the target at the irrelevant level, was higher for pseudoletters compared to letters (Cohen's d = 0.62 and =0.36 respectively). Note that the local condition is the most relevant one to determine if an interference effect exists from the global to the local level (cf. Lachmann *et. al.*,2014).

Hence, these results were as expected and replicated the classic effect in the literature: we confirmed the greater interference from the global level when participants attended to the local level than the reverse (global processing advantage) and that this effect is higher for pseudoletters in comparison with letters, probably because both materials rely on different processing strategies (more holistic for pseudoletters and more flexible for letters). For this reason, this task will be used as an external marker to assess the emergence of letter-specific processing of the new learned script after training. Importantly, no group effect ($F < 1$) or interactions involving the factor group (Fs < 1) were found at pre-training.

Therefore, any potential differences observed at post-training cannot be attributed to a priori differences between groups in their processing strategies and are then solely due to the impact of the type of training itself.

3.2. Learning benefits due to training

To assess the impact of training in both groups, we analyzed whether there was a modification in the processing mode adopted for pseudoletters of the new learned script after training (as assessed with the Navon Task), and also the benefits in reading (Reading I and Reading II). Furthermore, we examined the impact of training on the ability to discriminate the learned symbols (Recognition Task), as reflected in terms of response accuracy and oculomotor markers.

Navon Task

We calculated training benefits as the mean difference between post-training and pre-training regarding the interference effect ($M_{Irrelevant\ trials}$ – $M_{Absent\ trials}$) on the local condition, for each group. In the mixed Group (visual-motor *vs*. visual-only) × Stimulus (Letters *vs.* Pseudoletters) ANOVA, neither the main effects nor the two-way interaction was significant (all *F*s <1). These results indicates that the interference effect, and especially for pseudoletters, did not diminish in neither group from the first to the last Learning Phase (Day 1: $M_{Visual\text{-}Motor\ Group}$,, *d* = 0.68 ; $M_{Visual\text{-}Only\ Group}$, *d* = 0.57; Day 3: $M_{Visual\text{-}MotorGroup}$, *d* = 0.57 ; $M_{Visual\text{-}Only\ Group}$, *d* = 0.59). Even though there was a slight decrease in the Visual-Motor Group, it was not statistically significant.

3.3. Reading Tasks

Descriptive statistics indicated that in the last Learning Phase all the participants, in both groups, were able to read syllables, words and pseudowords written with the new script with an accuracy above 90% on the Reading I task and above 75% on Reading II, clearly indicating that an effective learning had occurred.

The performance on the Reading I task was analyzed with a Repeated Measures ANOVA, with Learning Phase (Day 2 – Day 3) as a within-subjects factor and Group (Visual-Motor Group – Visual-Only Group) as a between-subjects factor, and the Length effect ($M_{longer\ items}$ – $M_{shorter\ items}$) as the dependent measure. For accuracy, neither the main effects nor the two-way interaction were significant (all *F*s <1).Regarding the RT, we found a main effect of Day, $F(1,34) = 9.67$, $p = .004$, $n^2 = 0.221$, but no interaction with the factor Group (F<1), indicating that the length effect (longer RTs for longer compared to shorter items) decreased in both groups from Day 2 to Day 3. The main effect of Group effect was nonsignificant (*F* <1).

Regarding Reading Task II, we performed an independent sample t-test of the effect of length on Day 3. For accuracy, we found a marginal effect of the pseudoword length effect, $F(1,34) = 2.950$, $p = .049$. When the two groups were analysed separately, we observed only a marginal length effect on the Visual-Only Group, as accuracy scores tended to be higher in the 2 syllable condition that on the 3 syllable condition (p =.069), while the same effect was null on the Visual-Motor Group (p =.384).

For the RT analysis, no differences were found concerning the length effect (p = 0.437).

