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Abstract: The present study examined for the first time the impact of the presence of a phonological neighbor on word recognition when the target word and its neighbor co-occur in a spoken sentence. To do so, we developed a new task, the verb detection task, in which participants were instructed to respond as soon as they detected a verb in a sequence of words, thus allowing us to probe spoken word recognition processes in real time. We found that participants were faster at detecting a verb when it was phonologically related to the preceding noun than when it was phonologically unrelated. This effect was found with both correct sentences (Experiment 1) and with ungrammatical sequences of words (Experiment 2). The effect was also found in Experiment 3 where adjacent phonologically related words were included in the non-verb condition (i.e., word sequences not containing a verb), thus ruling out any strategic influences. These results suggest that activation persists across different words during spoken sentence processing such that processing of a word at position *n+1* benefits from the sublexical phonology activated during processing of the word at position *n*. We discuss how different models of spoken word recognition might be able (or not) to account for these findings.

Keywords: Phonological neighbors, sublexical facilitation, lexical inhibition, spoken word recognition.

There are numerous demonstrations from studies conducted on isolated words that spoken word recognition involves a process of activation of multiple candidates one of which must be selected for identification. One of the first studies to demonstrate this was the cross-modal (auditory-visual) semantic priming study of Zwitserlood (1989). In that study the processing of both the target words “GELD” (“money” in Dutch) and “BOOT” (ship) was facilitated when presented during the /t/ of the auditory primes “kapitaal” (capital) and “kapitein” (captain). However, when the target words were presented at the end of the primes, only the semantically related word was facilitated (i.e., “GELD” for “kapitaal” and “BOOT” for “kapitein”). Converging evidence was later obtained by Spinelli et al. (2001) in a within-modality (auditory-auditory) phonological priming study. These authors reported that monosyllabic word primes like “COU” (“neck” in French) facilitated the processing of target words like “COULISSE” (backstage) that shared their initial phonemes with the prime. This facilitation effect was however no longer observed when bisyllabic words like “COUTURE” (dressmaking) were used as primes. Together, these findings suggest that words sharing the initial phonemes with the auditory input are initially activated, and then deactivated when the information available in the speech input is in favor of another candidate and/or is no longer compatible with the target word. Parallel activation has also been demonstrated with more on-line measures of spoken word recognition, such as eye-tracking measures in the visual word paradigm. In a seminal study, Allopenna et al. (1998) examined the eye movements of participants who followed spoken instructions to manipulate objects pictured on a computer screen. They found that early in the processing of the target word “BEETLE” the pictures representing a BEAKER and BEETLE were equally fixated, and more often fixated than a control picture whose name was phonologically unrelated to the target (e.g., the picture of a CARRIAGE), thus again suggesting that words that are initially consistent with the incoming speech signal are activated and considered as possible target words.

Other studies have reported that similar sounding words are not only activated during spoken word recognition, but they also compete with the target word, thus delaying its recognition. Evidence for competition processes has been found in studies manipulating phonological neighborhood density and frequency (Dufour & Frauenfelder, 2010; Luce & Pisoni, 1998; Vitevitch & Luce, 1998, 1999). In a wide variety of tasks, these studies reported that words with many high-frequency neighbors are harder to recognize than words with a small number of low-frequency neighbors. In interactive-activation models (McClelland & Elman, 1986), this is explained by the higher levels of activation attained by words that are phonologically similar to the target and that are high-frequency, hence increasing the amount of competition that they generate. Complementary evidence has been obtained in auditory priming studies (Dufour & Peereman, 2003; Hamburger & Slowiaczek, 1996; Radeau et al., 1995). These studies showed that recognition of a target word can be delayed when a phonological neighbor is presented immediately before the target. This inhibitory effect has been found under specific conditions: when primes are of lower frequency than the targets; when primes have few phonological neighbors and when there is a high degree of phonemic overlap between primes and targets. Inhibitory phonological priming effects have been interpreted either as being due to inhibition of the target word during prime word processing (a higher-frequency phonologically related target would act as a strong competitor during prime word processing and therefore require inhibition), or as resulting from the reactivation of the prime neighbor during processing of the target word, thus slowing-down its recognition. Finally, evidence for lexical competition has been also reported in studies using the visual world paradigm. For example, Dahan et al. (2001) found that participants took longer to fixate a target picture (e.g., the picture of a "net" among a set of distractor pictures) when the target word had a competitor with the same onset (e.g., "neck"), and independently of whether or not the picture of the competitor word (i.e., the picture of a neck) was present in the display.

Perhaps the most impressive aspect of all these studies is that phoneme-to-word activation on the one hand, and word-to-word inhibition on the other hand, can be probed separately, by means of specific paradigms and/or specific experimental manipulations. However, to the best of our knowledge, evidence in favor of such activation/inhibition processes driven by phonological relatedness across words has been only obtained with words presented in isolation. Of course, some studies have manipulated the semantic context of a target word, and this has been shown to affect the relative activation of potential lexical candidates (e.g., Cervera-Crespo & González-Álvarez, 2019; Connine et al., 1991; Zwitserlood, 1989), and studies using the visual world paradigm have used a fixed context in the form of the instructions provided to participants. It therefore remains unclear whether or not activation and/or inhibition processes driven by phonological relatedness can be probed in "more natural" speech comprehension situations, when similar sounding words are embedded in sentences. This was the goal of the present study.

