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Literate humans sound out words during silent reading

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Running head: PHONOLOGICAL ACTIVATION IN READING

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Abstract

Whether humans spontaneously sound out words in their mind during silent reading is a matter of debate. Some models of reading postulate that skilled readers access meaning directly from print but others involve print-to-sound transcoding mechanisms. Here we provide evidence that silent reading activates the sound form of words prior to meaning access by comparing event-related potentials induced by highly expected words and their homophones. We found that expected words and words that sound the same but have a different orthography (homophones and pseudohomophones) reduce scalp activity to the same extent within 300 ms of presentation compared to unexpected words. This demonstrates that phonological access during silent reading, which is critical for literacy acquisition, remains active into adulthood.

Keywords: Event-related potential, reading, phonology, semantic access, N2, N400, homophone, pseudohomophone.

Introduction

Studies that have tested phonological effects during single word reading have shown brain activity modulations as early as 100 ms [1-4], suggesting a fundamental role for phonology. However, whether phonological information is spontaneously retrieved when accessing semantic information in reading is open to debate [5-7]. To test whether the phonological form of written words is activated during silent reading, we measured the N2 and N400 peaks of event-related potentials (ERPs), which reflect the degree of phonological and semantic mismatch, respectively, between a word and the context in which it appears [8-11]. For example, in the spoken sentence ‘an eagle is a bird of flare’, the word ‘flare’ would elicit a larger N2 and N400 compared to ‘prey’ since it is neither phonologically nor semantically expected in the sentence context [10]. Since the N2 is sensitive to phonological expectation about words, significant reduction in its amplitude for both an expected word and its homophone relative to an unexpected word in visually presented sentences would provide strong evidence that the sound form of words is retrieved during silent reading.

Most of the existing ERP studies investigating this question have not found convincing evidence for phonological involvement in accessing the meaning of written words. In the case of single word reading, one ERP study [11] testing phonological access in a semantic categorisation task found no N400 differences between homophones of category exemplars (e.g. “meet” for the category of food) as compared to orthographic controls (e.g. “melt”). In the context of behavioural data showing higher error rates in the homophone condition (homophones were more likely to be accepted as correct category members than orthographic control items), the conclusion was that the

phonological effects occur after semantic integration indexed by the N400. However, the possibility was raised that the increased processing demands of reading sentences for meaning might show greater phonological involvement [11].

Previous sentence reading studies have examined phonological activation by replacing semantically primed final words with unexpected words sharing initial phonemes [12], homophones [13-14] or pseudohomophones (pseudowords homophonic to a real word) [15]. Some have found evidence for phonological effects in semantic integration indexed by the N400 [14-15], while others have not [12-13]. Furthermore, these studies have found only weak earlier phonological reductions in the N2 range and moreover concluded that N2 modulations in reading are primarily related to orthographic violation [15]. However, these previous results have only provided limited insight regarding spontaneous phonological activation in silent reading, because they have either (a) not used a controlled task (e.g., no behavioural monitoring in the case of Refs. 12, 14, 15), (b) not used sentences with high cloze probability (Ref. 13), and/or (c) not controlled cloze probability across experimental conditions (i.e., they used different sentence contexts across conditions in 12, 15). Cloze probability is the numerical probability of a given word to be selected to complete a given sentence context (e.g., the cloze probability of 'prey' in the sentence starting 'An eagle is a bird of...' is close to 1).

Indirect evidence for phonological activation in sentence reading comes from a study on misspellings [16], in which expectancy was manipulated by presenting low- and high-cloze probability sentences containing a congruent word or its pseudohomophone. In the N2 time range (N270), differences between words and pseudohomophones were found in the context of low-cloze sentences but not that of high-cloze sentences.

Although the aim of the study was to investigate the processing of misspellings, this result is compatible with phonological mediation in silent reading, since pseudohomophones –when highly constrained by sentence context – are phonologically expected. In the same study, words and pseudohomophones also reduced ERP amplitudes in the N400 range when presented in a high-cloze probability sentence [16], suggesting that phonological activation during silent reading may extend into the window of semantic integration [15, 17].

