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Lexical orthographic knowledge acquisition in adults: the whole-word visual processing impact

L'apprentissage de l'orthographe lexicale chez les adultes : impact du traitement visuel simultané

Chaves Nathalie ^a, Ginestet Emilie ^b, & Bosse Marie-line ^b

^a Université Paris Est Créteil, Laboratoire CHArt, 75008 Paris, France

^b Univ. Grenoble Alpes, CNRS, LPNC, F-38000 Grenoble, France

Adresses

Corresponding author :

*Nathalie Chaves

Université Paris Est Créteil, Laboratoire CHArt EA 4004 2 rue Jean Macé 94380 Bonneuil s/ Marne

Email : nathalie.chaves@u-pec.fr

Phone : 06.29.45.87.14

Fax : 09.70.62.66 .53

Marie-Line Bosse and Emilie Ginestet

Université Grenoble Alpes, Laboratoire de Psychologie et Neurocognition CNRS UMR 5105
B.P. 47 – BSHM - 38040 Grenoble Cedex 09, France Phone : 33 476 82 56 73

Fax : 33 476 82 78 34

Email :

marie-line.Bosse@univ-grenoble-alpes.fr

emilie.ginestet@univ-grenoble-alpes.fr

Lexical orthographic knowledge acquisition in adults: the whole-word visual processing impact

L'apprentissage de l'orthographe lexicale chez les adultes : impact du traitement visuel simultané

Summary

Introduction

One of the most persistent difficulties in French written language acquisition is lexical orthographic memorization. Both theoretical models and behavioral studies have suggested that simultaneous visual processing of all the letters of a word could be important for the acquisition of its orthographic form.

Main goal

Two experiments are conducted to test this whole-word visual processing hypothesis.

Method

The paradigm used in both experiments is a self-teaching paradigm in which adult participants had to read orthographically complex bisyllabic pseudowords in isolation. In one reading condition, all the letters of the item are available at once, in the other the first and second syllables are seen successively. After reading, participants had to spell under dictation and to recognize the written items.

Results

Globally, the results showed that participants better recall the orthographic form of a word after having read it in the whole-word reading condition. The result of the recognition task, in the second experiment, was in line with the result of the spelling under dictation task.

Conclusion

These results, although they should be interpreted with caution, are in line with the whole-word visual processing hypothesis. Applied consequences for orthographic learning and teaching, as for remediation of specific orthographic disabilities, are discussed.

Keywords : self-teaching, spelling, reading, whole-word visual processing, adults

Résumé

Introduction

Une des difficultés les plus importantes dans l'apprentissage du français écrit concerne la mémorisation de l'orthographe. Des modèles théoriques et des études comportementales suggèrent que le traitement visuel simultané de toutes les lettres d'un mot serait important pour la mémorisation de son orthographe.

Objectif principal

Deux expériences ont été conduites pour tester cette hypothèse de l'importance du traitement visuel mot-entier.

Méthode

Le paradigme utilisé est un paradigme d'auto-apprentissage dans lequel les participants adultes doivent lire des mots bisyllabiques complexes présentés isolément. Dans une condition de lecture, toutes les lettres de l'item sont vues en même temps, dans l'autre les deux syllabes de l'item sont présentées successivement. Après la lecture, les participants doivent écrire les items sous la dictée, puis les reconnaître à l'écrit.

Résultats

Globalement, les résultats montrent que les participants retrouvent mieux l'orthographe d'un item après l'avoir lu dans la condition de lecture mot-entier. Le résultat de la tâche de reconnaissance, dans la seconde expérience, est en accord avec le résultat de la tâche de dictée.

Conclusion

Ces résultats, bien que devant être interprétés avec précaution, sont en accord avec l'hypothèse du traitement visuel mot-entier. Les conséquences appliquées de cette hypothèse sont discutées, pour l'apprentissage et l'enseignement de l'orthographe comme pour la remédiation aux troubles spécifiques d'acquisition de l'orthographe.

Mots clés : auto-apprentissage, orthographe, lecture, traitement visuel simultané, adultes

Introduction

Learning to read and write is of critical importance at school, but it is a long and complex process, especially in the case of nontransparent languages like English and French. Although it is generally admitted that reading and spelling production use the same processes, writing is often more inconsistent than reading, especially in French (Peereman, 1999; Veronis, 1998; Ziegler, Jacobs, & Stone, 1996). This complexity requires the acquisition of word-specific orthographic knowledge. This entails establishing connections between written and spoken forms of lexical units (Ehri, 2005). According to the self-teaching hypothesis (Share, 1995, 1999, 2004), when a word has been correctly decoded, we memorize its written form.

Most of the studies that have investigated orthographic learning so far have focused on children (Bosse et al., 2015; Bowey & Muller, 2005; Wang, Castles, Nickels, & Nation, 2011; Nation, Angell, & Castles, 2007; Share, 2004; Tamura, Castles, & Nation, 2017; Tucker, Castles, Laroche, & Deacon, 2016). All of these used variations of the self-teaching paradigm (Share, 1999), where children had to read novel words that were either embedded in short stories (Share, 1999, Exp. 1) or presented without any context at all (Share, 1999, Exp. 2 and 3). Word-specific knowledge was tested after a variable interval by means of spelling to dictation tasks, orthographic choice tasks in which children had to choose a target word from several different spellings, and naming tasks. Results showed that lexical orthographic learning took place after successful phonological decoding. Furthermore, Share (1999, Exp. 2) highlighted the importance of phonological processing, by asking children to read novel words silently whilst pronouncing a series of syllables. He showed that when phonological recoding was minimized, word-specific learning was less efficient. A number of studies have investigated the self-teaching hypothesis (Bosse et al., 2015; Bowey & Muller, 2005; Cunningham, 2006; Cunningham, Perry, Stanovich,

& Share, 2002; Kyte & Johnson, 2006; Martin-Chang, Levy, & O'Neil, 2007; Nation, Angell, & Castles, 2007; Ricketts, Bishop, Pimberton, & Nation, 2011; Share, 1999, 2004; Share & Shalev, 2004; Schwartz, Kahn-Horwitz, & Share, 2014; Tucker, Castles, Laroche, & Deacon, 2016). Each of them has yielded insights into self-teaching. Thus, the self-teaching hypothesis has been demonstrated with both pseudowords and real words (Bosse et al., 2015; Bowey & Muller, 2005; Cunningham, 2006; De Jong & Share, 2007; Kyte & Johnson, 2006; Nation et al., 2007), displayed either in context or in isolation (Nation et al., 2007; Share, 2004) in a variety of languages, including Hebrew (Share, 1999, 2004), Dutch (de Jong, Bitter, Van Setten & Marinus, 2009), English (Cunningham et al., 2002; Kyte & Johnson, 2006) and French (Bosse et al., 2015), and read either aloud or silently (Bowey & Miller, 2007; De Jong & Share, 2007; De Jong et al., 2009).

