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The role of speech production in phonological decoding during visual word recognition: evidence from phonotactic repair

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ABSTRACT

The phonological decoding of non-native letter sequences during visual word recognition has been shown to be influenced by phonotactic constraints of the reader's native language [Hallé, P. A., Dominguez, A., Cuetos, F., & Segui, J. (2008). Phonological mediation in visual masked priming: Evidence from phonotactic repair. *Journal of Experimental Psychology. Human Perception and Performance*, 34(1), 177–192]. We investigate the mechanisms underlying such phonotactic repair. We focus on a phonotactic constraint in French, according to which words cannot begin with /t/. Native speakers of French are known to perceive word-initial /t/ as /k/. Using a visual priming paradigm, we show that the same phonotactic repair also occurs when the cluster "tl" is presented visually, but, crucially, only when participants' speech production system is available; under articulatory suppression the repair fails to occur. Together, these results show that the speech production system is actively involved in phonological decoding during reading.

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Reading is a complex cognitive process that transforms printed symbols into meaning. Much research has shown that during visual word recognition, readers rely not only on a word's orthography, but also on the phonological code that is converted from print (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Harm & Seidenberg, 2004; Perry, Ziegler, & Zorzi, 2007). For instance, studies using visual priming procedures have shown shorter reaction times in English readers for target word identification or lexical decision when these words (e.g. "brain") are primed by pseudoword homophones (e.g. "brein") as compared to orthographic control primes (e.g. "broin") (Lukatela & Turvey, 1994; Perfetti & Bell, 1991). Activation of the phonological code has also been demonstrated using a letter detection task (Ziegler & Jacobs, 1995; Ziegler, Van Orden, & Jacobs, 1997). For instance, Ziegler and Jacobs (1995) showed that English readers falsely detect "i" in the pseudoword "brane", which is a homophone of the word "brain", and miss "i" in the pseudoword "crain", which is a homophone of the word "crane". These findings further suggest that the activation of the phonological code by print is automatic, as this activation hinders participants' performance.

While previous research primarily focused on the role of the phonological code during visual word recognition

and the time course of its generation (Ferrand & Grainger, 1993; Grainger, Kiyonaga, & Holcomb, 2006), few have examined how this code is generated and processed by the phonological system. Is it a systematic transformation from graphemes to phonemes, or is it also influenced by the organisation of the reader's phonological system? While hardly examined in the reading literature, the influence of one's native phonological system has been extensively studied in the domain of speech perception. This research has shown that listeners have difficulty perceiving non-native phonological structure (for a review, see Sebastián-Gallés, 2005). In particular, non-native sounds tend to be perceived as native ones. For instance, Japanese listeners perceptually confuse the English consonants /r/ and /l/, as their native language has only one liquid consonant (Goto, 1971). Here, we are interested by the fact that listeners are also influenced by the phonotactic constraints of their native language, and tend to perceive illegal sound sequences as legal ones, a phenomenon referred to as "phonotactic repair" (Dehaene-Lambertz, Dupoux, & Gout, 2000; Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Hallé & Best, 2007; Hallé, Segui, Frauenfelder, & Meunier, 1998; Theodore & Schmidt, 2003). For instance, Spanish disallows word-initial sequences of /s/ followed by another consonant, and Spanish listeners tend to

perceive /sC/-initial items (e.g. /sku/) as starting with /esC/ (/esku/) (Theodore & Schmidt, 2003).

Interestingly, Hallé, Dominguez, Cuetos, and Segui (2008) showed that the same phonological repair also occurs during reading. They examined the processing of visually presented /sC/-initial items by Spanish speakers. Specifically, using a visual priming paradigm, they compared reaction times for Spanish /VsC/-initial target words (e.g. “espejo” and “oscuro”) in a lexical decision task when they were preceded by a full repetition prime (“espejo” or “oscuro”) versus a partial repetition prime created by suppressing the targets’ first letter (“spejo” or “scuro”). In a series of experiments, they observed slower reaction times for “oscuro” following the prime “scuro” compared to the prime “oscuro”, while the reaction times for “espejo” following the primes “spejo” and “espejo”, respectively, did not differ. The authors argued that this priming difference is due to a phonotactic repair of the phonological code generated by the partial repetition primes. That is, the prime “spejo” is repaired into “espejo”, which is identical to the target word, while the prime “scuro” is repaired into “escuro”, which is a phonological neighbour of the target word. Furthermore, the authors also found that the temporal evolution of this /sC/-to-/esC/ repair resonates with the time course of phonological decoding during visual word recognition, as established in previous studies using similar priming procedures (Ferrand & Grainger, 1993; Grainger et al., 2006). This finding demonstrates that the phonological code that is generated by print undergoes the same transformations induced by native phonological constraints as the ones that are generated by speech. Hallé et al. (2008) suggested that, more specifically, visual word recognition might involve the same articulatory representations that underlie speech processing.

Research on L2 reading likewise provides evidence for phonological repair during visual word recognition (Ota, Hartsuiker, & Haywood, 2009, 2010). For instance, Japanese-English bilinguals show confusion between the English consonants /r/ and /l/ in a visual semantic-relatedness decision task. That is, they judge the word “key” to be semantically related to both the words “lock” and “rock” (Ota et al., 2009). This finding provides evidence that perceptual transformations induced by the L1 phonology occur not only during the perception of L2 sounds, but also during visual word recognition in L2.

The underlying mechanism of phonological repair during visual word recognition is still unknown. In the reading literature, several studies have shown that the phonological code generated during reading is detailed not only to the level of individual phonemes, but further down to the level of phonetic features (Abramson &

Goldinger, 1997; Lukatela, Eaton, Lee, & Turvey, 2001; Lukatela, Eaton, Sabadini, & Turvey, 2004). For example, Lukatela et al. (2001) observed that in English readers, the pseudoword “vea” primes the word “sea” less strongly than the pseudoword “zea”, even though both “vea” and “zea” differ from “sea” by just one phoneme (or letter). They argued that the priming difference is due to the fact that “zea” has larger overlap in terms of phonetic features with the target “sea” than “vea” does. Lukatela et al. (2004) further proposed that phonological decoding of print activates a representation of articulatory gestures, as they found that even non-distinctive vowel duration (as in the English words *bat* vs. *bad*) is coded in the phonological representation generated by print.

