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Pseudohomophone Effects Provide Evidence of Early Lexico-Phonological Processing in Visual Word Recognition

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Abstract: Previous research using event-related brain potentials (ERPs) suggested that phonological processing in visual word recognition occurs rather late, typically after semantic or syntactic processing. Here, we show that phonological activation in visual word recognition can be observed much earlier. Using a lexical decision task, we show that ERPs to pseudohomophones (PsHs) (e.g., ROZE) differed from well-matched spelling controls (e.g., ROFE) as early as 150 ms (P150) after stimulus onset. The PsH effect occurred as early as the word frequency effect suggesting that phonological activation occurs early enough to influence lexical access. Low-resolution electromagnetic tomography analysis (LORETA) revealed that left temporoparietal and right frontotemporal areas are the likely brain regions associated with the processing of phonological information at the lexical level. Altogether, the results show that phonological processes are activated early in visual word recognition and play an important role in lexical access.

Key words: phonology; lexical decision; ERP; P150; LORETA; supramarginal gyrus; superior temporal gyrus; inferior frontal gyrus; insula

INTRODUCTION

The literature on word recognition has converged to suggest that reading involves the joint activation of orthography, phonology, and semantics [e.g., Grainger and Jacobs, 1996; Seidenberg and McClelland, 1989]. However, there is an ongoing debate in cognitive neuroscience about the time courses and the functional relationship of these reading processes. Some key questions are whether these processes are independent from each other, whether they are performed sequentially or in parallel, and whether they are automatic or strategic [Rastle, 2007]. This study aims at elucidating the time course of visual word recognition with special emphasis on the role of phonological processing.

Although phonological codes are necessarily activated in reading aloud, silent reading could in principle be performed without the processing of phonological information. Indeed, two main hypotheses have been proposed concerning the role of phonology in lexical access. The direct access hypothesis [e.g., Seidenberg, 1985] proposes a direct pathway from orthography to meaning. According

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to this hypothesis, phonological encoding is done rather late after meaning is accessed (i.e., postlexically). In contrast, the phonological mediation hypothesis [Frost, 1998; Tan and Perfetti, 1999; Van Orden, 1987] suggests that semantic access depends on phonological activation. Therefore, phonology would be typically computed before people access the meaning of a word. According to this view, phonological activation occurs automatically during reading and should take place relatively early during the process of visual word recognition. Several recent computational models of visual word recognition, such as the dual-route cascaded model [DRC; Coltheart et al., 2001], the connectionist dual process model [CDP+; Perry et al., 2007], the triangle model [Plaut et al., 1996], or the multiple read-out model including phonology [MROM-p; Jacobs et al., 1998] implement both a "direct" orthographic and an "indirect" phonological pathway to lexical access.

Phonological effects in visual word recognition were found in a number of tasks, such as backward masking [Perfetti and Bell, 1991], naming [Mechelli et al., 2007; Rodriguez-Fornells et al., 2002], lexical decision [Pexman and Lupker, 2001; Ziegler et al., 2001], sentence reading [Newman and Connolly, 2004], letter search [Ziegler and Jacobs, 1995; Ziegler et al., 1997], and also semantic categorization [Van Orden, 1987].

Phonological Effects in Behavioral Studies

In a seminal study, Perfetti and Bell [1991] reported an evidence for early phonological processing in priming and backward masking. They found that briefly presented target words (e.g., MADE) that were followed by phonologically related nonword masks (e.g., MAYD) were identified more accurately as when the masks were phonologically unrelated (e.g., MARD). These effects were found for prime-target stimulus onset asynchrony (SOA)s as short as 45 ms indicating early phonological processing of written words. Perfetti and Bell interpreted their phonological priming effects to be located at a prelexical level although they did not rule out top–down contributions of the lexical level to phonemic processing.

Indeed, Humphreys and Evett [1982] suggested that phonological priming effects result from feedback from the lexical level. They found that identification accuracy was better for targets that were presented after phonologically related primes (e.g., SHOOT–CHUTE), compared with prime target pairs that were only orthographically related (e.g., SHOOT–SHORT) or unrelated pairs (e.g., SHOOT–TRAIN). However, there was no priming from phonologically related (nonword) primes to (word) target pairs (e.g., SMORL–SMALL). More recently, however, early phonological effects in masked priming have been found even for nonword primes [e.g., Ferrand and Grainger, 1994; Ziegler et al., 2000] suggesting that phonology is computed prelexically.

Van Orden [1987] reported phonological effects in the semantic categorization task. Participants had to decide if a presented target was a member of a certain semantic category. This resulted in higher error rates for targets that were homophones or pseudohomophones (PsHs) (e.g., classifying the word ROWS or the PsH ROZE as a member of the category flowers) compared with orthographically related controls (e.g., RONE or ROBS). This result suggests an important role for phonology in accessing meaning. Van Orden proposed that reading proceeds from sublexical orthography to sublexical phonology to semantics and that recognition of printed words is mainly constrained by phonology [but see Jared and Seidenberg, 1991].

Finally, Pexman and Lupker [2001] investigated homophone effects in lexical decision. They found longer Response time (RT)s for homophonic words compared with control words. The effect was typically found with low-frequency words except in the presence of PsHs, in which case the homophone disadvantage emerged also for high-frequency words. The authors attributed the homophone effect to feedback from phonological representations activating two competing orthographic representations. They concluded that "readers do have little if any strategic control over the activation of phonological information of visually presented words."

