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The use and nature of grapheme coding during sub-lexical processing and lexical access

Running head: Grapheme coding during word recognition

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Abstract

This work aimed to investigate grapheme coding during sub-lexical processing and lexical access. Using the letter detection task in Experiment 1, we compared letter pairs that could be considered as a grapheme unit or not depending on context (referred to as weakly cohesive complex, e.g.

Three experimental conditions were used, one of which was designed to prevent phonological influences. Data revealed that only highly cohesive complex graphemes were processed as units, not the weakly cohesive ones. The same pattern was found across experimental conditions, in favor of an orthographic mechanism. In Experiments 2 and 3, a primed lexical decision task was used with two SOAs and two different ranges of lexical frequency. We manipulated the number of graphemes removed from partial primes (*d**che* vs. *do**he-DOUCHE*) and relatedness. In contrast with Experiment 1, no evidence was provided in favor of a role of graphemes during lexical access. We suggest that graphemes can be conceived as sub-lexical orthographic units *per se* butcan only be captured within a sub-lexical route to reading.

Keywords:

Visual word recognition; Grapheme coding; Sub-lexical orthographic units; Letter detection task

One fundamental issue in the visual word recognition field is the nature of the several sub-lexical units that are extracted from the visual input and the mechanisms that make these units functional representations during silent word reading. The present study focuses on grapheme coding and examines to what extent graphemes might be processed as sub-lexical orthographic representations during sub-lexical processing and lexical access, thus addressing issues raised by some models of visual word recognition (Grainger & Ziegler, 2011; Perry, Ziegler & Zorzi, 2010). To date, letters and letter clusters such as bigrams have been the most acknowledged perceptual units of orthographic coding during visual word recognition. A large part of recent research has focused on letter position coding (Davis & Bowers, 2006; Grainger, 2008; Grainger & Holcomb, 2009; Grainger, Granier, Farioli, van Assche & van Heuven, 2006; Grainger & van Heuven, 2003; Lupker, Perea & Davis, 2008; Perea & Acha, 2009; Perea & Carreiras, 2006, 2008; Perea & Lupker, 2004) and the influence of letter identity, contrasting consonants with vowels (Carreiras, Vergara & Perea 2007**;** Chetail, Balota, Treiman & Content, 2014; Chetail & Content, 2012; Duñabeitia & Carreiras, 2011; Lupker, Perea & Davis, 2008; New & Nazzi, 2014; Perea & Acha, 2009; Perea & Lupker, 2004; Vergara-Martinez, Perea, Marin & Carreiras, 2011). Although letter identity effects are rarely addressed in current models of word recognition, a large number of recent theoretical proposals implement orthographic coding schemes that can successfully simulate letter-position effects uncovered in the literature (e.g. Davis, 2010; Dehaene, Cohen, Sigman & Vinckier, 2005; Gomez, Ratcliff & Perea, 2008; Grainger & van Heuven, 2003; Grainger & Ziegler, 2011; Whitney, 2001).

Despite the prevailing view that letters are the basic processing units during visual word recognition, other data have emerged during the last fifteen years on the functional role of graphemes. Graphemes are the orthographic correspondents of phonemes (Reggia, Marsland & Berndt, 1988) which, in writing systems of low sound-to-print transparency, can sometimes be represented as multiple letters. For instance, the English writing system includes many multi-letter graphemes, also termed complex graphemes, of vowel-vowel (VV) type such as “oa” or “ea” and consonant-consonant (CC) type such as “sh” or “th”. Words of the same syllabic and letter length can thus vary in their number of graphemes so that *belt* contains four graphemes but *bean* contains only three. Whether graphemes, and specifically complex graphemes, are processed as perceptual units during visual word recognition is still matter of debate (Lupker, Acha, Davis & Perea, 2012). In reading- aloud tasks that make high demands on phonological processing, grapheme complexity effects have been interpreted as supporting either letter- based or grapheme- based approaches on sub-lexical reading procedure. For instance, Rastle & Coltheart (1998) revealed longer naming latencies for pseudowords such as *fooph* that contain complex graphemes compared to those that contain only simple graphemes such as *frolp*. The effect was referred to as “whammy effect” (see also Joubert & Lecours, 2000, Schmalz, Porshnev & Marinus, 2016) and was interpreted by the authors as reflecting the activation of the wrong phoneme of the first letter of the complex grapheme, and thought to support the serial letter- by- letter processing mechanism postulated by the Dual Route Cascaded model (DRC model, Coltheart, Rastle, Perry, Langdon & Ziegler, 2001). Using the same task, Rey & Schiller (2005; experiment 3) found instead that words with complex graphemes were named *faster* than words of similar letter length without complex graphemes, a finding which could also be accounted by a grapheme parsing stage during sub-lexical procedure, as hypothesized by CDP+ framework (Perry, Ziegler & Zorzi, 2010, 2013; see also similar conclusions by Marinus & de Jong, 2008, 2010 in developing readers). The idea that graphemes would be processed as perceptual units is also supported by evidence of grapheme complexity effects in tasks that tap earlier stages of visual word processing, which do not overtly require phonological processing. Using the perceptual identification task in which the word is gradually displayed on the screen by regularly increasing its luminance until the participant has identified it, Rey, Jacobs, Schmidt-Weigand and Ziegler (1998) revealed longer identification latencies for words that contained complex graphemes (e.g. *teeth*) compared to only single letter graphemes (e.g. *blast*). This was observed in English and French words and independently of the consistency of the print-to-sound mapping (Rey & Schiller, 2005). Using the same task, this effect was also reported on nonword processing (Bolger, Borgwaldt & Jakab, 2009). The letter detection task has also been used to examine grapheme unitization, the process whereby multiple letters corresponding to one phoneme are combined and processed as a sub-lexical orthographic unit (Rey, Ziegler & Jacobs, 2000). This task requires the participant to decide whether a pre-determined letter is present or absent in a subsequent letter string, which is presented very briefly. Rey and colleagues (2000) showed in both English and French that detecting a letter embedded in a complex grapheme (e.g. detecting the letter A in *b**ea**ch*) was slower than detecting the same letter in a simple grapheme (e.g. A in *bl**a**ck*). More recent studies using the same task and procedure revealed a similar pattern in typical and dyslexic developing readers of Dutch (Marinus & De Jong, 2011) and in French adolescents learning English as a second language at secondary school (Commissaire, Duncan & Casalis, 2014).

As argued by Lupker (Lupker et al., 2012), grapheme complexity effects observed in the letter detection task have generally been assumed to reflect an orthographic mechanism, given the absence of any phonological response required in this task. Drawing on this approach, this effect would occur during grapheme parsing when the input letter string is divided into larger sub-lexical orthographic representations (CDP+, Perry et al., 2007). As a result, complex graphemes composed of multiple letters such as “ea” would compete with single-letter graphemes “e” and “a”, and so slow down letter detection (Rey et al., 2000).

According to this “orthographic” hypothesis, grapheme parsing, and thereby grapheme complexity effects, could arise partly independently of phonological activation, within the early steps of orthographic coding. While the hypothesis of a grapheme parsing stage has been supported by some studies (Marinus & de Jong, 2010; Schmalz et al., 2016), the extent to which grapheme complexity effects found in the letter detection task could also partly reflect phonological mechanisms that are known to be involved in this task (Commissaire et al., 2014; Rey et al., experiment 2; Spinelli et al., 2012) remains unclear; more, it is not known whether these effects are found when minimizing any phonological influence. Indeed, according to a “phonological” interpretation of grapheme complexity effects, one could also hypothesize that these effects emerge during grapheme-to-phoneme conversion (see recent naming study discussing this issue by Schmalz et al., 2016). Each letter of the complex grapheme would activate its corresponding grapheme and the complex grapheme itself, and each of them would rapidly connect to their corresponding phonological representations (e.g. “ea” in *bread* activates e → /i:/, a → /eI/ and ea → /e/). The letter detection cost for complex graphemes would only occur once their phonological counterparts were activated and would thereby reflect competition between activated phonemic representations.

Phonological influences during grapheme coding were indeed recently uncovered in the letter detection task by Spinelli, Kandel, Guerassimovitch & Ferrand (2012) . Spinelli and colleagues examined to what extent grapheme processing could be affected by the degree of grapheme *cohesion*, defined as the systematicity with which a bigram (i.e. two adjacent letters) refers to a grapheme unit in a language. In French, some bigrams such as “au” are always processed as units and these were referred to as highly cohesive complex graphemes. In contrast, other bigrams such as “an” can, in some contexts, be processed as units (corresponding to the phoneme /ã/) or not (processed as two graphemes “a”- “n” with the corresponding phonemes /a/-/n/ when followed by a vowel; these were considered weakly cohesive. The authors showed that letter detection times were longer for highly cohesive (e.g. detect O in *bij**ou***) compared to weakly cohesive (e.g. O in *gaz**on***) items. Longer programming times in a handwriting task were also observed for highly compared to weakly cohesive items. This grapheme cohesion effect was interpreted as reflecting the higher parsing ambiguity for weakly cohesive items due to multiple phonemic associations, and thus the involvement of phonological processes in the letter detection task. Yet, the lack of a simple grapheme condition (e.g. detect O in *gazol*) in their study made it impossible to investigate the influence of grapheme cohesion on the grapheme complexity effect *per se*; that is one cannot say whether both of these two types of complex graphemes are processed as orthographic units during visual word recognition, due to the absence of a simple grapheme baseline condition. Given the high parsing ambiguity of weakly cohesive complex graphemes, it could be that these combinations of letters are processed as units to a much lesser extent compared to highly cohesive graphemes.