3.4. Recognition Task

Global accuracy and Eye-movement data

One participant was excluded from this analysis because the task was not completed successfully. The analysis on accuracy scores on the last Learning Phase (Day 3) showed that both groups preformed the Recognition task with high level accuracy, with 98% of hits on the Visual-Motor Group and 96% on the Visual-Only Group and no statistically significant differences between the groups (p = 0.191).

Prior to the difference's analysis for the ocular measures between the two Learning Phases (Day 1 and Day 3) it is important to notice that in the first Learning Phase, no difference was found for ocular measures between target and distractors. This means that in both groups, the allocated attention was equally divided for target and distractors. We can then presume that all differences found in the last Learning Phase were due to the specific characteristics of the type of training (Visual-Motor, Visual-Only).

Regarding the eye-movements data, we first analyzed whether eye-movements towards the target (Correct response) change from Day 1 to Day 3. The mixed Group (Visual-Motor, Visual-only) by Learning Phase (Day 1, Day 3) ANOVA indicated a significant two-way interaction regarding Dwell Time (DT) measures. A Learning Phase effect was found, F (1,33) = 16.72, p < .001, n^2 = .336, as both groups had a significant increase of fixation time to the target between Learning Phases. However, an interaction Group x Learning Phase was also found, F (1,33) = 7.42, p =.010, n^2 = .184, because the Visual-Motor Group had a significantly higher increase in fixation time to the target when compared to the Visual-Only Group on the last Learning Phase. No significant effects were observed for the FFD (Learning Phase, p = .083; Group x Learning Phase, p = .165) and Fixation Count (FC) (Learning Phase, p = .523; Group x Learning Phase, p = .184) measures.

We then analyzed whether more overt attention occurred to the critical symbol (target) than to the distractors as a function of Group and Learning Phase. To examine this, difference scores were calculated by subtracting the oculomotor measures to each of the distractors from the oculomotor measures to the target. Difference scores reveal the magnitude and direction of any tendency to favor one type of symbol over another. A positive difference reveals a bias of looks towards the critical symbol over distractors, and a negative difference reveals a bias to look towards the distractors.

Overall, the results indicated that in the last Learning Phase (Day 3) the Visual-Motor Group spent more time in the target and less time in the distractors when compared to the Visual-Only Group. First, we will analyze eye-movement measures for the difference Target – Phonological Distractor, for each Group and Learning Phase. On Dwell Time measure, an effect of Learning Phase, F (1,33) = 24,58, p < .001, n^2 = .427, and interaction Group x Learning Phase interaction, F(1,33) = 24,58, p = .004, n^2 = .22.

These effects indicated that both groups had a significantly higher positive score on the last Learning Phase, meaning higher DT for the target than for the Phonological Distractor, however this preference for the target over the distractor was even higher on the Visual-Motor Group.

On TFT measures, the same pattern of results was found. A Learning Phase effect $F(1,33) = 24.47$, $p < .001$, $n^2 = .426$, and an interaction Group x Learning Phase interaction, $F(1,33) = 24.47$, $p < .001$, $n^2 = .426$ were found. Both groups significantly increased the TFT for the target between Learning Phases, however the Visual-Motor Group significantly increased attention located to the Target between the two Learning Phases that the Visual-Only Group.

Lastly, for Fixation Count measures, the pattern repeated. Once more, a Learning Phase effect was found, $F(1,33) = 7.19$, $p = .011$, $n^2 = .179$ such as a Group x Learning Phase interaction, $F(1,33) = 5.12$, $p < .05$, $n^2 = .134$, where both groups significantly increased the number of fixations directed to the target between the two Learning Phases, with the Visual-Motor Group having significantly higher number of fixations to the target when compared to the Visual-Only Group.

Next, we repeated the same analysis for the differences Target-Visual Distractor. On the Dwell Time analysis, a Learning Phase effect, $F(1,33) = 32.89$, $p < .001$, $n^2 = .499$ and Group x Learning Phase interaction were found, $F(1,33) = 7.82$, $p < .001$, $n^2 = .191$, with both groups increasing Dwell Time on the Target, with the Visual-Motor Group spending more viewing time in the Target when compared to the Visual-Only Group.