At a theoretical level, the use of sentences that include phonologically related adjacent words raises a novel and intriguing question regarding the spreading of activation/inhibition across different word positions in a sentence. TRACE (McClelland & Elman, 1986) encodes the temporal order of phoneme and word sequences by tiling copies of phoneme and word units over its sequence memory. Units that do not overlap in time do not (directly) interact, and it would appear that there is no way for an earlier copy of a word unit to influence a later copy of the same word. Thus, according to TRACE one would not expect to observe an effect of phonological relatedness across different words. As concerns models that implement simple recurrent networks (SRNs: e.g., Elman, 1990; Gaskell & Marslen-Wilson, 1997), because SRNs are typically trained to predict the next phoneme or word in a sequence, there would seem to be no reason to expect phonologically similar words to prime one another in a sequence unless the similar words actually co-occur in sequence during training. In contrast to these approaches, TISK (Hannagan et al., 2013) implements a time-invariant encoding of phoneme order. More precisely, at the sublexical level in TISK, the speech input activates time-invariant (position-independent) phoneme and open-diphone nodes. Since the sublexical nodes are time-invariant, persisting activation due to one word might serve as a basis to effectively prime a phonologically similar word (though TISK has not yet been extended to multi-word inputs).

This study is, to our knowledge, a first attempt at addressing the issue of whether or not presentation of a first non-target (or prime) word affects processing of the subsequent presentation of a phonologically related target word during auditory sentence processing. To do so, we tested spoken sentences such as *cette petite* ***sauce sauve*** *le plat* (English translation: "this little sauce saves the dish") that contain the target "sauve /sov/" and its phonological neighbor "sauce /sos/" against control sentences like *cette petite* ***sauce gâche*** *le plat* (English translation: "this little sauce spoils the dish") where the target "gâche /gaʃ/ is not phonologically related to the preceding word "sauce" /sos/. We chose phonologically related noun-verb pairs that shared their first phonemes given that previous studies have shown that words that share their initial phonemes with targets are more strongly activated than words that share their final phonemes with targets (e.g., Allopenna et al., 1998). Moreover, our target words and their phonologically related neighbors diverged only on the final phoneme because it is with this type of neighbor that the strongest inhibitory effects have been observed in priming studies (see Dufour & Peereman, 2003; Radeau et al., 1995; Hamburger & Slowiaczek, 1996).

One methodological hurdle that we had to overcome, however, concerned devising a task that enables one to probe effects in real time during the processing of one specific word in a sentence (the target word), and especially before any impact of excitatory and/or inhibitory processes has had time to dissipate. We introduce here a new task where we asked participants to detect the presence of a verb in sentences. Note that in a preliminary study, we used the grammatical decision task (see Mirault et al., 2018) in which participants had to decide whether the spoken sentences were grammatically correct (e.g., *la gentille* ***dame date*** *les papiers/ la gentille* ***dame signe*** *les papiers)* or not (e.g., *le chien noir court gros*). We found no effect − neither facilitatory nor inhibitory − of the presence of a phonological neighbor. Because in this specific paradigm, participants had to wait to the end of the sentence to make their decision, we believe that excitatory or inhibitory processes driven by phonological relatedness had had time to dissipate before participants' responses. Crucially here, they were instructed to respond as soon as they detected a verb, doing so even prior to the end of the sentence. The critical stimuli were pairs of nouns and verbs inserted in sentences in adjacent positions, and these noun-verb pairs could be phonological neighbors or not. In the case where activity generated during processing of a word at position *n* influences processing of a word at position *n+1*, our predictions regarding the direction of the effect of phonological relatedness are as follows. If our paradigm allows us to probe phoneme-to-word sublexical activation across adjacent words during spoken sentence processing, then we expected to find a facilitatory effect of the presence of a phonological neighbor. In contrast, if our paradigm is more sensitive to word-to-word lexical inhibition, we expected to find an inhibitory effect of the presence of a phonological neighbor.

Experiment 1

Experiment 1 tested spoken sentences such as *cette petite* ***sauce sauve*** *le plat* (English translation: "this little sauce saves the dish") that contain the target "sauve /sov/" and its phonological neighbor "sauce /sos/" against control sentences like *cette petite* ***sauce gâche*** *le plat* (English translation: "this little sauce spoils the dish") where the target "gâche /gaʃ/ is not phonologically related to the preceding word "sauce" /sos/.

Method

Participants. 100 participants were recruited via the Prolific platform for on-line experiments. This number of participants corresponds to the number tested in on-line study involving sentences in the visual modality (e.g., Mirault et al., 2018). They reported to be native speakers of French and their reported age was between 18 and 63 years. Note that only 5 participants among the 100 were over 60 years old. Exactly the same pattern of results was observed with and without these participants. So we decided to keep them. 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. Seventy-six phonologically related noun-verb pairs were selected from Lexique, a lexical database for French (New et al., 2004). The two members of the pairs were monosyllabic words of three to four phonemes in length and diverged only on the last phoneme (e.g., dame /dam/ “lady” – date /dat/ “date”). For each of the 76 nouns, 76 other monosyllabic verbs, of three to four phonemes, sharing no phoneme with the nouns were also selected (e.g., dame /dam/ “lady” – sign /siɲ/ “sign”). The characteristics of the related and unrelated verbs are given in Table 1.