The hypothesis that the articulatory system is involved during phonological decoding in reading is further supported by studies using neuroimaging techniques (Cornelissen et al., 2009; Kouider, Dehaene, Jobert, & Le Bihan, 2007; Wheat, Cornelissen, Frost, & Hansen, 2010; Wilson, Tregellas, Slason, Pasko, & Rojas, 2011). For instance, Kouider et al. (2007) reported an increase in activation of the left inferior frontal cortex and anterior insular cortex associated with phonological priming during visual word recognition. These regions are well known to be implicated in phonological and articulatory processing (Booth et al., 2002; Burton, 2001; Hickok & Poeppel, 2007; Mechelli et al., 2007), such as subvocal rehearsal (Fiez, Raichle, Balota, Tallal, & Petersen, 1996) and phonological short-term memory (Mechelli et al., 2007). Similarly, using magnetoencephalography, Wheat et al. (2010) observed a stronger priming response induced by pseudohomophones than by orthographic neighbours in regions like the pars opercularis of the left inferior frontal gyrus (IFG) and the left precentral gyrus (PCG), which are strongly associated with motor control of speech articulators (Brown, Ngan, & Liotti, 2008; Greenlee et al., 2004).

Neuroimaging studies mostly use a correlational approach, and therefore cannot determine a causal involvement of the speech production system in phonological processing during reading. Indeed, the activation of articulation-related areas during reading might be driven by corollary cortico-cortical connections and thus be unrelated to the process of word recognition itself (Toni, de Lange, Noordzij, & Hagoort, 2008). Moreover, these studies did not focus on phonological repair of printed words that violate readers’ native phonotactic constraints. In the present study, we therefore aimed to directly investigate the role of the speech articulatory system in phonological repair during reading, by modulating its availability for phonological decoding of visual input. To this end, we combined a

visual priming paradigm with articulatory suppression, whereby participants overtly articulate linguistic material that is irrelevant to the main task. Indeed, articulatory suppression has been shown to reduce the efficiency of phonological decoding (Eiter & Inhoff, 2010; Hanley & Bakopoulou, 2003).

We focused on a case of phonotactic repair in French. Contrary to languages such as Hebrew and Russian, French does not allow for words to start with a /tʎ/ cluster. Previous research in speech perception showed that French but not Hebrew listeners tend to perceive /tʎ/-initial items as /kʎ/-initial (Hallé & Best, 2007; Hallé et al., 1998).¹ Based on these findings, as well as those of Hallé et al. (2008) concerning the Spanish /sC/-to-/esC/ repair in both the auditory and visual modalities, we predicted that the /tʎ/-to/kʎ/-repair also applies to visual input, and set out to investigate the role of the articulatory system in this repair.

Participants were asked to perform a lexical decision task on visually presented /kʎ/-initial words and pseudo-words. Each uppercase target (e.g. CLAVIER /klavje/ “keyboard”) was associated with three types of lowercase pseudoword prime: an “unrelated” prime (“griture”), which has no orthographic overlap with the target; a “neighbour” prime (“plavier”), which was created by replacing the first letter of the target with “p”; and a “repair” prime (“tlavier”), which was created by replacing the first letter of the target with “t”. Since both “plavier” and “tlavier” are orthographic neighbours of “clavier”, they should prime the target. Hence, we should observe faster reaction times with these neighbour and repair primes than with the unrelated prime “griture”. In addition, under the assumption that the /tʎ/-to-/kʎ/ repair occurs during visual word recognition, “tlavier” /tlavje/ should be phonologically transformed into /klavje/ and therefore become homophonic with “clavier”, thus yielding phonological priming. By contrast, since /pl/-initial words are allowed in French, “plavier” should not go through any phonological transformation but activate a phonological code of /plavje/; thus, no additional phonological priming should be observed for /plavje/.

Crucially, half of the participants were asked to overtly articulate an irrelevant sound sequence throughout the stimulus presentation. If the articulatory system is critical to phonological decoding of printed words, occupation of this system by a competitive speech production task should interfere with the phonotactic repair of “tlavier” and therefore reduce its phonological priming advantage over “plavier”. Meanwhile, articulatory suppression should not interfere with basic visual processing during reading and should thus not affect the overall

orthographic priming effect of the two primes compared to the unrelated prime.

Materials and methods

Participants

Forty-eight native speakers of French (31 females; mean age 23.5 years, range 18–30 years) gave written informed consent to take part in this study and were paid for participation. All participants reported normal vision, audition and language abilities and declared having no knowledge of languages that allow /tʎ/-initial words such as Hebrew or Slavic languages. Half of the participants performed the task with articulatory suppression, the other half without.

Stimuli

Thirty French words beginning with /kʎ/ (orthographically: cl) were selected as test words (mean frequency = 7.65 per million according to the Lexique database (New, Pallier, & Ferrand, 2005); mean number of syllables = 1.87 (range: 1–3); mean number of letters = 7 (range: 6–10)) (see Appendix, Table A1). For each test word (e.g. “clavier”), three non-word primes were constructed, one by replacing the word’s first letter with “p”, (neighbour: “plavier”), one by replacing it with “t”, (repair: “tlavier”), and one by replacing the first letter of another French word that has the same number of syllables and letters as the test word, and that does not share any letter at the same position with the test word (unrelated: “griture”, from “friture”). The 30 test words were split into three lists (see Appendix – Table A1), such that the three priming conditions were counterbalanced across blocks for each participant (see Procedure for more details). The number of letters, the number of syllables, as well as the frequencies of occurrence did not differ across the three lists (all $F_s < 1$). In addition, 30 filler words that do not start with /kʎ/ (mean frequency = 7.3 per million; mean number of syllables = 1.9, range: 1–3; mean number of letters = 7, range: 6–10) were selected. Each filler word was associated with an unrelated prime and a phonotactically legal neighbour prime obtained by replacing the first letter. Two counterbalanced lists for these fillers were constructed in the same way as those for the /kʎ/-initial test words. Filler and test words did not differ in mean frequency, mean number of letters, or mean numbers of syllables (all $F_s < 1$). The presence of the filler words prevented participants from using a response strategy based on the first two letters only. Finally, 60 non-words were selected,

such that there were as many word and non-word target items. Thirty of the non-words began with /kl/ (orthographically: “cl”) and were associated with the same three prime types as the test words. The remaining 30 non-words did not begin with /kl/ and were associated with the same prime types as the filler words.

