Aural and Written Language Elicit the Same Processes: Further Evidence from the Missing-Phoneme Effect

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Open Practice Statement

The data and the stimuli are available on the Open Science Framework project page https://osf.io/c9kr7/?view_only=f4964d1f0d9746a2ba5c1fdeeecee8fb.

Abstract

When readers are asked to detect a target letter while reading for comprehension, they miss it more frequently when it is embedded in a frequent function word than in a less frequent content word. This missing-letter effect has been used to investigate the cognitive processes involved in reading. A similar effect, called the missing-phoneme effect has been found in aural language when participants listen to the narration of a text while searching for a target phoneme. In three experiments, we tested the hypothesis that both effects derived from the same cognitive processes, by isolating the role of word frequency and word function. In Experiment 1, we used a paper and pencil procedure for reading and a continuous narration for the listening task. In Experiment 2 and 3, we used a rapid serial visual or auditory presentation procedure to control for the effects of pre-processing upcoming information: parafoveal processing in reading and coarticulation in aural language processing. Parallel findings were observed in the reading and listening tasks. In all experiments, there was an effect of word function, and there was an effect of word frequency in Experiment 1 and 3. Results are interpreted in light of the Attentional Disengagement model.

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Many readers report hearing a voice in their head while they read, and readers take longer to silently read tongue-twister sentences than control sentences (see, e.g., Haber & Haber, 1982). The use of speech articulator muscles is also common when trying to establish internal speech while reading silently (see, e.g., Hardyck & Petrinovich, 1970; Helou et al., 2023). This phenomenological experience illustrates the intimate relation between reading and aural language. Here, we explore the relation between aural language and silent reading by contrasting performance on visual and auditory search tasks with verbal materials. More specifically, when participants are asked to search for a target letter while reading a prose passage for comprehension, they miss more letters embedded in frequent function words than in less frequent content words (see Klein & Saint-Aubin, 2016, for an overview). Over the last five decades, this pattern of omissions, known as the *missing-letter effect*, has been used to study the cognitive mechanisms involved in the visual processing of written language. In 2016, Saint-Aubin et al. extended this effect to the auditory modality by asking participants to search for a phoneme while listening to the narration of a text. Results revealed the presence of a missing-phoneme effect mimicking the missing-letter effect. The current study is aimed at testing the hypothesis that reading and listening are based on common cognitive processes driven by the allocation of attention. In order to achieve this goal, the contribution of word frequency, word function and pre-processing of upcoming information were investigated, because they have all been found to influence the missing-letter effect (see, e.g., Healy, 1976; Koriat & Greenberg, 1991; Roy-Charland et al., 2007, 2022; Saint-Aubin et al., 2005).

The distinction between content and function words is a fundamental one; it is present in all languages (Abney, 1987), and sensitivity to this distinction appears very early in development. For instance, using the habituation paradigm, Shi et al. (1999; Shi & Werker, 2001) showed that even newborns were sensitive to the distinction between function and content words, and that 6-month-old infants demonstrate a clear preference for listening to content over function words (see also, Marino et al., 2020). Furthermore, Babineau and Christophe (2022) showed that 8- and 11-month-old infants can track grammatical dependencies between function and content words. In the reading literature, it is also well-established that content and function words are processed differently (e.g., Drieghe et al., 2008). For instance, in the eye monitoring literature, it has been shown that function words are less likely to be fixated than content words (e.g., Drieghe et al., 2008; Gauthier et al., 2000; Chamberland et al., 2013; but see Schmauder et al., 2000). Reflecting the ubiquitous effect of word function in cognitive processing, authors in the missing-letter effect literature have repeatedly found more omissions for target letters embedded in function than in content words (see, Koriat & Greenberg, 1994, for an early review).