Nation et al. (2007) manipulated the number of readings, with pseudowords being displayed 1, 2 or 4 times. Their results on the orthographic choice task indicated that orthographic learning begins from the first reading but improves after four readings. Bowey and Muller (2005) reported a higher self-teaching score after eight readings than after just four. Although Share and Shalev (2004) found significant learning from the first exposure onwards in second graders, Nation et al. (2007) suggested that the transparency of the Hebrew language might explain this result: for more transparent languages, fewer readings could be required to memorize words. Some researchers have investigated the retention of the orthographic form in long-term memory, but the interval between the learning phase and post-tests varied and results were divergent. Bowey and Muller (2005) and Nation et al. (2007) reported that pseudowords were better recognized after a short interval (0 day for Nation et al., 2007, and 1 day for Bowey & Muller, 2005) than after a long one (6 and 7 days, respectively). Share (2004), meanwhile, observed retention 30 days after the learning phase. Methodological differences between studies may explain the results. For example, in Share (2004), children had to choose between two homophonic pseudowords, whereas in Nation et al. (2007) the choice was between four pseudowords.

The self-teaching paradigm has also been studied in bilingualism and biliteracy contexts (Schwartz et al., 2014), as well as in readers with learning disabilities (Share & Shalev, 2004). Results have consistently shown a significant positive association between target decoding success and orthographic learning in children. Recently, several computational modelizations of the self-teaching hypothesis have been implemented in a dual-route framework (Perry, Zorzi, & Ziegler, 2019; Pritchard, Coltheart, Marinus, & Castles, 2018; Ziegler, Perry, & Zorzi, 2014). Globally, these simulations confirm that decoding skills could be a sine qua non of lexical orthographic acquisition.

As we keep on learning to read and spell new words throughout our lives, what about self-teaching on adult expert readers? Actually, orthographic word acquisition has been also explored in adults, but mainly using intensive learning with repetitions and explicit instruction on artificial languages (Taylor, Plunkett, & Nation, 2011). However, a few researches have used the classical self-teaching paradigm with adults to explore some specific factors. For example, Sobaco, Treiman, Peereman, Borchardt, and Pacton, (2015) showed that self-teaching is influenced by the graphotactic legitimacy of the spellings. Two recent studies have used eye-tracking measures to explore the self-teaching of expert readers. Joseph, Wonacott, Forbes, and Nation (2014) explored eye movements while adult participants read pseudo-words embedded in sentences. Eye movement tracking revealed an effect of repeated exposure of pseudo-word on processing time, with shorter first fixation duration over exposures. Pagan and Nation (2019) measured eye movements as adult participants silently read meaningful sentences containing rare English words that were presented four times during the learning phase. Their results qualitatively show an effect of repeated exposures on eye movements, namely shorter processing time across exposures, as previously reported by Joseph and Nation (2014). Overall, these studies with adults show that processing time of new written words evolve rapidly with exposures, suggesting that new orthographic items are recognized after only a few readings. As their decoding skills are highly automated, it seems plausible that adults can learn very quickly the orthography of words

they read for the first time. However, it is likely that their self-teaching mechanisms are the same as those of children.

If decoding (phonological factor) is a precondition for acquiring orthographic knowledge, a growing number of data also suggests that it is probably not the only factor involved (e.g., Bosse, 2015; Nation & Castles, 2017). For example, good readers are not always good spellers (Fayol, Zorman & L  t  , 2009). At an item level, words that haven't been successfully decoded are sometimes successfully memorized and spelled (Castles & Nation, 2006; Castles & Nation, 2008; Nation, Angell, & Castles, 2007; Tucker, Castles, Laroche, & Deacon, 2016). While decoding accuracy during the learning phase has been shown to predict a significant amount of variance in orthographic learning, prior orthographic processing skills also regularly appears to contribute (Cunningham, Perry, & Stanovich, 2001; Cunningham, 2006). So, what could be the cognitive skills which influence self-teaching beyond decoding skills? Some researchers have suggested that a semantic factor is involved (Martin-Chang & Levesque, 2015; Ouellette, 2010; Ricketts et al., 2011). Accordingly, recent computational modelizations of self-teaching suggested that semantic context is particularly relevant to memorize irregular orthographic patterns (Ziegler et al., 2014; Pritchard et al., 2018). Some data also suggested a role for orthographic analogies and morphological processing in the self-teaching process (Pacton, Foulin, Casalis, & Treiman, 2013; Tucker et al., 2016).

Visual-orthographic processing has also been regularly mentioned in the literature as another influential factor for orthographic acquisition (e.g., Castles & Nation, 2008; Nation et al., 2007; Share, 2008). For example, Share (2008) showed that phonological processing explains the major part of variance in orthographic self-teaching when the language is transparent, but that visual-orthographic processing is the main predictor when the written language is opaque. In a self-teaching experiment using a lower-case format versus a mixed-case format (e.g., jung vs.

JuNg), which is supposed to disrupt the simultaneous processing of letter strings, Martens and de Jong (2006) showed that items are better recognized after been read in a lower-case format. These data suggest that orthographic memorization depends on the ability to simultaneously process all the letters of the item.

This hypothesis is in accordance with a computational modelization of polysyllabic word reading MTM (multitrace memory model), which includes a visual attentional window to process the letter strings (Ans, Carbonnel, & Valdois, 1998). Thanks to this window, of variable size, the model can process all the letters of a word simultaneously or sequentially. Although the MTM is an expert reading model, its implementation involves learning. A new word memory trace (i.e., an orthographic lexical form) is created each time the word's entire orthographic input and entire phonological input are simultaneously available, as in the self-teaching hypothesis. For this to take place, the visual attentional window has to extend across the word's entire letter string. Therefore, according to the MTM, what is important in the acquisition of lexical orthographic knowledge is the simultaneity of the phonological processing and the whole-word visual attentional processing. The existence of a whole-word visual processing was also hypothesized in both theoretical (Grainger & Ziegler, 2011) and computational (Pritchard et al., 2018) reading acquisition models using a classical dual-route framework (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001).

Simultaneous visual processing relates to the visual attention span defined as the number of distinct visual elements (e.g., letters) that can be simultaneously processed at a glance (Bosse et al., 2007). Several studies have investigated the relationships between lexical orthographic learning and visual attention span in both normal readers and children with dyslexia (Bosse et al., 2007; Bosse & Valdois, 2009; Valdois et al., 2011; Valdois et al., 2003; Valdois, Bosse, & Tainturier, 2004; Valdois, Roulin, & Bosse, 2019). In their cross-sectional study with 417 typical readers, Bosse and Valdois (2009) found that visual attention span contributes to reading

performance independently of the phonological factor, from the 1st to the 5th grade. Moreover, visual attention span contributes especially to reading speed and irregular word reading. A recent longitudinal study (Valdois et al., 2019) confirmed the causal link between visual attention span and reading speed, suggesting that simultaneous visual processing capacity for a letter string is specifically related with orthographic knowledge acquisition. Studies have also examined the link between visual attention span and reading skills in children with dyslexia. For instance, when Bosse et al. (2007) administered a battery of tests including reading, phonological and visual-attentional tasks to children with dyslexia, results indicated that their reading speed was predicted by their visual attention span. Other studies of children with learning disabilities have revealed that visual attention span deficits can be dissociated from phonological deficits (Dubois et al., 2010; Valdois, 2008) and short-term verbal memory (Lassus-Sangosse et al., 2008).

