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Role and activation time course of phonological and orthographic information during phoneme judgments

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Acquiring literacy establishes connections between the spoken and written system and modifies the functioning of the spoken system. As most evidence comes from on-line speech recognition tasks, it is still a matter of debate when and how these two systems interact in metaphonological tasks. The present event-related potentials study investigated the role and activation time course of the phonological and orthographic representations in an auditory same/different phoneme judgment task in which the congruency between phoneme and grapheme was orthogonally manipulated. We reported distinct time windows and topographies for phonological and orthographic effects. The phonological effect emerged early at central and parietal electrode sites and faded away later on, whereas the orthographic effect increased progressively, first observable at central and parietal sites before generalizing at the frontal site. These effects are clearly different from what has been reported in speech recognition tasks and suggest that our cognitive system is flexible enough to adjust its functioning to respond to the task demands in an optimal way.

1. Introduction

Nowadays, it is clearly demonstrated that processing spoken language does not rely only on the listeners' knowledge of the phonological representation of the utterances. Many studies have shown that other kinds of knowledge like syntactic, semantic or orthographic information also play an important role in the way speech is processed (e.g., Connolly & Phillips, 1994; Friederici, Meyer, & Von Cramon, 2000; Friederici, Pfeifer, & Hahne, 1993; Ziegler & Ferrand, 1998). Nevertheless, the nature of the cognitive and neural processes underlying the contribution of these different sources of information is still a matter of debate.

The present study specifically focused on the relations between the phonological and orthographic systems that have been established during reading acquisition. Since the first evidence reported by Seidenberg and Tanenhaus (1979) showing that performance in a purely auditory rhyme judgment task was affected by the participants' knowledge of word spelling (with faster recognition of spoken words as rhymes when they were spelled similarly, *tie-pie*, relative to dissimilar spellings, *tie-rye*), a fair amount of work has been reported that provide further evidence for the occurrence of *orthographic effects* in speech processing tasks.

As regards the mechanisms leading to the occurrence of orthographic effects, the most comprehensive findings come so far from the studies that investigated orthographic effects during speech recognition tasks, that is, the tasks that aim at accessing the lexico-semantic content of spoken words. For instance, Ziegler and Ferrand (1998) showed in a lexical decision task that words containing a phonological unit that has more than one possible spelling (e.g., k*ite*) are harder to process than words with a phonological unit that has only one possible spelling (e.g., m*ust*). Since this first evidence of the *orthographic consistency effect*, several event-related potential (ERP) studies further showed that this kind of orthographic effect takes place early, probably before lexical access (Pattamadilok, Perre, Dufau, & Ziegler, 2009; Perre, Midgley, & Ziegler, 2009; Perre & Ziegler, 2008; Perre, Pattamadilok, Montant, & Ziegler, 2009). Indeed, the consistency effect was observed around 300–350 ms after stimulus onset and clearly preceded the word frequency effect, which is a marker of lexical access (from 400 ms onward). Source localization (sLORETA, Perre, Pattamadilok et al., 2009) and transcranial magnetic stimulation (Pattamadilok, Knierim, Kawabata Duncan, & Devlin, 2010) studies that aimed at identifying the cortical origin of the orthographic consistency effect in speech recognition tasks further suggested that it occurs within the phonological system (the

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supramarginal gyrus) rather than within the orthographic one (the ventral occipito-temporal cortex). Nevertheless, contrary to the latter finding, Dehaene et al. (2010), who compared the brain activity of literate and illiterate adults during an auditory lexical decision task, observed stronger activation in literates in the ventral part of the occipito-temporal cortex, a brain area that processes written words, thus suggesting an implication of the orthographic system during active speech processing. Together, these different sets of findings provide crucial information on the architecture of spoken word recognition and on the functioning of the cognitive system in general. In fact, acquiring a new language code not only establishes connections between the existing (spoken) and the new (written) system but also modifies the functioning of the system from which the new code is derived (Grainger, Diependaele, Spinelli, Ferrand, & Farioli, 2003; Grainger & Ferrand, 1996; Harm & Seidenberg, 1999, 2004; Muneaux & Ziegler, 2004; Taft, Castles, Davis, Lazendic, & Nguyen-Hoan, 2007; Taft & Hambly, 1985; Ziegler & Goswami, 2005).

It is however unclear whether the conclusions drawn from speech recognition tasks are task-dependent and therefore can be extended to other tasks, like metaphonological ones. As argued by Hickok and Poeppel (2000, 2007), the neural systems and the associated cognitive processes supporting speech processing seem to vary as a function of the task. While simple speech comprehension involves the ventral-posterior structures in the vicinity of the left temporal–parietal–occipital junction, metaphonological tasks requiring sublexical analysis involve more specifically inferior frontal and inferior parietal structures. Coherently with this claim, the literature on aphasic patients also suggests a double dissociation between impairments in speech comprehension and in metaphonological abilities (Baker, Blumstein, & Goodglass, 1981; Miceli, Gainotti, Caltagirone, & Masullo, 1980).

Following this line of argument, it is likely that the mechanisms underlying the occurrence of orthographic effects in speech recognition tasks (Pattamadilok, Morais, Ventura, & Kolinsky, 2007; Peereman, Dufour, & Burt, 2009; Ventura, Morais, Pattamadilok, & Kolinsky, 2004; Ziegler & Ferrand, 1998) are different from the ones that support the occurrence of orthographic effects in metaphonological tasks (Damian & Bowers, 2009; Dijkstra, Roelofs, & Fieuws, 1995; Donnenwerth-Nolan, Tanenhaus, & Seidenberg, 1981; Seidenberg & Tanenhaus, 1979). One of our previous ERP studies directly tested this hypothesis. Using the same critical stimuli and a go/no-go paradigm as in the previous semantic judgment and lexical decision tasks (Pattamadilok et al., 2009; Perre, Pattamadilok et al., 2009, respectively), Pattamadilok, Perre, and Ziegler (2011) showed that orthographic inconsistency did not affect performance in the same way when participants performed rhyme judgment. In the lexico-semantic tasks, a larger ERP signal was obtained on orthographically inconsistent spoken words compared to consistent ones in a restricted time window (a negative component around 300–350 ms). The fact that this effect occurred early and before the frequency effect suggests that mismatches between spoken and written codes constrain lexical access. In contrast, the effects reported in the rhyme judgment task suggested that, although there was a transient frequency effect in the 300–350 ms time window showing that the stimuli were processed at the lexical level, this lexical process was unaffected by orthographic knowledge. A significant orthographic effect was found on other processes, namely on the explicit segmentation (a positive component in the 175–250 ms time window) and decision/comparison (a negative component in the 375–700 ms time window) components of the task.