Procedure

Lexical decision test

Participants sat in front of an LCD monitor with a viewing distance of 70 cm. The stimuli appeared at the centre of the screen as white characters (20 points, Courier New) on a black background. Each trial consisted of a precisely timed sequence of the following events (Figure 1a): (1) a fixation cross “+” presented at the centre of the screen for 500 ms; (2) a forward mask composed by a row of “%” marks presented for 300 ms; (3) the prime presented in lowercase for 42 ms; (4) a blank screen which also lasted for 42 ms; and (5) the target presented in uppercase for 500 ms. The number of “%” marks in the forward mask was always equal to the number of letters of the prime and the target. The prime-target stimulus onset asynchrony of 84 ms was chosen to be close to the one for which Hallé et al. (2008) obtained a phonotactic repair effect, and a short target duration was chosen to elicit a fast response and therefore maximise the influence of the prime on the response to the target. Finally, the insertion of a blank screen between the prime and the target was meant to maximise the opportunity for observing a phonological priming effect, following Kouider et al. (2007) and Wilson et al. (2011). Participants were instructed to respond, as quickly and accurately as possible, whether or not the uppercase target was a French word by pressing one of the two response buttons assigned to the “word” and “non-word” responses. The “word” response was always given by their dominant hand. For each trial, participants would have a response time window of 1000 ms (measured from the target onset). After the participants’ response or the elapse of the response time window, whichever came first, the target was replaced by a blank screen which lasted for 1000 ms before the beginning of the next trial.

Participants received a total of 360 trials, divided into three blocks. Each block contained 120 different trials, one for each of the 120 test and filler words and non-words (30 /kl/-initial word targets, 30 /kl/-initial non-word targets, 30 filler word targets, and 30 filler non-word targets). In each block, 10 of the /kl/-initial word targets were paired with the neighbour prime, 10 with the repair prime, and 10 with the unrelated prime. Participants were randomly assigned to

one of six groups, such that prime-target pairings were counterbalanced across the three lists of stimuli (see Appendix – Table A1) and the three blocks. For instance, for participants in the first group, targets from List 1 in the first block were paired with unrelated primes, those from List 2 with neighbour primes and those from List 3 with repair primes; in the second block, targets from List 1 were paired with neighbour primes, those from List 2 with repair primes and those from List 3 with unrelated primes; in the third block, targets from List 1 were paired with repair primes, those from List 2 with unrelated primes and those from List 3 with neighbour primes. Each participant thus responded to each /kl/-initial word target in all three priming conditions across the three blocks of the experiment. The trials were presented in a pseudorandom order, such that there were no more than three consecutive trials with a /kl/-initial word or non-word target.

The experiment started with a practice session composed of 12 trials with non-/kl/-initial filler targets (6 words and 6 non-words); half of them were associated with an unrelated prime and the other half with a neighbour prime. During this session, participants received visual feedback on their responses (“correct”, “incorrect”, or “too slow”). Results from this phase were excluded from the analyses.

The experiment was run using MATLAB Psychophysics Toolbox extensions (Brainard, 1997) with a parallel port button box as the response input device, which ensured a high timing precision of both the presentation of stimuli and the recording of responses.

Prime visibility test

After the lexical decision test, participants were informed about the presence of a hidden lowercase prime and were asked to perform a two-alternative forced-choice task designed to evaluate the visibility of the prime. Only the 60 /kl/-initial prime-target pairs (30 /kl/-initial words and 30 /kl/-initial non-words) from the first block of the lexical decision test were used. Each trial comprised the same sequence of events as in the lexical decision test, except that immediately following the presentation of the target, two non-word choice items were presented on the left and the right sides, respectively, of the screen (Figure 1b). One of the two alternatives corresponded to the prime while the other one did not. For unrelated primes (33% of the trials), the two alternative items were orthographically dissimilar (e.g. “rélitét” vs. “griture”). For neighbour and repair primes (67% of the trials), the two alternative items were orthographically similar, and differed from each other on either the first letter (e.g. “tlavier” vs. “plavier”), the last letter (e.g. “plaviet” vs. “plavier”), or

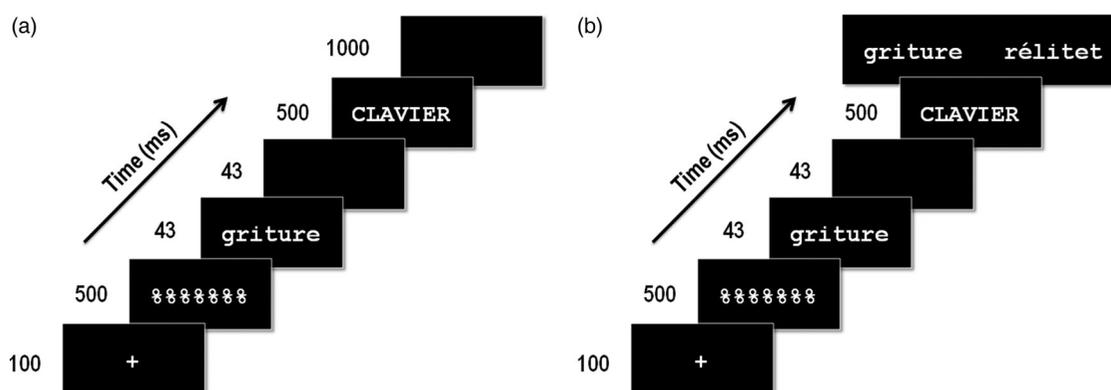


Figure 1. Experimental procedure for the lexical decision test (a) and the visibility test (b).

one of the letters in the middle (e.g. “plamier” vs. “plavier”), with equal probabilities. This design aimed to force the participant not to focus on a particular part of the stimulus. The correct alternative was presented on the left or right side of the screen with equal probability. Participants were told to choose the item that was identical to the prime by pressing the button on the same side. They were told that the response speed was no longer important and that they could take as much time as they wished. The two items remained on the screen until a response had been given. The test started with a practice session composed of 12 trials with primes presented for 300 ms. Participants received visual feedback on their responses (“correct” or “incorrect”). Only trials with /kl/-initial words were included in the analyses.