Orthographic and Phonological Processing in the Brain

Several recent studies examined the time course of orthographic processing in visual word recognition using event-related brain potentials (ERPs). Hauk et al. [2006b] reported early typicality and lexicality effects at about 100 and 160 ms. Maurer et al. [2005] showed orthographic expertise effects at 170 ms. Furthermore, it has been suggested that the recognition potential [e.g., Martin-Loeches et al., 1999] in the time range from 150 to 200 ms is an index of the structural analysis of words. Sauseng et al. [2004] found that ERPs to orthographically altered word forms (e.g., taksi) differed from their base words (e.g., taxi) at around 160 ms. Bles et al. [2007] used a gating paradigm to investigate cohort size reduction in visual word recognition and reported a relatively early P2 (212–280 ms) in response to presented letter strings assumed to give rise to the activation of lexical candidates. The obtained P2 was interpreted as reflecting the amount of inhibition of words that mismatches the orthographic/phonological input. Other ERP studies reported later orthographic effects [e.g., Braun et al., 2006; Hutzler et al., 2004].

Concerning effects of phonological processing in visual word recognition the ERP evidence is rather mixed. Ziegler et al. [1999] asked participants to perform a visual semantic categorization task identical to the one used by Van Orden [1987]. They found no early effects of phonology in ERPs. Simon et al. [2006] found phonological effects at 320 ms (N320) in a lexical decision task. Interestingly, the phonological effects were modulated by the orthographic transparency of the writing system pointing to a prelexical locus of the effect. Grainger et al. [2006] reported visual phonological priming effects at 250 ms in a primed semantic categorization task. Finally, a few other studies point to relatively early phonological influence on the P/N200 components [Barnea and Breznitz, 1998; Kramer and Donchin, 1987; Niznikiewicz and Squires, 1996]. However, these findings are not without problems. For example, Kramer and Donchin [1987] and Barnea and Breznitz [1998] used rhyme judgments to address the role of phonology, but rhyme judgments necessarily require the activation of phonology and therefore do not directly speak to the issue of automatic phonological activation during silent reading. Niznikiewicz and Squires [1996] reported an enhanced N200 to homophones, which they interpreted as reflecting sublexical conflict between orthography and phonology. However, there is no sublexical conflict when processing homophones unless one assumes that conflict arises because lexical phonology feeds back to competing orthographic representations, thus diluting the strict distinction between sublexical and lexical processing. The majority of research, however, has located phonological processing on the N400 component or even later [e.g., Bentin et al., 1999; Newman and Connolly, 2004; Proverbio et al., 2004; Rugg, 1984]. The currently available ERP data do not allow us to decide whether phonological information is necessarily involved in visual word recognition and whether it is computed before lexical access.

The Present Study

It is surprising that none of the aforementioned studies has used the well known PsH effect in lexical decision, which is the classic marker effect for phonological activation in visual word recognition [Jacobs and Grainger, 1994]. The PsH effect [Rubenstein et al., 1971] reflects the fact that nonwords that sound like words but are spelled differently (e.g., feal) result in slower response latencies compared with spelling controls, which do not sound like words (e.g., feep). The PsH effect has been used as a marker for phonological activation in reading development [Goswami et al., 2001] and it provides major constraints for computational models of visual word recognition [see Jacobs and Grainger, 1994; Seidenberg et al., 1996; Ziegler et al., 2001].

The standard explanation for the PsH effect is that a given PsH contacts the lexical entry of its phonologically identical base word in the mental lexicon. In the context of lexical decision, the phonological lexicon "signals" the presence of a word, whereas the orthographic lexicon "signals" the absence of a word. It is assumed that resolving this conflict takes time, and therefore participants show longer latencies when rejecting PsHs compared with spelling controls [Jacobs et al., 1998; Ziegler et al., 2001]. Although early research raised the possibility that PsH effects might be due to an orthographic similarity confound [Martin, 1982], subsequent research clearly showed that PsH effects are not due to orthographic confounds [e.g., Rastle and Brysbaert, 2006; Ziegler et al., 2001].

In this study, we used the PsH effect as a marker for phonological activation and the effect of word frequency as a marker for lexical access. There is evidence for very early lexical processing at around 100 ms after stimulus presentation [e.g., Pulvermüller et al., 2001; Sereno et al., 1998, 2003], although most studies locate lexical access later at around 250 ms [e.g., Cohen et al., 2000; Grainger et al., 2006; Nobre et al., 1994]. The earliest effects of word frequency were found at around 130 ms [e.g., Assadollahi and Pulvermüller, 2001; Dambacher et al., 2006; Sereno et al., 1998, 2003], but the majority of studies locate it later, at around 300 ms [e.g., Polich and Donchin, 1988; Van Petten and Kutas, 1990].

In summary, the aim of this study was to find evidence for an early phonological activation in visual word recognition. Most previous studies used explicit phonological tasks, such as rhyme judgments [e.g., Barnea and Breznitz, 1998; Kramer and Donchin, 1987; Rugg, 1984], to amplify phonological processing. In contrast, we investigated phonological effects in the lexical decision task, a classic visual word recognition task that could in principle be solved without phonological processing [Grainger and Jacobs, 1996]. If phonological processing constrains lexical access, as suggested by the phonological mediation hypothesis, then the PsH effect should occur together with or before the word frequency effect. If phonology is processed post-lexically, as suggested by the direct access hypothesis, then the PsH effect should occur after the word frequency effect. In addition, low-resolution electromagnetic tomography analysis (LORETA) was carried out to provide information about possible cortical generators of the ERP distributions recorded at the scalp.

MATERIALS AND METHODS

Participants

Twenty-five right-handed students (five men, mean age 21.3 years) from the Freie Universität of Berlin participated in the study. All participants were native German speakers and had normal or corrected to normal vision. After the analysis of response time data, seven participants were excluded because they showed no effects of word frequency (2), lexicality (3), or phonology (2) in the response time analysis. This resulted in a total of 18 sets of EEG data, which were subjected to ERP and LORETA analyses. No items were excluded from the analyses. Response times below 200 ms and above 2,000 ms were excluded (5.91%).