The ERP studies mentioned above clearly showed that the loci of orthographic effects vary with task demand. Nevertheless, the manipulation of orthographic consistency used in those studies did not allow varying the phonological and orthographic representations simultaneously. The only available information was the orthographic effect obtained by comparing the ERPs elicited by spoken words that ended with orthographically consistent rimes (e.g., "m*ust*") to the ERPs elicited by spoken words that ended with orthographically inconsistent rimes, (e.g., n*ight*). Based on these findings, it is impossible to dissociate the contribution of phonology and orthography on performance. In other words, the activation time course of the phonological and orthographic information as well as the cognitive processes that rely on such information remain unspecified. Although this issue has been extensively investigated in the visual word domain (e.g., Ferrand & Grainger, 1993; Grainger, Kiyonaga, & Holcomb, 2006; Kramer & Donchin, 1987; Polich, McCarthy, Wang, & Donchin, 1983; Rugg & Barrett, 1987; Seidenberg, 1985), evidence from the auditory domain is extremely scarce.

To our knowledge, Perre et al. study (2009) was the only one that reported the activation time course of the phonological and orthographic information during speech processing. Using the classic priming paradigm with a measure of ERPs, the authors manipulated the relation between phonology and orthography of primes and targets' rhyme: the prime and the target shared both phonology and orthography ($O+P+$ condition, e.g., *beef-reef*), phonology only ($O-P+$ condition, e.g., *leaf-reef*), or neither kind of information ($O-P-$ condition, e.g., *sick-reef*). The ERPs obtained in an auditory lexical decision task performed on the second stimulus of the pair showed that both phonological priming and orthographic priming reduced the amplitude of the early part of N400 component. However, the topographic distribution of these effects was different: the phonological effect observed in the N400 time window was mainly localized at the centro-posterior electrodes (C3, Cz, C4, P3, Pz, P4) while the orthographic effect was found at the anterior electrodes (F3, Fz, F4).

The finding that both phonological and orthographic priming effects were found within the same time window was somewhat surprising. Given that the stimuli were spoken words, one would expect the phonological representations to be processed before the orthographic ones. The priority of within-modal over cross-modal information has been clearly reported in the domain of visual word processing (Ferrand & Grainger, 1993; Grainger et al., 2006; Seidenberg, 1985). One possible explanation of the similar activation time course of phonology and orthography reported by Perre et al. (2009) is the fact that, unlike visual words, speech unfolds in time. The authors manipulated the orthographic congruency of the rhyme and more than 20% of the stimuli rhymed. It was therefore possible that, due to the salience of the rime (to which even young children are highly sensitive, e.g., Bradley & Bryant, 1983), the participants became more and more sensitive to this manipulation as the task progressed and, consciously or not, developed some expectations regarding prime–target relationship (see e.g., Norris, McQueen, & Cutler, 2002). Following this assumption, the participants might have had enough time to guess or recognize the entire word and to activate its corresponding orthographic representation by the time the rime actually arrived.

To provide a more complete picture of the phenomenon, the present study investigated the activation time course and the scalp distribution of the phonological and orthographic representations during a metaphonological task. Note that only one published ERP study has investigated this issue, manipulating the relation between phonology and orthography in a rhyme judgment task using either auditory or written words (McPherson, Ackerman, Holcomb, & Dykman, 1998). In half of rhyming and non-rhyming trials, the stimuli of the pair shared the same spelling, leading to four experimental conditions: (1) an orthographically similar rhyming word, e.g., *gift-lift*, (2) an orthographically dissimilar rhyming word, e.g., *dirt-hurt*, (3) an orthographically dissimilar non-rhyming word, e.g., *sing-door*, and (4) an orthographically similar non-rhyming word, e.g., *most-lost*. In the visual version of the task, the authors observed both phonological (as reflected by a reduction in parietal N400 for rhyming targets) and orthographic (as reflected by a large reduction in frontal N400 for matching orthography) effects. However, only a small phonological effect (with a left parietal N400 priming effect for rhyming targets) with no hint of orthographic effect was reported in the auditory modality. The absence of orthographic effect in these ERP data was rather surprising given the existence of a significant interaction between phonology and orthography in the behavioral data showing better performance on the rhyming pairs when words also shared the same spelling and on the non-rhyming pairs when words did not have the same spelling (McPherson, Ackerman, & Dykman, 1997; similar results were also reported in, e.g., Seidenberg & Tanenhaus, 1979; Tanenhaus, Flanigan, & Seidenberg, 1980). According to McPherson et al. (1998), the absence of an orthographic effect might have been due to the inhomogeneous age of their participants (mean age 15.5 years, range 13–18 years) that could have increased the variability of their ERPs and thus obscured the possible, yet small, ERP effects (see also Holcomb, Coffey, & Neville, 1992 for further details on the variation of the ERP waveforms across ages).

In order to reinvestigate this issue, we orthogonally manipulated the congruency between the phonological and orthographic information in the initial phoneme of spoken words. The manipulation of the initial phoneme (rather than rhyme) would maximize the possibility to reveal a difference in the activation time course of the phonological and orthographic information during metaphonological processing. We used a same/different phoneme judgment task in which participants had to decide whether or not the words started with the same phoneme. Based on previous behavioral studies that reported orthographic effects in metaphonological tasks (e.g., Dijkstra et al., 1995; Donnenwerth-Nolan et al., 1981; McPherson et al., 1997; Seidenberg & Tanenhaus, 1979; Tanenhaus et al., 1980), we hypothesized that at the behavioral level, words sharing both initial phonemes and graphemes (*P+O+* condition, e.g.,/ʒilɛ/-/ʒənu/; GILET-GENOU; *vest-knee*) would lead to faster "yes" responses and lower error rates than words that shared only their initial phonemes (*P+O−* condition, e.g.,/ʒɑ̃bɔ̃/-/ʒenu/; JAMBON-GENOU; *ham-knee)*. The opposite result was expected on negative trials, with better performance for words that did not share their initial graphemes (*P−O−* condition, e.g.,/kɔmɑ̃/-/ʒənu/; COMMENT-GENOU; *how-knee*) than when they did (*P−O+* condition, e.g.,/ɡato/-/ʒənu/; GATEAU-GENOU; *cake-knee*).