For the TFT, a Learning Phase effect found, $F(1,33) = 32.66$, $p < .001$, $n^2 = .497$ and a Group x Learning Phase interaction were found, $F(1,33) = 7.77$, $p < .005$, $n^2 =$

.191, with both groups increasing total viewing time on the target between the two Learning Phases, with the Visual-Motor Group showing a clear preference to the target (over the Visual Distractor) than the Visual-Only Group. Lastly, on Fixation Count measures, a Learning Phase effect was found, F(1,33) = 16.69, $p < .001$, $n^2 = .336$, with both groups increasing the number of fixations to the Target over the Visual Distractor between Learning Phases. Although no Group x Learning Phase interaction was found, the tendency observed was for the Visual-Motor Group showing a preference (higher number of fixations) to the target over the Visual Distractor in comparison to the Visual-Only Group.

Table 1- Oculomotor measures for the Recognition Task

	Visual-Only Group n=18	**Visual-Motor Group** n=18
Target – Phonological Distractor	**M (SD)**	**M (SD)**
First Fixation Duration (D1)	50.44 (89.64)	49.92 (99.80)
First Fixation Duration (D3)	75.30 (77.11)	143.92 (261.90)
Dwell Time (%) (D1)	30.60 (11.40)	26.30 (15,41)
Dwell Time (%) (D3)	34.72 (15.46)	44.80 (16.11)
Total Fixation Time (%) (D1)	29.63 (11.11)	25.30 (14.85)
Total Fixation Time (%) (D3)	33.67 (15.07)	43.28 (15.94)
Fixation Count (D1)	4.04 (1.50)	3.43 (1.87)
Fixation Count (D1)	4.14 (1.57)	4.87 (1.91)
Target – Visual Distractor		
First Fixation Duration (D1)	30.56 (67.27)	34.44 (88.15)
First Fixation Duration (D3)	49.69 (75.73)	108.22 (274.12)
Dwell Time (%) (D1)	24.60 (10.90)	22.52 (13.21)
Dwell Time (%) (D3)	30.94 (15.43)	41.79 (16.13)

4. Discussion

During the last years, digital writing devices are increasingly replacing handwriting with pencil and paper, and thus some authors have precociously announced the "death of handwriting" in the Digital Era (Heuer, 2016). However, recent research with pre-reading children and adults trained in a novel script have demonstrated that learning letters through handwriting compared to pure visual exposure to letters or other non-specific motor training conditions (e.g., typewriting) has more positive effects on letter learning, enhancing better visual letter discrimination and recognition (Longcamp *et. al.,* 2008) and long-term consolidation (Longcamp *et. al.*, 2003; Hulme, 1979; Naka & Naoi, 1995). Yet, the mechanisms behind this handwriting-driven benefit are largely unknown. Moreover, the results are not fully consensual (see, for example, Vinter & Chartrel, 2010).

In this study we wanted to investigate exactly how handwriting experience assists the visual learning and recognition of novel letters (pseudoletters) and compare it to a pure visual training. One of the original contributions of our study is the simulation of the process of letter acquisition (with an artificial-letter script) combined with a high-temporal resolution technique (eye-tracking) to obtain fine-grained information while participants perform a measure of perceptual learning. We know that eye-movements are affected by the psycholinguistic characteristics of words (Hyönä and Olson, 1995) and here we used eye-tracking to measure the dynamic allocation of attention that follows from the letter properties. For our aim, we compared two groups of participants: one that learn an unknow alphabet just through a pure visual-auditory exposure - Visual-Only learning group - and the other one that combined the visual exposure with a motor training - Visual-Motor learning group.

First, and to ensure that no pre-training differences would influence the results, we assured that groups were equivalent concerning reading level and specific processing of letters and pseudo letters (Navon Task). No significant pre-training differences were found, so we can assure that differences found between groups are exclusively due to specific training characteristics.