76 couples of sentences of five to nine words were then constructed. One sentence included the phonological related pairs (e.g., *la gentille* ***dame date*** *les papiers* “the nice lady dates the papers”) and the other sentence included the unrelated pairs (*la gentille* ***dame signe*** *les papiers* “the nice lady signs the papers”). Note that the two types of sentences (related vs. unrelated) were strictly identical in respect to the words that preceded and followed the critical noun-verb pairs. For the purpose of the verb detection task, 76 sentences of five to nine words containing no verb were also constructed (e.g., sa jolie poupée aux beaux habits “her pretty doll with nice clothes”). 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 the “related” and “unrelated” sentences were 1618 ms and 1621 ms, respectively. Related and unrelated sentences are provided in Appendix 1.

Because the 76 related sentences and the 76 unrelated sentences differed on only the verb which was either related or unrelated to the preceding noun, two counterbalanced lists of stimuli were constructed so that each noun was presented only once to the participants and was followed by both the related and unrelated verb across the two lists. Each list thus contained 38 noun-verb related sequences and 38 noun-verb unrelated sequences, and 76 sentences without a verb.

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 auditory sentence. For each sentence, participants were asked to decide as quickly and accurately as possible if the sentence contained a verb or not, by pressing the “right arrow” for the “verb” response and the “left arrow” for the “no verb” response. They also were instructed to respond as soon as they detected a verb, and therefore even prior to the end of the sentence. After each response, a feed-back consisting of a green circle in case of a correct response and a red circle in case of an incorrect response was presented for a duration of 1000 ms. The order of presentation of sentences was randomized for each participant, and RTs were measured from the onset of the sentences. Participants were tested on only one experimental list and began the experiment with 8 practice trials.

Results

Four participants were removed from the analyses. Two participants had an error rate greater than 30 %, the two others had excessively long RTs (greater than 2500 ms). One sentence that gave rise to an error rate of more than 50% in the related condition was also removed as well as the corresponding control sentence. RTs to “verb” responses (available at https://osf.io/j8uny/; Open Science Framework; Foster & Deardorff, 2017) were analyzed using linear mixed effects models with participants and sentences 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 359 data points out of 7200 (5%). RTs greater than 6,000 ms (0.2%) were considered as outliers and were also excluded from the analysis. 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 6827 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.

The effect of Relatedness was significant (b = -0.0335, SE = 0.0042, t = -7.98, p<.001). Participants were 54 ms faster in the related (Mean = 1643 ms) than in the unrelated (Mean=1697 ms) condition.[1]

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 again significant (b = 0.6741, SE = 0.1156, z= 5.83, p<.001). Participants made fewer errors in the related (Mean = 3%) than in the unrelated (Mean = 6%) condition.

Given that none of the filler sentences included pairs of words that were phonologically related, we examined a potential influence of strategic factors in our novel verb detection task. To do so, we compared the effects of phonological relatedness for the first 25% of trials vs. the last 25% of trials. The interaction between phonological relatedness and beginning vs. end of the experiment was not significant (t = 1.60; p = .11). Crucially, the effect was already significant on the first 25% of trials (related = 1637 ms; unrelated = 1677

[1] A correlation analysis performed on unrelated trials (3360 data points) showed a negative correlation (r=.55; p<.01) between verb detection RT and verb frequency. We are thus confident that our new task is able to capture the typical effects observed in isolated word recognition.

ms; t = -2.43, p<.05) and persisted over the course of the experiment (last 25%: related = 1648 ms; unrelated = 1710 ms; t = -4.68, p<.001). Furthermore, RTs on related trials did not decrease over the course of the experiment as would have been expected if a response strategy based on detecting phonological relatedness was responsible for our effect.

To sum-up, the presence of a phonological neighbor in a spoken sentence lead to a facilitation effect, which suggests that our new paradigm is more sensitive to phoneme-to-word sublexical activation than to word-to-word lexical inhibition. Perhaps more crucially, the results of Experiment 1 also suggest that activation persists across different words during spoken sentence processing such that the presence of a phonological neighbor at position n facilitates the processing of a word at position $n+1$. This facilitatory effect of phonological relatedness contrasts with the inhibitory effect typically observed in single word recognition studies (e.g., Dufour & Frauenfelder, 2010; Dufour & Peereman, 2003; Hamburger & Slowiaczek, 1996; Radeau et al., 1995; Vitevitch & Luce, 1998, 1999). Syntactic constrains could explain this discrepancy. In particular, the fact that we tested phonologically related noun-verb pairs could have reduced the likelihood of observing an interference effect, simply because a verb is highly probable after a noun, and thus it is rather unlikely that a verb act as a strong competitor of a noun. This was tested in Experiment 2.

Experiment 2

In Experiment 2, we changed the order of the words of the sentences used in Experiment 1 so that they became ungrammatical, and thus syntactically implausible. We reasoned that if syntactic constraints led to a verb being an improbable competitor for a noun in Experiment 1, then we should expect to observe an interference effect with ungrammatical sequences of words.

Method

Participants. As in Experiment 1, a total of 100 participants were recruited on-line for the experiment via the Prolific platform and were paid £8 per hour for their participation. They reported to be native speakers of French and their reported age was between 19 and 68 years. Note that only 6 participants among the 100 were over 60 years old. As in Experiment 1, exactly the same pattern of results was observed with and without these participants. So we decided to keep them. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously.