Concerning the time course pattern and the scalp distribution of the phonological and orthographic effects, the within-modal phonological representation would play a role at an early processing stage, over posterior and central regions. The influence of the orthographic information was expected at a later processing stage and most probably over the frontal regions (McPherson et al., 1998; Perre, Midgley et al., 2009).

2. Material and methods

2.1. Participants

Sixteen right-handed native French speakers (12 women) aged 18–28 years (mean: 23) participated as paid volunteers. All were normally-hearing and free of neurological or language disorders. The ethical committee of the Brugmann Hospital (Brussels, Belgium) approved the protocol.

2.2. Stimuli

Critical stimuli consisted of 33 sets of five spoken words from which four word pairs were constructed. Among the 33 sets, 19 included bisyllabic words and 14 included monosyllabic words. The stimuli of the same set always shared the same syllabic structure. Within each set, one of the five words served as second stimulus that was paired with the other four words, thus leading to four experimental conditions. In the first condition (P+O+), the words within the same pair shared the same initial phoneme and grapheme (e.g.,/ʒilɛ/-/ʒənu/; GILET-GENOU; *vest-knee*). In the second condition (P+O−), the two words shared the same initial phoneme but not the corresponding grapheme (e.g.,/ʒɑ̃bɔ̃/-/ʒənu/; JAMBON-GENOU; *ham-knee*). In the third condition (P−O−), the two words had a different initial phoneme and grapheme (e.g.,/kɔmɑ̃/-/ʒənu/; COMMENT-GENOU; *how-knee*). In the fourth condition (P−O+), the two words had a different initial phoneme but shared the same grapheme (e.g.,/ɡato/-/ʒənu/; GATEAU-GENOU; *cake-knee*) (cf. Appendix). Note that all critical stimuli began with one of the four phonemes:/ɡ/,/ʒ/,/s/,/k/ and their spelling began with one of the 6 letters: g, j, s, c, k, q.

In addition to the critical stimuli, 304 pairs of words sharing the same syllable structures were used as fillers. The filler pairs were constructed either from new words or from words that were used in the critical pairs. Throughout the entire material, each word used in the critical pairs occurred four times as first stimulus and four times as second stimulus.

2.3. Procedure

All words were recorded by a female speaker in a soundproof room on a Sony digital recorder (PCM-D50) using a Sennheiser microphone. They were digitized at a sampling rate of 44 kHz and with 16-bit analog-to-digital conversion, using the Sound Tools/DigiDesign editor.

Participants were tested individually in a soundproof room. Stimuli were presented binaurally at a comfortable listening level through headphones using Eevoke (ANT Sofware, The Netherlands) stimulation system. A standard auditory same/different phoneme judgment task was used. Within each trial, the participants were asked to listen carefully to the two words of a pair and to decide as quickly and accurately as possible by pressing one of the two buttons of a joystick placed in their right hand whether or not the words started with the same phoneme. The initial phoneme was defined as the first sound of the word. Some examples were provided to make sure that the participants understood the task. The session started with 12 practice trials to familiarize participants with the task. The inter-stimulus and inter-trial intervals were 320 and 1600 ms, respectively. Participants were told to blink only between two trials. No feedback was provided during the experiment. The 436 pairs of words were divided into six blocks of 44 pairs and four blocks of 43 pairs. Each block contained approximately the same number of monosyllabic and disyllabic pairs from the four experimental conditions. Although the critical stimuli were repeated several times across conditions, their presentation order was random. Reaction times (RTs) were recorded from the onset of the second stimulus of the pair to the button press response. The session lasted roughly 30 min.

2.4. EEG recording

Continuous EEG was recorded (sampling rate 512 Hz; analog passband 0.1–100 Hz; amplification × 20) with an ASA EEG/ERP system (ANT software, The Netherlands), using Ag–AgCl electrodes embedded in a waveguard cap from F3, Fz, F4, C3, Cz, C4, T7, T8, P3, Pz, P4 and from left and right mastoids (LM, RM), all referred to the tip of the nose. Vertical and horizontal eye movements were monitored using two bipolar recordings: one below and above the left eye and one lateral to the left and right external canthi. The impedances were kept below 5 kΩ. The signals from the average of the left and right mastoid electrodes were used off-line to re-reference the scalp recordings.

3. Results

3.1. Behavioral data

Response accuracy and response latency data were analyzed separately. Preliminary inspection of RTs led us to discard from further analyses deviant RTs, that is, those longer or shorter than the mean RT observed on correct trials plus or minus two standard deviations. This was done separately for each condition. With this criterion, 4.3% of the RT data were eliminated.

Repeated measures analyses of variance (ANOVAs) were conducted by subjects with phonology (same vs. different phoneme) and orthography (same vs. different grapheme) as within-subject factors. Given the small number of critical trials, the data obtained on monosyllables and disyllables were pooled.

The RT analyses showed a significant effect of phonology, with faster responses in the same compared to the different phoneme condition [754 vs. 805 ms, respectively; $F(1,15)=20.8$, $p<.0001$].