We will first put into discussion results found in behavioural tasks, followed by the analysis of oculomotor measures.

Post-training analysis of the Navon Task revealed an evidence of a GPE (Global Precedence Effect - faster processing of the global level and stronger interference due to incongruency with the local-level target responses) for pseudoletters similar to previous studies (Lachmann *et. al.*, 2014), suggesting that participants used a global, holistic processing strategy to this stimulus, contrarily to real letters, in which more flexible strategies (either analytic or holistic) are used depending on the task purpose. We expected that the interference effect for the new script would diminish (in result of a repetition effect), meaning that an automatization occurred for the letter-sound correspondence. However, the results did not confirm our hypothesis: none of the groups showed a significant decreased of the interference effect after training (slight decrease in the Visual-Motor Group, but not significant).

One possible explanation for this null result is addressed in a critical review conducted by Kimchi (1992), which claim that factors like exposure duration to the stimuli and amount of allocated attention are crucial to the magnitude of the observed interference effect. In our study, the exposure duration was controlled between groups and Learning Phases. A possible explanation is that participants probably did not have enough time to automatize letter-sound correspondences as we employed a short training (3-day design; see for example, Ungerleider, Doyon, & Karni 2002), explaining why the novel pseudoletters did not show a processing mode similar to letters. Indeed, we know that automaticity is reached late in typical reading acquisition. Thus, a longer acquisition period probably would be necessary to observe a reduction of the global precedence effect.

In our study, participants were also tested in reading in the new language, with stimulus length manipulated. A reduction of length effect throughout development is often used as a hallmark of reading ability (De Luca, Borrelli, Judica, Spinelli & Zoccolotti, 2002; Spinelli et. al., 2005). Thus, our hypothesis was that this effect would diminish across Learning Phases, and especially in the Visual-Motor Group. We observed a length effect across learning phases, with no reduction for any group after training and no interaction between group and length.Although an improvement in reading skills was registered for both groups in the post-training analysis (revealing that an effective learning of the new script occurred), we didn't find a reduction of the length effect as strong as we initially predicted. These results seem to confirm the hypothesis raised before, that participants didn't had enough time to assimilate letters-sound correspondences.

In Martens and de Jong (2008), second to fourth-grade children also performed a reading task with words and pseudowords for four days, and the observed length effect did not change across sessions. The authors proposed a possible explanation for this result: although the knowledge of the specific word form may be present, it does not necessarily imply that the automatic connections between written and spoken forms have already been acquired.

Regarding eye-movements, our hypothesis was that both groups would show an increase in all the ocular measures for the correct target response, while spending less viewing time on the distractors from Day 1 to Day 3, with the Visual-Motor Group showing some advantage over the Visual-Only Group.

In the first Learning Phase (before the acquisition) there was no difference in oculomotor measures towards the target and the distractors for both groups, which means that attention was equally divided between target and distractor, as expected. In the last Learning Phase, we did find significant differences on Dwell Time, Total Fixation Time and Fixation Count for distractors and the target letter, and critically, this effect was modulated by Group. That is, there was more overt attention directed to the target and less interference of distractors on the group that received graphomotor training allied with handwriting.

The results found on oculomotor measures during the visual recognition task bring to light the beneficial effect of a combined training (both visual and motor experience). First, our findings agree with recent studies that have shown that learning letters trough motor action, via handwriting, benefits visual recognition of the learned script (Longcamp *et. al.*, 2003; Hulme, 1979; Naka & Naoi, 1995) and seems to support the idea that handwriting experience reinforces the formation of a multicomponent neural network for reading, including visual, phonological, and motor representations (Nakamura *et. al.*,2012) Our results further suggest that motor experience with letters through handwriting leads to fine tuning of visual/phonological representations, with more overt attention being directed to the target than to the competitors. This attentional difference is expressed by the score difference obtained on oculomotor measures, confirming our initial hypothesis,

Summing up, the present findings led us to believe that behavioural measures may not always be strong enough to assess subtle differences in this language acquisition paradigm. Although we were able to find group differences in behavioural measures, it was only the oculomotor measures that were more significant. A notorious benefit from the combined training was clear when analysing oculomotor measures, since that from the First Learning Phase (Day 1) to the Last Learning Phase (Day 3) there was a shift of attention from the distractors to the target in both groups, with a significantly increase in the Visual-Motor Group. The fact that this group was the one with better results, highlights the training specific characteristics as an advantage in the visual recognition of a novel script.