Here, we tested whether participants reading silently for meaning would show phonological processing of stimuli that are orthographically and semantically inappropriate but phonologically expected, when reading highly constrained sentences. Our main question was whether homophones and pseudohomophones presented at the end of a highly constrained sentence would reduce the amplitude of the N2 peak relative to totally unexpected endings [10, 18]. Our predictions were as follows: If retrieval of the phonological form of written words is spontaneous during silent reading, we should observe a reduced N2 peak in all conditions except for totally unexpected completions. In addition, retrieval of the phonological form of a homophone or pseudohomophone was expected to activate the semantic representation of the best completion and thus similarly reduce the subsequent N400 [9, 17].

Method

Participants

Fifteen undergraduate students participated as partial fulfilment of a course requirement (11 females; Mean age 19.3 years, range 18–24 years) in our study approved by Bangor

University's Ethics Committee. All had normal, or corrected-to-normal, vision and were native speakers of English.

Stimuli

To ensure that the 'best completion' stimuli were highly predictable from the preceding sentence context, a separate group of 37 participants completed a series of sentences that were missing the final word with their most likely ending (e.g., "Rob looked at his watch to check the..." elicited the response "time"). Sentences were included on the basis of their percentage predictability: Each had a minimum of 0.80 Cloze Probability, with an average Cloze Probability of 0.84 for the final 'best completion' stimuli.

There were four experimental conditions: best completion (BC; e.g., "time"); homophone of the best completion (HO; e.g., "thyme"); pseudohomophone of the best completion (PH; orthographically legal pseudowords homophonic to the best completion; e.g., "tyme"); and unrelated (UN; words unrelated to the sentence context; e.g., "skull"). BC, HO and UN word lists were matched for lexical frequency (Mean Log = 1.13 ± 0.7), concreteness (Mean = 465 ± 99), length (Mean = 4.6 ± 1) and grammatical class [19]. Sentences ranged from 5 to 12 words in length.

Of the four stimulus conditions, three provided endings incongruent with the sentence whilst only one (best completion) provided a congruent completion. To avoid spurious P300 effects prompted by unbalanced proportion between best completion and other experiment conditions, we created a filler best completion condition [20]. These fillers comprised sentences with congruent endings but had no corresponding homophone or pseudohomophone equivalent and were not analyzed. The complete stimulus set

comprised a total of 240 words: 40 words in each of the four critical experimental conditions (BC, HO, PH, UN), and 80 words in the filler best completion condition.

Procedure

Participants were comfortably seated in a darkened, acoustically and electrically shielded room. A high-resolution CRT monitor was centred approximately 100 cm from participants' eyes. They were instructed to fixate the centre of the screen and to minimize eye and body movement throughout the ERP recording. Participants were asked to indicate whether the final word was congruent or incongruent with the preceding sentence by pressing either the 'F' or 'J' keys (with the left and right index fingers respectively). Response side was alternated between blocks and counterbalanced across participants. The 240 stimuli were divided into 4 blocks of 60 trials. In each trial, the sentence was presented one word at a time for 200 ms with an inter-stimulus-interval of 300 ms. Following presentation of the final word participants had 2 seconds to respond. Each word subtended a maximum visual angle of $4^\circ \times 0.8^\circ$. Individual reaction times (RTs) for correct responses were averaged as a function of experimental condition. Incorrect responses and non-responses were coded as errors.