Materials: Among the 76 pairs of sentences (related, control) used in Experiment 1, 54 pairs were reused in Experiment 2. The others were removed because the noun that preceded the target verb was homophonous with a verb. It results that when the order of words of these sentences is inverted, the "verb" response could be triggered by another word than the intended target verb. To achieve ungrammatical sentences, the order of the words, before and after the critical noun-verb pairs, of the 108 sentences was swapped (e.g., "cette dimanche ce ***tarte tarde*** four dans le*"* for the related sentence *"cette* ***tarte tarde*** *dans le four*"). Note that words were added at the beginning of the original sentences to obtain ungrammatical sentences as soon as the first words, and crucially before the critical pairs of noun-verb. The related and unrelated sentences with the order of word swapped are provided in Appendix 2, and the characteristics of the related and unrelated verbs are given in Table 2A. 54 sentences of experiment 1 that do not contain a verb were also reused in Experiment 2, and similarly the order of the words was swapped (e.g., "aux habits beaux sa poupée jolie" for "sa jolie poupée aux beaux habits"). As in Experiment 1, two counterbalanced lists of stimuli were constructed so that each noun was presented only once to the participants and was followed by both the related and unrelated verb across the two lists. Each list thus contained 27 noun-verb related ungrammatical sequences and 27 noun-verb unrelated ungrammatical sequences, and 54 ungrammatical sentences without a verb. As for Experiment 1, all the sentences were recorded using "text-to-speech" software for French and with the female voice called "Denise" and digitized at a sampling rate of 44100 Hz. The mean durations of the "related" and "unrelated" sentences were 2042 ms and 2030 ms, respectively.

Procedure: The same as in Experiment 1.

Results

Nine participants who had an error rate greater than 40 % were removed from the analyses. RTs to "verb" responses (available at https://osf.io/j8uny/; 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 1059 data points out of 4914 (22%). 17 RTs greater than 6,000 ms were considered as outliers and were also excluded from the analysis. 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 3838 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.

The effect of Relatedness was significant (b = -0.0190, SE = 0.0053, t = -3.57, p<.001). Participants were 61 ms faster in the related (Mean = 2192 ms) than in the unrelated (Mean = 2253 ms) 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 again significant (b = 0.2156, SE = 0.0752, z= 2.87, p<.01). Participants made fewer errors in the related (Mean = 20%) than in the unrelated (Mean = 23%) condition.

As indicated above, the percentage of errors reached 22% in Experiment 2 while it was only of 5% in Experiment 1. This high percentage of errors is likely due to the use of ungrammatical sequences that made it harder to detect the presence of a verb, in both the related and control conditions. A closer look at the data indicated, however, that the high percentage of errors was also caused by 15 pairs of ungrammatical sentences that gave rise to an error rate of more than 40% in one of the relatedness condition. We thus performed a second analysis in which these 15 pairs of sentences were removed. Note that after removal of these pairs, related and control target verbs remained matched across the two types of ungrammatical sentences (see in Table 2 B). This new analysis thus included 39 pairs of ungrammatical sentences and was performed on 3041 data points, which approximated the recommendations of Brysbaert and Stevens (2018) for having sufficient power.

The effect of Relatedness on RTs was again significant (b = -0.0232, SE = 0.0059, t = -3.91, p<.001). Participants were 90 ms faster in the related (Mean = 2160 ms) than in the unrelated (Mean=2250 ms) condition.

The effect of Relatedness on error rates was not significant (b = -0.1110, SE = 0.1005, z= -1.11, p>.20; Mean (Related) = 14%; Mean (unrelated) = 13%).

To sum-up, there was no sign of a competition effect when the sentences were rendered ungrammatical by swapping the order of the words. Again, participants were faster at detecting a verb when it was phonologically related to the preceding noun than when it was phonologically unrelated. Hence, the facilitation effect due to the presence of a phonological neighbor observed in Experiment 1 cannot simply be attributed to the syntactic constraints imposed by grammatically correct sentences.

Experiment 3

Given that none of the "no verb" sentences included pairs of words that were phonologically related, a possibility is that the facilitation effect found in Experiments 1 & 2 was at least in part due to strategic factors. Although a post-hoc analysis of the results of Experiment 1 comparing the effect at the beginning and at the end of the experiment suggests that it is rather unlikely that a response strategy was responsible for the effect, another way to completely rule-out any strategic influences would be to include "no verb" sentences composed for half of them of pairs of words (i.e., noun-noun or noun-adjective) that are phonologically related. Practically speaking, this is impossible to test in French with grammatical sentences like in Experiment 1 without making the "no verb" sentences semantically implausible. As a facilitation effect was also observed in Experiment 2, we re-tested the ungrammatical sequences of Experiment 2 and introduced two adjacent phonologically related words in half of the "no verb" sequences.

Method

<u>Participants</u>. As in Experiments 1 and 2, a total of 100 participants were recruited on-line for the experiment via the Prolific platform and were paid £8 per hour for their participation. They reported to be native speakers of French and their reported age was between 19 and 68 years. Only 6 participants among the 100 were over 60 years old. As in Experiments 1 and 2, exactly the same pattern of results was observed with and without these participants, so we

decided to keep them. Prior to the beginning of the experiment, participants provided informed consent and they were informed that the data would be collected anonymously.

Materials: The 54 related and unrelated ungrammatical sequences containing a verb in Experiment 2 were reused. Among the 54 “no verb” ungrammatical sequences of Experiment 2, 27 were reused and the 27 others were changed so that they contained two words, a noun or an adjective, that were phonologically related, and differing only on the last phoneme as in the following ungrammatical sequence “cheval **robe roche** la avec le noire”.