Limitations

Future studies should replicate our methodology with a bigger sample and a more extensive Learning Phase, as we believe that increasing the number of participants and the days of learning the conclusions taken from the oculomotor measures will also be reflected in the behavioural data. This belief is supported by the findings found in Karni (1996), where the authors stated that the acquisition of motor skills is a process that progresses over time, requiring several repetitions during successive training sessions in order to achieve automaticity. Other limitation in this study is the sample mortality, since it’s a three-day paradigm with learning, we need the same participant for three days in a row.

One last limitation that can be point out in this study is the fact that we used a sample composed exclusively by educated adults. The sample used in this study is already fluent in their native tongue which can possibly lead to a transfer effect of knowledge to the new learned pseudoletters. In other to overcome this limitation, future studies could use our approach in a longitudinal study of children.

5. Conclusion

This study has an important empirical contribution that may serve as a guideline for future studies. We were able to corroborate the results found in recent studies that stated the potential benefits of handwriting experience during learning to read and write on visual letter recognition, and we extended these studies by showing that this benefit is probably because handwriting training assists the fine tuning of visual and phonological representations. These results have also implications for Education, going beyond their contribution on the perceptual-motor coupling between reading and writing. Handwriting is (still) relevant when learning to read, even in the digital era.

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ANEXOS

Attachment A

Participant Questionnaire

Nome:____

Data de nascimento: ___/___/__ (__ anos e __ meses) - Escolaridade: _______________

Problemas de visão:	Sim		Não	
Problemas de audição:	Sim		Não	
Lateralidade:	Esquerda		Direita	

Dificuldades gerais de aprendizagem:	Sim		Não	
Dificuldades de leitura e de escrita?	Sim		Não	
(Se sim, tem diagnóstico?):				

OBSERVAÇÕES: ____

Provas Realizadas		
Dia1 (1h15') **Data __/__/__**	Leitura: Teste TIL 1 min (papel)	
	Leitura: Teste 3DM (Pc fixo; folha de resposta)	
	Navon Task (portátil)	Set 1 ◻ Set 2 ◻ Set 3 ◻ Set 4 ◻
	learnin I (tablet folha de resposta)	----------------------------
	Training II (portátil e folha de resposta)	----------------------------
	Recognition Task - eyetracking	
Dia 2 (30') **Data __/__/__**	Training I (tablet e folha de resposta)	----------------------------
	Training II (portátil e folha de resposta)	----------------------------
	Reading Task I (portátil e folha de resposta)	
Dia 3 (1h15') **Data __/__/__**	Training I (tablet folha de resposta)	----------------------------
	Training II (portátil e folha de resposta)	----------------------------
	Recognition Task - eyetracking	
	Reading Task I (portátil e folha de resposta)	
	Reading Task II (portátil e folha de resposta)	
	Navon Task	Set 1 ◻ Set 2 ◻ Set 3 ◻ Set 4 ◻

Attachment B

Written Consent Form

Consentimento Informado

Eu,____, aceito de livre vontade participar numa experiência científica devidamente integrada nas atividades de investigação do Grupo de Investigação em Neurociências Cognitivas da Universidade do Algarve.

Uma explicação breve sobre a experiência na qual vou participar foi-me dada e estou esclarecido(a) sobre a mesma. Tive oportunidade de colocar questões sobre a experiência, e estou satisfeito(a) com as respostas. Compreendo que a minha participação no estudo é voluntária e que posso interrompê-la a qualquer momento, sem fornecer qualquer explicação.

