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Phonological neighbors cooperate during spoken sentence processing:

Evidence from a nonword detection task

Sophie Dufour^{1,3} Colas Fournet² Jonathan Mirault^{2,4} and Jonathan Grainger^{2,3}

1. Aix-Marseille Université, CNRS, LPL, UMR 7309, 13100 Aix-en-Provence, France

2. Centre de Recherches en Psychologie et Neurosciences, Aix-Marseille Université & CNRS, France

3. Institute for Language, Communication, and the Brain, Aix-Marseille Université, Aix-en-Provence, France

4. Pôle pilote AMPIRIC, Institut National Supérieur du Professorat et de l'Éducation (INSPÉ), Aix-Marseille Université, France

Abstract: We used a novel nonword detection task to examine the lexical competition principle postulated in most models of spoken word recognition. To do so, in Experiment 1 we presented sequences of spoken words with half of the sequences containing a nonword, and the target nonword (i.e., press a response key whenever you detect a nonword in the sequence) could either be phonologically related (a phonological neighbor) or unrelated to the immediately preceding word. We reasoned that the reactivation of a phonological neighbor during target nonword processing should delay the moment at which a nonword decision can be made. Contrary to our hypothesis, participants were faster at detecting nonwords when they were preceded by a phonological neighbor compared with an unrelated word. In Experiment 2, an inhibitory effect of phonological relatedness on nonword decisions was observed in a classic priming situation using the same set of related and unrelated word-nonword pairs. We discuss the implications of these findings in regard to the main models of spoken word recognition and conclude that our specific experimental set-up with phonological neighbors embedded in spoken sentences is more sensitive to cooperative interactions between co-activated sublexical representations than lexical competition between co-activated lexical representations, with the latter being modulated by whether or not the words compete for the same slot in time.

Key words: Speech processing; Sentence comprehension; Nonword detection; Lexical inhibition

The negative impact that phonological neighbors have on target word processing has been repeatedly demonstrated in studies conducted in the field of spoken word recognition with isolated words (e.g., Dufour & Frauenfelder, 2010; Luce & Pisoni, 1998; Magnuson et al., 2007; Vitevitch & Luce, 1998; 1999; Ziegler et al., 2003). The most commonly used definition of phonological neighbors is all the words that can be formed by adding, substituting or deleting one phoneme in the target word (Luce & Pisoni, 1998). For example, the word CAT has neighbors such as SCAT where a phoneme is added, BAT, CUT, CAP where a phoneme is substituted, and _AT where a phoneme is deleted. In a wide variety of tasks, it has been shown that words with many neighbors take longer to recognize than words with few neighbors (e.g., Dufour & Frauenfelder, 2010; Luce & Pisoni, 1998; Magnuson et al., 2007; Vitevitch & Luce, 1998; 1999; Ziegler et al., 2003). These studies also showed that words with high-frequency neighbors are recognized more slowly than words with low-frequency neighbors. In addition, studies conducted in a priming context have revealed that the recognition of a target word is delayed when a phonological neighbor is presented immediately before the target (e.g., Dufour & Peereman, 2003; Hamburger & Slowiaczek, 1996; Radeau et al., 1995). The inhibitory influence of phonological neighbors is compatible with most of models of spoken word recognition in which activation and competition processes constitute the two core mechanisms of several influential models of spoken word recognition (TISK: Hannagan et al., 2013; NAM: Luce & Pisoni, 1998; Cohort: Marslen-Wilson, 1990; TRACE: McClelland & Elman, 1986; Shortlist: Norris, 1994). In these models, during the processing of a target word similar sounding words (i.e., phonological neighbors) are activated and compete with the target word either directly by inhibiting the level of activation of the target word (Hannagan et al., 2013; McClelland & Elman, 1986; Norris,

1994) or indirectly by delaying the moment at which the target word can be reliably identified (Marslen-Wilson, 1990; Luce & Pisoni, 1998)¹.