Stimuli

The critical stimulus set contained 480 stimuli (240 words and 240 nonwords). Of the 240 word stimuli 120 served as fillers. Of the 240 nonwords half were PsHs and half were spelling controls. To rule out orthographic similarity as the basis of the PsH effect, we constructed our PsHs and spelling controls according to the criteria put

TABLE I. Matched variables for pseudohomophones, spelling controls, and words

	Frequency		
	Low	High	Mean
Pseudohomophones			
BF (type)	31.5	41.6	36.6
BF (token)	2698.9	3633.9	3166.4
N	3.4	3.5	3.5
Spelling controls			
BF (type)	31.5	41.6	36.6
BF (token)	4857.5	8440.7	6649.1
N	3.4	3.6	3.5
Words			
BF (type)	46.9	57.3	52.1
FN	188944.2	39777.0	114360.6
HFN	1.9	0.8	1.35
N	3.3	4.3	3.8
Syl	1.5	1.3	1.4

BF (type), summed positional bigram count; BF (token), summed positional bigram frequency count; N, number of neighbors; FN, summed frequency of orthographic neighbors; HFN, number of higher frequency orthographic neighbors; Syl, number of syllables.

forward by Martin [1982]. That is, both item types were generated from the same base words, changing only one letter at the same position and controlling for frequency and number of neighbors. In addition, the two groups were matched for sublexical measures of bigram frequency (type and token, see Table I).

PsHs had the same phonology but differed in spelling from their base words. Spelling controls differed in spelling and in phonology from their base words. For example, the PsH "SAHL" and the spelling control "SARL" were derived from the base word "SAAL" (room). Of the PsHs and the spelling controls one-third had three, one-third had four, and one-third had five letters. Half of the PsHs and spelling controls of each length were derived from high-frequency base words (more than 20 occurrences per million, mean 820.54). The other half of the PsHs and spelling controls were derived from base words of low frequency (less than 20 occurrences per million, mean 5.88). Frequency estimates were taken from the CELEX database [Baayen et al., 1995].

Of the 120 word stimuli, one-third had three, one-third had four, and one-third had five letters. One half of the word stimuli of each word length were of high frequency (more than 11 occurrences per million, mean 1405.62) and the other half were of low frequency (less than 11 occurrences per million, mean 3.93). The word stimuli were matched on bigram frequency (type count), number of syllables (Syl), number of neighbors (N), summed frequency neighbors (FN), and number of higher frequency neighbors (HFN).

Procedure

Participants were seated in front of a computer screen at a distance of ~50 cm and were given written instructions. They were told that they were going to see letter strings, some of which were German words and some were nonwords. Participants were instructed to indicate by button press as fast as possible, but not to the expense of accuracy whether the stimulus was a German word or not using the left and right index finger of the respective hand. The response hands were counterbalanced across participants. A short break appeared after every 40 trials. Participants received 30 practice trials to familiarize them with the task. The experimental trials were presented in randomized order for each participant. Each trial began with a 700 ms presentation of a fixation mark (+) in the center of the screen. The fixation mark was replaced by the stimulus, which remained on the screen until button press. After the stimulus, a mask of hash marks (######) indicated the possibility for eye blinks for another 1.5 s. After a blank screen of 500 ms, the next trial started with the fixation mark. The stimuli were displayed in white on a black background. They were typed in upper case letters using a standard (Times New Roman) 20 pt font. The whole experiment took about 60 min.

ERP Recordings and Analyses

Brain electrical activity was continuously recorded from 27 Ag/AgCl scalp electrodes placed on an elastic cap (EASYCAP, No. 22, Germany) referenced to linked left and right mastoids. A sampling rate of 250 Hz and a low-pass filter of 50 Hz was applied. To monitor eye movement artifacts, the horizontal EOG was recorded from the inner and outer canthus of each eye. The vertical EOG was recorded from electrodes placed above and below the right eye. Impedances for scalp and mastoid electrodes were less then 5 kΩ, eye electrodes below 20 kΩ. All signals were written continuously to hard disk. The EEG was analyzed off-line after the experimental session with BrainVision Analyzer Software (BrainProducts, Germany). EEG waveforms were filtered with a bandwidth from 0.1 to 30 Hz (24 dB/oct) and controlled for artifacts using an automatic rejection procedure, rejecting trials with peak-to-peak potential differences larger than 75 μV in at least one EEG channel followed by a visual inspection. Single participant averages were calculated for each of the conditions followed by a grand average in a time window from 200 ms before and until 800 ms after stimulus onset.

In the averaged data, for each channel the mean amplitude of a 100 ms prestimulus interval was subtracted from all sampling points for baseline correction. Root mean square (RMS) was used to extract time windows with the highest difference between conditions, which were then chosen for further analyses. All subsequent analyses were calculated for mean amplitudes of the selected time windows.

Loreta Analyses

LORETA was used to determine the possible underlying cortical generators of the surface activity. LORETA identifies the most plausible three-dimensional distribution of cortical current density, which accounts for a certain observed scalp EEG signal with an average localization error of ~10 mm [Cuffin et al., 2001]. To determine statistical significances of differences in regional neural activity between the experimental conditions, statistical nonparametric mapping procedures as implemented into the LORETA software package were used. Paired *t*-tests comparing the conditions were computed on a voxel-by-voxel basis over all participants. Voxels with *t*-values above the critical threshold ($P < 0.05$, one-tailed) were considered to represent regions of differential activation.

RESULTS

Response Times

Response times were submitted to three ANOVAs: a 2 × 2 repeated measurement ANOVA with phonology (PsHs vs. spelling controls) and base word frequency (high vs. low) as within-subject factors as well as two one-way ANOVAs—one with word-frequency (high vs. low) and one with lexicality (nonwords vs. words) as within-subject factor. In case of significant effects in the subject-based (F1) analysis, the generalizability over stimulus material was examined with items as cases (F2), whereby all factors were between-item factors. In case of violation of sphericity, degrees of freedom (df)s were adjusted according to the Greenhouse-Geisser correction [Greenhouse & Geisser, 1959].