Articulatory suppression

For the application of articulatory suppression, we used a task that could be performed with minimal engagement of processing resources: participants were asked to articulate a syllable aloud and continuously during both the lexical decision test and the visibility test. Eight CV syllables (“ma”, “na”, “la”, “sa”, “mo”, “no”, “lo”, and “so”) were shown on the screen for participants to choose among both at the beginning of the experiment and in between blocks and tasks.

Participants’ articulation was verified using a voice-recording system. During the experiment, participants’ voices were recorded with a high-sensitivity microphone that was placed close to their mouth. The fixation cross that was presented at the beginning of each trial served as the sign for participants to start articulating the syllable they had chosen. Presentation of the stimuli (forward mask, prime, and target) was only triggered when the articulation volume exceeded a set threshold. Participants were instructed to repeat the chosen syllable aloud at a comfortable pace and to

repeat it without distinct breaks until they saw a “x” mark presented at the centre of the screen as the stop sign. This cross mark was always presented 500 ms after participants had given their response, such that they had to continue the articulation throughout the entire trial. Their articulation was recorded and its duration was checked automatically after each trial. If a participant had stopped the articulation before the appearance of the stop sign, an articulation error was noted and an alarm message displayed. Participants were allowed to change the syllable, among the eight propositions, after each trial. They were familiarised with the articulatory suppression task during an additional practice session of 12 trials at the beginning of the test. During the practice session, trials in which participants made an articulation error (i.e. they ceased to articulate before the stop sign or their articulation was not loud enough) were repeated until successful articulation was recorded. All participants were generally very good in complying with the instructions, although some encouragement was needed at the beginning.

Results

Lexical decision

For participants in the condition with articulatory suppression, trials with an articulation error (corresponding to 6% of the data) were excluded from the analyses. Reaction times were log-transformed in order to obtain a normal distribution. For each priming condition, trials with a reaction time above or below two standard deviations from the mean either per participant or per item were then removed (corresponding to 7% of the data). Errors are defined as trials with either an incorrect response or no response within the 1000 ms. response time window. Mean error rates for trials with /kl/-initial words, as well as reaction times for trials with a correct response (not log-transformed), are shown in [Figure 2](#);

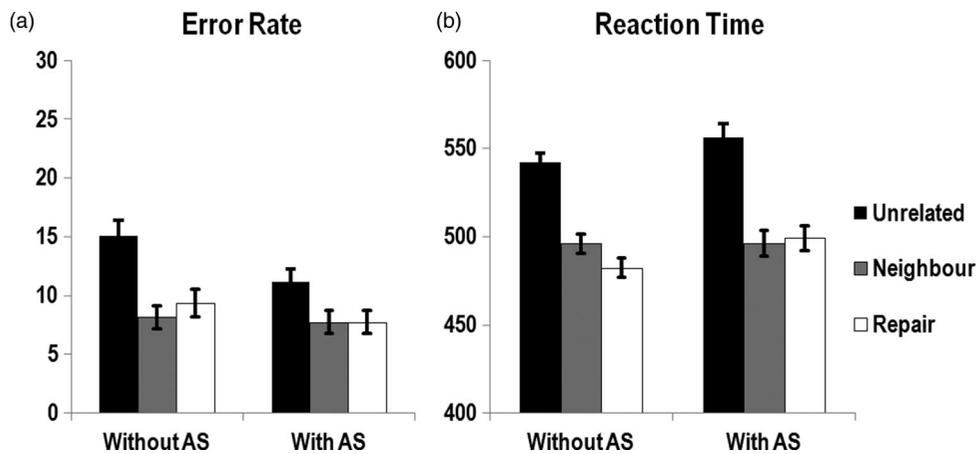


Figure 2. Mean error rates (a) and mean reaction times (b) as a function of Prime Type (unrelated vs. neighbour vs. repair) and Articulatory Suppression (with AS vs. without AS) in the lexical decision test. Error bars indicate the standard error across participants.

for a complete table of results per block, see Appendix – Table A2.

By-participant and by-item analyses were performed on both error rates and log-transformed reaction times. For error rates, analysis of variance (ANOVAs) with the factors Articulatory Suppression (without AS vs. with AS), Prime Type (unrelated vs. neighbour vs. repair), and Block revealed only a main effect of Prime Type, $F_1(2, 72) = 16.29, p < .0001$; $F_2(2, 58) = 11.98, p < .0001$, as error rates for trials with unrelated primes (13.1%) were significantly higher than for those with neighbour primes (7.8%), $F_1(1, 47) = 19.07, p < .0001, F_2(1, 29) = 14.48, p < .0007$, and repair primes (8.5%), $F_1(1, 47) = 21.04, p < .0001$; $F_2(1, 29) = 13.10, p < 0.002$, whereas there was no difference between neighbour and repair primes, both $F < 1$. There was a marginal effect of Articulatory Suppression, but only in the by-item analysis, $F_1(1, 46) = 2.81, p > .1$; $F_2(1, 29) = 3.79, p = .06$, and no interaction between Articulatory Suppression and Prime Type, $F_1(2, 72) = 1.66, p > .1$; $F_2 < 1$.