A stronger validation of the above-cited models of spoken word recognition, that were mainly developed on the basis of results obtained from studies conducted with isolated words, would be to show that the inhibitory influence of phonological neighbors is not limited to isolated word recognition, but can also be observed in the context of more natural language comprehension, when phonological neighbors are physically present and co-occur in a spoken sentence. Note that we draw the key distinction between “physically absent” neighbors, as classically studied in single word recognition studies, including those with a sentence context such as studies using the visual world paradigm (e.g., Allopenna et al., 1998), and studies where target and neighbor are physically present in a sequence of words. Some studies conducted on visual word recognition have already tested the influence of the presence of an orthographic neighbor during sentence processing, and have reported an inhibitory influence (Mirault et al., 2022; Paterson et al., 2009). To the best of our knowledge, only one study conducted by some of the present authors has examined inhibition process driven by phonological relatedness when similar sounding words are embedded in sentences (Dufour et al., 2024). To probe real time processes, the Dufour et al. study used a verb detection task in which participants had to respond as soon as they detected a verb in spoken sentences. However, rather than observing an inhibitory effect of phonological relatedness it was the opposite effect that was found in that study. Participants were faster at detecting a verb when it was phonologically related to the preceding noun (e.g., *la gentille **dame** **date** les papiers* “the nice lady dates the papers”) than when it was phonologically unrelated (e.g., *la gentille*

¹ Although the above cited models have not yet been developed to simulate priming effects, inhibitory priming effects are conceptually compatible with all of these models in which the re-activation of a phonological neighbor during target word processing should delay its recognition.

dame signe les papiers “the nice lady signs the papers”). This facilitatory effect of the presence of a phonological neighbor was also observed with ungrammatical sequences and when two adjacent phonologically related words were present in the filler “no verb” sequences, thus discarding the possibility that the effect was only due to either syntactic constraints or strategic influences.

It is clear that the facilitation effect of phonological relatedness reported by Dufour et al. (2024) during spoken sentence processing contrasts with the inhibition effect generally found in studies of isolated spoken word recognition. The authors interpreted the facilitation effect as reflecting phoneme-to-word activation and suggested that the sentence context could give more weight to pre-lexical influences than to lexical influences. In the present work we aimed to enhance lexical influences during sentence processing, with the aim to observe an inhibitory effect of phonological relatedness. To do so, we used a nonword detection task which is a variant of the go/no-go task (words vs. nonwords) often used in the visual modality (see Gomez et al., 2007 for a review), except that in the present study participants had to respond to the nonwords and not to the words. We reasoned that the reactivation of a phonological neighbor during nonword processing should delay the moment at which a nonword decision can be made (cf. the models of lexical decision proposed by Ratcliff et al., 2004, and Dufau et al., 2012). Hence, nonword detection should be slower when the nonword target is preceded by a phonologically related word than when preceded by an unrelated word.

Experiment 1

Experiment 1 tested spoken sentences such as “la gentille **dame dape** les papiers” that contain the target nonword “dape /dap/” and its phonological neighbor “dame /dam/ lady” against control sentences like “la gentille **soeur dape** les papiers” where the target nonword target “dape /dap/” is not phonologically related to the preceding word “soeur/sœʁ/ sister”. Participants had to respond as soon as they detected a nonword embedded in a sequence of spoken words, and to do so even prior to the end of the word sequence.

Method

Participants: 100 participants were recruited via the Prolific platform for on-line experiments. This number of participants corresponds to the number tested in the previous on-line study involving spoken sentences (Dufour et al., 2024). They reported to be native speakers of French and their reported age was between 21 and 60 years. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously. Participants received £8 per hour in compensation.