Other phonologically-related effects have been reported using the same paradigm, revealing the involvement of early phonological processes in this task. Using the letter detection task with adult English speakers, Rey et al. (2000; Experiment 2) reported longer detection times in cases of phonological dissimilarity between the letter to be detected (i.e. the letter sound) and the phonemic correspondent of the grapheme within the word (e.g. detect O in *prove* or *cloud* where O → /u:/ and /aʊ/, respectively) compared to cases of phonological similarity (e.g. detect O in *slope* or *float* where O → /əʊ/). Using a similar procedure with French adolescents learning English as a second language (L2) in secondary school, Commissaire, Duncan & Casalis (2014) uncovered cross-language congruency effects: letter detection times in L2 were longer when the letter to detect had an incongruent print-to-sound mapping relative to L1 conversion rules (e.g. detect I in *bird*) compared to a congruent one (e.g. detect I in *hill* where I → /i/ in both French and English). Note that another unitization effect at the level of syllable onset was also reported with this task. Brand, Giroux, Puijalon & Rey (2007; see also Gross, Treiman & Inman, 2000) revealed longer detection times when detecting a letter located in the second position of a multi-letter syllable onset (e.g. detect L in *tablier*) compared to when presented as a single letter onset (e.g. detect L in é*colier*). In any case, these studies point to the fact that early phonological activation could be involved in this task, despite the short processing time of target words that is allowed during it (commonly 50-55 ms). Thus, according to a "phonological hypothesis, grapheme complexity effects could emerge once phonology is connected only and, more specifically, during grapheme-to-phoneme conversion.

Until recently, mainly two models acknowledged the role of grapheme units in addition to letters, and included a stage dedicated to grapheme processing: the Bimodal Interactive Activation Model or BIAM (Diependaele, Ziegler & Grainger, 2010; Grainger & Holcomb, 2009) and the Connectionist Dual-Process models or CDP/+/++ (Perry, Ziegler, & Zorzi, 2007, 2010, 2013, 2014). Both models take a large view on reading by investigating both silent reading and reading aloud, and by considering multiple routes to reading including lexical and sub-lexical reading routes. In both theoretical frameworks, the grapheme processing stage is refers to as the two-layer associative network (hereafter TLA) and is part of the sub-lexical route to reading. It is defined as two consecutive mechanisms: grapheme parsing, which is considered to be a serial mechanism that operates from left to right so that an attentional window moves along the letters, converting them into grapheme units while following a syllable-like structure (i.e. onset–vowel–coda, see Perry et al., 2007), and grapheme-to-phoneme conversion. These models assume that words can be parsed into grapheme units *before* any phonological sub-lexical activation, and thus that these units could be considered as orthographic units per se. Yet, these models also assume that these orthographic representations are activated within a sub-lexical route to reading only, not during more direct contact to the orthographic lexicon. In line with this approach, most reading models focusing on *lexical access* did not incorporate graphemes as orthographic sub-lexical units but rather letters and/or bigrams (Davis, 2010; Dehaene, Cohen, Sigman & Vinckier, 2005; Grainger & van Heuven, 2003; McClelland & Rumelhart, 1981; Whitney, 2001).

Only recently did some authors suggest that grapheme units might be used as orthographic representations during sub-lexical processing *and* lexical access. Grainger & Ziegler (2011) proposed the dual-route approach to orthographic coding that suggests the existence of grapheme units as an intermediate layer between letters and the orthographic lexicon. According to this proposal, letter representations would provide information to two orthographic codes: a "coarse-grained" one representing open-bigrams (Grainger & van Heuven, 2003) and a "fine-grained" one representing various letter chunks such as graphemes or morphemes. While only the fine-grained orthographic code would connect to sub-lexical processes such as the phonological decoding of words (via graphemes) or morphological decomposition (via morphemes), the two orthographic codes, either coarse- or fine-grained, would connect to the orthographic lexicon. According to this model, graphemes are thought to be functional units during lexical access, as well as during sub-lexical processing, but the hypothesis has only been tested once by Lupker, Acha, Davis & Perea (2012) who concluded *against* a specific role of grapheme units in lexical access. In the present study, Experiments 1a/b/c aimed to investigate grapheme coding during *sub-lexical processing* by using the letter detection task, and thus to further investigate the mechanisms underlying grapheme parsing

(CDP+ framework, Perry et al., 2007, 2010). Whether grapheme complexity effects were found for both highly and weakly cohesive graphemes was of interest. We also tested whether such effects are found when minimizing phonological activation during the task. Following on from Lupker et al. (2012) and using the masked lexical decision task, Experiment 2a/b and 3 aimed to examine whether graphemes could also be processed as perceptual units during *lexical access* and to directly test the hypothesis made by Grainger & Ziegler (2011)

Experiments 1a, 1b and 1c

Experiments 1a, 1b and 1c were designed to investigate further the mechanisms underlying grapheme coding using the letter detection task. Our *first* goal was to examine whether a grapheme complexity effect occurs for different types of complex graphemes that can be considered more or less cohesive from a phonological approach. Following on from Spinelli et al. (2012), we used two types of complex graphemes considered highly cohesive (e.g. detect A in *ch**au**d* where "au" always connects to /o/) or weakly cohesive (e.g. A in *ch**an**t* where "an" here connects to /ã/ but can, in other contexts, connect to two different phonemes, /a/ /n/). Contrary to the work of Spinelli and colleagues, these two complex grapheme conditions were compared to a simple grapheme condition considered a baseline condition (e.g. A in *pl**a**ce*) in order to investigate the unitization process of these two types of units, more or less cohesive, and thus to understand further the mechanisms underlying grapheme complexity effects in the letter detection task. It is noteworthy that most of the experiments investigating grapheme complexity effects in English, French or Dutch have used highly cohesive complex graphemes. This was also the case in the one experiment conducted in the

French language by Rey et al. (2000) in which highly cohesive complex graphemes constituted 75% of their stimuli. So, although this complexity effect was expected for highly cohesive complex graphemes, it was of interest to discover whether weakly cohesive graphemes could also be considered perceptual units, despite their lower phonological cohesion. These graphemes are indeed more ambiguous as they do or do not correspond to a unit depending on the context (e.g. ‘an’ is a unit in *chant* but not in *cane*). Their representation could therefore be less activated during the task, leading to lower competition with the letter level and so small or even null processing cost compared to the simple grapheme condition. Thus, while a grapheme *cohesion* effect, that is longer detection times for highly cohesive compared to weakly cohesive complex graphemes, was expected following on from Spinelli et al. (2012), whether a complexity effect could be observed for the latter was unclear given that no baseline was included in their study.

Our *second* goal, partly related to the first, was to investigate the nature of grapheme complexity effects by manipulating the degree of phonological activation allowed in the task via different task parameters. To enable phonological activation during the letter detection task, Experiment 1a used a 57 ms target word presentation, a task parameter that has previously been used when assessing phonological effects with this task (Brand et al., 2007; Rey et al., 2000). This experimental condition was compared to Experiment 1b in which the duration was reduced to 33 ms, and to Experiment 1c, which combined a 33 ms presentation with a concurrent articulation task in which participants had to repeat continuously and overtly a nonsense sequence /patipato/ (Chetail & Content, 2012). Whereas it was unclear whether the phonological code would be activated in Experiment 1b, Experiment 1c was clearly designed to minimise phonological activation during the task while using the same grapheme conditions and stimuli composition. Whether grapheme units could be activated as units when little phonological activation was allowed remained unclear. Considering that experimental conditions 1b and 1c mostly tapped into early orthographic coding of the target words, with little or even no time for phonological activation (experiment 1c was clearly designed to remove any phonological influence), we hypothesised that if grapheme units can only be activated when activating word sub-lexical phonology and thus are not orthographic units *per se*, then an interaction between grapheme and experimental conditions should be observed with no grapheme complexity effect for experimental conditions 1b and 1c. This should help to understand the nature of the grapheme complexity effect and determine at which grapheme processing step of the two-layer associative network (TLA, Perry, Ziegler & Zorzi, 2007) it occurs: grapheme parsing and/or grapheme-to-phoneme conversion.