For the analysis of reaction times, we first conducted ANOVAs with the factors Articulatory Suppression (without AS vs. with AS), Prime Type (unrelated vs. neighbour vs. repair), and Block. These analyses revealed an effect of Block, $F_1(2, 92) = 45.22, p < .0001$; $F_2(2, 58) = 60.88, p < .0001$, as the reaction times decreased over the course of the experiment. They also revealed an effect of Prime Type $F_1(2, 92) = 194.24, p < .0001$; $F_2(2, 58) = 153.00, p < .0001$, as the overall reaction times for unrelated primes (549 ms) were higher than those for neighbour primes (496 ms), $F_1(1, 46) = 315.17, p < .0001$; $F_2(1, 29) = 144.50, p < .0001$, and repair primes (490 ms), $F_1(1, 46) = 263.87, p < .0001$; $F_2(1, 29) = 229.10, p < .0001$, whereas the difference between neighbour and repair primes was only significant in the by-item analysis, $F_1(1, 46) = 3.83, p = .056$; $F_2(1, 29) =$

$5.42, p < .05$. The effect of articulatory suppression was only significant in the by-item analysis, $F_1 < 1$; $F_2(1, 29) = 4.98, p < .05$. Furthermore, there were interactions between Prime Type and Articulatory Suppression, $F_1(2, 92) = 4.27, p < .02$; $F_2(2, 58) = 4.26, p < .02$, between Prime Type and Block, $F_1(4, 184) = 3.26, p < .02$; $F_2(4, 116) = 1.80, p > .1$, and there was a marginal interaction between Block and Articulatory Suppression, $F_1(2, 92) = 3.07, p = 0.51$; $F_2(2, 58) = 4.62, p < .02$. No other main effects or interactions were significant.

Next, we computed the size of priming provided by neighbour and repair primes by subtracting the reaction times of trials in the neighbour and repair priming conditions, respectively, from those of trials in the unrelated priming condition. The overall priming sizes were significantly larger than 0 (unrelated minus neighbour: 53 ms; $F_1(1, 47) = 288.10, p < .0001$; $F_2(1, 29) = 165.00, p < .0001$; unrelated minus repair: 59 ms; $F_1(1, 47) = 260.10, p < .0001$; $F_2(1, 29) = 256.30, p < .0001$). The priming sizes were submitted to ANOVAs with the factors Articulatory Suppression (without AS vs. with AS), Block, and Prime Type (neighbour vs. repair). These analyses revealed, first of all, a main effect of Block, $F_1(2, 92) = 5.80, p < .005$; $F_2(2, 58) = 3.39, p < .05$, as overall, the priming size increased over the course of the experiment. The effect of Prime Type was marginally significant in the by-participant analysis, $F_1(1, 46) = 3.83, p = 0.056$, and significant in the by-item analysis, $F_2(1, 29) = 5.43, p < 0.03$, as the overall priming size was larger for repair than for neighbour primes. Crucially, there was also an interaction between Prime Type and Articulatory Suppression, $F_1(1, 46) = 8.33, p < .006$; $F_2(1, 29) = 7.92, p < .009$. No other main effects or interactions were significant; in particular, there was no effect of Articulatory Suppression, $F_1 < 1$; $F_2(1, 29) = 1.23, p > .1$.

Restricted analyses showed that in the absence of articulatory suppression, the priming size was larger for repair than for neighbour primes (unrelated minus repair: 61 ms; unrelated minus neighbour: 46 ms), $F_1(1, 23) = 13.70$, $p < .002$; $F_2(1, 29) = 19.95$, $p < .0002$, while no difference between the two primes was obtained in its presence (unrelated minus repair: 57 ms; unrelated minus neighbour), 60 ms; both $F < 1$. By contrast, the priming sizes for repair and neighbour primes did not differ between the conditions with and without articulatory suppression. Indeed, there was no significant difference either for repair primes (without AS: 61 ms; with AS: 57), both $F_s < 1$, or for neighbour primes (without AS: 46; with AS: 60 ms), $F_1(1, 46) = 1.82$, $p > .1$; $F_2(1, 29) = 3.89$, $p = .058$.

Prime visibility

All participants declared that they had been unaware of the presence of the lowercase primes during the lexical decision test and that they had only begun to see those primes during the visibility test. The overall success rate on the visibility test was significantly higher than the 50% chance level (mean: 67%), $t_1(47) = 12.18$, $p < .0001$; $t_2(29) = 12.44$, $p < .0001$. Mean success rates are shown in Table 1.

We submitted these data to by-participant and by-item ANOVAs with the factors Articulatory Suppression (without AS vs. with AS) and Prime Type (unrelated vs. neighbour vs. repair). These analyses revealed main effects of Articulatory Suppression, $F_1(1, 46) = 5.46$, $p < .03$; $F_2(1, 59) = 4.27$, $p < .05$, as success rates were lower with articulatory suppression than without, and of Prime Type, $F_1(2, 92) = 21.17$, $p < .0001$; $F_2(2, 118) = 28.18$, $p < .0001$, as the overall success rate was higher for unrelated primes (77%) than for neighbour primes (60%), $F_1(1, 47) = 35.04$, $p < .0001$; $F_2(1, 29) = 32.49$, $p < .0001$, and for repair primes (62%), $F_1(1, 47) = 30.47$, $p < .0001$; $F_2(1, 29) = 21.61$, $p < .0001$, whereas there was no difference between neighbour and repair primes, both $F < 1$. There was no interaction between Prime Type and Articulatory Suppression, $F_1 < 1$; $F_2(2, 58) = 1.04$, $p > 0.1$. Finally, an ANOVA with the same factors but without the unrelated priming condition revealed

only a marginal effect of Prime Type in the by-item analysis, $F_1 < 1$; $F_2(1, 59) = 3.38$, $p = 0.07$. Hence, there was neither a main effect of Articulatory Suppression, $F_1(1, 46) = 2.11$, $p > 0.1$; $F_2 < 1$, nor an interaction between Prime Type and Articulatory Suppression, both $F < 1$.