Entendo também que, caso o deseje, poderei vir a solicitar um resumo dos resultados do estudo.

-- ---/---/---

ASSINATURA DO PARTICIPANTE DATA

A ser preenchido pelo investigador

O participante supramencionado foi informado sobre a natureza da experiência. O participante foi informado que a experiência será imediatamente interrompida se requerido e que isso não afetará o cuidado que merece.

Assinatura e Data:

Attachment C

Reading Fluency Task

PROVA DE LEITURA - 3DM

Alta Frequência

Folha 1		**Folha 2**		**Folha 3**		**Folha 4**		**Folha 5**	
Lata		Ferro		Circo		Espelho		Escrever	
Foca		Mocho		Barco		Trabalho		Estrelas	
Pele		Banho		Fruta		Carnaval		Depressa	
Bico		Bicho		Grupo		Devagar		Narrador	
Fato		Burro		Jardim		Cigarra		Problema	
Dono		Milho		Pasta		Hospital		Lavrador	
Ramo		Sonho		Clara		Segredo		Conversa	
Fogo		Passa		Pedir		Conhecer		Procurar	
Sono		Carro		Trigo		Esperto		Floresta	
Bolo		Fundo		Jornal		Vermelho		Personagem	
Mata		Palha		Chover		Mensagem		Espantalho	
Belo		Monte		Pastor		Estrada		Importante	
Saco		Linha		Jantar		Presente		Professora	
Vila		Massa		Pardal		Pergunta		Borboletas	
Fome		Ninho		Grilo		Surpresa		Diferentes	
	/15		/15		/15		/15		/15

Total Lidas:

Total de lidas corretas:

Total Erros:

Tempo/item: $\frac{\textit{Lidas Corretas}}{30} =$

Baixa Frequência

Folha 1		**Folha 2**		**Folha 3**		**Folha 4**		**Folha 5**	
Lota		Forro		Cerco		Espelha		Escravos	
Foco		Macho		Barca		Presilha		Espremer	
Pala		Banha		Frota		Cardinal		Caruncho	
Beco		Bucha		Gripe		Divagar		Massagem	
Feto		Birra		Marfim		Cigarro		Grossura	
Duna		Milha		Pasto		Marginal		Pastilha	
Rama		Senha		Cloro		Sagrado		Concurso	
Fuga		Fossa		Podar		Sonhador		Contrato	
Sina		Coche		Prego		Esperta		Frisados	
Bala		Fenda		Farnel		Sardinha		Consumidor	
Mito		Malha		Chocar		Consolar		Desfolhada	
Bule		Manta		Pastar		Estrado		Cintilante	
Soco		Linho		Conter		Presunto		Comprimido	
Vala		Posse		Portal		Surfista		Convocados	
Fama		Pinho		Greve		Discreto		Disfarçado	
	/15		/15		/15		/15		/15

Total Lidas:

Total de lidas corretas:

Total Erros:

Tempo/item: $\frac{\boldsymbol{Lidas\ Corretas}}{\mathbf{30}} =$

Pseudopalavras

Folha 1		**Folha 2**		**Folha 3**		**Folha 4**		**Folha 5**	
Lano		Felha		Cirta		Espretal		Espresa	
Fomo		Rinho		Barlo		Tragunda		Derralas	
Pefa		Bacho		Frugo		Carsagar		Escrema	
Bito		Binho		Gruco		Depeval		Natredor	
Fata		Bussa		Jarnal		Cinalho		Proverta	
Dole		Ticho		Pasco		Hosmeta		Concurar	
Raca		Sorro		Clata		Segrelho		Lablever	
Folo		Palho		Petor		Copergem		Flovrassa	
Sogo		Canha		Tripo		Esgate		Proresdor	
Boco		Funte		Jordir		Versento		Perfetates	
Maco		Panho		Chodim		Mentrasa		Esbotante	
Beme		Monfa		Pasver		Espicer		Impanlegem	
Salo		Lirro		Jandal		Prebarra		Prosossolho	
Vita		Malco		Partar		Pernhedo		Borferentas	
Fono		Nissa		Grira		Survalho		Dipornara	
	/15		/15		/15		/15		/15

Total Lidas:

Total de lidas corretas:

Total Erros:

Tempo/item: $\frac{\textit{Lidas Corretas}}{30} =$

Attachment D

Reading Age Test (TIL)

NOME:.. DATA: .../.../...