As evident from Table II, a main effect of phonology in the two-way ANOVA revealed that responses to PsHs were 32 ms slower than those to spelling controls [$F1(1,17) = 53.64$, $P < 0.001$, MSE = 42483; $F2(1,118) = 22.17$, $P < 0.001$, MSE = 166467]. A main effect of base word frequency indicated that response times for items derived from low-frequency base words were slower than those response times for items derived from high-frequency base words [$F1(1,17) = 20.84$, $P < 0.001$, MSE = 9958; $F2(1,118) = 4.71$, $P = 0.031$, MSE = 35366]. The phonology by base word frequency interaction was not significant [$F1(1,17) = 2.57$, $P = 0.13$, MSE = 4706; $F2(1,236) = 2.21$, $P = 0.14$, MSE = 16583].

The first one-way ANOVA revealed a main effect of word-frequency indicating that high-frequency words were responded to faster than low-frequency words, [$F1(1,17) = 21.03$, $P < 0.001$, MSE = 69192; $F2(1,118) = 8.52$, $P < 0.001$, MSE = 365300]. The second one-way ANOVA revealed a main effect of lexicality showing that the lexical status of the items did affect response times: nonwords were responded to 100 ms slower than words [$F1(1,17) = 15.09$, $P = 0.001$, MSE = 149026; $F2(1,233) = 62.10$, $P < 0.0001$, MSE = 563688]. An inspection of Table II reveals that accuracy of responses was close to ceiling for all types of stimulus material; error rates were therefore not submitted to statistical analysis. In sum, the response time analysis revealed the expected effects of phonology, base word frequency, word frequency, and lexicality.

TABLE II. Reaction time means and error rates for pseudohomophones, spelling controls, and words

	Reaction time (ms)		Error rates (%)	
	(Base word) frequency		(Base word) frequency	
	Low	High	Low	High
PH	882.44	842.75	2.11	1.50
SC	817.69	810.33	1.39	1.37
WO	746.41	700.10	4.03	1.33

PH, pseudohomophones; SC, spelling controls; WO, words.

ERP Analyses

20.3% of the trials were rejected because of artifacts. The ERP morphology starts with a negative deflection occurring at 100 ms from stimulus onset (N1). This was followed by a positive deflection peaking at ~200 ms (P200). A negativity followed the P200, with a peak around 400 ms (N400). Figure 1 shows response time means and standard errors as well as RMS of all participants for the different conditions over all electrode positions and the voltage curves for selected electrode positions for the effects of phonology, word frequency, and lexicality.

Statistical analyses comprised a stepwise procedure. First, global analyses for the respective conditions were calculated by means of repeated measurement ANOVAs with hemisphere (left vs. right) and region (frontal vs. posterior) as within-subject factors. In case of a significant main effect or interaction, separate repeated measurement ANOVAs for each of the four regions (frontal left and right, posterior left and right) were calculated. If this quadrant analysis resulted in significant effects, paired *t*-tests for single electrodes for the different conditions in the respective quadrants were computed.

For the different experimental conditions, three time windows were chosen for analyses: 152–184 ms (low-frequency PsHs vs. low-frequency spelling controls), 152–216 ms (low-frequency words vs. high-frequency words), and 260–760 ms (low-frequency PsHs and spelling controls vs. high-and low-frequency words).

The ERP data revealed an early difference between PsHs and spelling controls for low-frequency items in the time window from 152 to 184 ms. For the low-frequency items only, the repeated measures ANOVA revealed significant effects of phonology [$F(1,17) = 5.85$, $P = 0.027$, MSE = 17], of region [$F(1,17) = 23.28$, $P < 0.001$, MSE = 330] and a marginally significant phonology-by-region interaction [$F(1,17) = 3.97$ $P = 0.063$, MSE = 2]. The subsequent quadrant ANOVAs revealed main effects of phonology and electrodes for left and right posterior regions, but not for frontal regions. Left posterior: phonology [$F(1,17) = 8.20$, $P = 0.011$, MSE = 36] and electrodes [$F(4,68) = 44.38$, $P < 0.001$, MSE = 690]. Right posterior: phonology [$F(1,17) = 9.04$, $P = 0.008$, MSE = 38] and electrodes [$F(4,68) = 33.27$, $P < 0.001$, MSE = 441].