Materials: Forty-six sentences of five to eight words in length and that contained two phonologically related adjacent words were taken from Dufour et al. (2024). In each sentence (e.g., la gentille **dame date** les papiers; *English translation*: “the nice lady dates the papers”), the second word (e.g., **date** /dat/) of the phonologically related pair (e.g., **dame** /dam/ - **date** /dat/) was transformed into a nonword (e.g., **dape** /dap/) by changing the last phoneme of the word. From these 46 related sentences (e.g., “la gentille **dame dape** les papiers”), 46

unrelated sentences were created by replacing the related word by another word that shared no phonemes with the nonword target (e.g., “la gentille **soeur dape** les papiers”). All the nonword targets (i.e., 46 in total) were monosyllabic and were three to four phonemes in length. The characteristics of the related and control words, and of the nonword targets are summarized in Table 1. For the purpose of the nonword detection task, 46 filler sentences of five to eight words in length were added to the 92 test sentences. Half of the filler sentences contained two phonologically related words (e.g., ce grand **char chasse** les ennemis; *English translation*: “this big tank hunts enemies”) and the other half contained unrelated words (e.g., un gros car bloque la rue; *English translation*: “a big bus blocks the street”). All the sentences were recorded using “text-to-speech” software (<https://ttsfree.com/>) for French and with the female voice called “Denise” and digitized at a sampling rate of 44100 Hz. The mean durations of both the “related” and “unrelated” test sentences were 1720 ms. Unrelated and related test sentences are listed in Appendix 1. The lexical characteristics and the durations of each word and nonword are given in Appendix 2.

Because the 46 target nonwords were preceded by both a related and unrelated word, two counterbalanced lists of stimuli were constructed so that each nonword was presented only once to the participants, and was preceded by both a related and an unrelated word across the two lists. Each list thus included 23 sentences containing a related word-nonword pair and 23 sentences containing an unrelated word-nonword pair, and the 46 filler sentences.

Procedure: The experiment was programmed using Labvanced software (Finger et al., 2017). Participants were instructed to put on their headphones and adjust the volume to a comfortable sound level. A trial began with a centrally aligned fixation cross for a duration of 500 ms, followed by the auditorily presented sequence of words, half of which contained a single nonword. Participants were asked to press the “right arrow” whenever they detected a

nonword in the sequence. They were also instructed to respond as soon as they detected a nonword, and not to wait to the end of the sequence to respond. The next trial began 4000 ms after the beginning of the previous sequence. The order of presentation of sequences was randomized for each participant, and RTs were measured from the onset of the sequence. Participants were tested on only one experimental list and began the experiment with 4 practice trials.

Results

Twelve participants who had an error rate greater than 60% were removed from the analyses. Four sequences that gave rise to an error rate of more than 60% were also removed. RTs to “nonword” responses (available at <https://osf.io/atsuq/>; Open Science Framework; Foster & Deardorff, 2017) were analyzed using linear mixed effects models with participants and items as crossed random factors, using R software and the lme4 package (Baayen et al., 2008). The RT analysis was performed on correct responses, thus removing 589 data points out of 3696 (16%). In each condition, RTs greater than three standard deviations above the participant’s mean were also excluded from the analysis (<1%). For the model to meet the assumptions of normally-distributed residuals and homogeneity of variance, a log transformation was applied to the RTs (Baayen & Milin, 2010) prior to running the model. The model was run on 3089 data points. We tested a model with the variable Relatedness (related, unrelated) entered as a fixed effect. The reference was the unrelated condition, and we used the default (0, 1) coding. The model also included random intercepts for participants and items, plus random participant and item slopes (Barr et al., 2013). Condition means are shown in Table 2.

The effect of Relatedness was significant ($b = -0.0442$, $SE = 0.0212$, $t = -2.09$, $p < .05$). Participants were 73 ms faster in the related than in the unrelated condition.

The percentage of correct responses was analyzed using a mixed-effects logit model (Jaeger, 2008) following the same procedure as for RTs. The effect of Relatedness was not significant ($b = 0.0991$, $SE = 0.2745$, $z = 0.36$, $p > .20$).

To sum up, we found no evidence of an inhibitory influence of phonological relatedness during the processing of auditorily presented sequences of word containing a nonword target. As in Dufour et al. (2024), we observed a facilitatory effect of the presence of a phonological neighbor, but this time in a nonword detection task. That is participants were faster at detecting a nonword in the sequences of auditory stimuli when it was preceded by a phonologically related word than when it was preceded by an unrelated word. Prior to discussing the implications of this finding regarding the main models of spoken word recognition, we first wanted to make sure that an inhibitory effect of phonological relatedness would be found in a classic priming situation with the same lexical decision task (with critical responses to nonword targets) and the same critical word-nonword pairs as in Experiment 1.