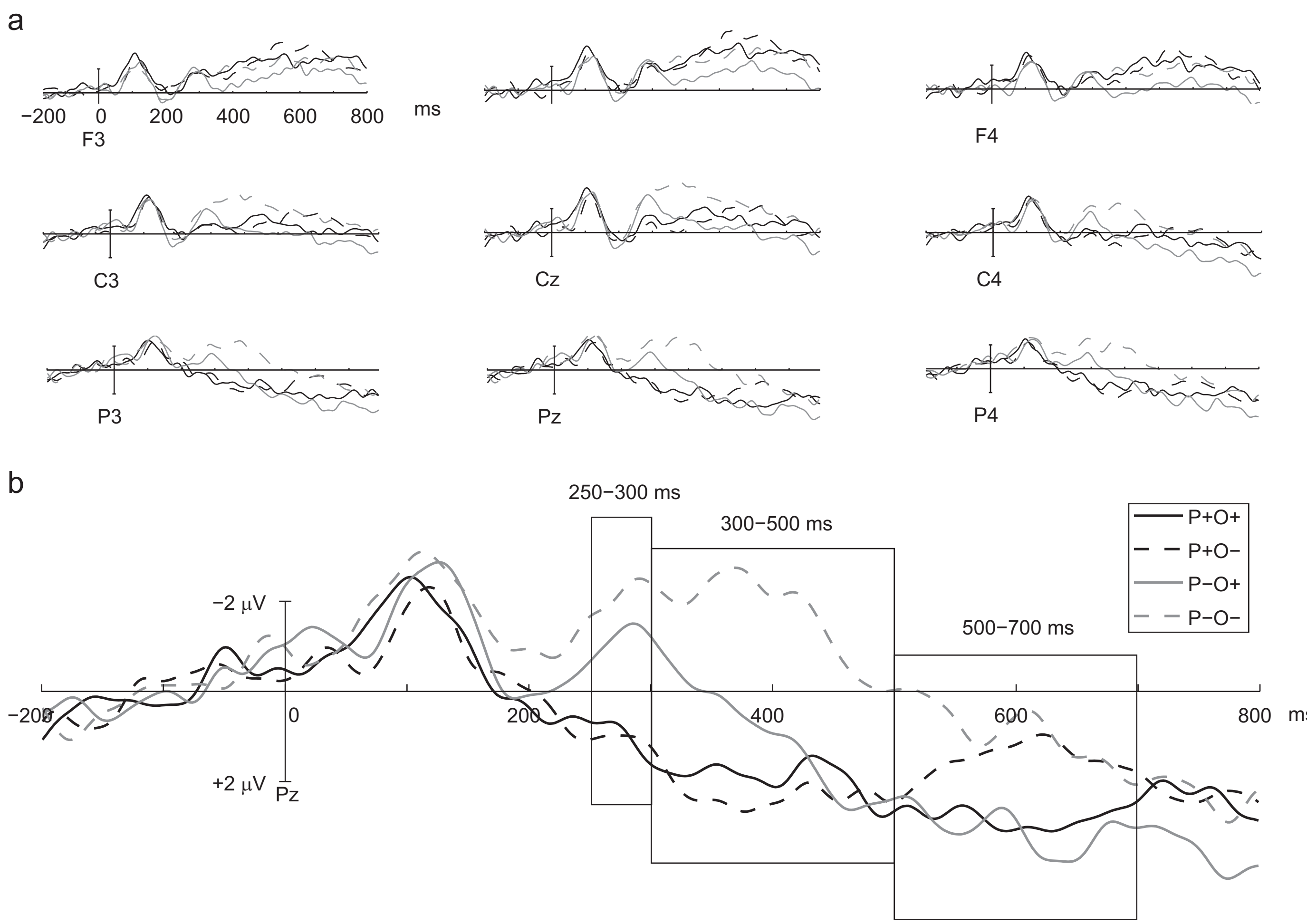

Fig. 1. (A) mean amplitude in μV of the ERPs obtained on F3, Fz, F4, C3, Cz, C4, P3, Pz and P4 in the P+O+ (black plain line), P+O− (black dash line), P−O− (gray dash line line) and P−O+ (gray plain line) conditions. (B) mean amplitude in μV of the ERPs obtained on Pz in the P+O+ (black plain line), P+O− (black dash line), P−O− (gray dash line) and P−O+ (gray plain line) conditions.

Neither the main effect of orthography nor the interaction between orthography and phonology was significant (both Fs < 1). The same result pattern was observed on the error rates: participants made less errors in the same than in the different phoneme condition [2.9 vs. 6.3%, respectively; $F(1,15)=10.6$, $p=.005$]. Again, neither the main effect of orthography [$F(1,15)=1.3$, $p>.25$] nor its interaction with phonology [$F(1,15)=3.1$, $p=.10$] was found.

3.2. Electrophysiological data

Continuous EEG was segmented offline in 1000 ms time-windows including a 200 ms pre-stimulus onset baseline (as referred to the onset of the second stimulus of each pair). Averaged waveforms were computed for each subject and each experimental condition. Only trials eliciting a correct response were averaged. Time-windows with voltage variation above or below 70 μV at any electrode except T7 and T8 were discarded. The data on T7 and T8 were not included in the analyses because of unusual noises contained in the signal. A digital filter (low-pass: 20 Hz) was applied for illustration purposes only. For each participant, at least 18 trials per condition were kept for the statistical analyses.

Visual inspection showed that the difference between conditions emerged around 250 ms and continued until 700 ms. The ERP pattern within this time-window led us to subdivide it into three adjacent time-windows: 250–300 ms, 300–500 ms and 500–700 ms (Fig. 1A and B).

Within each time-window, repeated measures ANOVAs were performed on mean amplitude of the entire time-window with phonology (same vs. different phoneme), orthography (same vs. different grapheme), laterality (left, center, right) and electrode site (frontal, central, parietal) as within-subject factors. As for the behavioral data, the data on monosyllabic and disyllabic stimuli were pooled. The Greenhouse and Geisser (1959) correction was applied when appropriate. Since ERP waveforms generally vary from one electrode to another, the main effects of electrode site, laterality and the interaction between these two factors, which were significant in some analyses but irrelevant to the present study, are not reported here.

3.3. 250–300 ms time-window

As shown in Fig. 1A and B, there was a clear difference between the signals obtained in the P+O+ and P+O− conditions, on the one hand, and those obtained in the P−O+ and P−O− conditions, on the other hand. A larger negativity was found in the latter two conditions, that is, when the words did not share their initial phoneme. This pattern was confirmed by the ANOVA showing a significant main effect of phonology [$F(1,15)=6.1$, $p<.05$]. This factor also interacted with electrode site [$F(2,30)=13.8$, $p=.001$]: the effect of phonology was restricted to the central [$F(1,15)=6.5$, $p<.025$] and parietal [$F(1,15)=10.8$, $p=.005$] electrodes. Importantly, no effect of orthography or interaction between orthography and phonology was observed in this early time-window (both Fs < 1).