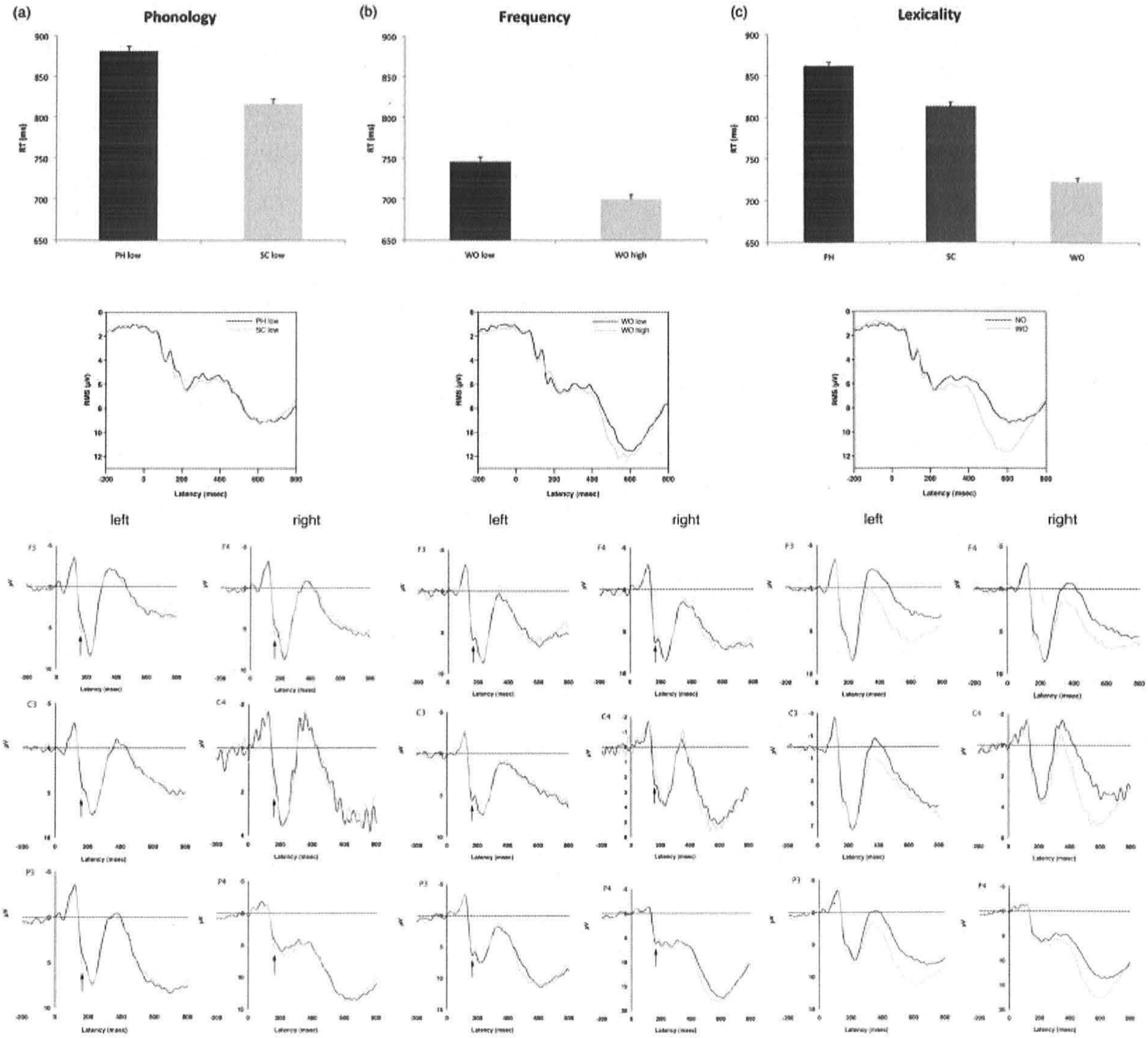

Figure 1.

Response time means and standard errors as well as root-mean-square (RMS) and voltage curves for selected electrodes for the effects of (a) phonology, (b) word frequency, and (c) lexicality. Note: WO, words; NO, nonwords; PH low, low-frequency pseudohomophones; SC low, low-frequency spelling controls; WO low, low-frequency words; WO high, high-frequency words.

In the time window from 152 to 216 ms, low-frequency words differed from high-frequency words. The repeated measures ANOVA revealed significant effects of frequency [$F(1,17) = 7.66$, $P = 0.013$, MSE = 29], of hemisphere [$F(1,17) = 5.55$, $P < 0.031$, MSE = 11], and region [$F(1,17) = 6.88$, $P = 0.018$, MSE = 11] as well as a significant interaction of hemisphere and region [$F(1,17) = 22.21$, $P < 0.001$, MSE = 25]. The subsequent quadrant ANOVAs revealed main effects of frequency and electrodes for all four quadrants and a significant interaction of frequency-by-electrodes at left anterior sites. Left anterior: frequency [$F(1,17) = 5.67$, $P = 0.029$, MSE = 23], electrodes [$F(3,51) = 20.46$, $P < 0.001$, MSE = 319], frequency-by-electrodes $F(3,51) = 3.24$, $P = 0.049$, MSE = 3]. Right anterior: frequency [$F(1,17) = 7.08$, $P = 0.016$, MSE = 22], electrodes [$F(3,51) = 16.69$, $P < 0.001$, MSE = 593]. Left posterior: frequency [$F(1,17) = 6.10$, $P = 0.024$, MSE = 34], electrodes [$F(4,68) = 6.44$, $P = 0.007$, MSE = 95]. Right posterior: frequency [$F(1,17) =$

TABLE III. Electrodes showing differences for phonology (pseudohomophones vs. spelling controls) and word frequency (low vs. high) effects, $P < 0.05$

Region	Phonology (152–184 ms)				Frequency (152–216 ms)		
Left anterior	–	–	–	–	F3	F7	–
Right anterior	–	–	–	–	F8	FC6	–
Left posterior	CP1	CP5	P3	P7	CP1	P3	P7
Right posterior	CP2	P4	P8	O2	CP6	P8	–

Electrode labels refer to electrodes, which showed significant differences ($P < 0.05$) after significant ANOVAs in the previous quadrant analysis for the selected conditions and time windows. Empty cells refer to nonsignificant ($P > 1$) effects.

7.60, $P = 0.013$, MSE = 41], electrodes [$F(4,68) = 10.77$, $P < 0.001$, MSE = 54].

Nonwords differed from words in the time window from 260 to 760 ms from peaking at 400 ms (N400). The repeated measures ANOVA revealed significant effects of lexicality [$F(1,17) = 21.01$, $P < 0.001$, MSE = 160], of hemisphere [$F(1,17) = 16.12$, $P = 0.001$, MSE = 43], and region [$F(1,17) = 53.58$, $P < 0.001$, MSE = 269] as well as a significant interaction of lexicality and region [$F(1,17) = 21.43$, $P < 0.001$, MSE = 1.83]. The subsequent quadrant ANOVAs revealed main effects of lexicality and electrodes for all four quadrants and a significant interaction of lexicality-by-electrodes at left anterior and right posterior sites. Left anterior: lexicality [$F(1,17) = 21.15$, $P < 0.001$, 136 = 23], electrodes [$F(3,51) = 21.48$, $P < 0.001$, MSE = 639], lexicality-by-electrodes $F(3,51) = 7.28$, $P = 0.006$, MSE = 12]. Right anterior: lexicality [$F(1,17) = 18.84$, $P < 0.001$, MSE = 97.88], electrodes [$F(3,51) = 11.28$, $P < 0.001$, MSE = 290]. Left posterior: lexicality [$F(1,17) = 23.38$, $P < 0.001$, MSE = 248], electrodes [$F(4,68) = 29.09$, $P < 0.001$, MSE = 95]. Right posterior: lexicality [$F(1,17) = 21.32$, $P < 0.001$, MSE = 242], electrodes [$F(4,68) < 29$, $P < 0.001$, MSE = 416]. Table III shows significant electrodes for the effects of phonology and frequency in the corresponding time windows.