Method

Participants

A total of sixty French-speakers participated in the study and were divided into three groups of twenty according to the experimental conditions (Experiment 1a: 57 ms, mean age: 20;6; Experiment 1b: 33 ms, mean age: 20;3; Experiment 1c: 33 ms + concurrent articulation, mean age: 20;8). Participants were undergraduate students from the Faculty of Psychology of the University of Strasbourg with normal or corrected vision. They were tested for French reading skills using the text Le Pollueur (ECLA-16+, Gola-Asmussen, Lequette, Pouget, Rouyet & Zorman, 2007) which contains 296 words and must be read as accurately and quickly as possible. The three groups did not differ in either reading speed or accuracy, all Fs < 1, n.s.

Materials

A total of fifty-four letter-present word trials were constructed. These were divided into three lists of eighteen items each representing the experimental conditions: 1) simple graphemes, in which the target letter such as A was presented as a single letter in the word (e.g. *ph**a**re,* meaning *lighthouse*); 2) highly cohesive complex graphemes, in which the target letter was embedded in a complex grapheme composed of two adjacent vowels (e.g. *ch**au**d*, meaning *warm*); and 3) weakly cohesive complex graphemes, in which the letter was embedded in a complex grapheme composed of a vowel followed by a consonant (e.g. *ch**an**t,* meaning *sing*). The stimuli were four-to-five-letter monosyllabic words and the letter to be detected was in the second or third position in the word, respectively. Importantly, when the target letter occurred in a complex grapheme, it always appeared as the first letter of the multi-letter grapheme (e.g. A in *ch**a**ud* and in *ch**a**nt*). Stimuli were created on the basis of triplets matched on a one-to-one basis on word CV structure, number of letters (mean: 4.39, SD: .50, $F < 1$, n.s.). They were also matched on lexical frequency [simple grapheme condition: mean 155 occurrences per million, opm (SD: .168), highly cohesive complex grapheme condition: 153 opm (SD: 129) and weakly cohesive complex grapheme condition: 159 opm (SD: 174), $F < 1$, n.s.] and on minimal token bigram frequency [1] [simple grapheme condition: mean 2161 (SD: 2062), highly cohesive complex grapheme condition: 3290 (SD: 2833) and weakly cohesive complex grapheme condition: 4124 (SD: 3122), $F(2,51) = 2.382$, $p = .11$, n.s.] which were estimated using the Lexique database (New, Pallier, Ferrand & Matos, 2001). The two complex grapheme conditions were also matched on phoneme length (mean: 2.44, SD: .51, $F < 1$, n.s.), token bigram frequency [highly cohesive complex grapheme condition: 10564 (SD: 9889) and weakly cohesive complex grapheme condition: 12942 (SD: 8904), $F < 1$, n.s.], and number of words in which they appeared as units, thus corresponding to one phoneme ($t < 1$, n.s., using LEXop database, Peereman & Content, 1999). A total of fifty-four target-absent trials were also constructed in the same way as the letter-present trials. In order not to induce a response strategy, 85% of the letter-absent words in this condition also included the target letters to be detected (A, E and O; although not the congruent one, e.g. detect A in the word *blond*).

Procedure

A target detection task was performed following Rey et al.'s (2000) procedure. The target letter was first presented for 700 ms in uppercase in the middle of the screen followed by a fixation point for 1000 ms. The target word then appeared in lowercase for a duration that varied across experimental conditions (see below). It was replaced by a blank screen presented for 70 ms followed by 50 ms mask consisting of hashes. Participants had to press "yes" with their dominant hand if they detected the target letter in the word or else "no" with their non-dominant hand. Three different experimental conditions were used: 1) Experiment 1a in which the target word was presented for 57 ms; 2) Experiment 1b in which its presentation duration was 33 ms, and 3) Experiment 1c with a presentation duration of 33 ms but in which participants were asked to repeat continuously and overtly the phonological sequence /patipato/ (Chetail & Content, 2012). The experiment was preceded by a 10-trial training phase. The whole testing procedure lasted around 20 minutes.

Results

Table 1 presents the mean RTs and percentage errors (and SDs) for the letter-present target words in the three experimental conditions 1a, 1b and 1c. An ANOVA was conducted on RTs and errors both by participants (F_1) and by items (F_2) for each experimental condition. Ggrapheme condition was entered as within-subjects by participants but as between-subjects by items. Data cleaning was performed by removing all RTs below 250 ms and above 2000 ms and then discarding each data point more than 2.5 SDs from the mean experimental condition RTs (<3% of accurate responses). In addition, one participant from the experimental condition 1b was removed from the analyses due to high error rates (22%, more than 2.5 SDs above the mean group accuracy). Given the variability across the experimental conditions, RTs were inverse transformed in order to normalise the distribution.

Experimental condition 1a

Reaction times

The effect of grapheme condition was significant, $F_1(2,38) = 7.568$, $p < .01$, $\eta_p^2 = .28$, $F_2(2,51) = 3.66$, $p < .04$, $\eta_p^2 = .13$. Planned comparisons revealed longer RTs for the highly cohesive complex condition compared to the simple condition, $F_1(1,19) = 14.13$, $p < .01$, $F_2(1,51) = 7.01$, $p < .02$ and, to a lesser extent, compared to the weakly cohesive complex condition, $F_1(1,19) = 4.56$, $p < .05$, $F_2(1,51) = 3.24$, $p = .078$. The difference between the weakly cohesive complex condition and the simple condition did not reach significance, $F_1(1,19) = 3.14$, $p = .10$, n.s., $F_2 < 1$, n.s.

Errors

The effect of grapheme condition was not significant, $F_1(2,38) = 1.33$, $p = .28$, n.s., $F_2 < 1$, n.s.

Experimental condition 1b

Reaction times

The effect of grapheme condition was significant although as a trend by participants, $F_1(2,36) = 3.2$, $p = .05$, $\eta_p^2 = .15$, $F_2(2,51) = 3.53$, $p < .04$, $\eta_p^2 = .12$. Again, planned comparisons revealed longer RTs for the highly cohesive complex condition compared to the simple condition although less robustly by participants, $F_1(1,18) = 4.15$, $p = .056$, $F_2(1,51) = 6.1$, $p < .02$, and compared to the weakly cohesive complex condition, $F_1(1,18) = 5.02$, $p < .04$, $F_2(1,51) = 4.35$, $p < .05$. The difference between the weakly cohesive complex condition and the simple condition did not reach significance, all Fs < 1, n.s.

Errors

The effect of grapheme condition reached significance, $F_1(2,36) = 3.39$, $p < .05$, $\eta_p^2 = .16$, n.s., $F_2(2,51) = 3.19$, $p < .05$, $\eta_p^2 = .11$, and revealed more errors in the weakly cohesive complex grapheme condition compared to the simple condition (5% difference, $p < .04$).

Experimental condition 1c

Reaction times

The effect of grapheme condition was significant, $F_1(2,38) = 3.47$, $p < .05$, $\eta_p^2 = .15$, $F_2(2,51) = 4.755$, $p < .02$, $\eta_p^2 = .16$. Planned comparisons revealed longer RTs for the highly cohesive complex condition compared to the simple condition, $F_1(1,19) = 6.63$, $p < .02$, $F_2(1,51) = 9.51$, $p < .01$, but no significant difference compared to the weakly cohesive complex grapheme condition, $F_1(1,19) = 1.34$, $p = .26$, n.s., $F_2(1,51) = 2.25$, $p = .14$, n.s. The difference between the weakly cohesive complex condition and the simple condition did not reach significance, $F_1(1,19) = 2.19$, $p = .15$, n.s., $F_2(1,51) = 2.51$, $p = .12$, n.s.

Errors

The effect of grapheme condition was not significant, all *F*s < 1, n.s.

Combined analysis

The experimental condition was entered as a between-subjects variable in the analysis by participants, but as within-subjects by items; grapheme condition was entered as within-subjects by participants but as between-subjects by items. Again, RTs were inverse transformed in order to normalise the distribution.

Reaction times

The effect of the experimental condition was significant, $F_1(2,56) = 4.97$, $p < .02$, $\eta_p^2 = .1$, $F_2(2,102) = 168.92$, $p < .001$, $\eta_p^2 = .77$. This reflected overall longer detection times in Experiment 1c compared to 1a, $F_1(1,56) = 4.36$, $p < .05$, $F_2(1,51) = 128.76$, $p < .001$, and to

1b, $F_1(1,56) = 9.51$, $p < .01$, $F_2(1,53) = 327.33$, $p < .001$. Detection times were also slower in Experiment 1a compared to 1b, although only significant by-items, $F_1 < 1$, n.s., $F_2(1,51) = 41.05$, $p < .001$. The effect of grapheme condition was also significant $F_1(2,112) = 12.16$, $p < .001$, $\eta_p^2 = .18$, $F_2(2,51) = 12.78$, $p < .001$, $\eta_p^2 = .33$. Planned comparisons revealed longer RTs for the highly cohesive complex condition compared to the simple condition, $F_1(1,56) = 22.43$, $p < .001$, $F_2(1,51) = 24.89$, $p < .001$, and to the weakly cohesive complex condition, $F_1(1,56) = 10.32$, $p < .01$, $F_2(1,51) = 10.3$, $p < .01$. The difference between the weakly cohesive complex condition and the simple condition did not reach significance, $F_1(1,56) = 2.65$, $p = .11$, n.s., $F_2(1,51) = 3.17$, $p = .08$. The interaction between the experimental and grapheme conditions was not significant, both F_1 and $F_2 < 1$, n.s.