Procedure: The same as in Experiments 1 & 2.

Results

Fifteen participants with an error rate greater than 40 % were removed from the analyses. RTs to “verb” responses (available at https://osf.io/j8uny/; Open Science Framework; Foster & Deardorff, 2017) were analyzed using linear mixed effects models following the same procedure as in Experiments 1 & 2. The RT analysis was performed on correct responses, thus removing 1149 data points out of 4590 (25%). 15 RTs greater than 6,000 ms were considered as outliers and were also excluded from the analysis. 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 3426 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.

The effect of Relatedness was significant (b = -0.0150, SE = 0.0058, t = -2.58, p<.05). Participants were 38 ms faster in the related (Mean = 2214 ms) than in the unrelated (Mean=2252 ms) 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 = 0.0210, SE = 0.0724, z= 0.29, p>.20; Mean (Related) = 25%; Mean (unrelated) = 25%).

As in Experiment 2, the percentage of errors was relatively high and reached 25% in the two relatedness conditions, and this is likely due to the use of ungrammatical sequences that made it harder to detect the presence of a verb. Again, a closer look of the data indicated that the high percentage of errors were also caused by 17 pairs of ungrammatical sequences that gave rise to an error rate of more than 40% in one of the relatedness condition. We thus performed a second analysis in which these 17 pairs of sequences were removed. Note that after the suppression of these pairs, related and control target verbs remained matched across the two types of ungrammatical sentences (see in Table 3). This new analysis thus included 37 pairs of ungrammatical sentences and was performed on 2621 data points.

The effect of Relatedness on RTs was again significant (b = -0.0202, SE = 0.0064, t = -3.14, p<.01). Participants were 54 ms faster in the related (Mean = 2172 ms) than in the unrelated (Mean=2226 ms) condition.

The effect of Relatedness on error rates was not significant (b = -0.1334, SE = 0.0986, z= -1.35, p=.18; Mean (Related) = 15%; Mean (unrelated) = 17%).

To sum-up, although the magnitude of the effect of relatedness was somewhat lower in comparison to Experiments 1 and 2, with no significant difference in accuracy in Experiment 3, the facilitation effect of the presence of a phonological neighbor remained significant in the RT analyses, and this despite the fact that phonologically related words were included in the "no verb" sequences. This suggests that the facilitatory effect of phonological relatedness found in the present experiments is not strategically driven.

General Discussion

This study addressed the intriguing issue of whether activity generated during the processing of word *n* during spoken sentence processing can affect the processing of the following word at position *n+1*. Our focus was on the effects of phonological relatedness between adjacent words in a sentence. To examine this, we introduced a new task, the verb detection task, where a given target verb was preceded either by a phonologically related noun or a phonologically unrelated noun. These critical noun-verb pairs appeared in the middle of sentences. We found that participants were faster at detecting a verb when it was phonologically related to the preceding noun than when it was phonologically unrelated. The results are clear-cut and reveal persistent activation across adjacent words such that the processing of word at position *n+1* benefits from the activity generated during processing of the word at position *n*. Crucially the facilitatory effect of phonological relatedness was observed with ungrammatical sequences and when two adjacent phonologically related words were present in the filler “no verb” sequences. This clearly demonstrates that our effect cannot simply be explained by either syntactic constrains or strategic influences.

As noted above, the facilitatory effect reported in this study contrasts with the inhibitory effect found in priming studies with exactly the same type of phonological neighbors - that is words that diverge from the auditory input on only the last phoneme (see Hamburger & Slowiaczek, 1996; Dufour & Peereman, 2003; Radeau et al., 1995). It should be noted that the inhibitory effect found in priming studies has mainly been reported with the shadowing task. A possible source of the discrepancy between these past studies and the present study could therefore simply be due to the task used, with one task (i.e., the shadowing task) being more sensitive to lexical competition, and the other (i.e., the verb detection task) being more sensitive to sublexical facilitation. Also, the inhibition effect found in phonological priming studies has been generally observed with noun-noun or noun-adjective pairs, whereas in the present study we tested noun-verb pairs. This is yet another difference that could explain the discrepancy between priming studies and the present work, and future research should test noun-verb pairs in a priming context and also noun-adjective pairs in spoken sentences with an adjective detection task. 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), but 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.

At a theoretical level, and as discussed in the Introduction, the present findings constitute a strong challenge for computational models of speech processing such as TRACE (McClelland & Elman, 1986) and SRNs (e.g., Elman, 1990; Gaskell & Marslen-Wilson, 1997), that predicted no influence of phonological relatedness across adjacent words. It is our opinion that the only computational model that might possibly be able to account for the present results (pending extension of the model to the case of multi-word processing) is TISK (Hannagan et al., 2013). It is interesting to note that TISK, via its time-invariant (position-independent) phoneme and di-phone representations, also provides a possible account of transposed-phoneme effects in spoken word recognition (e.g., Dufour et al., 2021; Toscano et al., 2013) which pose a problem for other models. Within the framework of the TISK model, the most likely locus of any observed influence of phonologically related words in our verb detection task is a facilitatory effect driven by sublexical activation that transfers from processing at position *n* to processing at position *n+1.*