Source Analysis

LORETA analysis was applied to find possible underlying generators of the effect of phonology in the time window from 152 to 184 ms. Inspection of the mean activity for PsHs and spelling controls revealed the highest activity in the medial frontal gyrus (MFG, BA6; $x = -3$, $y = -4$, $z = 64$) for both conditions followed by activity in the posterior central gyrus (PCG, BA40; $x = -59$, $y = -25$, $z = 22$). The LORETA images of current density distributions for the effect of phonology were separately averaged across subjects for the respective conditions and the differences between conditions were examined. Statistical significance of the differences in the distributions between conditions was assessed by voxel-by-voxel t-tests of the LORETA images, using the current density with no data transformation and subject-wise normalization separately for both conditions. The voxel-by-voxel P-values were corrected for multiple testing according to Nichols and Holmes [2002]. The analysis revealed a highly significant difference for the contrasts of PsHs and spelling controls in the left supramarginal gyrus (SMG, BA40; $x = -52$, $y = -53$, $z = 36$) [$t = -3.45$, $P = 0.003$] and a difference in the right superior temporal gyrus (STG, BA22; $x = 53$, $y = 3$, $z = 8$) [$t = 2.99$, $P = 0.036$]. Figure 2a,b shows the results of the LORETA analysis for low-frequency PsHs and low-frequency spelling controls.

DISCUSSION

The PsH effect was used to investigate early automatic phonological activation in visual word recognition. The behavioral results clearly replicate those from previous studies reporting slower response times and higher error rates for PsHs compared with spelling controls in lexical decision. Therefore, these results point to an important role of phonological processing in visual word recognition. The PsH effect was strongest for items derived from low-frequency base words, a finding that is consistent with previous research [e.g., Rubenstein et al., 1971; Ziegler et al., 2001]. This pattern can be understood in the context of current dual route models [Coltheart et al., 2001; Perry et al., 2007]. In these models, there is a fine balance between orthographic (lexical) and phonological (nonlexical) processing. In the case of PsHs, there is conflict between the two routes because the phonological route provides evidence in favor of word representations, whereas no symmetrical activation is found in the orthographic lexicon. Thus, the orthographic route needs to inhibit the "misleading" information from the phonological lexicon. In the case of a low-frequency base word, orthographic activation will be weaker than in the case of a high-frequency base word, thus giving more time to the phonological route to boost its activation. As a consequence, PsHs derived from low-frequency base words will provide stronger phonological activation, thus causing greater conflict within the system than PsHs from high-frequency base words.

Effects of word frequency are taken as an upper limit for lexical access [e.g., Forster and Chambers, 1973; Hauk and Pulvermüller, 2004; Rubenstein et al., 1970; Sereno et al., 1998, but see Balota and Chumbley, 1984 for a different view]. Lexical access involves the matching of features extracted from the stimulus to internal representations of words. Current models of visual word recognition (e.g., DRC or MROM-p) implement frequency-sensitive representations. Word frequency is believed to determine the availability of lexical representations by affecting the resting levels of these representations. Therefore, according to these models, high-frequency words are responded to faster in lexical decision because their representations have higher resting levels compared with low-frequency words thus, giving rise to a head start. Responses to high-frequency words in our study were about 46 ms faster than those to low-frequency words. We interpret this word fre-

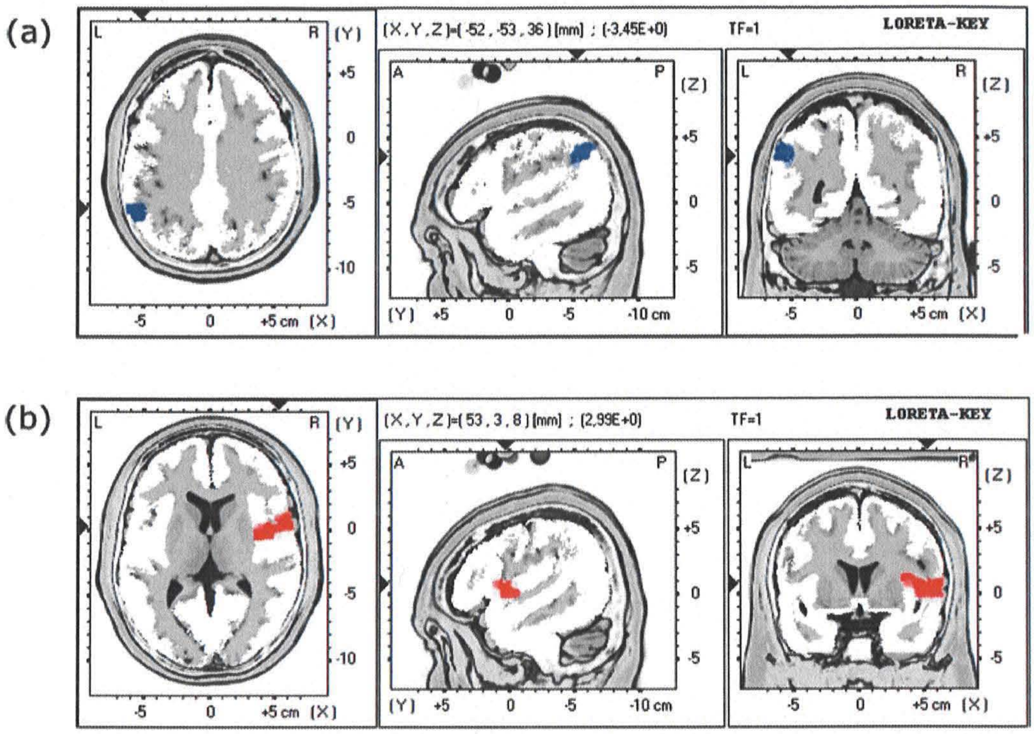

Figure 2.