EEG recording and analysis

Electrophysiological (EEG) data were recorded (1 kHz sampling rate; SynAmps2 amplifiers; Neuroscan Inc., El Paso, USA) from 32 Ag/AgCl electrodes in reference to Cz (impedance $< 11 \text{ k}\Omega$). Electrodes were placed in accordance with the International 10-20 System at frontal (Fp1, Fp2, Fz, F3, F4, F7, F8), central (C3, C4), temporal (T7, T8), parietal (Pz, P3, P4, P7, P8) and occipital (O1, O2) sites, with additional electrodes in anterior frontal (AFz), fronto-temporal (FT9, FT10), fronto-central (FC1, FC2, FC5,

FC6), central-parietal (CP1, CP2, CP5, CP6) and parieto-occipital (PO9, PO10) locations. Electrodes above and below the left eye monitored eye blink activity. EEG signal was filtered online between 0.1 and 100 Hz and re-filtered offline using a zero-phase shift using a 20 Hz cut-off low pass. Neuroscan software (Scan 4.2) was used to mathematically correct eye blinks. Epochs ranged from -100 to 1000 ms after final word onset. Baseline correction was performed in reference to 100 ms pre-stimulus activity. At least 30 correct response epochs were obtained for each experimental condition (acceptance of best completions; rejections for the remainder) for each participant. Individual averages, which were digitally re-referenced to the global average reference, were averaged to produce the grand-average ERPs. Mean amplitudes were measured at electrodes FC1, FC2 and Fz between 250 and 350 ms for the N2 and CP1, CP2 and Pz between 350 and 500 ms for the N400. For both peaks, individual mean amplitudes and peak latencies for each condition were subjected to repeated measures ANOVAs with within subject factors of condition (BC, HO, PH, UN) and electrode (3 electrodes).

Results

Behavioural Data

Repeated measures ANOVA indicated that experimental conditions significantly affected reaction times [$F(3,14)=6.57$, $P < .05$], with PH stimuli eliciting faster responses compared to other conditions [All $P_s < .05$; Fig. 1]. Error rates also differed between experimental conditions [$F(3,14)=12.25$, $P < .01$; see Fig. 1]. Both BC and PH conditions yielded lower error rates than the HO and UN conditions [all $P_s < .05$]. Differences between BC and PH on the one hand, and between HO and UN on the other hand were non-significant [all $P_s > .1$].

Please insert Figure 1 about here

Electrophysiological Data

P1 and N1 components elicited by words in final position peaked at 115 and 223 ms, respectively, and were unaffected by experimental conditions either in amplitude or latency. The N2 peaked at 317 ms over the frontal area, and was maximal at Fz. The N400 was a broad negative wave maximal at centroparietal electrodes.

N2 peak latency was insensitive to experimental conditions [$P > .1$], but its mean amplitude was affected by experimental condition [$F(3, 14)=7.81, P < .05$; Fig. 2]. *Post hoc* t-tests indicated that the N2 elicited by the UN condition was larger compared to all other conditions: [BC-UN: $t(14)=2.03, P < .05$; HO-UN: $t(14)= 2.82, P < .05$; PH-UN $t(14)=2.70, P < .05$], while differences between BC, HO and PH considered in pairs were non-significant.

Please insert Figure 2 about here

N400 amplitude was modulated by experimental condition, [$F(3,14)=21.26, P < .05$]. *Post hoc* comparisons showed that the N400 component was significantly more negative for the UN condition than in the other three experimental conditions [BC-UN $t(14)=6.24, P < .05$; HO-UN $t(14)=5.67, P < .05$; PH-UN $t(14)=8.57, P < .05$]. The BC, HO and PH conditions showed a substantially reduced wave and there were no differences between them [$P > .05$; Fig. 2]. Due to the absence of peak in the N400 range in BC, HO and PH, no latency analysis was performed in the N400 range.