To conclude, the present study demonstrates for the first time that during spoken sentence processing the word at position *n+1* benefits from the activation generated when processing the word at position *n*. To do so, the main hurdle we had to cross was to devise a task that enables probing effects of phonological relatedness in real time during sentence processing before the effects dissipate. We introduced a new task applicable to spoken sentences, the verb detection task, in which participants were instructed to respond as soon as they recognize a verb in the sentence they were listening to. We believe that the nature of the task, as well as the speed constraints imposed on the participants, makes this a useful tool for probing real time processing during spoken sentence processing, and in particular we were able to probe phoneme-to-word sublexical activation during sentence processing, which is one of the key mechanisms postulated by the main models of spoken word recognition. Finally, our study offers a new direction for research investigating the impact of phonological neighbors during spoken sentence comprehension. The key aspect of the new task is that participants are required to make a decision on a single word during sentence processing. We suspect that variations of this paradigm (i.e., other than verb detection) will provide a valuable new avenue for behavioral research on spoken language comprehension.

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Table 1: Characteristics of the target verbs (mean values) of Experiment 1.

	Related	Control
Frequency [1]	1.50	1.60
Neighborhood density[2]	26	24
Number of higher frequency neighbors[2]	7	6
Positional phoneme frequency[1,3]	3.83	3.85
Positional biphone frequency[1,4]	2.72	2.76
Number of phonemes	3.28	3.39
Duration[5]	246	241

Note: [1]In log; [2]using Luce and Pisoni's (1998) definition; [3]how often a particular segment occurs in a given position in a word; [4]segment-to-segment co-occurrence. Positional phoneme and biphone frequencies were calculated from the Lexique 2 French Data Base (New et al. 2004); [5] in milliseconds.

Table 2A: Characteristics of the target verbs (mean values) for the complete set of ungrammatical word sequences (n=54) of Experiments 2 & 3.

	Related	Control
Frequency [1]	1.58	1.70
Neighborhood density[2]	26	25
Number of higher frequency neighbors[2]	7	7
Positional phoneme frequency[1,3]	3.84	3.86
Positional biphone frequency[1,4]	2.72	2.76
Number of phonemes	3.26	3.28
Duration[5]	248	239

Table 2B: Characteristics of the target verbs (mean values) for the subset of sequences (n=39) included in the additional analysis of Experiment 2.

	Related	Control
Frequency [1]	1.59	1.76
Neighborhood density[2]	25	24
Number of higher frequency neighbors[2]	7	6
Positional phoneme frequency[1,3]	3.84	3.85
Positional biphone frequency[1,4]	2.73	2.73
Number of phonemes	3.28	3.31
Duration[5]	250	245

Note: [1]In log; [2]using Luce and Pisoni's (1998) definition; [3]how often a particular segment occurs in a given position in a word; [4]segment-to-segment co-occurrence. Positional phoneme and biphone frequencies were calculated from the Lexique 2 French Data Base (New et al. 2004); [5] in milliseconds.

Table 3: Characteristics of the target verbs (mean values) for the subset of sequences (n=37) included in the additional analysis of Experiment 3.

	Related	Control
Frequency [1]	1.62	1.70
Neighborhood density[2]	26	24
Number of higher frequency neighbors[2]	7	6
Positional phoneme frequency[1,3]	3.85	3.84
Positional biphone frequency[1,4]	2.75	2.71
Number of phonemes	3.27	3.32
Duration[5]	253	246

Note: [1]In log; [2]using Luce and Pisoni's (1998) definition; [3]how often a particular segment occurs in a given position in a word; [4]segment-to-segment co-occurrence. Positional phoneme and biphone frequencies were calculated from the Lexique 2 French Data Base (New et al. 2004); [5] in milliseconds.

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Appendix 1: Related and unrelated sentences used in Experiment 1