Experiment 2

In Experiment 2, the same word-nonword pairs as in Experiment 1 were used, and were again tested in a nonword detection task (lexical decision). The unique difference with Experiment 1 is that our word-nonword pairs were tested in isolation, and were not embedded

in spoken word sequences. This reproduces the classic priming situation under which an inhibitory influence of phonological relatedness has been repeatedly observed with pairs of phonologically related words. Participants were instructed to respond to the second stimulus of the pairs (i.e., the target) only if they considered it to be a nonword, and to not respond if it was a word.

Method

Participants: As in Experiment 1, 100 participants were recruited via the Prolific platform for on-line experiments. They reported to be native speakers of French and their reported age was between 21 and 60 years. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously. Participants received £8 per hour in compensation.

Materials: Exactly the same test and filler pairs and the same experimental lists as in Experiment 1 were used. All the words and nonwords were recorded in isolation using “text-to-speech” software (<https://ttsfree.com/>) for French and with the female voice called “Denise” and digitized at a sampling rate of 44100 Hz. The mean durations of the words and nonwords is given in Table 1.

Procedure: The experiment was programmed using Labvanced software (Finger et al., 2017). Participants were instructed to put on their headphones and adjust the volume to a comfortable sound level. A trial began with a centrally aligned fixation cross for a duration of 500 ms. The auditory prime was then presented and followed 50 ms later by the auditory target. Participants were asked to press the “right arrow” when the target was a nonword. The

next trial began when 2500 ms had elapsed from the beginning of the auditory target. The prime-targets pairs were presented randomly, and RTs were measured from the onset of the target. Counterbalancing was performed as in Experiment 1, and participants were tested on only one experimental list and began the experiment with 4 practice trials.

Results

Four participants who had an error rate greater than 60% were removed from the analyses. Two target nonwords that gave rise to an error rate of more than 60% were also removed. RTs to “nonword” responses (available at <https://osf.io/atsuq/>; Open Science Framework; Foster & Deardorff, 2017) were analyzed using linear mixed effects models following the same procedure as in Experiment 1. The RT analysis was performed on correct responses, thus removing 253 data points out of 4224 (6%). In each condition, RTs greater than three standard deviations above the participant’s mean were also excluded from the analysis (1.36%). For the model to meet the assumptions of normally-distributed residuals and homogeneity of variance, a log transformation was applied to the RTs (Baayen & Milin, 2010) prior to running the model. The model was run on 3917 data points. We tested a model with the variable Relatedness (related, unrelated) entered as a fixed effect. The reference was the unrelated condition, and we used the default (0, 1) coding. Note that the model failed to converge when random participant and item slopes were included (Barr et al., 2013). Therefore, the final model only included random intercepts for participants and items. Condition means are shown in Table 2.

The effect of Relatedness was significant ($b = 0.0148$, $SE = 0.0054$, $t = 2.76$, $p < .01$). Participants were 14 ms slower in the related than in the unrelated condition.

The percentage of correct responses was analyzed using a mixed-effects logit model (Jaeger, 2008) following the same procedure as for RTs. The effect of Relatedness was not significant ($b = -0.1327$, $SE = 0.1350$, $z = -0.98$, $p > .20$).

To sum up, using the same word-nonword pairs and a task that is very similar to the one used in Experiment 1 (i.e., nonword decisions vs. nonword detection), we reproduced the classic inhibitory effect found with the priming paradigm. The size of the inhibitory effect is rather small compared to the facilitative effect found in Experiment 1, but it is in line with the size of the inhibitory effects found in previous priming studies, which rarely exceeded 20 ms.