Discussion

This study investigated online phonological activation during silent reading and its implication for semantic integration mechanisms. We found that unexpected sentence completions prompted an N2 effect. As predicted, the N2 amplitude was significantly reduced for phonologically congruent completions (whether orthographically expected or not) as compared to unexpected completions. Furthermore, a large amplitude N400 indexing violation of semantic expectancy was found only in the unexpected completion condition whereas the N400 elicited by phonologically congruent sentence completions (best completion, homophone, pseudohomophone) was substantially reduced and non-discriminative. Thus, in a context where orthographic and semantic expectation was maximal and despite the fact that phonological retrieval was detrimental to the task at hand –since homophone and pseudohomophone had to be judged as incorrect completions– participants systematically accessed the sound form of the printed word within 300 ms. Furthermore, the N400 reduction observed for all homophone conditions indicates that phonological activation of the best completion sound form triggered semantic access.

From a behavioural point of view, we found that orthography discriminated between the expected and homophonic completions. Error rates were higher in the homophone condition than in other conditions. Moreover, participants were faster and more accurate in rejecting pseudohomophones than any other stimulus type. Since both homophone and pseudohomophone conditions shared phonological representations with best completions, orthography is the only basis upon which correct rejections could be made. Therefore, different performance in the two homophonic conditions was probably due to relative differences in orthographic familiarity [21]: Pseudohomophones were

orthographically unfamiliar, making it easier to reject them than homophones, which were real words.

It may be argued that amplitude reductions observed in the N2 and N400 ranges could have been prompted by orthographic rather than phonological similarity between BC, HO and PH conditions [22]. However, orthographic similarity is unlikely to account for the degree of attenuation observed here because (i) Since homophones and pseudohomophones were correctly rejected and best completion words accepted, the N2 reduction found in former conditions should not have been as pronounced as that seen in the best completion condition if this decision had been made based on orthography alone; (ii) Non-homophonic pseudowords usually elicit larger N400 amplitudes than pseudohomophones, even when they are matched for orthographic similarity with word targets [23] (orthographically-driven effects have even been found as early as 150 ms [3]); and (iii) Unexpected orthographic *neighbours* of highly expected words have been shown to elicit significantly larger N400 waves than expected sentence completions [24]. As in the present study homophones and pseudohomophones were less than 60% orthographically similar to best completion words (HO mean similarity .59 based on normalised edit distance, NED [25], SD .18; PH NED .55, SD .20) one would have expected larger N400 amplitudes if the effect had been driven by orthographic similarity.

Overall our results appear inconsistent with previous studies showing larger N2 peaks to homophones [13-14] and pseudohomophones [15] as compared to semantically congruent words. However, in our study sentence cloze probability was manipulated so as to make phonological priming effects particularly strong (see also ref. 16) which we

assume lead to automatic phonological activation overriding effects of orthographic expectation until after the window of semantic integration. We speculate that the previous conflicting findings regarding phonological integration indexed by the N2 may be accounted for by the absence of strong phonological expectations in the reader [12-15]. In this situation, phonological activation may be at a sub-threshold level vulnerable to interference from mismatch responses elicited by dissonant orthographic forms and would result in the observed increased N2 modulations [12, 13, 15], indexing early conflicts between orthographic and phonological processing [15, 18]. Such a conflict would presumably reduce phonological integration and subsequent semantic access triggered by the stimulus [e.g., Ref. 11].

Conclusion

Despite being correctly rejected as inappropriate sentence completions, homophones and pseudohomophones appear to elicit N2s and N400s of similar amplitude to those elicited by predictable words. This result provides new evidence that whilst final meaning selection may be constrained by orthography, phonological information is accessed and mediates semantic access during sentence reading.

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Fig. 1 a. Reaction times for correct trials (bars) and error rates (circles) in the 4 experimental conditions. b. Mean peak amplitude of the N2 and N400 in the 4 experimental conditions. BC: Best Completion, HO: Homophone, PH: Pseudohomophone, UN: Unexpected Completion. Error bars depict the standard error of the mean in all cases.

Fig. 2. ERP waves over the fronto-central region (linear derivation of electrodes FC1, FC2 and Fz) and centro-parietal region (linear derivation of electrodes CP1, CP2 and Pz) averaged across the 15 participants.