To summarize, several studies indicate that the visual orthographic factor postulated by different researchers (Cunningham et al., 2002; Nation et al., 2007; Share, 1995, 1999) could be defined as whole-word visual processing. This concept, drawn from the MTM (Ans et al., 1998), can be defined as the ability to distribute visual attention across a set of written signs in order to process them simultaneously (Bosse et al., 2007; Valdois et al., 2019). Various studies have highlighted the relationship between visual attention span and lexical orthographic knowledge acquisition in both normal readers and children with dyslexia, and a recent longitudinal study provided evidence of a causal link between whole-word visual processing and reading speed (Valdois et al., 2019). Bosse et al. (2015) explored this causal link using a self-teaching paradigm in which the availability of the visual information was manipulated. Children had to read isolated pseudowords on a computer screen. In one reading condition, all the letters of the word were available at once, and whole-word visual processing was therefore possible. In the other reading condition, the pseudowords were displayed syllable by syllable, thus preventing whole-word

visual processing. Then, participants performed two tasks to measure their orthographic learning; a spelling dictation task and an orthographic choice task. Results in the orthographic choice task indicated that the possibility of simultaneously processing the entire orthographic letter string contributed to a better orthographic memorization. Thus, this experiment, for the first time, suggested that simultaneous visual processing of the whole letter string enhances orthographic learning. However, the paradigm had some weaknesses which introduced uncontrolled variability. In particular, the duration of item presentation was not fixed and the participants had to use the spacebar to control syllable scrolling.

The main goal of the two experiments described below was to try to replicate the results obtained by Bosse et al. (2015) with a better controlled paradigm. In the new paradigm, as in the one of Bosse et al., (2015), two reading conditions were compared, one which avoids a simultaneous processing of letters during reading and the other which permits this simultaneous processing. However, unlike the paradigm of Bosse et al. (2015), the item duration was fixed for all items in both reading conditions, and the only task of the participants during the learning phase was to read. The two experiments had the same main objective, but their material differ slightly in order to better control eye movements during items reading. Experiments were conducted on French adults. As mentioned earlier, adults probably memorize the orthography of words they read, faster than children. As the present paradigm strongly constrained reading (each syllable is only seen during 200ms), adult participants were more relevant.

Beyond the theoretical issues, a better understanding of the cognitive mechanisms involved in orthographic acquisition could be useful in several applied domains. In non-transparent orthographies like French, the orthographic acquisition is very hard (e.g., Manesse & Cogis, 2007) and teachers are regularly helpless in the face of students' spelling difficulties. With a better knowledge of visual processing mechanisms, new methods to improve orthographic acquisition could be developed.

Experiment 1

Method

Participants

Twenty-three students (19 women) from a teacher training college in Grenoble (France) took part in this study. They were all native French speakers and had normal or corrected-to-normal vision. Their mean chronological age was 39 years ($SD = 9$), and they had spent 3.5 years on average in higher education ($SD = 1.6$; from 2 to 8 years after the bachelor's degree). The level of general orthographic knowledge of the participants was assessed by a dictation task comprising 60 irregular or inconsistent words. Their mean score was 46.2 ($SD = 7.7$, range 24-56). Participants' visual attention span was assessed with the global and partial report tasks developed at the Psychology and NeuroCognition Laboratory (LPNC) of Grenoble University (Bosse et al., 2007; Bosse & Valdois, 2009; Dubois, Lafaye de Micheaux, Noël, & Valdois, 2007). Their mean score was 86.8% ($SD = 16.1$, range = 34.3-98.7).

Material

Control tasks

General orthographic knowledge, word dictation task

Sixty inconsistent or irregular words (see **Appendix**) were drawn from the Lexique database (New, Pallier, Ferrand, & Matos, 2001). Thirty words were very infrequent (mean book frequency = .44, $SD = .29$, range = .07-.95) and 30 words were very frequent (mean book frequency = 7.70, $SD = 7.45$, range = 1.15-33.24). The mean word length was seven letters ($SD = 1.7$, range = 4-11), five phonemes ($SD = 1.5$, range = 2-10) and two syllables ($SD = .7$, range = 1-4).

Visual attention span

Global report and partial report were used to assess participants' visual attention span.

Global report. We constructed 20 random 5-letter strings with 10 consonants (*B, P, T, F, L, M, D, S, R, H*). Each letter appeared 10 times (twice in each position). None was presented twice in succession, and no two consecutive letters could form a grapheme (e.g., *PH*). The uppercase letters were displayed in Geneva size 24 font in black on a white background, 1 cm apart, to minimize lateral masking. A central fixation point was displayed for 1000 ms, followed by a blank screen for 500 ms. Each letter string was displayed in the center of the screen for 150 ms. Participants were required to orally recall the five letters immediately after they had disappeared. Two scores were recorded: the first corresponded to the number of 5-letter strings that were accurately reported (max = 20), and the second to the number of letters that were accurately reported across the 20 trials (max = 100).

Partial recall. Fifty random five-letter strings were constructed with the same uppercase consonants that had been used for the global recall. Each letter occurred 25 times, five in each position. The font and presentation were the same as for the global recall. A central fixation point was displayed for 1000 ms, followed by a blank screen for 500 ms. A five-letter string then appeared for 150 ms. When this five-letter string disappeared, a vertical bar was displayed for 50 ms, 1 cm below the target letter. Participants therefore had to orally recall a single cued letter from the five-letter string. The score corresponded to the number of letters that were accurately reported (max = 50).

We calculated a composite score from these three scores, corresponding to the mean percentage of success (max = 100%).

Orthographic learning task

Target pseudowords

We began by making a list of 14 single phonemes or phoneme pairs, each of which could be written with two or more complex graphemes (Table 1). Using this list, we then created 28 bisyllabic pseudowords ranging in length from five to nine letters (mean = 7.1, $SD = 0.9$).

Insert Table 1

Each syllable of the pseudoword included two complex graphemes. No syllable was a real word in French, and no pseudoword had an orthographic neighbor, i.e. a word of the same length that contains the same letters except one (New, Pallier, Ferrand, & Matos, 2001). Twenty-eight pseudowords were created and allocated into two sets (Table 2). Each set contained a same homophonic pseudoword written with different spelling (e.g., /betar/ was *baitare* in Set A and *beitart* in Set B). The 28 complex graphemes appeared in each set. Then, we subdivided each set into two subsets in which appeared one of the two complex graphemes spelling (Table 2).