General Discussion

The results are clear-cut. Nonwords embedded in sentences were detected faster when they were preceded by a phonologically related word than when they were preceded by an unrelated word. This study thus replicates, using a different task, the facilitative effect of phonological relatedness during auditory sentence processing found in the verb detection task of Dufour et al. (2024). Crucially, in Experiment 2 we were able to replicate the inhibitory effect of phonological relatedness classically found with the priming paradigm and isolated word/nonword targets using the exact same set of related and unrelated stimulus pairs as in Experiment 1.

What are the implications of these findings for the main models of spoken word recognition (TISK: Hannagan et al., 2013; NAM: Luce & Pisoni, 1998; Cohort: Marslen-Wilson, 1990; TRACE: McClelland & Elman, 1986; Shortlist: Norris, 1994)? One might be tempted to suggest that lexical competition, a central ingredient of these models, is in fact an artifact of research conducted with isolated words and not representative of more natural language comprehension. Although we did indeed fail to find an inhibitory influence of phonological relatedness during sentence processing, we do not adhere to this scenario. In this respect it is important to note that a number of studies have indeed found evidence in favor of lexical competition with words embedded in spoken sentences (e.g., Cervera-Crespo & González-Álvarez, 2019; Sommers & Danielson, 1999). Contrary to the present study, in these studies phonological neighbors were not presented in the spoken sentences and lexical competition was assessed by testing both neighborhood density and neighborhood frequency effects from virtual neighbors (i.e., words that were not actually physically present in the experiment). It has been shown that words are better identified when they have few and low-frequency neighbors than when they have many and high-frequency neighbors. Perhaps more crucially, neighborhood density effects and neighborhood frequency effects have been observed with both neutral and semantically constrained sentences, thus indicating that when words are highly predictable from the semantic context, this does not prevent similar sounding words to be activated in memory and to inhibit target word recognition. Hence, lexical competition appears to be a core mechanism of spoken word recognition whether the words are presented in isolation or embedded in sentences.

Very generally speaking, given the results of the present study and those of Dufour et al. (2024), it would appear that presenting phonologically related stimuli in a sentence context neutralizes the impact of lexical competition in favor of facilitatory sub-lexical influences.

That is, phonologically related stimuli in a sequence of words would have the opposite impact on language comprehension compared with phonologically related stimuli presented in isolation in a priming context. Perhaps the most impressive aspect of the present results is that the two key mechanisms postulated in the main models of spoken word recognition, namely pre-lexical activation on the one hand and lexical competition on the other hand can be probed separately with exactly the same stimuli simply by changing how the related words are presented (in a priming context vs. a sentence context). We suggest that in the context of a sentence or word sequence, when the preceding word is a phonological neighbor of the following nonword, their shared phonemes facilitate processing of the nonword target via an increased activation in the shared phonemes. This would in turn facilitate comparison of the phonemes activated during processing of the nonword target with phonological representations of words stored in long-term memory, hence facilitating nonword decisions. In other words, we suspect that the facilitatory effect we observed in Experiment 1 is a sublexical effect operating at the level of phoneme representations. It should also be noted that we tested adjacent phonological neighbors. However, research examining the impact of orthographic neighbors during sentence reading indicates that non-adjacent neighbors (e.g., there was a *blur* as the *blue* light of the police car...) cause inhibition (Paterson et al., 2009), while adjacent neighbors cause a facilitatory effect when the effect is measured during processing of the target word (e.g., Snell et al., 2017), and an inhibitory effect when a measure of global sentence processing is used (Mirault et al., 2022). It would therefore appear that there are two necessary conditions for observing facilitatory neighborhood effects during spoken or written sentence processing: 1) the neighbors must occupy adjacent positions in the sentence; and 2) the dependent measure must be made during processing of the critical target word.