(Table 1 about here)

Errors

The effect of experimental condition was significant, $F_1(2,56) = 6.22$, $p < .01$, $\eta_p^2 = .18$, $F_2(2,102) = 11.67$, $p < .001$, $\eta_p^2 = .19$ reflecting more errors in Experiment 1c compared to 1a, $F_1(1,56) = 7.76$, $p < .01$, $F_2(1,51) = 16.28$, $p < .001$, and to 1b, $F_1(1,56) = 10.61$, $p < .01$, $F_2(1,53) = 17.22$, $p < .001$. No difference emerged between Experiments 1a and 1b, all *F*s < 1, n.s. The grapheme effect did not reach significance, F_1 $(2,112) = 2.39$, $p = .10$, n.s., F_2 $(2,51) = 1.63$, $p = .21$, n.s., and neither did the interaction between grapheme and experimental conditions, F_1 $(4,112) = 1.04$, $p = .39$, n.s., F_2 $(4,102) = 1.14$, $p = .34$, n.s.

Discussion

The goal of the present experiments was twofold: 1) to investigate grapheme complexity effects in adult expert readers by introducing a distinction between two categories of complex graphemes depending on their degree of phonological cohesion, highly cohesive (e.g. “ou”) or weakly cohesive (e.g. “on”), and 2) to examine the nature of grapheme complexity effects by manipulating the degree of phonological activation enabled during the letter detection task. Participants were presented with a letter detection task during which they were asked to detect whether a predetermined target letter was present or absent in a target word. The letter could appear as a single grapheme in the word (e.g. detect O in *ch**o**se*) or embedded in a complex grapheme of either high cohesion (e.g. detect O in *fr**oi**d*) or weak cohesion (e.g. detect O in *bl**on**d*). Phonological activation was manipulated by varying the duration of presentation of the target word, i.e. 57 ms in Experiment 1a versus 33 ms in Experiment 1b. As decreasing the presentation duration might not have been sufficient to prevent phonological information arising, a concurrent articulation task was added to Experiment 1c, associated with 33 ms of presentation, to minimise phonological activation further.

As expected, whether the letter to detect was presented as a simple grapheme or embedded in a complex grapheme was relevant during the task and this is in line with previous studies on monolingual adults (Rey et al., 1998, 2000, 2005) and children (Commissaire et al., 2014; Marinus & de Jong, 2011), showing that both letter and grapheme units can be simultaneously coded during visual word recognition. However, only highly cohesive complex graphemes yielded a significant grapheme complexity effect. This finding was observed consistently across all experimental conditions. Thus, the degree of cohesion seemed to have an impact on the unitization process in that only complex graphemes that were systematically processed as units, i.e., highly cohesive graphemes, triggered a processing cost during letter detection compared to the simple grapheme condition. This is in line with two previous letter detection studies using similar types of highly cohesive complex graphemes (Commissaire et al., 2014; Rey et al., 2000). The more ambiguous complex graphemes (e.g. weakly cohesive graphemes such as "an" and "on" in French) seemed to be processed as individual letters. It is noteworthy that the two complex conditions were matched on bigram frequency and grapheme- to- phoneme consistency, excluding the impact of other sub-lexical variables [2]. Moreover, the data yielded a grapheme cohesion effect; that is longer detection times when the letter was embedded in a highly cohesive compared to a weakly cohesive complex grapheme, a result in line with Spinelli et al. (2012). Separate analyses, however, revealed that this effect did not reach significance in Experiment 1c in which phonological activation was prevented. Yet, while Spinelli et al. (2012) thought that the impact of cohesion on grapheme coding reflected the influence of a phonological variable, this interpretation is not supported by the current data. The use of a simple grapheme condition, thought to represent a baseline, enabled grapheme cohesion to be disentangled from complexity effects. Grapheme cohesion effects seemed to emerge because only graphemes that were highly cohesive were processed as units, unlike weakly cohesive ones that seemed to be processed as two simple graphemes.

More, our finding of this effect in all experimental conditions, including Experiments 1b and 1c that were designed to minimise the influence of phonology, supports the hypothesis of an early orthographic mechanism, possibly during grapheme parsing (Perry et al., 2007). This is in line with two previous letter detection studies using a short presentation of the target word (33 ms, Commissaire et al., 2014; Rey et al., 2000) and extends it to a dual-task context in which participants were asked to repeat simultaneously a nonsense phonological sequence. Complex graphemes are coded as units when accessing their phonological representations, as demonstrated by the grapheme complexity effects observed in naming tasks, but even earlier, as orthographic units or chunks *per se* (see similar conclusions by Marinus & de Jong, 2010). After some reading experience, one could imagine that these units become sub-lexical orthographic units, relatively independent of phonological representations. These units would be activated within the sub-lexical route to reading, as similar results are generally observed whether the letter to detect appears in a word or a nonword (Commissaire et al., 2014). These data are in line with reading models that incorporate a two-stage grapheme processing level during sub-lexical route to reading such as BIAM (Diependaele et al., 2010) or CDP/+ (Perry et al., 2010). Whether graphemes are processed as perceptual units during *lexical access* as well, a stronger hypothesis made by Grainger & Ziegler (2011) in their dual route- approach of orthographic coding was investigated in the following experiments using the lexical decision task associated with the masked priming paradigm.

Experiments 2a and 2b

The goal of Experiments 2a and 2b was to test whether graphemes are also orthographic coding units during lexical access. Although we showed in Experiment 1 that these units could be activated under little or no phonological activation, and thus be processed as orthographic units *per se*, the letter detection task that was used does not precisely assess lexical access, as the response required could be provided without accessing the lexical representation of the word. In fact, previous studies have reported comparable patterns with words and pseudowords (Commissaire et al., 2014). Lupker and colleagues recently questioned the role of grapheme units in lexical access by using the masked primed lexical decision task in a set of four experiments. Their rationale was that if graphemes have a special role in lexical access, beyond letters, then manipulating the grapheme structure between primes and targets could affect orthographic priming. In their study, primes were constructed by *removing, transposing,* or *replacing* two letters from a word, which constituted either a multi-letter grapheme unit (e.g. *bl**ch-BLEACH, anhtem-ANTHEM,* and *ankfem-ANTHEM*, respectively) or two adjacent letters each representing a grapheme (e.g. *b**ach-BLEACH*, *emlbem-EMBLEM*, *emfdem-EMBLEM*, respectively), and were contrasted with orthographically unrelated primes. In all experiments, using both English and Spanish stimuli, orthographic facilitation priming effects were obtained independently of whether the letters that were changed within the primes appeared as a multi-letter grapheme unit or two different single-letter graphemes. The finding of comparable priming effects for the two grapheme conditions led the authors to conclude that there was no special representational status for multi-letter graphemes as orthographic units during lexical access. Lupker and colleagues broadened their conclusion by challenging the existence of grapheme orthographic units during sub-lexical processing by arguing that grapheme complexity effects obtained in silent reading tasks such as the letter detection task would probably reflect the involvement of phonological mechanisms, a conclusion that is challenged by our previous data from Experiment 1.