Discussion

Using a visual priming paradigm with French participants, we found that without articulatory suppression, “tlavier” provides stronger priming for the lexical retrieval of “clavier” than “plavier” does. This priming difference cannot be related to an orthographic difference, because both primes present the same orthographic overlap with the word “clavier”. Thus, it must reflect a phonological advantage of “tlavier” over “plavier” for the recognition of “clavier”, due to the /tl/-to-/kl/ phonotactic repair. This result is in line with similar findings of Hallé et al. (2008) concerning the processing of illegal word-initial /sC/-clusters by Spanish readers. They suggest that the phonological code generated by visual input shares the same features with the one generated by auditory input, and that the processing of this code is likewise modulated by phonotactic constraints of the native language.

Crucially, we found that the priming advantage of “tlavier” over “plavier” disappeared under articulatory suppression. This result showed that occupation of the participant’s speech articulatory system impeded the phonotactic repair which transforms “tlavier” into “clavier”. Moreover, articulatory suppression did not change the overall size of the orthographic priming effect, which indicates that this secondary task only affected the phonological processing of the primes and did not hinder their basic orthographic processing. This interpretation is confirmed by results from the off-line visibility test, showing that articulatory suppression did not interfere with participants’ visual access to the primes. Finally, articulatory suppression did not change the error rates either and hence did not affect participants’ overall performance on the lexical decision task. This result further confirms that the disappearance of the priming advantage of “tlavier” over “plavier” under articulatory suppression is not due to an alteration of participants’ general cognitive processing by the addition of a secondary task.

One might wonder if an alternative explanation for the priming advantage of “tlavier” over “plavier” for the recognition of “clavier” could be that the letter “t” is visually more similar to the letter “c” than “p” is. According to this interpretation, the observed priming advantage would reflect an effect of visual similarity and be unrelated to phonological decoding. However, this

Table 1. Mean success rates for /kl/-initial words as a function of Prime Type (unrelated vs. neighbour vs. repair) and Articulatory Suppression (with AS vs. without AS) in the visibility test.

	Without AS	With AS
Unrelated	82.1 (2.4)	72.5 (3.4)
Neighbour	61.3 (2.4)	59.2 (3.4)
Repair	65.8 (3.4)	59.2 (2.6)

Note: Standard errors are shown in parentheses.

interpretation cannot explain why the priming advantage disappeared under articulatory suppression. That is, since our results showed no interference of articulatory suppression with the visual processing of the primes, the priming advantage of “tlavier” over “plavier” should have remained stable under articulatory suppression, contrary to fact. It should also be noted that previous research with visual priming paradigms has provided evidence against a visual similarity account (Bowers, Vigliocco, & Haan, 1998; Kinoshita, Robidoux, Mills, & Norris, 2014; Perea & Panadero, 2014). For instance, Kinoshita et al. (2014) showed that primes with letters that are visually similar (e.g. HRHNDON) to the target (ABANDON) produce no more priming than primes with dissimilar letters (DWDNDON) do. Thus, based on our own data as well as on previous findings, we rule out the alternative interpretation according to which the priming advantage of “tlavier” over “plavier” is due to a visual similarity effect.

One aspect of our results that deserves some scrutiny concerns the comparison of neighbour and repair priming sizes between the conditions with and without articulatory suppression. Given our hypothesis, articulatory suppression should interfere with phonological but not with orthographic processing. Consequently, we would expect a decrease in the repair priming effect under articulatory suppression. However, we observed no such decrease, and, if anything, there seemed to be an increase in the neighbour priming effect. Specifically, the repair priming size decreased by only 4 ms in the presence of articulatory suppression while the neighbour priming size increased by 14 ms. Even though neither of these differences is significant, the numerical pattern might seem puzzling. It should be noted, however, that the phonological pathway is less available for participants whose articulatory system is occupied by an irrelevant task. These participants, then, must rely more on the orthographic pathway. In other words, an increase in the neighbour priming effect would not invalidate our hypothesis.

The priming paradigm used in the current study differs from those of classical visual masked priming experiments. In particular, we inserted a short blank screen between the prime and the target, instead of a backward mask. This was done in order to increase the opportunity for observing a phonological priming effect. Indeed, since the main objective was to investigate whether the speech articulation system is involved in phonological processing during reading, it was crucial to observe a robust phonological priming effect in the condition without articulatory suppression. Recent research has suggested that the phonological pathway is not always involved in lexical decision. Indeed,

phonological priming in lexical decision can only be observed when there is a large overlap between prime and target (Carreiras, Ferrand, Grainger, & Perea, 2005; Carreiras, Perea, Vergara, & Pollatsek, 2009), whereas a shared onset segment between prime and target alone is sufficient to induce phonological priming in reading aloud (for a review, see Timmer & Schiller, 2014). Unfortunately, we could not use a reading aloud task, due to the incompatibility with articulatory suppression. Since the involvement of the phonological pathway is not essential in lexical decision, the phonological priming effect is rather small in size (10 ms, according to a meta-analysis by Rastle & Brysbaert, 2006) and it is sensitive to prime visibility (Kouider et al., 2007; Kouider & Dupoux, 2001). In particular, Kouider et al. (2007) observed pseudohomophone priming only when a blank screen was inserted between the prime and target. We thus adopted this design feature, but kept the duration of the blank screen very short (42 ms) in order to prevent participants from developing “uncontrolled” strategies during the lexical decision task. Our manipulation was successful: in the condition without articulatory suppression we observed a robust phonological priming effect, while none of the participants reported awareness of the lowercase primes during the lexical decision task. Moreover, participants could only visualise part of the primes even after having been informed of the presence of primes and having been asked to focus on them. This partial visibility was confirmed by the results from the visibility test, showing higher performance when the two alternatives were orthographically dissimilar (for unrelated primes) than when they were similar (for neighbour and repair primes). Whether the current phonological priming effect can be observed in severe masking conditions remains to be tested in future investigations.