Related sentences	Unrelated sentences
cette petite **troupe trouve** son chemin	cette petite **troupe fraye** son chemin
sur cette **route roulent** beaucoup de voitures	sur cette **route fuient** beaucoup de voiture
les **lottes logent** dans les eaux fraîches	les **lottes vivent** dans les eaux fraîches
la **chance change** assez vite	la **chance vire** assez vite
un grand **orme orne** la petite maison	un grand **orme couvre** la petite maison
la crème **brune brûle** dans la casserole	la crème **brune suinte** dans la casserole
tout le **monde monte** en voiture	tout le **monde dort** en voiture
la **poule pousse** les œufs dans le panier	la **poule vole** les œufs dans le panier
le petit **crabe crame** dans la poêle	le petit **crabe flambe** dans la poêle
cette **page passe** du blanc au noir	cette **page fonce** du blanc au noir
cette **tarte tarde** dans le four	cette **tarte chauffe** dans le four
et que cette **serpe serve** assez longtemps	Et que cette **serpe tienne** assez longtemps
cette belle **soupe souille** la casserole	cette belle **soupe tache** la casserole
la gentille **dame date** les papiers	la gentille **dame signe** les papiers
la gentille **reine rêve** dans son fauteuil	la gentille **reine chante** dans son fauteuil
ce beau **tram trace** sa route	ce beau **trame suit** sa route
ce grand **lâche lave** sa belle voiture	ce grand **lâche brique** sa belle voiture
cette belle **cave cache** du bon vin	cette belle **cave garde** du bon vin
ce grand **duc dupe** ses fidèles	ce grand **duc tape** ses fidèles
la vilaine **guêpe guette** la viande	la vilaine **guêpe pique** la viande
cette grande **jupe jure** avec ce pull	cette grande **jupe tranche** avec ce pull
Ce grand **bouc bouffe** toute l'herbe	ce grand **bouc mange** toute l'herbe
la jolie **canne cale** la porte d'entrée	la jolie **canne bloque** la porte d'entrée
la petite **fille file** à toute vitesse	la petite **fille marche** à toute vitesse
cette belle **messe mène** à l'heure du réveillon	cette belle **messe stoppe** à l'heure du réveillon
ce **brave brasse** de l'argent	ce **brave perd** de l'argent
la gentille **bonne bosse** pour peu d'argent	la gentille **bonne trime** pour peu d'argent
ces petites **couches coupent** la peau	ces petites **couches blessent** la peau
ce pull en **laine laisse** plein de bouloches	ce pull en **laine donne** plein de bouloche
cette belle **louve louche** dans la forêt	cette belle **louve bave** dans la forêt
ce vieux **type tire** sur les pigeons	ce vieux **type crache** sur les pigeons
ce grand **bal barre** toute la place	ce grand **bal prend** toute la place
la **belle bêche** dans son jardin	la **belle danse** dans son jardin
ces pauvres **bêtes baignent** dans leur sang	ces pauvres **bêtes gisent** dans leur sang
cette grosse **brique brille** à nouveau	cette grosse **brique penche** à nouveau
ce grand **flic flippe** devant la manifestation	ce grand **flic jouit** devant cette manifestation
cette jolie **quille quitte** le jeu rapidement	cette jolie **quille fausse** le jeu assez rapidement
cet homme **sourd soude** régulièrement	cet homme **sourd pêche** régulièrement
ces deux **frères freinent** brusquement	ces deux **frères crient** brusquement
cette eau **froide froisse** les tissus	cette eau **froide tasse** les tissus
la **foule fouille** le plateau de télé	la **foule pille** le plateau télé
la **galle gagne** du terrain	la **galle prend** du terrain

l'ensemble de la **classe clame** son innocence	l'ensemble de la **classe plaide** son innocence
ce joli **coq colle** son propriétaire	ce joli **coq fuit** son propriétaire
la femme **laide lèche** son miroir	la femme **laide crasse** son miroir
et que la **suite suive** assez rapidement	et que la **suite vienne** assez rapidement
la petite **lune lutte** à coté du soleil	la petite **lune peine** à coté du soleil
ce **mythe mine** la population	ce **mythe soûle** la population
ce **mime mise** tout sur son spectacle	ce **mime base** tout sur son spectacle
cette femme **moche mord** son époux	cette femme **moche largue** son époux
de cette **neige naissent** des cristaux	de cette **neige tombent** des cristaux
Ces gentilles **nonnes nomment** une commission pour les victimes	ces gentilles **nonnes ouvrent** une commission pour les victimes
le **pape part** en déplacement	le **pape veille** en déplacement
cette **pièce piège** les visiteurs	cette **pièce fige** les visiteurs
la **pionne pioche** dans les cartables	la **pionne cherche** dans les cartables
cette grande **planche planque** les vis	cette grande **planche masque** les vis
la **plonge plombe** les serveurs	la **plonge mine** les serveurs
mon **pote poche** ses œufs frais	mon **pote couvre** ses œufs frais
cette petite **sauce sauve** le plat	cette petite **sauce gâche** le plat
ces chiens de **race rament** dans ce chenil	ces chiens de **race pleurent** dans ce chenil
la jolie **rate rase** les murs	la jolie **rate griffe** les murs
cette **sainte singe** son patron	cette **sainte drague** son patron
ces pauvres **cerfs saignent** beaucoup	ces pauvres **cerfs boivent** beaucoup
cette femme **riche ride** énormément	cette femme **riche parle** énormément
ce **set cesse** rapidement	ce **set stoppe** rapidement
l'arrivée du **soir soigne** tous les maux	l'arrivée du **soir vire** tous les maux
ce grand **char chasse** les ennemis	ce grand **char pousse** les ennemis
cette affreuse **chope choque** les serveurs	cette affreuse **chope marque** les serveurs
ma grande **tante tangue** après un repas arrosé	ma grande **tante rote** après un repas arrosé
sa petite **tronche trompe** tout le monde	sa petite **tronche biaise** tout le monde
ce grand **naze nage** avec son pantalon	ce grand **naze coule** avec son pantalon
la petite **boule bouge** sur le tapis	la petite **boule saute** sur le tapis
la **vache vaque** à son broutage	la **vache court** à son broutage
le **gel gêne** les voitures	le **gel casse** les voitures
la **mangue manque** dans ce plat	la **mangue pèle** dans ce plat
cette belle **tourte tourne** dans le four	cette belle **tourte grille** dans le four

Appendix 2: Related and unrelated ungrammatical sentences used in Experiments 2 & 3