Insert Table 2

Reading condition

The 14 pseudowords appeared, one at a time, in random order. The randomized list was read twice. Participants had to read aloud the target pseudoword which appeared. These pseudowords were displayed in bold black letters (Courier New size 24 font) in the center of the white screen. Half of the target pseudowords were seen in a simultaneous reading condition (SIM), and the other half were seen in a sequential reading condition (SEQ). In the SIM condition, after the central fixation point, all the letters of the pseudoword were displayed on the screen for 200 ms, and participants had to read the pseudoword aloud (Figure 1A). In the SEQ condition, after the central fixation point, the first syllable was displayed for 200 ms and participants had to read it

silently. The second syllable was then displayed for 200 ms, while the first was masked (Figure 1B). Participants had to read aloud the pseudoword as quickly as possible.

In both reading conditions, the presentation time for each letter was 200 ms. Target presentation was computed with E-Prime software (Version 2.0; Psychology Software Tools, Pittsburgh, PA, US).

Insert Figure 1.

Orthographic learning measurements

Participants performed two tasks to measure their orthographic learning.

Spelling dictation task

The experimenter dictated the 14 pseudowords (random order) and participants had to write them on separate sheets of paper. If needed, each pseudoword was repeated a second time. Two scores were recorded: the number of entire words that were correctly written (max = 14) and the number of complex graphemes that were correctly written (max = 28).

Orthographic choice task

This computer-based task was computed with E-Prime (Version 2.0; Psychology Software Tools, Pittsburgh, PA, US). After a central fixation point, each pair of homophonic pseudowords (e.g., baitare - beirtart) was immediately displayed in bold letters on the screen (Courier New size 24 font; Figure 2). Participants had to press the Q or M key, depending on whether they recognize the pseudoword read on learning phase on the left or on the right. The pair remained on the screen until participants had made their choice. We recorded their reaction time (RT). The recording was triggered with the onset of the pair of homophones and ended when the participant pressed one of the keys.

Insert Figure 2

Procedure

Each participant was seen individually twice, on two consecutive days. Each session lasted approximately twenty-five minutes. The first day, the visual report tasks are followed by the learning phase. Randomly, 12 adults read the 14 pseudowords of set A, and 11 adults read those of set B. Training was first provided with 5 simple bisyllabic pseudowords read in the SIM condition and 5 in SEQ condition. Feedback was given during training. During the learning phase, each participant read 28 items, consisting of 14 pseudowords (seven in the SIM condition and seven in the SEQ condition) presented twice in random order. Their reading was recorded and the number of decoding errors was taken into account.

The next day, participants performed the spelling dictation and orthographic choice tasks featuring the 14 pseudowords they had previously read, ending with the 60-word spelling dictation control task.

Results

Preliminary analyses

Preliminary analyses were carried out to assess whether pseudoword reading accuracy differed according to the reading condition. Indeed, in order to be able to interpret the results on spelling learning, it was very important to control that the sequential reading condition does not modify reading performance during the learning phase. A t test was performed to compare the mean numbers of decoding errors produced during the learning phase in each reading condition. No difference was found, $t(22) = -1.12$, ns . There were 6.2% errors on average in the SIM condition and 8.7% in the SEQ condition. The words were read well in both reading conditions.

Pseudoword spelling dictation task

We began by analyzing the whole-word dictation score (Table 3). The exercise had proved very difficult. Few pseudowords were correctly spelled (16.7% in the SIM condition and 8.7% in the SEQ condition). However, there was a significant reading condition effect, $t(22) = 2.41, p < .05$. In line with our hypothesis, spelling was better when all the letters of the item had been simultaneously available to participants.

We then analyzed the numbers of correctly written graphemes (Table 3). In each reading condition, 14 graphemes could be correctly written (two for each pseudoword). No significant effect was found between the reading conditions, $t(22) = 0.77, ns$.

Correlations were calculated in order to examine the relations between the dictation scores and 3 control measures: pseudoword reading accuracy, general orthographic knowledge and visual attention span. The whole-word dictation score correlated with none of these control measures. The number of correctly written graphemes significantly correlated with decoding accuracy ($r = .42, p < .05$), the other correlations are not significant.

Orthographic choice task

The scores were the number of correctly recognized pseudowords and their RTs. RTs below 150 ms were removed. We then carried out a final selection, retaining RTs within two standard deviations of the mean. Finally, a logarithmic transformation was undertaken.

Insert Table 3

We ran a chi-square test on the number of correctly recognized pseudowords in the SIM condition, to check that participants had not chosen between the two homophonic pseudowords at random ($\chi^2 = 89.9, p < .0001$). We then did the same for the answers in the SEQ condition ($\chi^2 = 85.22, p < .0001$). This orthographic choice task revealed successful learning. Almost 75% of

pseudowords were correctly recognized on average. We had expected that participants would recognize more items when they had been read in the SIM condition in the learning phase. However, the differences between the two reading conditions, in terms of the numbers of correctly recognized pseudowords and RTs, were not significant, respectively $t(22) = 1.63$, *ns*, and $t(22) = -1.87$, $p = .08$, although there was a tendency for participants to recognize the target item more quickly when it was read in the SIM condition.

As for the dictation scores, correlations were calculated in order to examine the relations between the orthographic choice scores and the 3 control measures. There was no significant correlations between these control measures and the number of correctly recognized items. The only significant correlation was between the RTs and the visual attention span ($r = -.55$, $p < .01$).

Discussion

Results of this study revealed that, regardless of reading condition (SIM vs. SEQ), pseudowords were correctly decoded. The syllable presentation time (200 ms) was sufficiently long for them to be read in both conditions. Dictation task results seemed to support our hypothesis. The entire orthographic form of the pseudowords was better memorized when whole-word visual processing was possible. Furthermore, it is important to note that the reading condition had an impact on the whole-word score but not on the grapheme score. Thus, the simultaneous processing seems to promote only the memorization of entire word orthography that is, in our case, the combination of several complex graphemes in a single word, but not the memorization of complex graphemes themselves.

Nevertheless, the orthographic choice task results were not significant. In line with our hypothesis, we only observed a trend toward significance for RTs. Thus, in this self-teaching study with adults, we observed an effect of reading condition in the pseudoword spelling

dictation task, but not in the orthographic choice task, in contrast to the results reported by Bosse et al. (2015). These unstable results commit us to better consider the factors that could make them vary.