Given the hypothesis of Grainger & Ziegler (2011) about a direct link between grapheme units and the orthographic lexicon, the "fine-grained" orthographic code, but the contradictory empirical data found by Lupker and colleagues, our goal was to address this issue again while exploring different task parameters (i.e. SOA) and taking into account the possible limitations of their study (by controlling other relevant variables when constructing the stimuli). In the following experiments (as in Lupker's Experiment 1), target words were preceded by four prime conditions, which varied in the number of graphemes changed (one grapheme vs. two graphemes) and relatedness (related vs. unrelated). For example, the French target word *DOUCHE* could be preceded by two types of orthographically related primes: either one that substituted one multi-letter or complex grapheme (e.g. *d**che – DOUCHE, shower,* where ** replaces "ou" → /u/) or one that substituted two different graphemes (e.g. *do**he – DOUCHE* where ** broke the complex grapheme "ou"). These two orthographically related prime words were each contrasted with unrelated primes (e.g. *f**sse* and *fa**se-DOUCHE* for the one-grapheme and two-grapheme conditions, respectively). Given our previous results from Experiment 1, we chose to focus on highly cohesive complex graphemes of the same type as in Experiment 1 and, more specifically, multi-vowel VV complex graphemes (e.g. “ai”, “au”, “ou”...) that are more common in French compared to multi-consonant (CC) complex graphemes (e.g. “ch”, “th”). Although Lupker et al. (2012) mostly focused on transposition priming experiments (e.g. *duoche* vs. *docuhe-DOUCHE* for the one-grapheme vs. the two-grapheme condition, respectively), our choice was to use partial words as primes (*d**che – DOUCHE*) to avoid strong limitations when matching our primes on their degree of graphotactics (e.g. *duoche* might be more orthographically legal in French compared to *docuhe*) and on the syllable length of the primes (e.g. *duoche* is monosyllabic while *docuhe* is disyllabic) across both grapheme conditions. The use of partial priming, however, meant that we used a new specific set of items, different from those used in Experiment 1 as these were too short (4-5 letters in length) to create primes with *internal* substituted symbols only, and not external ones (e.g. *ch**d* vs. *cha**-CHAUD* in the one-grapheme vs. the two-grapheme condition). In addition, the prime exposure of Lupker et al. (i.e. 50 ms) has been shown to elicit both orthographic and phonological activation involving multiple and possibly counteracting effects [3]. Experiment 2 was therefore designed to explore two different SOAs by using a between-subjects design (50 and 33 ms in Experiments 2a and 2b, respectively). Moreover, some variables were controlled: all target words were monosyllabic and so our priming conditions did not raise methodological issues in terms of the syllabic length of the primes and syllabic segmentation. Importantly, we controlled for the shared neighborhood between the prime and the target (shared neighborhood size and frequency of the most frequent shared neighbor). The relevance of neighborhood variables when examining orthographic priming effects was reported by Van Heuven, Dijkstra, Grainger & Schriefers (2001, examining shared N-size) who found stronger facilitation effects when pseudoword primes and targets shared few neighbors compared to when they shared many, and thus we ensured that both grapheme conditions were matched on these variables.

Thus, Experiment 2 tested orthographic priming effects in French speakers and manipulated both grapheme conditions (number of graphemes changed between the prime and the target) and SOA (50 ms and 33 ms). Our hypothesis was that if graphemes can be considered orthographic coding units during lexical access, as hypothesised by Grainger & Ziegler (2011), then orthographic priming effects should differ between the two grapheme conditions in that facilitation effects should be stronger in the one-grapheme condition (contrasting related and unrelated conditions, e.g. *d**che-DOUCHE* vs. *f**sse-DOUCHE*) in which the grapheme structure between the prime and the target is preserved, compared to the two-grapheme condition (e.g. *do**he-DOUCHE* vs. *fa**se – DOUCHE*). Given previous data using a similar procedure (Lupker et al., 2012, Experiment 1), this pattern could however only be observed when using a very short SOA (33 ms), which specifically taps orthographic coding, and not a slightly longer one (50 ms).

Method

Participants

A total of 50 French-speakers participated in the study, 23 with the 50 ms SOA (mean age: 21;2; Experiment 2a) and 27 with the 33 ms SOA (mean age: 20;8; Experiment 2b). Participants were undergraduate students from the University of Strasbourg with normal or corrected vision. As in Experiment 1, they were tested for French reading skills using the text Le Pollueur (ECLA-16+, Gola-Asmussen et al., 2007). Participants from Experiments 2a and

2b were matched on reading level (all *t*s < 1, n.s. for both reading speed and accuracy).

Materials

A total of 64 monosyllabic words were selected as word targets. They were five to seven letters long and contained a medial vowel complex grapheme (e.g. au, ou, oi). The mean word frequency (obtained from Lexique.org, New et al., 2001) was 69 occurrences per million (opm; SD: 128). These target words were preceded by four prime conditions, corresponding to the orthogonal manipulation of two variables: grapheme condition (one grapheme vs. two graphemes) and relatedness (related vs. unrelated). For instance, the target word *DOUCHE* (*shower*) could be preceded by the related prime word *d**che* in the one-grapheme condition, in which the two "**" replaced the complex grapheme "ou", and by *do**he* in the two-grapheme condition, in which the two "**" replaced a part of the complex grapheme and an adjacent letter. Unrelated primes were constructed in a parallel manner but using another base word that did not share any common letter with the target, except in some cases for the final –e (e.g. here *f**sse* and *fa**se* from the real word *FAUSSE* for the one-grapheme vs. the two-grapheme condition, respectively). Importantly, the shared neighborhood between related primes and target words was matched across both grapheme conditions, using both the index of shared neighborhood size (N-size) and the frequency of the most frequently shared neighbor [4]. In other words, the mean shared N-size between primes and targets was .73 (SD: 1.5) and .75 (SD: 1.83) in the one- and two-grapheme conditions, respectively, $t < 1$, n.s. The mean frequency of the most frequent shared neighbor word was 4.48 (SD: 15.21) and 7.79 (SD: 26.93) in the one- and two-grapheme conditions, respectively, $t < 1$, n.s. Nonword targets were constructed by changing one letter in the target words, in either the initial (e.g. *NEURRE* from the real word *BEURRE*, *butter*) or medial (e.g. *DOUCRE* from the real word *DOUCHE*) position. Nonword targets were also preceded by four prime conditions that were designed in a similar way to the target words, that is by manipulating both the grapheme condition (one grapheme vs. two graphemes) and relatedness (related vs. unrelated).

Four lists were created so that each target word appeared with one specific prime in each of the lists. Each list contained a similar number of one/two graphemes and related/unrelated primes. Participants saw two lists during the experiment (with a counterbalanced order) so that a target word was seen twice, with either its related or its unrelated prime within the one-grapheme condition (e.g. the target word *DOUCHE* was preceded by *d**che* and *f**sse* in lists 1-2, and by *do**he* and *fa**se* in lists 3-4). We ensured that shared neighborhood variables between related primes and targets were also matched across grapheme conditions within each list (all *p*s = n.s.)

Procedure

The experiment was run using E-Prime 2 experimental software on an HP ZBook 15. Participants were tested individually in a quiet room. They were instructed to decide as quickly and accurately as possible if the letter string was a real French word or not by pressing one of two buttons on the keyboard. No mention of the prime was made. Each trial started with a fixation point for 1000 ms followed by a forward masked (i.e. #######) for 500 ms. The prime was then presented in lowercase letters for 50 ms (Experiment 2a) or 33 ms (Experiment 2b). The target then appeared in uppercase for 3 s or until the participant responded. Ten practice trials were provided before the experiment and the whole session lasted for 20-30 minutes including the control reading test, which was presented to the participants between the two experimental lists.

Results

Data were cleaned by removing all RTs below 250 ms and above 2000 ms and then discarding each data point more than 2.5 SDs from the mean (< 4% of accurate responses). In addition, one participant from the 50 ms SOA condition was removed from the analyses due to high error rates (35%, more than 2.5 SDs above the mean group accuracy). The mean reaction times and percentages of errors (and standard deviations) per SOA (50 vs. 33 ms), grapheme condition (one grapheme vs. two graphemes) and relatedness (related vs. unrelated) are presented in Table 2. In the analysis by participants (F_1), SOA was entered as a between-subjects variable while grapheme condition and relatedness were within-subjects. In the analysis by items (F_2), all variables were entered as within-subjects. As in Experiment 1, RTs were inverse transformed in order to normalise the distribution.

Reaction times

The main effect of relatedness was significant by participants and items, $F_1(1,47) = 99.961$, $p < .001$, $\eta_p^2 = .68$, $F_2(1,63) = 86.976$, $p < .001$, $\eta_p^2 = .58$ and showed significant facilitation by related compared to unrelated primes (27 ms). The interaction between relatedness and SOA also reached significance, $F_1(1,47) = 11.874$, $p < .01$, $\eta_p^2 = .20$, $F_2(1,63) = 9.234$, $p < .01$, $\eta_p^2 = .13$, and revealed twice as much facilitation effect at 50 ms compared to 33 ms SOA, although both effects appeared to be significant when using Bonferroni t-tests (36 ms and 19 ms, respectively, *p*s < .001). The effects of SOA and of grapheme condition were not significant (all *F*s < 1, n.s.) and neither was the interaction between grapheme condition and relatedness, $F_1(1,47) = 1.691$, $p = .20$, n.s., $F_2(1,63) = 1.4$, $p = .24$, n.s.

(Table 2 about here)

Errors

The main effect of relatedness reached significance by participants and as a trend by items, $F_1(1,47) = 4.25$, $p < .05$, $\eta_p^2 = .08$, $F_2(1,63) = 2.965$, $p = .09$, $\eta_p^2 = .04$ revealing fewer errors in the related compared to the unrelated condition (1% difference). The effect of SOA was also significant by items, $F_2(1,63) = 3.935$, $p = .052$, $\eta_p^2 = .06$, but not by participants, $F_1 < 1$, n.s. This reflected fewer errors in the 33 ms SOA (7%) compared to the 50 ms SOA condition (8%).