*#petite cette jolie **troupe trouve** chemin un	*#petite cette jolie **troupe fraye** chemin un
sur cette souvent **route roulent** de voitures beaucoup	sur cette souvent **route fuient** de voiture beaucoup
*#les d'habitude **lottes logent** fraîches les eaux dans	*#les d'habitude **lottes vivent** fraîches les eaux dans
la coutume de **chance change** rapidement assez	la coutume de **chance vire** rapidement assez
un grand l'été **orme orne** petite maison la	un grand l'été **orme couvre** petite maison la
la souvent crème **brune brûle** la casserole dans	la souvent crème **brune suinte** la casserole dans
tout le aujourd'hui **monde monte** voiture en	tout le aujourd'hui **monde dort** voiture en
en la soirée **poule pousse** les panier dans le œufs	en la soirée **poule vole** les panier dans le œufs
petit beau le **crabe crame** la dans poêle	petit beau le **crabe flambe** la dans poêle
*#la l'imprimante sur **page passe** au du blanc noir	*#la l'imprimante sur **page fonce** au du blanc noir
cette dimanche ce **tarte tarde** four dans le	cette dimanche ce **tarte chauffe** four dans le
cette que **serpe serve** longtemps assez	cette que **serpe dure** longtemps assez
gentille la souvent **reine rêve** le fauteuil dans	gentille la souvent **reine chante** le fauteuil dans
grande cette étonnamment **cave cache** vin bon du	grande cette étonnamment **cave garde** vin bon du
#ce fois grand chaque **duc dupe** fidèles les	#ce fois grand chaque **duc tape** fidèles les
vilaines les l'été **guêpes guettent** viande la	vilaines les l'été **guêpes piquent** viande la
longue cette étonnamment **jupe jure** ce avec pull	longue cette étonnamment **jupe tranche** ce avec pull
grand printemps ce au **bouc bouffe** l'herbe toute	grand printemps ce au **bouc mange** l'herbe toute
jolie cette souvent **canne cale** d'entrée porte la	jolie cette souvent **canne bloque** d'entrée porte la
petite comme la d'habitude **fille file** rapidement assez	petite comme la d'habitude **fille tombe** rapidement assez
longue cette habituellement **messe mène** réveillon au	longue cette habituellement **messe gêne** réveillon le
*#d'habitude gentille la comme **bonne bosse** d'argent peu pour	*#d'habitude gentille la comme **bonne trime** d'argent peu pour
#en pull ce **laine laisse** bouloches de plein	#en pull ce **laine donne** bouloches de plein
magnifique cette grande **louve louche** la forêt dans	magnifique cette grande **louve bave** la forêt dans
vieux ce souvent **type tire** les sur pigeons	vieux ce souvent **type crache** les sur pigeons
grand d'habitude ce comme **bal barre** la toute scène	grand d'habitude ce comme **bal prend** la toute scène
malheureusement pauvres les **bêtes baignent** leur sang dans	malheureusement pauvres les **bêtes gîsent** leur sang dans
ce homme vieil **sourd soude** régulièrement assez	ce homme vieil **sourd pêche** régulièrement assez
les grands deux **frères freinent** brusquement assez	les grands deux **frères crient** brusquement assez
*#étonnamment eau cette **froide froisse** tissus les	*#étonnamment eau cette **froide tasse** tissus les
*#la hier depuis **galle gagne** terrain du	*#la hier depuis **galle perd** terrain du
*joli petit le **coq colle** propriétaire le	*joli petit le **coq fuit** propriétaire le
*#grosse femme la **laide lèche** miroir le	*#grosse femme la **laide tache** miroir le
la que **suite suive** rapidement assez	la que **suite trace** rapidement assez
petite jolie la **lune lutte** du près soleil	petite jolie la **lune peine** du près soleil
*#toujours ce comme **mythe mine** population la	*#toujours ce comme **mythe soûle** population la
*#femme vieille cette **moche mord** hommes les	*#femme vieille cette **moche suit** hommes les
gentilles les fréquemment **nonnes nomment** les une pour commission victimes	gentilles les fréquemment **nonnes ouvrent** les une pour commission victimes
*#vieux le souvent **pape part** déplacement en	*#vieux le souvent **pape veille** déplacement en
#vieille cette d'habitude **pièce piège** visiteurs les	#vieille cette d'habitude **pièce fige** visiteurs les
jeune la souvent **pionne pioche** dans cartables les	jeune la souvent **pionne fouille** dans cartables les
*#mon d'habitude comme **pote poche** frais œufs les	*#mon d'habitude comme **pote gâche** frais œufs les
chiens les de **race rament** ce dans chenil	chiens les de **race pleurent** ce dans chenil
*#cette d'habitude comme **sainte singe** patron le	*#cette d'habitude comme **sainte casse** patron le

#vieille femme cette **riche ride** trop beaucoup	#vieille femme cette **riche parle** trop beaucoup
*les jeu ce dans **sets cessent** vite trop	*les jeu ce dans **sets stoppent** vite trop
souvent du l'arrivée **soir soigne** maux les tout	souvent du l'arrivée **soir vire** maux les tout
ce grand rapidement **char chasse** ennemis les	ce grand rapidement **char pousse** ennemis les
petite jolie sa **tronche trompe** le tout monde	petite jolie sa **tronche fausse** le tout monde
*#grand ce souvent **naze nage** un avec pantalon	*# grand ce souvent **naze coule** un avec pantalon
la matins les tout **vache vaque** le broutage pour	la matins les tout **vache court** le broutage pour
la d'habitude comme **mangue manque** plat ce dans	la d'habitude comme **mangue pèle** plat ce dans
une dimanches jolie les **tourte tourne** le four dans	une dimanches jolie les **tourte grille** le four dans
surement les que **nerfs naissent** cérébral tronc du	surement les que **nerfs sortent** cérébral tronc du

Notes: *sentences removed from the additional analysis of Experiment 2; #sentences removed from the additional analysis of Experiment 3.