In the SIM condition, participants could simultaneously see all the letters in the pseudowords, whereas in the SEQ condition, they could not. However, there was a further difference between the two reading conditions. In the SIM condition, as the entire pseudoword was displayed 200ms in a central position on the screen after the central fixation point, participants did not need to make any saccade to read. In the SEQ condition, however, the first syllable appeared to the left of the fixation point during 200ms, and the second appeared to the right during 200ms also. Therefore, participants had time to make a saccade, and they probably made one to look **at** the second syllable when it appears. This may have hampered the processing of the items and affected memorization. Thus, the learning difference we observed between the two reading conditions may have been due not to the possibility of engaging in simultaneous visual processing, but to the inconvenience caused by the inevitable saccade in the SEQ condition. In the following experiment, we modified the experimental paradigm to allow us to control the impact of the saccade on memorizing the orthographic forms of the pseudowords.

Experiment 2

In the SEQ condition of Experiment 1, the first syllable was displayed to the left of the fixation point, and the second to the right. Readers presumably had to perform a saccade, which may have prevented them from allocate their attention normally, especially to second syllable. In this second experiment, we changed the presentation of items in the SEQ condition so as not to induce any saccades.

Based on our hypothesis that orthographic learning relies on whole-word visual processing, we predicted that, even without a saccade, the SEQ condition would still hinder the acquisition of orthographic knowledge.

Participants

Twenty-eight individuals (24 women) drawn from all socio-occupational categories took part in this experiment. They were all native French speakers and had normal or corrected-to-normal vision. Their mean chronological age was 27 years ($SD = 4$), and they had spent 3.5 years on average in higher education ($SD = 1,8$; from 0 to 8 years after the bachelor's degree). As before, we assessed the participants' level of orthographic knowledge with the dictation task featuring 60 irregular or inconsistent words. Their mean score was 40.8 ($SD = 9$, range = 18-55). Their mean visual attention span was 87.25% ($SD = 10.8$, range = 62-100).

Material

Orthographic learning task

Target pseudowords

The phoneme list was the same as in Experiment 1. However, with a view to improving the material, we took a further criterion into account when constructing the pseudowords, namely syllable occurrence.

For these new pseudowords, no syllable resembled a real word in French, but all the syllables existed in the French language, according to the Lexique database (New, Pallier, Ferrand, & Matos, 2001). For instance, the first syllable of *handeau* can be found in the word *hanche*, and the second in *cadeau*. By contrast, the second syllable in the pseudoword *hancheau* (Experiment 1) does not exist in French.

The 28 pseudowords were divided into two sets and two subsets (Table 4), as in Experiment 1.

Thus, the phoneme /ɛ/ appeared in the pseudowords /bɛkar / and /lɛfö /. It was spelled *ei* in the

pseudoword *beicart* in Set A and *leiphon* in Set B, and also *ai* in *laiffon* in Set A and *baicare* in Set B. The set (A or B), subset (1 or 2) and syllable (S1 or S2) variables were entered into an analysis of variance (ANOVA). Results showed no difference in syllable occurrences between sets and subsets ($F < 1$).

Insert Table 4

Reading condition

The learning phase was the same as in Experiment 1. Participants had to read aloud 2 times the 14 pseudowords displayed on the screen in isolation and in random order. Half the items were seen in a SIM condition like the one in Experiment 1 (presentation duration was 200 ms). The other half were seen in a SEQ condition that differed from the first experiment in that each syllable was displayed in a central position for 200 ms (Figure 3B). Thus, in this condition no saccade was required to visually process each syllable, and the second syllable served to mask the first one.

Insert Figure 3

Orthographic learning measurements

The tasks were the same as in Experiment 1 (spelling dictation task followed by an orthographic choice task).

Procedure

Participants were tested individually in two separate sessions on successive days. Each session lasted approximately twenty-five minutes. The 28 participants were randomly allocated to set A or set B, with 14 in each set. Session 1 began with the visual report tasks, followed by the

pseudoword learning phase, after participants had practiced with 10 simple items. During the learning phase, we recorded two scores: the number of correctly decoded words and reading speed.

In Session 2, the following day, we tested the participants' orthographic learning with the pseudoword spelling dictation task, followed by the orthographic choice task. For each task, we recorded two scores: the numbers of words and graphemes correctly written for the dictation task, and the number of correctly recognized words and RTs for the orthographic choice task. Finally, participants performed the 60-word control dictation task to check their spelling level.

Results

Preliminary analyses

It was important to check that reading performances were equivalent in both conditions. Pseudowords were generally well decoded (88% in SIM and 87.5% in SEQ). Student's t test was used to compare the mean number of pseudowords correctly decoded in each reading condition (SIM vs. SEQ). There was no significant result, $t(27) = 0.33$, ns , indicating that the presentation in the SEQ condition did not hamper participants' reading. We also measured reading speed. In the SIM condition, it took participants 582 ms on average to read the pseudowords, compared with 544 ms in the SEQ condition. Analysis following a logarithmic transformation (Howell, 2007; Ratcliff, 1993) did not reveal any impact of reading condition on reading speed, $t(26) = .55$, ns . Thus, pseudowords could be quickly and correctly read in both learning conditions.

Spelling dictation task

Overall, dictation performances were relatively weak, despite better control of pseudoword construction. Only 19% of pseudowords were correctly written in the SIM condition, and 12% in the SEQ (Table 5). However, despite these poor scores, statistical analysis indicated the same

results as in Experiment 1, with a better score on the dictation task in the SIM condition, $t(27) = 2.25$, $p < .05$, in terms of the number of correctly spelled words. Reading condition ceased to have a significant effect when we considered the number of correctly written graphemes, $t(27) = 1.77$, *ns*. These results therefore replicate those of experiment 1. Whole-word visual processing of the pseudowords specifically promoted entire word spelling acquisition, that is the association of several specific graphemes in the same word, but not the acquisition of isolated specific graphemes.

As in Experiment 1, correlations were calculated in order to examine the relations between the dictation scores and 3 control measures: pseudoword reading accuracy, general orthographic knowledge and visual attention span. No correlation was significant.

Orthographic choice task

The scores were the number of correctly recognized pseudowords and their RTs. RTs below 150 ms were removed. We then carried out a final selection, retaining RTs within two standard deviations of the mean. Finally, a logarithmic transformation was undertaken.

In contrast to Experiment 1, results on the recognition task confirmed the effect of reading condition, with 74% of correctly recognized pseudowords in the SIM condition and 62% in the SEQ (see Table 5), the difference was significant: $t(27) = 2.33$, $p < .05$. The effect of reading condition on RT was not significant, $t(26) = 0.24$, *ns*.

As in Experiment 1, correlations were calculated in order to examine the relations between the orthographic choice task and 3 control measures: pseudoword reading accuracy, general orthographic knowledge and visual attention span. No correlation was significant.