Results of the low-resolution electromagnetic tomography (LORETA) *t*-statistics comparing event-related potentials time locked to the presentation for the contrast of low-frequency pseudohomophones vs. low-frequency spelling controls (a) left temporoparietal (SMG) activation and (b) right frontotemporal (IFG, STG, insula) activation. The images show LORETA slices in Talairach space for the estimated source distributions of activation differences.

quency effect to reflect lexical access which is faster for high-frequency words than for low-frequency words.

Previous research suggested that phonological processing in visual word recognition occurs rather late, typically after semantic or syntactic processing [Bentin et al., 1999; Rugg, 1984; Ziegler et al., 1999]. In contrast, the present results clearly show that phonological activation in visual word recognition can be observed much earlier. Indeed, in this study, ERPs to PsHs derived from low-frequency base words differed as early as 150 ms (P150) after stimulus onset compared with well-matched spelling controls. Spelling controls evoked a more positive peak than PsHs, which is most likely because the mismatch between orthography and phonology is more easily detected in spelling controls than in PsHs.

We consider this P150 as the brain electrical response to the conflict between orthographic and phonological word representations in memory. PsHs activate their corresponding phonological word representation. There is conflict because the orthographic representation does not match the phonological representation. In contrast, neither words nor spelling controls do produce such a conflict. In the case of words, there is no conflict because the orthographic representation matches the phonological representation. In the case of spelling controls, there is no conflict because spelling controls do not fully activate existing phonological representations. Similarly, Sauseng et al. [2004] reported early differences between PsHs and words in a frontal and posterior P/N160 component poststimulus and proposed that at this point of time PsHs contact the stored visual orthographic representations of words. Furthermore, the orthographic deviation of the PsHs from their base words was thought to result in the reduction of P160/N160 amplitudes.

Time course analyses clearly showed that the phonological marker (i.e., the PsH effect) co-occurred with the lexical marker (i.e., the word frequency effect) and these effects were observed in nearly the same time window (152–216 ms). This finding adds further support to the claim that phonological activation occurs early enough to affect lexical access. Indeed, Hauk and Pulvermüller [2004] also reported word frequency effects in a very similar time window between 150 and 200 ms [see also Assadollahi and Pulvermüller, 2001; Dambacher et al., 2006; Sereno et al., 2003, but see Polich and Donchin, 1988; Pulvermüller et al., 2001; Rugg, 1990; Van Petten and Kutas, 1990 for later effects of word frequency]. Finally, Hauk et al. [2006a] reported lexical and semantic processing as early as 160 ms employing linear regression analysis on neurophysiological data from a visual lexical decision task.

These findings suggest that lexical access from written words can occur as early as 200 ms after stimulus presentation. Words in our study differed from nonwords (PsHs and spelling controls) in the time window from 260 to 760 ms after stimulus presentation peaking at 400 ms (N400). N400 activity modulation is mostly found when the eliciting stimulus is semantically evaluated following the prior activation of a context or by presenting sentences containing the target [e.g., Kutas and Hillyard, 1980], which is not the case in this study.

If we take the early frequency effects as a reliable index for lexical access, we suggest that later occurring lexicality and frequency effects peaking around 400 ms poststimulus might reflect reprocessing or semantic integration, consistent with a postlexical interpretation of mechanisms underlying the N400 [e.g., Brown and Hagoort, 1993; Holcomb, 1993].

The source analysis supports the results of the ERP analysis in suggesting an early influence of phonological information in visual word recognition. The contrast of PsHs and spelling controls revealed the largest differences in a left temporoparietal area including the SMG (BA40) and in a right frontotemporal area at the border of the inferior frontal gyrus (IFG, BA44,45), the insula (BA13), the supplementary motor area (SMA, BA6), and the STG (BA22). In fact, previous imaging studies have proposed that the SMG, the pars triangularis, and the SMA are part of Baddeley's phonological loop [Baddeley, 1986] linking IFG activity to articulatory rehearsal and SMG activity to phonological storage [Demonet et al., 1994; Gold and Buckner, 2002; Paulesu et al., 1993; Tan et al., 2005].

Further support for an involvement of these areas in phonological processing is provided by a number of studies [e.g., Borowsky et al., 2006; Carreiras et al., 2006, 2007; Dietz et al., 2005; Fiebach et al., 2002; Ischebeck et al., 2004; Mechelli et al., 2007; Owen et al., 2004; Posner and Raichle, 1994; Rumsey et al., 1997] and also from imaging studies using PsHs in visual word recognition reporting left and right IFG activity (pars opercularis and triangularis) for PsHs when compared with pseudowords [e.g., Edwards et al., 2005; Kronbichler et al., 2007].

Furthermore, bilateral insula activity seems to be involved in grapheme–phoneme conversion in visual word recognition [e.g., Fiebach et al., 2002; Fiez and Petersen, 1998] as well as in phonological lexical access [e.g., Borowsky et al., 2006]. Borowsky et al. [2006] reported posterior insula activity for exception words and anterior insula activity for PsHs in a naming task. They proposed that the anterior and posterior insula reflect different levels of processing. Exception words should be read by lexical memory and PsHs should be read by sublexical grapheme–phoneme conversion. Therefore, they concluded that the insula is sensitive to both sublexical and lexical processing.