Data de Nascimento: .../.../... Ano Escolar:

Nome do(a) Professor(a):...

Jogo de Treino

1. Vou lavar a louça amanhã de manhã porque estou cansado e prefiro ir para a (fila, cola, rádio, cama, cara).
2. O meu irmão fez uma viagem a África e trouxe uma (vila, estátua, marta, estrada, estação).
3. É Primavera e os jardins estão floridos com (rotas, rosalinas, rodas, rosas, folhas).
4. Um homem que conduz um veiculo chama-se (mecânico, companheiro, afinador, condutor, cantor).

TIL/ Fernandes *et. al.*, 2017

1. Pega na saca e vai-me comprar (artes, laranjas, sombras, lâminas, lavatórios)
2. Não comas já o bolo porque ainda está (mente, lento, quente, bom, doce).
3. Todos os cães têm quatro (bocas, patas, pinças, pêras, orelhas).
4. Ele ligou o rádio e ouviu as (notícias, delícias, natas, noites, nervuras).
5. Ele fugiu a correr porque viu um (loto, porco, lago, lado, lobo).
6. Eu gostava de ir para a praia e tomar banho no (nenúfar, mar, marte, morto, muro).
7. A estação é no meio da (piedade, cidade, seriedade, tarde, vontade).
8. Ele partiu a loiça e por isso foi (levado, cortado, premiado, querido, castigado).
9. Um local onde se guardam livros chama-se (pêra, cozinha, divisão, biblioteca, porta).
10. Veste o casaco antes de saíres porque está (calor, frio, freio, fogo, tio).
11. Eles trabalham o dia inteiro, e à noite (olham, quebram, penteiam, descartam, descansam).
12. Podias limpar a sala com uma (tesoura, vassoura, vela, taça, caneta).
13. Ele saiu para ir à caça e por isso levou a sua (guarda, estrela, espingarda, parte, estaca).
14. Ele inclinou-se sobre o poço e caiu ao (fundo, fulo, freio, fato, forno).
15. O meu tio, depois de muito estudar, tornou-se um (médio, médico, maior, senhor, meio).
16. Se tens frio na cama porque é que não pões um (coberto, lenço, cobertor, coelho, coração).
17. Quando se anda na rua é preciso ter muita atenção aos carros para não se ser (dado, transportado, partido, empurrado, atropelado).
18. Durante a noite, espero que tenhas bons (sonhos, olhos, lápis, sorrisos, peixes).