Figure 1
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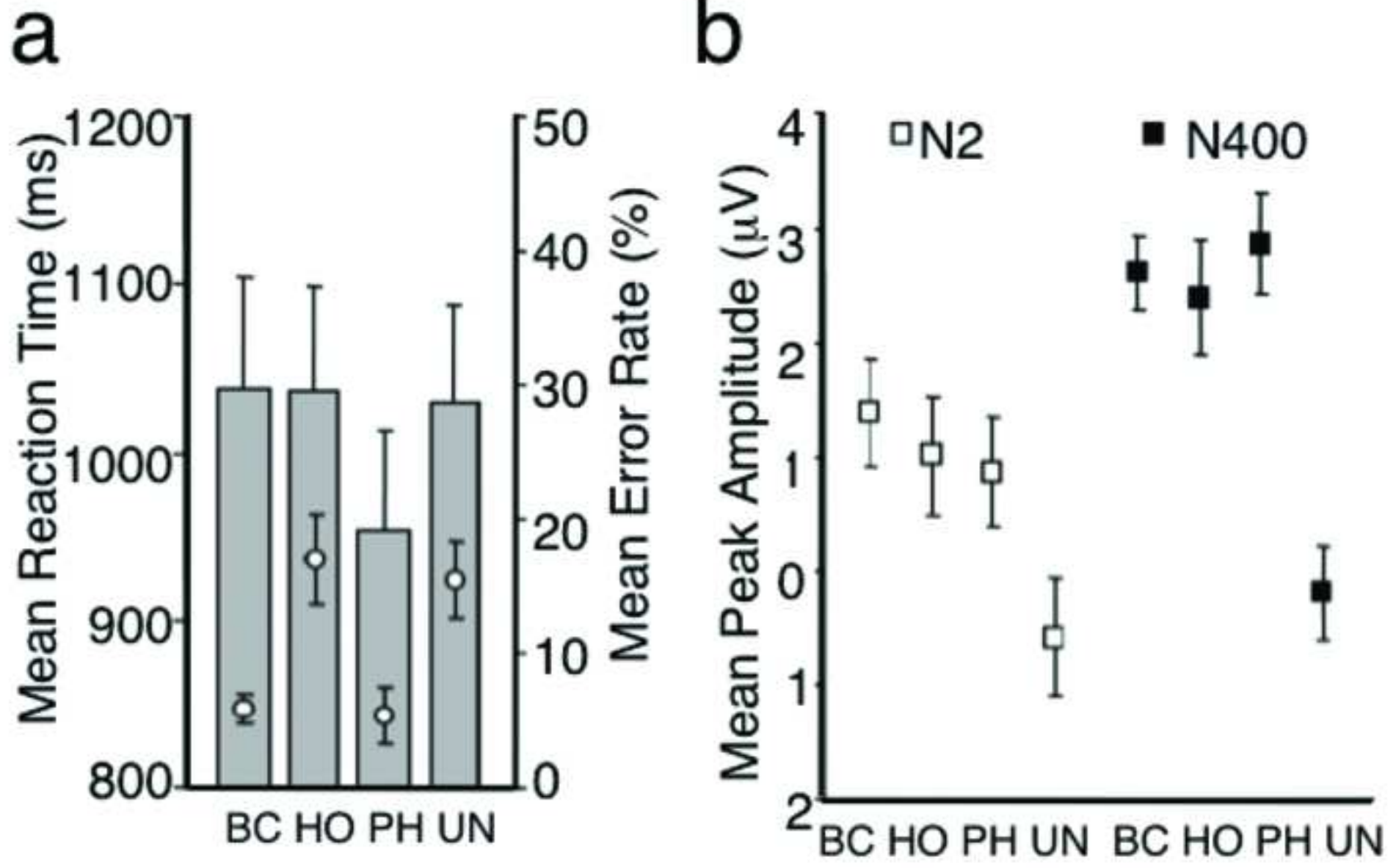


Figure 2
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