Insert Table 5

Discussion Experiment 2

The results of the second experiment replicate those of the first one on the dictation task, suggesting once again that the entire orthographic form of the pseudowords was better memorized when whole-word visual processing was possible. Once again, the difference between the two learning conditions was significant only on the whole-word orthographic knowledge and not on the number of complex graphemes remembered. This result confirms the hypothesis that the simultaneous letter-string processing favors the whole-word memorization but not the memorization of complex graphemes themselves. Moreover, the analysis of the orthographic choice task in the second experiment also showed a significant effect of the learning conditions. In line with the hypothesis, items were better recognized after having been read in the simultaneous condition.

General Discussion

Reading is a fundamental situation of orthographic self-teaching. All the literature suggests that other cognitive processes are involved in this acquisition, besides reading-decoding skills. Visual orthographic processing is frequently mentioned in this context (Lennox & Siegel, 1994, 1998; Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, 2004; Rocher & Chanquoy, 2004; Share, 1995, 1999; Snowling, Goulandris, & Stackhouse, 1994), but generally in rather vague terms. In accordance with the MTM model of reading (Ans et al., 1998) and studies of visual attention span (e.g., Bosse et al., 2007; Dubois et al., 2010; Valdois et al. 2003; Valdois et al., 2004; Valdois et al., 2019), we hypothesized that whole-word visual processing influences orthographic form memorization, with orthographic self-teaching through reading depending not only on decoding skills, but also on the simultaneous availability of all the letters forming the word. The

aim of the two experiments we carried out here was to explore the role of whole-word visual processing in orthographic acquisition in a self-teaching paradigm (Share, 1999, 2004). We contrasted a reading condition where all the letters of the items were simultaneously displayed (SIM) during training, to allow whole-word visual processing, with one where the items were sequentially displayed (SEQ), meaning that the letters of the items were never all visible at the same time. We discuss our results in the light of both the self-teaching hypothesis and the whole-word visual processing hypothesis.

Self-Teaching Hypothesis and Orthographic Learning

Our experiments with adults provided additional support for the self-teaching hypothesis, which has been developed on the context of children learning to read and spell but which can be extended to all situations where readers, even expert ones, discover new orthographic items. First, we checked that pseudoword reading accuracy during the learning phase was equivalent across the two reading conditions. Pseudoword reading was very good in both experiments (approximately 90% success rate in both experiments), showing that 200 ms were sufficient for pseudoword reading. In accordance with the self-teaching hypothesis that a new orthographic form can be learned when it has been correctly read, the participants have learned, but not perfectly, the complex orthographic form of pseudowords they read only 2 times. Interestingly, decoding accuracy during the learning phase is positively correlated with the number of graphemes correctly spelled in the dictation task, but not with the whole-word score. This result suggests that decoding accuracy is more important for memorizing specific graphemes than for memorizing a whole orthographic pattern. However, the absence of significant correlation between their pseudoword decoding ability and the whole-word spelling score could also be due to the good reading performance (ceiling effect) and the small sample size. As a whole, because of their excellent reading skills, it seems not pertinent to test the relation between decoding skills

and orthographic learning with adult participants. On the contrary, this situation seems extremely interesting to test the other factors which could influence orthographic learning, beyond decoding skills.

Results on the orthographic choice task showed that nearly 70% of pseudowords were well recognized in both experiments, more than by chance (i.e., 50%). Scores on the pseudoword spelling dictation task were extremely low (13%) in Experiment 1, and slightly higher (25%) in Experiment 2. Spelling to dictation is a more difficult task, as all the letters of the word have to be written in the right order, whereas an orthographic choice task does not require letter-by-letter processing. The difference in spelling to dictation scores between the two experiments can be explained by the difference of items. In Experiment 2 pseudowords had been better controlled so that they contained more plausible spellings for French spellers (all of their syllables were existing syllables in French). Then, the better spelling score in Experiment 2 could be linked to the influence of graphotactic frequencies on spelling acquisition (Pacton, Sobaco, Fayol, & Treiman, 2013). On the whole, the absence of ceiling performance in orthographic tasks, even in the easier recognition task, confirms that lexical orthographic acquisition could begin from the first encounters with the new word (e.g., Share & Shalev, 2004), but needs much more occurrences than two to be perfect.

Whole-Word Visual Processing hypothesis and Orthographic Learning

The main result of our two experiments is that whole-word visual processing allows for lexical orthographic acquisition, whereas sequential processing necessarily hinders this acquisition. This finding was confirmed with different paradigms and different pseudowords. In both experiments, self-teaching of the specific spelling of new items through reading was poorer when the pseudoword presentation prevented whole-word visual processing (SEQ condition). As the self-teaching hypothesis indicates that reading accuracy is the most important factor affecting

orthographic learning, we systematically compared decoding accuracy across the reading conditions (SIM vs. SEQ). In both experiments, pseudoword reading was just as successful in the SIM condition as in the SEQ condition. In the second experiment, where we checked reading times, the difference was not significant, confirming that the SEQ condition did not hinder decoding.

However, consistently in both experiments, the words read in the SIM condition were better spelled under dictation than those read in the SEQ condition. This effect was not significant for grapheme spelling scores. Thus, simultaneous processing of all the letters of the word seems to specifically promote the memorization of the entire word orthography that is, in our case, the combination of several complex graphemes in a single word. On the contrary, the memorization of complex graphemes themselves is equivalent in both reading conditions. The sequential (syllable by syllable) presentation allows to memorize the complex grapheme seen in a syllable just as the global presentation, but it is less efficient than the global presentation to memorize the association of two complex graphemes in a single disyllabic word. The effect of SIM versus SEQ reading condition on the recognition score was also significant in Experiment 2 and in accordance with the spelling results. In summary, these results are in line with the hypothesis that, beyond decoding skills, whole-word visual processing skills are important for whole-word orthographic acquisition by a self-teaching mechanism.

In the SEQ condition of Experiment 1, the first and second syllables were presented on each side of the fixation point, leading to a potential saccadic eye movement during the word processing. Therefore, in Experiment 2, we administered a different experimental paradigm that did not require saccadic eye movements. In the SEQ condition of this second experiment, the two syllables were successively displayed in the central position. Results, once again highlighting an effect of the SIM condition on orthographic learning, confirm the whole-word visual processing hypothesis and minimize the potential role of eye movement during word visual processing.

However, eye movement characteristics are known to differ between populations (Kwon, Legge, & Dubbels, 2007). Children with dyslexia, for instance, make more fixations, with longer fixation times and shorter saccades than normal readers (Prado, Dubois, & Valdois, 2007). Saccades are also shorter in children than in adults (Kowler & Martin, 2010). It would be interesting to replicate this experimental paradigm without saccades (Experiment 2) with children, to confirm the results of Bosse et al. (2015) and check that orthographic learning is indeed dependent upon whole-word visual processing.