19. Aconteceu uma coisa engraçada a um pescador: pescou uma (carpa, pescada, sapatilha, truta, sardinha).
20. Ele trilhou a mão na porta e desatou a chorar aos (bolos, ditos, atritos, gritos, golos).
21. Todos saíram de casa para ir ver os estragos provocados pela (explosão, exposição, ascensão, expedição, excepção).
22. Os frigoríficos impedem a comida de se (apagar, escaldar, manchar, gelar, estragar).
23. Eles combinaram ir assistir à corrida no próximo domingo porque gostam de ver os carros a correr na (pista, lista, mata, rota, mina).
24. Qual é o teu jogo favorito? Ping-pong, bilhar, dominó ou (camisas, cartas, malas, focas, mãos).
25. Da cratera do vulcão vão saindo ondas de (vaga, lava, fava, cave, lapa).
26. Porque é que não usas a faca para comer o (bico, baile, bife, brinco, bibe).
27. Um amigo empurrou-o e ele caiu pelas (cadeiras, escadas, manadas, camadas, mesas).
28. Os nossos vizinhos compraram um cão grande e mau para ficar à porta de casa, de (corda, fuga, coleira, grade, guarda).
29. É Inverno e de noite choveu muito; as gotas de água eram (gemadas, tiradas, geladas, pinheiros, socos).
30. Fomos passear ao Parque e apanhámos (cascavéis, castanhas, castelos, camelos, cachimbos).
31. Se pusermos o rádio muito alto, arriscamo-nos a incomodar os (peixinhos, dedinhos, azevinhos, vizinhos, adivinhos).
32. Quando lhe ralham e a castigam, ela fica (contente, grande, amável, alerta, triste).
33. O faquir, ao pôr uma faca na palma da mão, deixou-nos (pagos, adiados, escavados, amedrontados, magoados).
34. As pessoas gostam do que é novidade porque isso satisfaz a sua (bondade, amizade, curiosidade, vaidade, justiça).
35. O marido de uma filha é para a mãe dessa filha o (gigante, agente, genro, gesso, gente).
36. Fomos de carro até ao pinhal e depois sentámo-nos a comer a nossa (eleição, rola, refeição, cal, feição).

Attachment E

Production Training (Training II)

Training II Group: M ☐ V ☐ Subj. nº_____

PLetter	Sound	Response		
		Day 1	Day 2	Day 3
PL1	PÁ			
PL6	NÉ			
PL9	CÂ			
PL2	VÉ			
PL8	BU			
PL4	LÂ			
PL12	NI			
PL7	CÁ			
PL5	NU			
PL11	PÉ			
PL3	TU			
PL10	VI			
PL7	CÁ			
PL12	NI			
PL1	PÁ			
PL3	TU			
PL6	NÉ			
PL9	CÂ			
PL2	VÉ			
PL4	LÂ			
PL8	BU			
PL10	VI			
PL11	PÉ			
PL5	NU			
PL4	LÂ			
PL12	NI			
PL7	CÁ			
PL3	TU			
PL10	VI			
PL5	NU			
PL6	NÉ			
PL8	BU			
PL2	VÉ			
PL9	CÂ			
PL11	PÉ			
PL1	PÁ			

Attachment F

Reading Task I

Reading I Group: M ☐ V ☐ Subj. nº_____

Reading Task I	Resposta		
	DIA 1	**DIA 2**	**DIA 3**
Tu			
Pá			
Nu			
Pé			
Cá			
Vi			
Né			
Lâ			
Vé			
Ni			
Bu			
Câ			
Pato			
Cabo			
Bula			
Nuca			
Pála			
Vila			
Bonito			
Canino			
Boneca			
Novela			
Capela			
Tucano			
Butu			
Cáni			
Nuvi			
Pábu			
Páni			
Vivé			
Néca			
Tulâ			
Nicâ			
Pétu			
Pávi			
Nubu			

Bovitu			
Bunuca			
Canica			
Tunéla			
Nupéla			
Cavéca			
Tunila			
Pávitu			
Bupaca			
Vilatu			
Nitula			
Cánuvi			

Attachment G

Reading Task II

Reading II Group: M ☐ V ☐ Subj. nº_____

Reading Task II	Resposta
Pano	
Cano	
Tubo	
Neto	
Cacto	
Véla	
Bovino	
Caneca	
Túnica	
Lapela	
Cábula	
Canela	
Páca	
Cávi	
Tuca	
Néni	
Cáni	
Vénu	
Bupéla	
Canuca	
Túvéca	
Lanuto	
Pátula	
Canibu	

Attachment H

The influence of sensorimotor training in learning a novel script:

A comparison between handwriting and visual training

Catronas, D., Reis, A., Faísca, L., Fernandes, T. & Araújo, S. (2019). *The influence of sensorimotor training in learning a novel script: A comparison between handwriting and visual learning.* 14º Encontro da Associação Portuguesa de Psicologia Experimental, 3 e 4 de Maio de 2019, Universidade de Évora, Évora.