These findings suggest that activity in these regions is related to phonological processing. This holds also for bilateral STG activation [e.g., Booth et al., 2002a; Tan et al., 2005]. Activity in the STG was reported in response to individual speech sounds and letters [van Atteveldt et al., 2004] and to written and spoken narratives [Spitsyna et al., 2006] suggesting heteromodal processing and an involvement of the STG in cross-modal integration and multisensory convergence. Booth et al. [2002a] also reported heteromodal STG activity for spoken words and visual rhyming. Thus, the STG is supposed to process auditory and visual information and to be the site where auditory and visual pathways converge enabling automatic reciprocal processing of spoken and written language [Dijkstra et al., 1993].

There is also reasonable evidence that STG activity reflects processing of phonological and semantic information [e.g., Mesulam, 1990] and that the STG probably hosts the phonological word form lexicon, which is obviously involved in phonological lexical access. Thus, the STG could be the site where phonologically mediated lexical access takes place [e.g., Booth et al., 2002a,b; Graves et al., 2007; Price et al., 1994; Rumsey et al., 1997]. Therefore, we propose that the activity in the frontotemporal area including the STG, as revealed by the contrast of PsHs and spelling controls, reflects access to whole word phonological and probably semantic representations in the case of PsHs.

Results from silent reading and visual lexical decision tasks further suggest that AG and SMG activity reflects lexical access. Joubert et al. [2004] compared silent reading of high-frequency words assumed to index lexical processing and low-frequency words and nonwords assumed to index sublexical processing. They found activation at the border of SMG and AG for silent reading of high-frequency words and left inferior prefrontal gyrus activation for low-frequency words and nonwords. They proposed that SMG/AG comprise the visual orthographic lexicon and that activation in this region reflects the mapping of orthographic whole word representations onto phonological whole word representations. Consistent with this view, Binder et al. [2003] reported AG and SMG activity to be higher for words than to word-like nonwords in a visual lexical decision task and attributed this activity to reflect semantic access. Moreover, Hofmann et al. [2008] reported left AG and SMG activity in visual lexical decision to words and nonwords using functional near infrared spectroscopy (fNIRS) and attributed this activity to reflect the connection of orthographic, phonological, and semantic representations. Finally, Kronbichler et al. [2007] reported higher AG activity to PsHs compared with pseudowords in a visual phonological decision task. These findings add further support to the idea that AG/SMG activity is involved in whole-word processing, and furthermore that PsHs probably activate their phonologically identical base words and thus signal lexical access.

Concerning the proposed conflict in the processing of PsHs, we believe that the reported activity is not due to conflict monitoring or response conflict reported in the conflict literature. Response conflict or conflict monitoring is mostly linked to activity in the prefrontal cortex comprising the SMA (BA6), the anterior cingulate cortex (ACC, BA24), and the cingulate cortex [CC, BA32; e.g., Botvinick et al., 2004; Ridderinkhof et al., 1999; Smith and Jonides, 1999; Yeung et al., 2004].

We suggested that processing of PsHs is more demanding than processing of spelling controls because of conflicting information in the phonological and orthographic lexicon. Therefore, PsHs should produce higher activity in regions believed to process this information and/or in regions that are known to reflect conflict processing. The results of this study should, therefore, provide an answer to the locus of this kind of conflict processing if it is located at a lexical or at an extra-lexical level or both. Recently, Fiebach et al. [2007] reported ACC activity in a study on neighborhood effects in visual word recognition. Fiebach et al. proposed that ACC activity signals involvement of a domain-general, extra-lexical process, and to play an important role for executive control functions during visual word recognition.

Prefrontal cortex activity for PsHs and spelling controls was also obtained in this study but this activity was cancelled out in the contrast of PsHs and spelling controls, suggesting that activity in this area reflects a kind of processing which is present for both item groups. We, therefore, think that the current results cannot be explained by response conflict. Rather, we propose that the P150 is too early to be related to decision processes and more likely to reflect an early interaction of structural and lexico-semantic processes [e.g., Hauk et al., 2006b].

In support of this interpretation is a recent study by Bitan et al. [2007] who showed that children engage in automatic orthographic and phonological processing regardless of task requirements. Bitan et al. manipulated orthographic and phonological similarity between visually presented word pairs and compared conflicting and non-conflicting conditions in spelling and rhyme judgments. They found higher activity for the conflicting orthographic condition in bilateral inferior/superior parietal lobule (SPL) and higher activity for the conflicting phonological condition in the bilateral IFG that is in areas which are close to those reported in this study. This activity in the conflicting conditions are assumed to reflect repetitive mapping between orthography and phonology, and that increased phonological segmentation and covert articulation is necessary to verify the accuracy of the outcome. Bitan et al. proposed competition at two stages when readers encounter conflict between orthographic and phonological information. The first stage is early and comprises the generation or access to a representation; the second is later and comprises processes of response selection, which are assumed to be reflected in the obtained activity in the anterior cingulate/medial frontal cortex.

Therefore, we propose that our findings indicate that activity in the left temporoparietal region, comprising the SMG, and in the right frontotemporal region, comprising the IFG, the insula, and the STG, probably reflect lexical rather than extra-lexical processing. PsHs in contrast to spelling controls activate whole word phonological representations of their underlying base words.

The results of this study showed that orthographic and phonological information interact at early stages of processing. This interaction is probably associated with the activation in left temporoparietal (SMG) and right frontotemporal regions (STG, IFG, and insula) as revealed by the source analysis. This activation in the left temporoparietal and the right frontotemporal area is in line with previous research and further supports the hypothesis that an early mapping between orthography and phonology is an integral part of lexical access.

In conclusion, our results (RTs, ERPs, and LORETA) demonstrate rapid phonological activation in silent reading and thus, provide evidence for the phonological mediation hypothesis and the claim that phonological processes are involved in lexical access in visual word recognition.

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