It is important to note that in both experiments, the SIM condition should have put participants at a disadvantage, because the visual processing of all the letters of the word should be done during the same 200 ms. In the SEQ condition, the visual processing of all the letters of the word lasted for 400 ms, meaning 200 ms for each syllable. If, as might be expected, longer processing promotes orthographic form memorization, then the SEQ condition should have favored participants. The fact that the SIM reading condition actually favored orthographic learning further underlines the importance of whole-word visual processing in orthographic form memorization. Although participants had twice as much time to take in the visual information about the word in the SEQ condition, pseudowords were recalled better in the SIM reading condition, strengthening the idea that letter presentation time is not a relevant variable for self-teaching, contrarily to whole-word visual processing skills.

The hypothesis that whole-word visual processing is important for lexical orthographic acquisition had been suggested by Bosse et al., (2015) with a close paradigm, using simultaneous versus sequential items' presentation during the reading phase, just as the present study. The main differences with the present experiment was that participants were children and that participants monitored the syllable scrolling. They found a significant effect of the reading conditions on the orthographic choice task but not on the spelling to dictation task. In the present experiments, we obtained a systematic effect of the reading conditions on spelling to dictation

task and the effect on the recognition task was significant only in Experiment 2. This difference suggests that tasks used to evaluate orthographic memorization have to be cautiously chosen. Especially with complex items as disyllabic French ones, spelling to dictation seems appropriate for adult participants but certainly too hard for children. The orthographic recognition task was sometimes too easy and has to be carefully built in order to be sensitive enough (Castles & Nation, 2008).

The hypothesis that whole-word visual processing is crucial for word orthographic acquisition, suggested by the present results, seems in accordance with results showing a causal relationship between visual attention ability and reading speed of young readers (Valdois et al., 2019). Indeed, reading speed can be considered as an indicator of lexical orthographic knowledge. Moreover, in our first experiment, visual attention span was significantly correlated with the reaction time in the orthographic choice task. Together with the effect of SIM versus SEQ conditions, this correlational data is in line with the idea that the ability to simultaneously process a large number of letters permits to read faster and to memorize the orthographic forms better. Indeed, two main factors enhance reading speed of readers. Firstly, they read faster when their decoding skills are better automatized (efficiency of the non-lexical route in a dual-route framework). Secondly, they read faster because they recognized words which have been orthographically memorized, instead of decoding them (using the lexical route). An efficient whole-word visual processing permits to read faster by acting on this second factor.

Limits of the study

It should be noted that our studies are conducted on a limited number of participants, so it seems crucial to interpret the results cautiously and to replicate the results before drawing strong conclusions. More globally, the whole-word visual processing hypothesis has to be tested on different samples and with different paradigms. Furthermore, as the orthographic choice task

results are different between the two experiments, it seems more difficult to generalize these results and we suggest that the orthographic choice task is not an appropriate task to evaluate adult's orthographic knowledge. A recognition task with one word presented at once might be more discriminant and lead to more reliable data (Wang, Castles, Nickels, & Nation, 2011).

Applied consequences of the Whole-Word Visual Processing hypothesis

A better understanding of the cognitive mechanisms involved in orthographic acquisition could help to develop new pedagogical methods and tools specifically built to improve pupils' orthographic acquisition. The main results of the present study suggest that simultaneous processing of all the letters of the words is crucial for the acquisition of the words' orthographic forms. Then, it could be useful to improve the ability of pupils to process in parallel all the letters of the words they read. To do this, one proposal is to train directly visual attention. Several studies have shown that visual and attentional training improves children's reading performances (Facoetti, Lorusso, Paganoni, Umiltà, & Mascetti, 2003; Habib & Joly-Pottuz, 2008; Lorusso et al., 2006). Interestingly, action video game training seems to improve not only some attentional components but also reading abilities (e.g., Franceschini, Trevisan, Ronconi, Bertoni, Colmar, Double, Facoetti, & Gori, 2017). However, these studies focus on reading performance of dyslexic children and not on orthographic knowledge performance of normal readers. Moreover, visual attentional trainings generally train the speed of attentional shifting but not the ability of pupils to process in parallel all the letters.

Another way to improve simultaneous processing of all the letters of the words and consequently lexical orthographic acquisition, could be to force readers to treat each word at a glance, by increasing their reading speed. Then we would expect fluency training to have a positive impact on lexical orthographic learning. Actually, studies of fluency training have demonstrated a positive impact on reading: participants decode, understand (Breznitz, 1997) and recognize the

words (De Cara & Plaza, 2010) better after a fluency training. However, we lack data on the impact of fluency training on orthographic learning. Moreover, there are a lot of different methodologies to train reading fluency (for an inventory of the main methods, see Dubé, Bessette, & Ouellet, 2016) and they probably do not all have the same impact on how words are visually treated.

Finally, the best proposition may be to combine the two previous ones. The idea could be to conceive a fluency training which constrain the reader to treat each word at a glance. One proposition could be to guide the reader's gaze on the words with visual clues, like a karaoke reading game (Godde, Bailly & Bosse, 2019).

In summary, the main results of the present article suggest that whole-word visual processing, that is the simultaneous processing of all the letters of the word during reading, is involved in the mechanisms of orthographic knowledge acquisition. When the whole-word visual processing is impossible, the lexical orthographic forms of the words read are less well learned. This hypothesis leads us to think that a promising idea for orthographic learning and remediation of orthographic specific disabilities, will be to develop and test training programs focusing on visual processing during reading.

Conflict of interest: none

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Appendix

The 60 items of the control word dictation task:

orgueil charisme accès phobie addition belladone équateur skipper verveine rhétorique larynx
escarcelle anthracite coquelicot couenne artichaut thym chanfrein accroc connexion comète
thyroïde hareng pylône wagon fainéant nerf cristallisé marais anorak mausolée sketch excellence
adhérent essaim pléthore perclus pamphlet taureau obséquieux humble agate harnais badaud
attelage onyx faisceau ayatollah tonneau kopeck faïence grivois étang kayak comtesse
phacochère solennel menhir mammoth pathologie

TABLES

Table 1. List of the 14 single phonemes or phonemes pairs chosen to construct the target pseudowords, together with their position in the word and two corresponding spellings.

	Word position	Graphem 1	Graphem 2
/o/	middle	au	ô
/ε / ou /e/	middle	ai	ei
/k/	beginning	k	qu
/k/	end	que	k
/s/	beginning	c	sc
/ẽ/	middle	ain	ein
/ã/	beginning	han	hen
/f/	middle	ff	ph
/r/	end	re	rt
/l/	end	lle	le
/t/	middle	tt	th
/o/	end	au	eau
/ri/	beginning	rhi	ry
/on/	end	onne	aune

Table 2. The 28 pseudowords divided into sets (A, B) and subsets (1, 2)

Set A	Set B	Subset
pauffou	pôphou	1
baitare	beitart	1
quavonne	kavaune	1
cipulle	scipule	1
daintho	deintto	1
ryteau	rhitau	1
hanlouque	henlouk	1
deiphon	daiffon	2
kaltart	qualtare	2
sciraune	cironne	2
teingule	taingulle	2
bôtti	bauthi	2
rhinak	rynaque	2
hENCHAU	hancheau	2

Table 3. Mean scores (standard deviation) on spelling dictation and orthographic choice tasks in according to reading condition (simultaneous = SIM, sequential = SEQ).