3.4. 300–500 ms time-window

As illustrated in Fig. 1A and B, in the middle time-window, the orthographic effect seems to emerge in the conditions where the stimuli did not share their initial phoneme (P−O+ and P−O−). Indeed, the ANOVA showed that while the main effect of phonology was no longer significant [$F(1,15)=2.8$, $p>.10$], the main effect of orthography emerged and almost reached significance [$F(1,15)=4.3$, $p=.056$], reflecting stronger negative-going waveforms when the two words did not start with the same grapheme. However, phonology interacted with orthography [$F(1,15)=9.1$, $p<.01$] and with electrode site [$F(2,30)=23.3$, $p<.001$]. The interaction between phonology and orthography clearly showed that the effect of orthography was significant only when the words did not start with the same phoneme [$F(1,15)=16.1$, $p=.001$; for identical phonemes: $F<1$]. The analyses performed at each electrode site showed that although this result pattern was observed across electrode sites, the level of significance increased progressively from anterior to posterior electrodes. Indeed, at the frontal electrodes, neither phonology [$F(1,15)=1.5$, $p>.1$] nor orthography [$F(1,15)=2.6$, $p>.1$] showed a significant effect. The interaction between them was nevertheless marginal [$F(1,15)=4.03$, $p=.063$]. At the central electrodes, there were marginal effects of phonology [$F(1,15)=3.7$, $p=.074$] and orthography [$F(1,15)=3.8$, $p=.069$], and their interaction was significant [$F(1,15)=9.9$, $p<.01$]. Finally, at the parietal site, the effects of phonology [$F(1,15)=13.7$, $p<.005$] and orthography [$F(1,15)=4.6$, $p<.05$] were both significant, as was their interaction [$F(1,15)=10.6$, $p=.005$].

3.5. 500–700 ms time-window

The latest time-window showed the opposite result to the one observed in the earliest time-window. As illustrated in Fig. 1A and B, the ERP signals clustered as a function of the orthographic similarity between the stimuli, with negative-going waveforms being observed only in the conditions where the words did not start with the same spelling (P+O− and P−O−). This pattern was confirmed by the ANOVA showing a significant orthographic effect [$F(1,15)=5$, $p<.05$]. Interestingly, orthography no longer interacted with phonology or with electrode site ($Fs<1$), suggesting a widespread effect of orthographic information at all electrode sites and regardless of the phonological relationship between stimuli. The main effect of phonology was no longer significant ($F<1$). Although phonology interacted with electrode site [$F(2,30)=4.307$, $p<.05$], the analyses performed separately at each site did not show any significant result [frontal, $F(1,15)=3.3$, $p<.10$; central and parietal, both $Fs<1$].

4. Discussion

A large number of studies have already demonstrated that knowledge of written code influences the way speech is processed (e.g., Seidenberg & Tanenhaus, 1979; Treiman & Cassar, 1997; Ziegler & Ferrand, 1998). However, little is known about when and how the spoken and written codes affect the cognitive processes that come into play in a specific context. The present study investigated this issue in a metaphonological task, by combining the behavioral and ERP measures in a situation where participants were required to make phoneme judgments on pairs of spoken words. The relation between the phonological and orthographic representations of the initial phonemes was manipulated such that they were congruent in half of the trials, and incongruent in the others.

In contrast to most behavioral studies that have reported an orthographic effect in metaphonological tasks (Dijkstra et al., 1995; Donnenwerth-Nolan et al., 1981; McPherson et al., 1997; Seidenberg & Tanenhaus, 1979; Tanenhaus et al., 1980; but see Cutler, Treiman, & van Ooijen, 2010; Damian & Bowers, 2009), in the present study neither accuracy, nor RTs were affected by the mismatch between the phonological and orthographic information. The participants' performance was affected only by phonological information, with better performance for the word pairs that shared their initial phoneme.

Although no orthographic effect was found in the behavioral data, the ERP measures clearly showed that the cognitive processes underlying phoneme judgment were sensitive to knowledge of word spelling. Unlike the finding reported in Perre et al.'s study (2009), where the phonological and orthographic effects emerged within exactly the same time-window, we found that the role of the spoken and written code evolves in time, although in opposite directions. Being absent in the earliest time-window, the orthographic influence increased progressively and became generalized in the latest time-window. Along with this increasing influence of orthography, the role of phonology faded away gradually and was completely absent at the end of the process. In the following paragraphs, we will comment on how the differential effects of phonology and orthography observed in three consecutive time-windows may be related to different cognitive processes underlying phoneme judgment.

4.1. 250–300 ms time-window: pre-lexical phonological processing

As expected, the cognitive processes that take place in this early time-window were only affected by phonology, which is within-modal information. A larger negativity was found in the conditions where the initial phonemes were mismatched (P−O+ and P−O−). Consistently with what was reported in some previous studies, this phonological effect was observed on the centro-parietal electrodes (Connolly, Phillips, & Forbes, 1995; Hagoort & Brown, 2000; McPherson et al., 1998; Perre, Midgley et al., 2009). Given its characteristics, this ERP component can be assimilated to the *phonological mismatch negativity* (PMN); a negative-going ERP appearing in situations where there is a phonological mismatch between an expected phonological representation and the one actually presented in the auditory input (Connolly, 2001; Newman, Connolly, & McIvor, 2003). Given that this component is absent in visual tasks, it is argued to be specific to the auditory modality. The PMN is typically observed between 250 and 350 ms from the stimulus onset and located at the fronto-central (Connolly, 2001; Newman et al., 2003; Newman & Connolly, 2009) or centro-parietal electrode sites (Connolly et al., 1995; Hagoort & Brown, 2000). Since this component is not sensitive to the lexicality of the stimuli or to their semantic relation, it is considered as reflecting an early stage of phonological processing (Connolly & Phillips, 1994; Connolly et al., 1995; Connolly, 2001; Newman et al., 2003; Newman & Connolly, 2009). As argued by Newman et al. (2003), a single phoneme in the acoustic stream may be sufficient to increase the PMN amplitude to a level equal to that produced by a stimulus that totally mismatches expectations.