Findings from the current study provide evidence that the articulatory system is actively involved in the decoding of the phonological code generated by print. The involvement of the speech production system in phonological decoding during reading has been suggested in previous neuroimaging studies, which showed increased activation of frontal brain areas that are related to speech articulation (e.g. left IFG and insula cortex) in reading tasks involving phonological processing (Cornelissen et al., 2009; Kouider et al., 2007; Mechelli et al., 2007; Wheat et al., 2010; Wilson et al., 2011; for a review, see Taylor, Rastle, & Davis, 2013). Our study extends these previous findings by demonstrating that phonological decoding during visual word recognition can be directly modulated by changing the availability of the speech articulation system. Thus, our finding provides evidence for an active role for this system in phonological

decoding, in particular, for a repair of the generated phonological code in compliance with the phonological structure of the readers' native language.

What is the underlying mechanism of this phonological repair in visual word recognition? In speech perception, non-native sounds or phonotactically illegal sound sequences are transformed into legal ones during the mapping of auditory input onto abstract phonological representations. Visual word recognition, however, does not involve any auditory input. We therefore argue for a two-stage model, as suggested by Hallé et al. (2008): visually presented illegal letter sequences, in the present case word-initial "tl", are first converted into a phonological code (here: /tl/) via the grapheme-to-phoneme conversion; this generated illegal sound sequence is subsequently repaired into a permissible sequence (here: /kl/).

The initial generation of the illegal sound sequence /tl/ by the grapheme-to-phoneme conversion is in accordance with three influential theoretical models of reading, i.e. the triangle model (Plaut, McClelland, Seidenberg, & Patterson, 1996), the dual-route cascade (DRC) model (Coltheart et al., 2001), and the connectionist-dual process (CDP+) model (Perry et al., 2007). Although these models differ in the underlying mechanisms, they all use language-specific grapheme-to-phoneme correspondences to convert letters into sounds. Since the combination of "t" and "l" does not form a single grapheme in French, it will thus be transformed into a sequence of two sounds. However, while the issue of illegal letter/sound sequences is dealt with by all three models, none of them yields the required outcome of /tl/-to-/kl/ repair. The CDP+ model does not propose any repair mechanism for illegal sequences. It simply reads out the individual phonemes one after the other (Perry et al., 2007). The triangle and the DRC models, by contrast, propose mechanisms to correct phonotactically illegal sound sequences. The triangle model can rearrange the phonemes such that the phonotactic constraints of the language are met (Plaut et al., 1996). Rearrangement, though, only takes place within syllabic constituents (onset, nucleus, and coda). Thus, this mechanism is not applicable in the case of "tlavier", because neither /tl/ nor /lt/ is a legal onset in French. The DRC model is the only one that proposes a correction of illegal sound sequences by means of segment substitution. According to this model, the initially generated phonological code will be subjected to a set of phonological output rules which transform illegal sound sequences into legal ones (Coltheart et al., 2001). For instance, the letter string "ink" is initially converted to /ink/, which is subsequently corrected to /ɪnk/ to comply with the phonology of English, according to

which /k/ cannot be preceded by /n/ in the same syllable. Note that this correction mechanism hinges on the presence of an existing alternative grapheme-to-phoneme correspondence. Thus, both /ŋ/ and /n/ correspond to the grapheme "n" in English. This mechanism does not allow for a repair from /tl/ to /kl/ in French, since /k/ does not correspond to the grapheme "t". In summary, none of three dominant theoretical models of reading, at least in their current form, provides support for phonotactic repair of illegal letter sequences during grapheme-to-phoneme conversion, such as the French /tl-to-/kl/ repair.

Additionally, a recent study by Manoiloff, Segui, and Hallé (2015), who used a phoneme monitoring task with target pictures and visual word primes, showed that the grapheme-to-phoneme conversion of native words is not sensitive to articulatory suppression. This finding suggests that the speech articulatory system is not involved in grapheme-to-phoneme conversion under normal circumstances. Since our results showed that the articulatory system is actively involved in the phonotactic repair of non-native, illegal sound sequences, this is evidence that the phonotactic repair should occur after the initial grapheme-to-phoneme conversion.

Evidence from neuroimaging also provides support for a two-stage model: A meta-analysis of 36 neuroimaging studies of reading highlighted three cortical regions that show greater activity for pseudowords than for words and that are hence implicated in phonological processing (Taylor et al., 2013). The first region consists of putative visual word-form areas such as the left posterior fusiform gyrus and occipitotemporal cortex; the second one is the left inferior parietal cortex, for which the authors suggest a specific role in grapheme-to-phoneme mapping; the third region contains frontal motor areas such as the left IFG (opercularis and triangularis), the insula cortex, and the PCG. Although the authors related the frontal areas with phonological short-term memory and the resolution of phonological output, our findings suggest an additional role for these regions. That is, it transforms the phonological code initially generated by the grapheme-to-phoneme conversion mechanism such that it complies with the native phonology. This transformation is due to subvocal rehearsal of the generated phonological code in the phonological loop (Baddeley, 1992). Specifically, the initial phonological code is updated as a function of the output of subvocal rehearsal. Thus, our finding suggests that during reading, the speech motor system is not only involved in phonological output, but also contributes to the mapping of a generated sound pattern onto native phonological representations. This view is congruent

with findings in speech perception that suggest a role of the motor system in resolving difficulty with the perception of speech sounds (D'Ausilio, Bufalari, Salmas, & Fadiga, 2012; D'Ausilio et al., 2009), especially non-native ones (Wilson & Iacoboni, 2006).