The key issue to now be resolved is why pre-lexical processing is emphasized when adjacent phonological neighbors are embedded in sentences, leading thus to a facilitative effect (Experiment 1; see also Dufour et al., 2024) whereas lexical processing is emphasized when phonological neighbors are presented one after the other in a priming set-up, leading thus to an inhibition effect (Experiment 2; see also Hamburger & Slowiaczek, 1996; Dufour & Peereman, 2003; Radeau et al., 1996)? Here, we tentatively suggest that it is a fundamental difference in task requirements that give a different weight to the two levels of processing (sublexical/lexical) postulated in the main models of spoken word recognition. Notably, when processing a sentence, the listener would try to associate each word with a specific temporal slot in the sequence of words in order to accurately encode word order, an essential source of information for the computation of syntactic information in languages such as English and French (but see Elman, 1990, for an alternative, implicit means of computing syntactic and semantic information when processing sequences of words). Exactly how this is achieved, and the degree of flexibility of the process, remains a matter of debate (see e.g., Dufour et al., 2022, for evidence for flexible word-order encoding during spoken sentence processing). We further surmise that when words are associated with distinct temporal slots, then this removes, or at least alleviates, competitive processes, hence allowing the facilitatory effects of shared phonemes to emerge. On the other hand, word order encoding is not a requirement in the context of priming, and we suspect that in these conditions phonological neighbors compete for a single identification slot, thus leading to confusion as to which word is the target. In a more general way, such reasoning would suggest that during sentence processing lexical competition is more visible on a specific word-slot than across word-slots, thus explaining why evidence in favor of a lexical competition process has been found in previous studies using spoken sentences when the phonological relatedness is imputed to only one specific word-slot (e.g., Cervera-Crespo & González-Álvarez, 2019; Sommers & Danielson, 1999),

and not to two words-slots. Hence, future research could re-use the verb detection task of Dufour et al. (2024) and the nonword detection task of the present study to examine whether verb detection and nonword detection are influenced not by the presence of a phonological neighbor but by the neighborhood density and the neighborhood frequency of the target verb/nonword.

To conclude, this study provides further evidence for a facilitative influence of phonological neighbors during spoken sentence processing. Although the results of this study might appear to contradict one of the core mechanisms of most of models of spoken word recognition (lexical competition), it nonetheless emphasizes another key mechanism of these models, namely sub-lexical activation. We discussed some lines of research in which lexical competition could emerge with detection tasks such as the nonword detection task used in the present study and the verb detection task used in Dufour et al.'s (2024) study. Finally, we believe that such paradigms in which phonological neighbors are present in spoken sentences offer a new avenue for future research aimed at investigating the interplay of sublexical and lexical processes during spoken language comprehension.

Declarations

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Conflicts of interest: The authors have no conflict of interest to declare.

Ethics approval: The experiments were performed in accordance with the provisions of the World Medical Association Declaration of Helsinki.

Consent to participate: Informed consent was obtained from all participants included in the experiments.

Consent to publication: The authors affirm that all participants provided informed consent for publication of their data.

Availability of data and materials: The data of the two experiments are available at <https://osf.io/atsuq/>

Code Availability: The scripts used to analyze the data are available at <https://osf.io/atsuq/>

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Table 1: Characteristics of the words and nonwords (mean values) used in Experiments 1 & 2

	Control words	Related words	Nonword targets
Frequency ¹	102	84	-
Neighborhood ² density	21	22	16
Neighborhood frequency	2358	2592	1811
Higher frequency neighbors	4	5	-
Cohort ³ density	210	225	226
Cohort frequency	1492	2373	2457
Higher frequency cohort members	9	13	-
Duration ⁴ in sentences (Exp.1)	279	273	276 vs. 271 ⁵
Duration in isolation (Exp.2)	447	450	447

Note. ¹ in occurrences per million; ² words that can be formed by adding, substituting, or deleting one phoneme (Luce & Pisoni, 1998); ³ words that share their first phonemes; ⁴ in milliseconds; ⁵ when produced in control and related sentences respectively.

Table 2. Condition means (RTs and % correct) for the related and unrelated conditions tested in Experiment 1 (nonword detection in word sequences) and Experiment 2 (single word/nonword priming).

	Unrelated	Related	Priming effect
Experiment 1 (sentence)			
RT	1912	1839	+73
Correct Responses	85	84	
Experiment 2 (priming)			
RT	1068	1082	-14
Correct Responses	94	94	