Discussion

In Experiment 2, we tested grapheme coding during lexical access by using masked lexical decision task. Compared to the study by Lupker et al. (2012), we controlled for a large number of relevant variables such as orthographic neighborhood and explored orthographic priming using two SOAs (33 vs. 50 ms). An orthographic facilitation priming effect was found on both reaction time and error data: participants were faster and made fewer errors in related compared to unrelated priming conditions. This facilitation effect was twice as large for the 50 ms SOA compared to the 33 ms SOA although both were significant. Thus, although we had expected stronger orthographic priming at 33ms SOA based on Ferrand & Grainger (1992), and thus greater opportunity to catch any grapheme effect, we found an opposite pattern: an increase of orthographic activation between 33 ms and 50 ms prime exposure[5]. In any case, the interaction between grapheme condition and relatedness did not reach significance in either experiment: priming effects were numerically very close for both 50 ms SOA (one grapheme: 38 ms, two graphemes: 34 ms) and 33 ms SOA (one grapheme: 19 ms, two graphemes: 18 ms). Thus, our data replicated Lupker et al.'s findings and extended them to a shorter SOA of 33 ms. This pattern was found while controlling for additional variables that could have prevented finding the hypothesised effect and accurately interpreting the data (syllabic length of target words, shared neighborhood size and frequency of the most frequent shared neighbor between primes and targets) and despite the one-grapheme prime condition having more consonant letters than the two-grapheme condition [6].

Thus, our data confirm the only previous priming study on grapheme coding and demonstrate that no special role of graphemes as orthographic coding units during lexical access could be evidenced using the lexical decision task associated with the masked priming paradigm. When tapping early stages of lexical access, only letters, not multi-letter graphemes, were shown to be used as functional units. Note that this does not preclude other coding units from being involved in visual word recognition such as open-bigrams. However, this issue was not tested in the present experiment. This contrasts with previous findings on the role of grapheme units during sub-lexical processing (Commissaire et al., 2014; Marinus & de Jong, 2011; Rey et al., 2000) and with our data from Experiment 1. Before these findings and their theoretical implications are discussed, one hypothesis remains to be tested. What was intended to be tested in Experiment 2 was the fine-grained orthographic code (Grainger & Ziegler, 2011) which involves the processing of large co-occurring units such as graphemes. However, it is possible that the stimulus list composition favored the coarse-grained orthographic code instead, which refers to a flexible code whereby letter combinations are computed in the absence of positional information [7]. This code is based on the open-bigram concept (Grainger & van Heuven, 2003), as attested by the numerous transposed-letter (Carreiras, Vergara & Perea 2007; Perea & Lupker, 2004) and relative-position (van Assche & Grainger, 2006; De Moor & Brysbaert, 2000) priming effects found in the literature, and is the fastest route to the orthographic lexicon. Given the relatively high frequency of the words used in Experiment 2 (69 occurrences per million, SD: 178), but also in the study by Lupker et al (37.3 occurrences per million), it is likely that this code was activated faster than the fine-grained code. In experiments 3, we tested whether grapheme units might be used during lexical access in very low lexical frequency words.

Experiment 3

In Experiment 3, target words were low-frequency words (less than 1 occurrence per million) preceded, as in Experiment 2, by orthographically related or unrelated primes of two grapheme conditions (one grapheme vs. two graphemes). A 50ms SOA was used to enable comparison with the study by Lupker et al (2012). We hypothesised that the lexical orthographic representations of these target words would reach identification thresholds more slowly than those of the higher-frequency words used in Experiment 2, a condition that should foster the use of a fine-grained orthographic code and help uncover a role for graphemes as sub-lexical orthographic units during lexical access.

Method

Participants

A group of 19 French-speakers participated in the study. They were undergraduate students from the University of Strasbourg with normal or corrected vision. Participants' reading performances were again assessed and revealed no differences with previous groups of participants from Experiments 2a and 2b.

Materials

A set of 25 monosyllabic low-frequency words was selected as word targets. They were five to seven letters long and contained a medial vowel complex grapheme (e.g. au, ou, oi). The mean word frequency (obtained from Lexique.org, New et al., 2001) was less than 1 occurrence per million (mean: .77, SD: .52). As in Experiment 2, target words were preceded by four prime conditions; related vs. unrelated, one-grapheme condition (*t**rte* vs. *b**gle*-*TOURTE*, pie) and related vs. unrelated, two-grapheme condition (*to**te* vs. *be**le*-*TOURTE*). Related primes from both grapheme conditions (one grapheme vs. two graphemes) were matched on shared neighborhood size (N-size, $t < 1$, n.s.) and frequency of the most frequent shared neighbor ($t < 1$, n.s.). Nonword targets were constructed by changing one letter in the target words and were also preceded by four prime conditions that were designed in a similar way to the target words. Four lists were created so that each target word appeared with one specific prime in each list. Participants saw two lists during the experiment (with a counterbalanced order) so that a target word was seen twice, with either its related or its unrelated prime within a grapheme condition.

Procedure

The same procedure was used as in Experiment 2a and Lupker et al (2012; 50 ms SOA). Ten practice trials were provided before the experiment and the whole session lasted for 15 minutes including the control reading test.

Results and discussion

Data were cleaned as in Experiment 2 leading to the removal of less than 3% of accurate responses. In addition, one participant whose error rate was more than 2.5 SDs above the mean of the group was removed from the sample. The mean reaction times and percentages of errors (and standard deviations) per grapheme condition (one grapheme vs. two graphemes) and relatedness (related vs. unrelated) are presented in Table 3. In both analyses by participants (F_1), and items (F_2), grapheme condition and relatedness were entered as within-subjects variables. As in previous experiments, reaction times were inverse transformed.

Reaction times

The main effect of relatedness was significant by participants and items, $F_1(1,17) = 8.182$, $p < .02$, $\eta_p^2 = .32$, $F_2(1,24) = 16.054$, $p < .001$, $\eta_p^2 = .40$ and showed a significant facilitation priming effect (41 ms). The effect of grapheme condition did not reach significance, $F_1(1,17) = 1.323$, $p = .27$, n.s., $F_2(1,24) = 3.252$, $p = .08$, n.s., and neither did the interaction between the two variables, all Fs < 1, n.s.

(Table 3 about here)

Errors

None of the main effects reached significance [grapheme condition: all *F*s < 1, n.s.; relatedness: $F_1(1,17) = 1.343$, $p = .26$, n.s., $F_2(1,24) = 2.037$, $p = .17$, n.s.]. The interaction between grapheme condition and relatedness was not significant either, $F_1(1,17) = 1.643$, $p = .22$, n.s., $F_2(1,24) = 1.886$, $p = .18$, n.s.

Experiment 3 aimed to test again whether graphemes were processed as functional units during lexical access by using very low frequency target words. Except from their lexical frequency, the stimuli used in Experiments 2a/b and 3 were highly comparable (similar syllabic and letter length) and constructed by controlling the same variables. As in Experiment 2, we found no interaction between grapheme condition and relatedness. We can only mention higher error rate in Experiment 3 due to the low frequency of items. Thus, even when encouraging the activation of fine-grained orthographic coding by using very low-frequency words, our pattern of results remained comparable to those of Experiments 2a and 2b and Lupker and colleagues' findings (2012).

General Discussion

The present work aimed to understand better the mechanisms underlying grapheme coding both during sub-lexical reading procedure (Experiments 1a/b/c) and lexical access (Experiments 2 and 3). In Experiment 1, a grapheme complexity effect was found in the letter detection task using three experimental conditions varying according to the duration of presentation of the target word (57 ms in Experiment 1a vs. 33 ms in Experiments 1b and 1c) and the presence of a concurrent task in order to remove phonological activation (concurrent articulation task in Experiment 1c). Importantly, this grapheme complexity effect was observed for highly cohesive complex graphemes (e.g. "au" in French) but not for weakly cohesive ones (e.g. "an") and this pattern of results was consistent across all experimental conditions. In Experiments 2 and 3, the role of grapheme units was assessed through a masked primed lexical decision task. It is noteworthy that the stimuli used in these two masked lexical decision experiments were very comparable to the words used in the highly cohesive complex grapheme condition of Experiment 1[8].Yet in contrast with Experiment 1, no special role could be evidenced for graphemes as relevant sub-lexical orthographic units during lexical access with both 50 ms and 33 ms SOA (Experiments 2a and 2b, respectively) or when using very low-frequency target words (Experiment 3).