The occurrence of the PMN in the present study is coherent with the nature of the task. The presentation of the first stimulus of a pair might provide the participants with a phonological model corresponding to the first phoneme of the word. On positive trials (P+O+ and P+O−) where the two stimuli shared the same initial phoneme, this model or expected phoneme matched the incoming phonological representation of the second word and therefore resulted in a reduction of the PMN. On negative trials (P−O+ and P−O−), the model turned out to be incorrect. Obviously, the failure to match the model with the auditory input was a cost for the cognitive system. First, it led to an increase of the PMN, which suggests that the phonological system continued to process the stimulus in order to build a new model that allowed the system to correctly recognize it (Newman et al., 2003). Second, as developed below, this attempt to build a new valid model seems to lead the system to consider other kinds of information that *a priori* are not relevant to the task, such as the orthographic one.

There is however a caveat regarding the interpretation of the phonological effect. In the present design, the phonological manipulation was confounded with the yes/no response assignment. Thus, although participants needed to draw on phonological information in order to make a correct response, any differences in response times or ERP to words sharing their initial phoneme compared to those that did not, could arise from the response difference. However, we argue that even though the response difference might indeed contribute to the difference in RTs obtained in the same and different phoneme condition, several arguments indicate that it is unlikely to account for the ERP data. First, the reported ERP effect occurred too early to reflect the moment at which the cognitive system is able to distinguish between task-related yes and no responses. In Pattamadilok et al.'s previous studies on the influence of orthographic knowledge on speech processing, where a go/no-go paradigm was used (Pattamadilok et al., 2009, 2011), the authors investigated the moment at which the cognitive system distinguished go from no-go trials. In both speech recognition (semantic decision) and metaphonological (rhyme judgment) tasks, ERP differences between these trials only emerged around 400–450 ms and covered a relatively large time-window of about 300 ms. These characteristics are different from those of the phonological ERP effect reported here, which occurred much earlier and was extremely transient. Second, assuming that the ERP component reported here in a relatively early time-window corresponds to response differentiation processes, the time lag of 500 ms between the onset of this effect (250–300 ms) and the RT data (response times around 750–800 ms) would be far too long to reflect the processing time needed for response preparation. Given the RT data, one would expect the moment at which the task-related response difference was detected in ERP data to be closer to the observed RTs and lag behind the moment at which the initial phonological information was processed. Finally, as argued above, the characteristics of the ERP waveform observed here correspond perfectly to the PMN component. No existing study has associated this component with response differences. For these reasons, it seems unlikely that the ERP phonological effect reported here reflects (at least only or mainly) response-dependent processes.

4.2. 300–500 ms time-window: lexical phonological and orthographic processing

Only 50 ms after the onset of the PMN, we observed an increasing influence of the orthographic representations in the word pairs that did not share the same initial phoneme: A larger negative-going waveform was observed for the pairs that were spelled differently (P−O−) than for those that shared the same spelling (P−O+). Following the assumption that the PMN is specific to the auditory modality, it is unlikely that the ERP component reflecting orthographic mismatch that occurred in the time-window adjacent to the PMN was part of a late PMN. Considering its latency, polarity, and scalp distribution – mostly at the centro-parietal electrodes –, this ERP component appears to be part of the N400 family (Holcomb & Grainger, 2006; see also Connolly et al., 1995; Newman et al., 2003 for a debate on the distinction between the PMN and N400 components).

Although the N400 was originally considered to reflect semantic processing (e.g., Friederici et al., 1993; Hagoort & Brown, 2000; Kutas & Hillyard, 1984), many studies showed that it is also sensitive to other kinds of lexical representations. For instance, Dumay et al. (2001) and Praamstra, Meyer, and Levelt (1994) showed that the amplitude of N400 is modulated by phonological overlap between two successive spoken words. Given that orthography is a form of lexical knowledge, we argue that this information affects the amplitude of the N400 in the same way as phonological information.

The mechanism underlying the N400 is still subject to debate. On the one hand, the spread activation account (Dumay et al., 2001; Kutas & Hillyard, 1984) claims that the reduction of N400 amplitude results from a reduced activation threshold of the stimuli that have already received some degree of activation from previously presented stimuli with close semantic or phonological relationship. On the other hand, the N400 is considered to reflect post-recognition integration processes (Brown & Hagoort, 1993). This framework was primarily put forward to account for the reduction of the N400 in the context of semantic priming in which participants attempted to integrate the meaning of primes and targets.

The interpretation that the N400 reflects an integration of semantic information seems however unlikely in the context of a phoneme judgment task where participants were explicitly required to focus on the phonological representations and could not benefit from the comprehension of the target words (Holcomb, 1993). Yet, one could still argue that the integration process also operates on the phonological and orthographic representations. If this were the case, the operation would have led to an increase of the N400 amplitude in the conditions where these two kinds of information mismatched, that is, when the integration failed (in the P+O− and P−O+ conditions). This was not at all what we found.

A spread activation mechanism seems to provide a more comprehensive explanation. In this specific time-window, the negative-going waveforms were found in the situations where stimuli did not share the same initial phoneme (P−O− and P−O+) and the amplitude of the waveforms was reduced by orthographic overlap. Given this observation, we argue that the processing of the phonological representations was facilitated by the spread activation of shared orthographic representations. In other words, the orthographic overlap reduced the processing cost due to the phonological mismatch that had been detected in the previous time-window. As illustrated in Fig. 1B, the negativity of ERP elicited by the P−O+ stimuli decreased progressively while the one elicited by the P−O− stimuli continued to increase.

However, it remains to explain why the orthographic effect was restricted to the phonological mismatching trials (P−O− and P−O+). A possible explanation is that the activation of orthographic representations only occurred in situations that favor the intervention of *a priori* irrelevant information from other sources, for instance, during difficult or slow speech processing situations. This idea is supported by a previous study that investigated the orthographic consistency effect in a speech recognition task. Indeed, in a shadowing task in which participants had to repeat spoken words, the orthographic consistency effect was found only when the presentation condition of the stimuli was degraded by a background noise (Pattamadilok, Morais, & Kolinsky, 2011).

In the present study, a similar mechanism might account for the fact that orthographic representations only affected the phoneme mismatched trials. As a matter of fact, our behavioral data clearly showed that processing the phoneme-mismatched trials required more effort than processing the matched ones. This more difficult and time-consuming situation might favor the intervention of higher-level cognitive processes and of lexical information, in this case orthographic knowledge.