Finally, one might wonder whether knowledge of a second language could yield a reduction or even the disappearance of the effect of phonotactic repair during reading. It has been shown that learning to read in L2 can interact with phonological decoding during L1 reading. In particular, new letter-to-sound correspondences of L2 can be activated while performing a reading task in L1. This is evidenced by the fact that for Dutch–English bilinguals, a visual presentation of the English word “kite” but not of that of “knee” facilitates the reading aloud of a Dutch word beginning with /k/, despite the fact that in Dutch, the letter sequence “kn” corresponds to the phoneme sequence /kn/ (Timmer, Ganushchak, Ceusters, & Schiller, 2014). These findings suggest that the grapheme-to-phoneme processes for L1 and L2 are interconnected, such that each grapheme simultaneously activates the corresponding phonemes in both languages. It should be noted, though, that whereas learning a language in which words can begin with /t/ would provide French readers with knowledge about the legality of word-initial /t/, the involvement of the speech articulation system during visual word recognition implies that they would still have to cope with the difficulty of producing and encoding this non-native sound sequence. Therefore, we expect that the extent to which the effect of the /t/-to-/k/ phonotactic repair would be reduced is correlated with the individual ability to correctly produce word-initial /t/ and to encode this sequence in their phonological short-term store.

To conclude, we have shown that visually presented letter sequences representing non-words that violate a phonotactic constraint of the reader's native language are repaired into legal sequences. This repair applies to the phonological code generated from print and is achieved by covert articulation of this code. The active involvement of the speech articulation system in phonological decoding during visual word recognition suggests that reading depends on an interactive network that involves both the language perception and production modules.

Note

1. Similarly, word-initial /dl/ tends to be perceived as /gl/. As the repair effect is stronger for /t/, we focused on /t/-initial words.

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Appendix

Table A1. /k/-initial words and their primes as a function of counterbalancing list. Frequency values correspond to the “fréquence livre” reported in the database Lexique 3.71 (New et al., 2005), which corresponds to the words’ frequency of occurrence in 218 novels published in French between 1950 and 2000.

List	Prime Type			Target	Frequency	Nb of syllables	Nb of letters	
	Unrelated	Neighbour	Repair					
1	tullement	plairière	tlairière	clairière	14.59	2	9	
	léniche	plameur	tlameur	clameur	5.61	2	7	
	ébscur	plarté	tlarté	clarté	28.24	2	6	
	griture	plavier	tlavier	clavier	3.24	2	7	
	viceps	plergé	tlergé	clergé	3.78	2	6	
	gésoudre	plinique	tlinique	clinique	10.81	2	8	
	perviable	plochette	tlochette	clochette	2.5	2	9	
	mactose	plonage	tlonage	clonage	0.07	2	7	
	nangle	ploque	tloque	cloque	1.89	1	6	
	veurt	plown	tlown	clown	6.49	1	5	
				Mean	7.72	1.8	7	
	2	frévisible	plandestin	tlandestin	clandestin	5.07	3	10
		mebond	plapet	tlapet	clapet	0.68	2	6
		outomate	plapotis	tlapotis	clapotis	5.41	3	8
mauvisme		plaquage	tlaquage	claquage	0.07	2	8	
tougue		plause	tlause	clause	1.01	1	6	
fros		pléf	tléf	cléf	35.61	1	4	
icheteur		plémence	tlémence	clémence	2.43	2	8	
gelge		plerc	tlerc	clerc	5.68	1	5	
solumé		plimat	tlimat	climat	17.16	2	6	
brisaille		pliquetis	tliquetis	cliquetis	8.04	2	9	
				Mean	8.11	1.9	7	
3		dotoire	plairon	tlairon	clairon	4.32	2	7
		laignoire	plassique	tlassique	classique	15.81	2	9
		talpêtre	plavecin	tlavecin	clavecin	2.3	2	8
	nénétique	plavicule	tlavicule	clavicule	0.68	3	9	
	vamine	pliché	tliché	cliché	5.34	2	6	
	zuse	plip	tlip	clip	0.61	1	4	
	lableur	pliquet	tliquet	cliquet	0.07	2	7	
	toeurs	ploche	tlоче	cloche	18.24	1	6	
	lermeté	plocher	tlочer	clocher	11.01	2	7	
	fordure	plouison	tlouison	cloison	12.77	2	7	
				Mean	7.11	1.9	7	

Table A2. Mean error rates for /k/-initial words and reaction times (RT) for correct responses to these words as a function of Prime Type, Block, and Articulatory Suppression (AS), as well as the size of priming for neighbour and repair primes, in the lexical decision test.

AS	Prime Type		% Error	RT (ms)	Priming (ms)
Without AS	Unrelated	Block 1	16.6 (2.7)	553 (10.4)	
		Block 2	12.9 (2.3)	540 (7.3)	
		Block 3	15.4 (2.1)	532 (9.8)	
		Mean	15.0 (1.4)	542 (5.4)	
	Neighbour	Block 1	7.9 (1.6)	515 (9.4)	38 (6.7)
		Block 2	10.0 (2.1)	494 (8.8)	47 (6.9)
		Block 3	6.3 (1.3)	479 (9.1)	53 (7.5)
		Mean	8.1 (1.0)	496 (5.5)	46 (4.1)
	Repair	Block 1	9.1 (1.8)	496 (10.0)	56 (7.1)
		Block 2	6.7 (2.0)	482 (8.4)	59 (6.1)
		Block 3	12.1 (2.2)	466 (9.0)	67 (9.4)
		Mean	9.3 (1.2)	481 (5.4)	61 (4.4)
With AS	Unrelated	Block 1	11.1 (1.7)	578 (14.0)	
		Block 2	9.6 (1.7)	543 (14.0)	
		Block 3	12.5 (2.2)	548 (12.8)	
		Mean	11.1 (1.1)	556 (7.9)	
	Neighbour	Block 1	9.1 (2.1)	524 (11.7)	54 (7.4)
		Block 2	7.8 (1.8)	489 (12.0)	54 (10.0)
		Block 3	6.1 (1.5)	476 (12.6)	72 (7.2)
		Mean	7.7 (1.0)	496 (7.3)	60 (4.8)
	Repair	Block 1	9.0 (1.4)	529 (11.2)	49 (7.3)
		Block 2	6.7 (2.0)	493 (12.7)	49 (10.1)
		Block 3	7.3 (1.6)	473 (9.9)	76 (9.7)
		Mean	7.7 (1.0)	499 (7.0)	57 (5.4)

Note: Standard errors are shown in parentheses.