Mechanisms underlying grapheme complexity and cohesion effects

The first goal of this study was to explore grapheme coding mechanisms during sub-lexical route to reading using the letter detection task and, more specifically, to examine whether grapheme complexity effects could be evidenced for different types of complex graphemes, which differ in their degree of phonological cohesion. Grapheme complexity effects have been reported in various populations of adult expert readers (Rey et al., 2000), developing readers aged 11-12 (Marinus & de Jong, 2011) and second language (L2) young learners aged 12-14 (Commissaire et al., 2014), and in different languages (English, French and Dutch). Longer detection times in complex grapheme conditions (e.g. A in *b**ea**ch*) compared to simple conditions (e.g. A in *bl**a**ck*) are explained by the co-activation of two competing levels: letters and graphemes. Our data from Experiment 1 showed that graphemes were processed as units during the letter detection task, even when the letter to be detected was in the first position of the complex grapheme (e.g. A in *ch**au**d*). Although this finding contrasts with the study by Brand, Giroux, Puijalon & Rey (2007), who concluded that the effect is constrained to the second letter of multi-letter graphemes (e.g. A in *b**oa**t*), it is in line with the recent findings of Marinus & de Jong (2011) in Dutch children who found no difference whether the letter to detect appeared in first or second position of the complex grapheme. This supports the idea of parallel letter coding within grapheme units, further discussed below, against the serial mechanism postulated in the DRC model (Coltheart et al., 2001). Importantly, we aimed to explore grapheme complexity effects for two types of complex graphemes: highly vs. weakly cohesive. In several languages such as English, most complex graphemes composed of two or more letters are processed as units when appearing as a bigram (e.g. “oa” is always processed as a unit when the two letters “o” and “a” are contiguous, and is thus considered highly cohesive). Interestingly, the French language is composed of both highly and weakly cohesive complex graphemes: some are always processed as units (e.g. “au”) while others are processed as units or not depending on the context (e.g. “an”). Our data revealed that only highly cohesive complex graphemes were processed as units: weakly cohesive complex graphemes, which are more ambiguous in terms of grapheme parsing, seemed to be processed as two separate letters, not a unit, even when more time was provided for phonological information to arise (with 57 ms of word exposure, Experiment 1a). Beyond the theoretical implications for models of silent reading, which are discussed below, this finding also clarifies what were referred to as grapheme cohesion effects by Spinelli et al. (2012). These authors discovered that detecting a letter embedded in a highly cohesive complex grapheme took longer than when it was embedded in a weakly cohesive one. Although we found such an effect in Experiments 1a and 1b, the inclusion of a baseline condition, i.e. the simple grapheme condition, made it possible to put forward another interpretation in terms of unitization processes (Rey et al., 2000). Longer detection times for highly cohesive compared to weakly cohesive complex graphemes seem to have reflected that only the latter were processed as units and triggered competition between the letter and grapheme levels.

Use and nature of grapheme coding during visual word recognition

Our data from Experiment 1 provided evidence for the orthographic nature of the grapheme complexity effect since a similar pattern of results was found across experimental conditions, thus even with little or no phonological activation (Experiments 1b and 1c). Graphemes are orthographic units that are, by definition, highly related to phonology. Nevertheless, our data shows that grapheme units are activated independently of phonology and can be considered as sub-lexical orthographic units *per se* in expert readers. Such unitization process was also evidenced with other type of salient units such as syllables (Taft, 1992) and more recently consonant-vowel (CV) clusters (Schmalz, Porshnev & Marinus, 2016). Schmalz and colleagues investigated whether Russian speakers process CV clusters as orthographic sub-lexical units. In Russian, most consonants' pronunciations are determined by taking into account the identity of the vowel that follows and the authors therefore hypothesized that a level of sub-lexical representation could exist for CV units, beyond letters, due to their functional relevance. The authors used a naming task associated with a visual disruption paradigm. The rationale was that unitization is evidenced if the reading cost is higher when the visual disruption is embedded within the unit than between units, compared to a situation without disruption. The authors revealed indeed that CV clusters are processed as sub-lexical units in Russian and that this type of parsing was independent of print- to-sound conversion, in line with our own data.

Whether these units are used within a sub-lexical route to reading only, as confirmed by the present letter detection data (e.g. processed within a graphemic parser, Diependaele, Ziegler & Grainger, 2010; Perry, Ziegler & Zorzi, 2010; see converging data by Lupker et al.,

2012) and also during more direct lexical access (Grainger & Ziegler, 2010) was the question raised by Experiments 2a, 2b and 3. Using the lexical decision task in a masked priming paradigm, we found that orthographic facilitation priming effects when using partial word primes did not differ regardless of whether the two letters removed from the primes corresponded to one grapheme (e.g. *l**tre-LOUTRE*) or to two graphemes (e.g. *lo**re-LOUTRE*). This finding is in line with Lupker et al. (2012) and extends their conclusions to a group of French speakers and to varying task and stimuli parameters: the use of two different SOAs (50 ms and 33 ms in Experiments 2a and 2b, respectively) and two conditions of word lexical frequency (high frequency in Experiments 2a and 2b vs. very low frequency in Experiment 3), the use of monosyllabic words only, and the control of the neighborhood between primes and targets. As Lupker and colleagues themselves concluded, such findings do not provide evidence for a role of grapheme units during lexical access. While these masked priming data might seem to contradict the letter detection data, we suggest here that we can overcome this discrepancy. It seems that the choice of the task enables or not the emergence of graphemic effects, which provide information on how these units are coded during visual word recognition.

Merging the findings: theoretical implications and conclusions

Graphemes seem to be coded as sub-lexical orthographic units *per se*, before any phonological activation; this is in line with proposals by Perry, Ziegler & Zorzi (2010, 2013) within the CDP theoretical framework, suggesting the existence of a graphemic parser within the sub-lexical route to reading before contact with phonological correspondences is made. Our finding of such grapheme complexity effect in conditions in which the letter to be detected appeared as the first letter of the complex graphemes (e.g. detect A in *ch**a**ud*) seems to point to a parallel letter coding within grapheme units. While this contradicts the DRC proposals of Coltheart et al. (2001) who suggested a sequential coding within grapheme units, this result again fits well within the CDP framework. Thus, when grapheme units are activated, both of their letters are simultaneously activated, and not in a sequential left-to-right direction (see Marinus & deJong, 2010, for similar conclusions). Importantly, while most research on the topic has not distinguished between different types of complex graphemes, we showed that only complex graphemes that are always processed as units in a given language (referred to as highly cohesive complex graphemes) trigger competition with the letter level and a detection cost in the letter detection task. Weakly cohesive complex graphemes, which are not always processed as units and are thus more ambiguous, do not generate a grapheme complexity effect as activation of the grapheme level might be slower and/or weaker and thus does not lead to competition with the letter level. This finding enables the mechanisms involved during grapheme parsing to be identified by taking into account the cohesion of the grapheme unit; that is how often adjacent letters are processed as a unit rather than as separate letters. We should note however that another difference between highly and weakly cohesive complex graphemes lies in the status of the letters that compose them: vowel-vowel versus vowel-consonant for the highly and weakly cohesive conditions respectively. The identity of letters, vowel or consonant, has been shown to influence sub-lexical processing (Chetail, Balota, Treiman & Content, 2014; Chetail & Content, 2012) and we cannot exclude at this point that grapheme cohesion effects were possibly partly explained by letter identity. The fact that weakly cohesive graphemes always consist of a vowel followed by the consonants ‘n’ or ‘m’ and are thus less diverse compared to highly cohesive graphemes could also have impacted our findings and caution should therefore be taken as future investigation of this effect is needed.

The current study also aimed to address the proposal by Grainger & Ziegler (2011) of a role for grapheme units, beyond letters, within a “fine-grained” orthographic code, which would directly relate them to lexical orthographic representations. While our failure to evidence a role for grapheme units during lexical access could have been explained by the predominant use of the “coarse-grained” orthographic code in Experiments 2a and 2b, this hypothesis does not explain our data from Experiment 3 in which the use of very low-frequency target words should have encouraged the use of the slower “fine-grained” orthographic code. Note here that the complex graphemes used in Experiments 2 and 3 were highly cohesive and so the stimuli for these experiments were comparable to those of Experiment 1 and corresponded to a situation that should have maximised the possibility of observing grapheme coding. Our findings from Experiments 2 and 3 therefore seem to support theoretical models such as the CDP+ (Perry et al., 2010, 2013) or BIAM (Diependaele et al., 2010) whereby graphemes do not directly connect to the orthographic lexicon - although they *can* be considered pure sub-lexical orthographic representations - but challenge Grainger & Ziegler’s proposal (2011; see also Grainger, Dufau & Ziegler, 2016). To summarise, our study draws a clearer picture of grapheme coding during visual word recognition and highlights the importance of task-specific mechanisms. More research is now needed to understand how graphemes become processed as sub-lexical orthographic units during reading acquisition, independent of their phonological counterparts and, more specifically, how models of silent reading in both expert and developing readers might simulate the different developmental processes between highly and weakly cohesive graphemes.

Footnotes

1 The minimal bigram frequency was shown to be a more adequate variable compared to the mean bigram frequency (Westbury & Buchanan, 2002). Token bigram frequencies were chosen as they have been shown to be adequate predictors of word identification times (Knight & Muncer, 2011; see also Conrad, Carreiras & Jacobs, 2008, examining syllabic frequency effects).