Another complementary explanation relies on findings on sentence processing suggesting that language is not processed in a single step. Studies on semantic and syntactic processing make a distinction between the first-pass parsing processes that are highly automatic and second-pass parsing processes that are more under participants' control. The second part is argued to reflect more in-depth processes that repair or reanalyze incongruent information detected during the first stage (e.g., Friederici, 2002; Hahne & Friederici, 1999; Kutas & Hillyard, 1980; Shtyrov, 2010). Here, we argue that a similar rationale could be applied to single word processing. Given that the N400, which reflects the reprocessing or "second look" of incongruent semantic information (Kutas & Hillyard, 1980), is also sensitive to phonological information (Dumay et al., 2001; Praamstra et al., 1994; Praamstra & Stegeman, 1993), an incongruity at this level could also lead to a repair or reanalysis process that calls upon orthographic information.

4.3. 500–700 ms time-window: post-lexical orthographic processing

Finally, in the latest time-window, the effect of phonology disappeared completely, giving way to a generalized effect of orthography with negative-going waveforms being observed only in the conditions where words did not share the same spelling (P+O−, P−O−). In terms of cortical distribution, the effect was found at the frontal in addition to central and parietal electrode sites. Given the difference in characteristics of the orthographic effect observed in this late and the previous N400 time-window, it seems unlikely that we are dealing with the same underlying process.

Late ERP components are typically associated with post-recognition or post-lexical processes. In the reading domain, some studies showed an influence of the phonological representations that arrived once the operations related to lexical process, as reflected in the N400 component, are completed (Ziegler, Benraiss, & Besson, 1999; Liu, Perfetti, & Hart, 2003). According to us, a similar phenomenon could also take place during a metaphonological task that requires an explicit analysis of phoneme. As already demonstrated in several behavioral studies, the ability to perform this task depends strongly on reading ability (Morais, Cary, Alegria, & Bertelson, 1979; Wagner, Torgesen, & Rashotte, 1994; Wagner et al. 1997). In addition, the cortical distribution of this late and most probably task-dependent activation of orthographic representations (i.e., expansion of the effect to frontal areas) is coherent with previous studies reporting the connection between frontal activity and orthographic processing (Rugg & Barrett, 1987; Montant, Schön, Anton, & Ziegler, 2011; McPherson et al., 1998). Interestingly, an activation of the same areas has also been reported in metaphonological processing tasks that required analyses at phoneme level (Zatorre, Meyer, Gjedde, & Evans, 1996; Burton, Small, & Blumstein, 2000). Although the role of orthographic knowledge was not mentioned, our finding raises the possibility that orthographic representations might have somehow been involved.

One final aspect of the present findings that might seem surprising is the absence of orthographic effect in the behavioral data. In the present study, the participants were required to focus on the initial phoneme and to response as quickly as possible without making errors. After a few trials, they might have realized that word spelling was not only irrelevant but can also be deleterious to performance. One way to do the task efficiently is to adopt a strategy that consists in responding as soon as the initial phoneme of the second stimulus became available. Consequently, their decision might have been taken even before the second word was fully recognized. Assuming that this was the case, the cognitive system might nevertheless continue to process the information at least until the recognition of the second word even though the detection of orthographic mismatch during the lexical and post-lexical stages might not occur early enough to influence participants' decision (that focused exclusively on sub-lexical phonological representations).

Taken together, our findings highlight the interest of recording ERPs and behavioral data concurrently and suggest that a step-by-step analysis of the cognitive processes is necessary. As concerns the current study, a conclusion that relied only on the behavioral data might have been extremely misleading. The failure to reveal the orthographic effect on the behavioral measures could be due to different factors. As mentioned above, the responses might have already been decided upon prior to the 300–500 ms window, the earliest moment when orthographic effect emerged. Also, the observed RTs (and the accuracy scores) that are the final outcome of several sub-processes that take place during the task could not provide insights into what happen during each sub-process. This lack of sensitivity is particularly problematic in speech processing situations where the effects under investigation are small, transient or dependent upon the way participants perform the tasks or process the stimuli. In such situations, the effects might have faded away by the time the behavioral measures were recorded or might have been obscured by noise in the data or by the variability that arises as the processing time is accumulated across different stages. In any case, we believe that the step-by-step analysis of the effects could shed some light on contradictory findings in the field (e.g., Damian & Bowers, 2009 vs. Seidenberg & Tanenhaus, 1979; Pattamadilok, Kolinsky, Ventura, Radeau, & Morais, 2007 vs. Taft et al., 2007).

Finally, the present study also provides us insights into the mechanisms underlying the orthographic influence on speech processing. Previous studies in the field suggest that orthographic knowledge could affect speech processing either by being co-activated during the processing of the phonological representations (Dehaene et al., 2010; Grainger & Ferrand, 1996; Stone & Van Orden, 1994; Ziegler & Ferrand, 1998) or by modifying the functioning or representations of the phonological system itself (Dehaene et al., 2010; Muneaux & Ziegler, 2004; Pattamadilok et al., 2010; Perre, Pattamadilok et al., 2009; Taft & Hambly, 1985; Taft, 2006). Concerning the latter claim, Taft (2011) proposed that there are two distinct phonological systems involved in speech processing. The first one includes representations that correspond to the phonemic version of phonetic inputs, while the other one includes orthographically influenced phonological representations (OIP), i.e., representations that reflect the pronunciation of word spelling (Taft, 2006). A mismatch between these two kinds of phonological representations would lead to the same prediction as a mismatch between phonology and orthography, without direct involvement of orthographic representations. These two underlying mechanisms are difficult to tease apart on the basis of the behavioral data. However, some elements in our findings and existing brain imaging studies favor the interpretation that the phonological and orthographic effects reported in our phoneme judgment task might stem from two separated systems, i.e., the phonological and the orthographic one, rather than from the phonological systems alone.

First, the phonological and orthographic effects are temporally and spatially dissociated. While it seems plausible that, in a purely auditory situation, the effect of orthography lags behind and is spatially separated from the effect of phonology, it is difficult to understand why and how the effects of the OIP and the phonetic input which are both phonological in essence would be separated in time and in space. Additionally, in the latest time-window, the ERPs clustered as a function of orthographic similarity (P−O− and P+O− vs. P+O+ and P−O+), with the orthographically dissimilar conditions showing a negative-going waveform. This result pattern is difficult to account for in terms of the OIP representations that would predict a graded effect of phonological similarity in the following direction: P+O+ > P+O− > P−O+ > P−O−. Finally, although the low spatial resolution technique used here could not provide evidence regarding the implication of the ventral occipito-temporal cortex – a brain area involved in orthographic processing –, several brain imaging studies have already shown an activation of this area during metaphonological tasks (Booth et al. 2002, 2004; Burton et al., 2000; Yoncheva, Zevin, Maurer, & McCandliss, 2010; Zatorre et al., 1996).