	SIM	SEQ
Spelling dictation task		
Whole word score (max = 7)	1.17 (.94)	.61 (.66)
Grapheme score (max = 14)	4.91 (1.95)	4.52 (1.78)
Orthographic choice task		
Score (max =7)	5 (1.24)	4.48 (.90)
Reaction time (ms)	1327 (419)	1429 (369)

Table 4. Pseudowords in Experiment 2 divided into sets (A, B) and subsets (1,2).

Set A	Set B	Subset
beicart	baicare	1
dautti	dôthie	1
fainphon	feinffon	1
hantaque	hentak	1
karône	quaronne	1
ryteau	rhitau	1
scivale	civalle	1
cironne	scirône	2
feinvalle	fainvale	2
hendau	handeau	2
laiffon	leiphon	2
pôtha	pautta	2
qualcare	kalcart	2
rhitak	rytaque	2

Table 5. Mean scores (standard deviation) on spelling dictation and orthographic choice tasks in according to reading condition (simultaneous = SIM, sequential = SEQ).

	SIM	SEQ
Spelling dictation task		
Whole word score (max = 7)	1.11 (1.07)	.57 (1.07)
Grapheme score (max = 14)	5.04 (2.19)	4.43 (1.87)
Orthographic choice task		
Score (max =7)	5.14 (1.33)	4.32 (1.56)
Reaction time (ms)	1356 (431)	1355 (488)

Figures

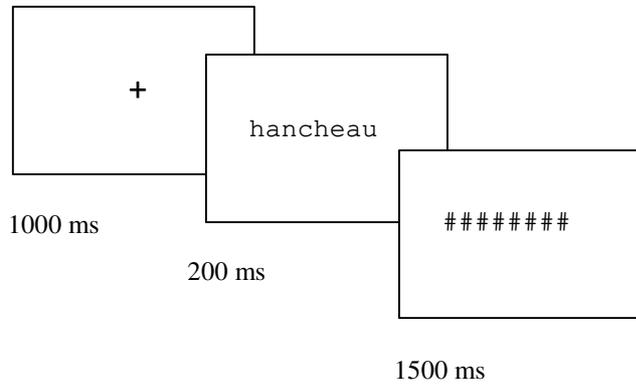
Figure 1. Simultaneous reading condition (SIM, A) and Sequential reading condition (SEQ, B) in learning phase.

Figure 2. Orthographic choice task between 2 homophonic pseudowords.

Figure 3. Simultaneous reading condition (SIM, A) and Sequential reading condition without saccade (SEQ, B) in learning phase.

Figure 1. Simultaneous reading condition (SIM, A) and Sequential reading condition (SEQ, B) in learning phase, experiment 1.

A) Simultaneous reading condition (SIM)



B) Sequential reading condition (SEQ)

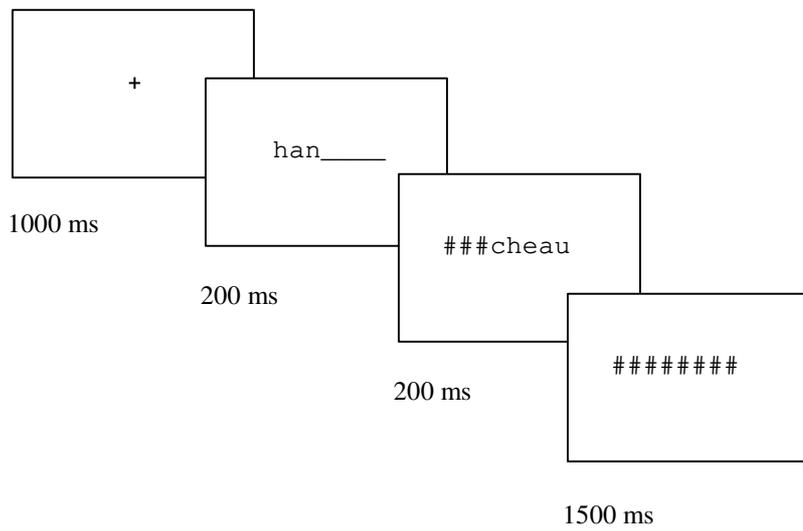


Figure 2. Orthographic choice task between 2 homophonic pseudowords.

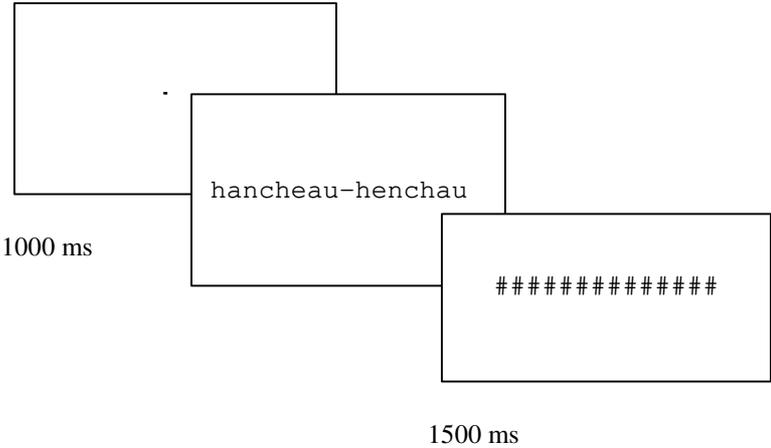
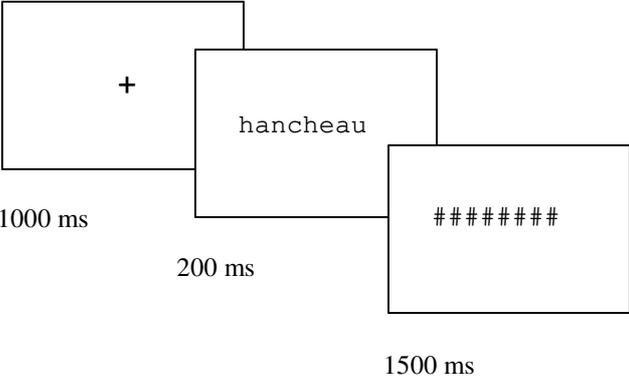


Figure 3. Simultaneous reading condition (SIM, A) and Sequential reading condition without saccade (SEQ, B) in learning phase, experiment 2.

A) Simultaneous reading condition (SIM)



B) Sequential reading condition (SEQ)