2 Among our stimuli, the letter to be detected had the same phoneme in all words in which it appeared (e.g. 'a' → /a/) except in three items in which the letter to detect had a different phonological mapping compared to the other items with the same letter (i.e., *rose* and *chose* where 'o' → /o/ while other words had the following 'o' → /ɔ/ mapping, and *peur* where 'eu' → /œ/ while other words had the following 'eu'→ /ə/). A post-hoc analysis without these three items revealed no differences with the pattern observed in the global analysis.

3 Using six prime exposures (17, 33, 50, 67, 83, 100 ms), Ferrand & Grainger (1993) revealed different time courses for orthographic (computed as the difference between O+P- nonword primes, e.g. *lonc-LONG*, and unrelated primes, e.g. *tabe-LONG*) and phonological effects (computed as the difference between the O+P- condition and an O+P+ nonword prime condition, e.g. *lont-LONG*) during masked priming, the former being significant from 17 ms up to 50 ms and the latter from 50 ms to 100 ms. At 50 ms, both orthographic and phonological influences of the nonword prime were thus recorded.

4 For example, in the g**tte-GOUTTE related prime condition, the prime g**tte could also have activated the French word GROTTE. Thus, we computed the number and frequency of those words that shared letters with the prime but were not used as targets.

5 This discrepancy could be explained by the different experimental designs between our respective studies as fewer shared letters between the prime and the target were available in our experiment (i.e. using only partial primes, e.g. *d**che-DOUCHE*) compared to theirs (i.e. using pseudoword primes, e.g. *lont-LONG*).

6 In fact, the one-grapheme prime condition had more consonant letters (mean: 3.11, SD: .48) compared to the two-grapheme condition (mean: 2.09, SD: .46), $t(126) = 12.26$, $p < .001$. As priming facilitation effects have been shown to be stronger when primes share many consonants with targets (Carreiras, Vergara & Perea, 2007; Perea & Lupker, 2004), there was an intrinsic advantage for the one-grapheme condition that could have helped to find a stronger facilitation effect (Lupker et al., 2012).

7 We thank an anonymous reviewer for making this suggestion.

8 Note that words from Experiment 1 were a little shorter (4-5 letters long) than those from Experiments 2 and 3 (5-7 letters long).

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Appendix 1: Stimuli for Experiments 1a, 1b and 1c

Target letter	Simple grapheme	Highly cohesive complex grapheme	Weakly cohesive complex grapheme
A	place	frais	blanc
A	phare	chaud	chant
A	plate	trait	franc
A	page	faux	banc
A	rare	saut	rang
E	clerc	creux	prend
E	vert	peur	sens
E	sept	feux	dent
E	cerf	ceux	cent
O	chose	froid	blond
O	score	croix	tronc
O	sport	droit	front
O	fort	noir	donc
O	port	bout	long
O	rose	toit	fond
O	hors	noix	mont
O	mode	doux	pont
O	mort	mois	rond

Appendix 2: Stimuli for Experiments 2a and 2b

	One-grapheme prime condition		Two-grapheme prime condition	
Target word	Related	Unrelated	Related	Unrelated
BOURG	b**rg	n**ve	bo**g	ne**e
MEURT	m**rt	s**le	me**t	so**e
SOURD	s**rd	n**ge	so**d	ne**e
LOURD	l**rd	p**ne	lo**d	pe**e
NEIGE	n**ge	m**rt	ne**e	ma**t
COURT	c**rt	h**ne	co**t	ha**e
PEINE	p**ne	l**rd	pe**e	lo**d
HEURE	h**re	p**me	he**e	pa**e
TOUTE	t**te	b**ns	to**e	ba**s
POULPE	p**lpe	d**gne	po**pe	da**ne
YOURTE	y**rte	p**gne	yo**te	pe**ne
FOURBE	f**rbe	p**ple	fo**be	pe**le
POUFFE	p**ffe	v**lle	po**fe	ve**le
DAIGNE	d**gne	t**che	da**ne	to**he
FREINE	fr**ne	gl**re	fre**e	glo**e
HEURTE	h**rte	p**lpe	he**te	po**pe
TOUSSE	t**sse	b**rre	to**se	be**re
GOURDE	g**rde	m**ble	go**de	me**le
SOUCHE	s**che	p**vre	so**he	pa**re
COIFFE	c**ffe	h**sse	co**fe	ha**se
PEIGNE	p**gne	l**che	pe**ne	lo**he
LOUCHE	l**che	b**sse	lo**he	ba**se
HAUSSE	h**sse	b**ffe	ha**se	bo**fe
BOURSE	b**rse	g**che	bo**se	ga**he
BOUFFE	b**ffe	l**sse	bo**fe	la**se
BOUCLE	b**cle	h**rte	bo**le	he**te
MEUBLE	m**ble	d**che	me**le	do**he
COURBE	c**rbe	m**gle	co**be	me**le

ROUSSE	r**sse	l**rre	ro**se	le**re
DOUCHE	d**che	f**sse	do**he	fa**se
MOUSSE	m**sse	f**lle	mo**se	fa**le
BEURRE	b**rre	m**sse	be**re	mo**se
FAUSSE	f**sse	g**tte	fa**se	go**te
GOUTTE	g**tte	p**lle	go**te	pa**le
SOURCE	s**rce	f**ble	so**ce	fa**le
TOUCHE	t**che	s**vre	to**he	su**re
FLEUVE	fl**ve	cr**re	fle**e	cro**e
COUCHE	c**che	q**tte	co**he	qu**te
COUPLE	c**ple	g**gne	co**le	gu**ne
GLOIRE	gl**re	fr**ne	glo**e	fre**e
FROIDE	fr**de	pl**ne	fro**e	ple**e
COURSE	c**rse	s**gne	co**se	sa**ne
TOURNE	t**rne	f**che	to**ne	fa**he
LOURDE	l**rde	p**gne	lo**de	pe**ne
PEUPLE	p**ple	c**rbe	pe**le	co**be
VEILLE	v**lle	r**sse	ve**le	ro**se
PLEINE	pl**ne	tr**ve	ple**e	tro**e
LAISSE	l**sse	p**ffe	la**se	po**fe
TROUVE	tr**ve	fl**de	tro**e	flu**e
PAUVRE	p**vre	b**cle	pa**re	bo**le
DROITE	dr**te	pl**de	dro**e	pla**e
GAUCHE	g**che	c**ple	ga**he	co**le
BOUCHE	b**che	f**sse	bo**he	fa**se
GLOUSSE	gl**sse	ch**ffe	glo**se	cha**fe
CHAUFFE	ch**ffe	gl**sse	cha**fe	glo**se
TROUSSE	tr**sse	gl**que	tro**se	gla**ue
FOURCHE	f**rche	v**ille	fo**che	ve**lle
GLAUQUE	gl**que	tr**sse	gla**ue	tro**se
POURPRE	p**rpre	g**nche	po**pre	gu**che
BROUSSE	br**sse	pl**tre	bro**se	ple**re
GOUFFRE	g**ffre	d**ille	go**fre	de**lle

MEURTRE	m**rtre	g**nche	me**tre	gu**che
GRAISSE	gr**sse	bl**res	gra**se	blo**es
SOUFFLE	s**ffle	v**ncre	so**fle	va**cre

Appendix 3: Stimuli for Experiment 3

	One-grapheme prime condition		Two-grapheme prime condition	
Target word	Related	Unrelated	Related	Unrelated
PLAID	pl**d	ch**x	p**id	c**ux
BEUGLE	b**gle	y**rte	be**le	yo**te
BOURBE	b**rbe	f**tre	bo**be	fe**re
BOURDE	b**rde	m**ble	bo**de	me**le
BRAIRE	br**re	ch**ve	b**ire	c**uve
BROUTE	br**te	pl**ne	b**ute	p**ine
CROULE	cr**le	gl**re	c**ule	g**ire
DRAINE	dr**ne	fl**ve	dra**e	fle**e
FEIGNE	f**gne	t**rte	fe**ne	to**te
FOURBE	f**rbe	p**vre	fo**be	pa**re
FOURME	f**rme	g**che	fo**me	ga**he
GOITRE	g**tre	s**che	go**re	se**he
JOUXTE	j**xte	f**gne	jo**te	fe**ne
PSAUME	ps**me	dr**ne	p**ume	d**ine
SEICHE	s**che	b**rde	se**he	bo**de
TEIGNE	t**gne	f**rbe	te**ne	fo**be
TOURTE	t**rte	b**gle	to**te	be**le
TRAIRE	tr**re	ps**me	t**ire	p**ume
YOURTE	y**rte	t**gne	yo**te	te**ne
CHAUSSE	ch**sse	pl**gne	c**usse	p**igne
CRAIGNE	cr**gne	gl**sse	c**igne	g**usse
CROISSE	cr**sse	gl**que	c**isse	g**uque
FROISSE	fr**sse	ch**ffe	f**isse	c**uffe
GLOUSSE	gl**sse	cr**gne	glo**se	cra**ne
PLAIGNE	pl**gne	ch**sse	p**igne	c**usse