The fact that the current data suggest that the spoken and written codes are co-activated during phoneme judgments does not run against our previous claim (Pattamadilok et al., 2010; Perre et al., 2009) that the phonological representations involved in lexico-semantic processing are modified by one's knowledge of written code. The apparent divergence of the findings obtained in different studies using different experimental paradigms should be taken as evidence for the flexibility of the cognitive system that is able to adjust its functioning to respond to the task demands.

In rather demanding metaphonological tasks like rhyme or phoneme judgments, the cognitive system recruits a large neural network comprising the areas involved in spoken and written language processing as well as the areas within the inferior frontal gyrus (Booth et al., 2002, 2004; Burton et al., 2000; Yoncheva et al., 2010; Zatorre et al., 1996). In terms of functional role, an online activation of orthographic knowledge would be beneficial during explicit phoneme manipulation as it provides an additional code to perform such complex tasks that rely on fine-grained and probably unstable representations. At the same time, an activation of these "double codes" may also complicate the process whenever there is a conflict between them. In this specific context of explicit phoneme processing, it is nevertheless important to note that the activation of written code during phoneme judgment should be distinguished from another main consequence of reading acquisition, that is, the development of phoneme awareness that allows one to perform the task. Although more research is needed to understand the cognitive and neural mechanism underlying the emergence of phoneme awareness, it seems reasonable to assume that this ability is somehow related to a modulation of the organization of the speech processing system itself via the contact with an alphabetic writing system.

The mechanism by which orthography affects the processing of lexico-semantic representations might somehow be different from the one described in phoneme judgment. In fact, accessing lexico-semantic information of spoken words is much less demanding in terms of phonological analysis and the activation of other sources of information, like orthography, might be less crucial. Several brain imaging studies have indeed shown that these more elementary speech recognition tasks recruit more restricted neural networks than do metaphonological tasks especially within the inferior frontal gyrus and the occipito-temporal cortex (e.g., Booth et al., 2002, 2004; Cao et al., 2009; Desroches et al., 2010; Yoncheva et al., 2010). Coherently, the orthographic effects observed in this kind of task reflect a modification within the phonological system, presumably through reading acquisition, rather than a co-activation of the orthographic representations (Pattamadilok et al., 2010; Perre et al., 2009). Although an involvement of the written language network during lexico-semantic tasks is sometimes reported (e.g., Dehaene et al., 2010), this is much less consistent than in metaphonological tasks. An additional support to the idea that the involvement of the written language system decreases in less demanding speech processing situations is provided by the absence of activation of the brain areas processing written language during passive speech listening (Dehaene et al., 2010; Vannest et al. 2009).

5. Conclusion

Several studies have demonstrated that orthography influences the way speech is processed. However, very few of them used an experimental paradigm that could reveal the activation time course of the phonological and orthographic representations during speech processing. Our study addressed this issue in a context of metaphonological task and showed that at an early processing stage, only phonology, which is within-modal information, was taken into account. Later on in the speech processing route, when the stimulus was processed at the lexical level, both phonology and orthography played a role. However, the presence of an interaction between these two kinds of representation suggests that phonology has priority over orthography insofar as the orthographic effect was only restricted to the situation where the cognitive system encountered difficulty in processing the phonological representations. Finally, at the post-lexical stage, the phonological representation was no longer processed. The system was sensitive to orthography only.

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Appendix

See Table A1.

Table A1

P+O+	**P+O−**	**P−O−**	**P−O+**
gel-genre	jaune-genre	cause-genre	gare-genre
genre-gym	jupe-gym	cache-gym	gauche-gym
gym-gel	jambe-gel	comme-gel	guide-gel
geste-gifle	jongle-gifle	calme-gifle	gonfle-gifle
gifle-givre	jungle-givre	carte-givre	gourde-givre
givre-geste	juste-geste	couple-geste	garde-geste
cache-cause	quinze-cause	gauche-cause	cinq-cause
comme-cache	quinze-cache	gare-cache	cil-cache
contre-calme	quatre-calme	gonfle-calme	cirque-calme
calme-carte	quatre-carte	garde-carte	cible-carte
cible-cirque	sable-cirque	jongle-cirque	carte-cirque
cirque-centre	sucre-centre	jungle-	couple-centre
centre-cible	souffle-cible	juste-cible	contre-cible
cil-cinq	sur-cinq	jaune-cinq	cache-cinq
gilet-genou	jambon-genou	comment-genou	gateau-genou
genou-gentil	jeudi-gentil	coté-gentil	gamin-gentil
gentil-génie	jamais-génie	café-génie	gaité-génie
génie-gilet	joli-gilet	content-gilet	galop-gilet
gencive-girafe	jalouse-girafe	couleur-girafe	garage-girafe
girafe-gênante	jumelle-gênante	colère-gênante	guitare-gênante
gênante-gencive	jeunesse-gencive	courage-gencive	galette-gencive
coté-comment	quitter-comment	gateau-comment	ciné-comment
comment-cadeau	kiwi-cadeau	gamin-cadeau	ciseau-cadeau
cadeau-coté	kilo-coté	gaité-coté	cela-coté
ciné-cela	super-cela	jamais-cela	content-cela
cela-ciseau	salut-ciseau	joli-ciseau	café-ciseau
ciseau-ciné	sujet-ciné	jeudi-ciné	copain-ciné
cerveau-citron	secret-citron	journée-citron	carnet-citron
citron-cerceau	samedi-cerceau	jardin-cerceau	carton-cerceau
cerceau-cerveau	surtout-cerveau	jongler-cerveau	complet-cerveau
centaine-ceinture	seconde-ceinture	jeunesse-ceinture	couleur-ceinture
ceinture-cerise	sourire-cerise	jalouse-cerise	colère-cerise
cerise-centaine	silence-centaine	jumelle-centaine	courage-centaine

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