Among the many characteristics that distinguish function and content words, frequency plays an important role. In effect, function words have a special status in the lexicon by being a closed class of words compared to content words which form an open class of words. Given the limited number of available function words and their recurrent usage in sentences to provide the syntactic structure of the text, they are more frequently used, on average, than content words. For example, an analysis of a large corpus of French words revealed that the average frequency count of content words is 3.91 occurrences per million, while the average frequency count of function words is 1667.13 occurrences per million (New et al., 2004). Not surprisingly, in the reading literature, word function and word frequency are often confounded, and missing-letter effect studies are no exception. However, because distinct processes are associated to each factor, studies have been conducted to assess their unique contributions. Results have shown that readers miss more letters in function than in content words and in frequent than in rare words (see, e.g., Healy, 1976, 1994; Minkoff & Raney, 2000; Roy-Charland et al, 2022; Saint-Aubin & Poirier, 1997; Saint-Aubin et al., 2005). For instance, Saint-Aubin and Poirier have shown that readers miss more *r*s in the function usage of the polysemous French word *or* [whereas] than in its content usage [gold], even if both meanings have a similar frequency. In addition, Minkoff and Raney (2000) showed that readers miss more *t*s in high-frequency content words like *time* and *cost* than in low-frequency content words like *tine* and *cyst*. Accordingly, the missing-letter effect is officially defined as the higher omission rate for letters embedded in function than in content words and in frequent than in rare words, and these two factors have been at the heart of theoretical debates (see, e.g., Greenberg et al., 2004).

It is well-established that listening and reading comprehension are two closely related skills (see, e.g., Ruan et al., 2018). In fact, from an evolutionary perspective, it has been claimed that "...reading is too recent a human invention to have been directly shaped by evolution. Nonetheless, the human brain does contain language and visual pattern recognition modules, as delineated by Fodor (1983), which have been honed by evolutionary pressures and are used in reading" (Klein & McMullen, 1999, p.1). In support of this view, brain imaging studies have shown that semantic processing calls upon the same network of brain activation, whether the input is visual or auditory (see, e.g., Booth et al., 2002). These findings fit well the suggestion made by Koriat and Greenberg (1994), while developing their structural account of the missing-letter effect. More specifically, they suggested that the processes underlying the comprehension of both spoken and written messages recapitulate the speech production mechanism in which structural processing of the sentence precedes word retrieval processes (for similar ideas see, Bock & Ferreira, 2014). According to this view, whether detection of verbal materials is performed in a reading or a listening task, the same pattern of function and content word omissions should emerge to produce either a missing-letter effect or a congruous missing-phoneme effect.

The possibility of finding an aural analogue to the missing-letter effect was first investigated by Schneider et al. (1989, 1991). In their studies, participants listened to the narration of a short text and were asked to write down all words containing the target letter. Results of this letter detection task with an aural presentation were inconsistent, with the word frequency effect only being observed in some experiments. However, in a narration, phonemes are presented instead of letters. Therefore, in these studies, participants were required to convert phonemes to letters, and the impact of this additional conversion process is unknown. Schneider et al. (1991) addressed this phoneme to letter conversion problem in their sixth experiment, by asking one group of participants to read one or two sentences and to search for letters, while asking another group to listen to the narration of one or two sentences while searching for phonemes. They contrasted the word *of* with the word *if* and other words with the letter *f* (e.g., *flour, soft, interfere*). Because the phoneme associated to the letter *f* in *of* is not the same as the phoneme associated to the letter *f* in the other words, participants were asked to simultaneously search for the phoneme /f/ and /v/ and for the letter *f* and *v*. With the reading (letter detection) task and the listening (phoneme monitoring) task, more omissions were observed when the target was embedded in the word *of* than in the other words. However, at the listening task, it is impossible to know if the difference is due to the words, as is the case for the reading task in which the critical letter was always *f*, or to the phoneme since an omission on *of* implied that the phoneme /v/ was missed, while an omission on the other words implied that the phoneme /f/ was missed. Because some phonemes are harder to detect than others, the omission rate difference between *of* and the other words could be unrelated to reading processes and simply due to the relative difficulty of finding a specific phoneme (Wagner & Ernestus, 2008).

To investigate the possibility of finding an aural analogue to the missing-letter effect while overcoming the issues found in earlier studies by Schneider et al. (1989, 1991), Saint-Aubin et al. (2016) presented the narration of a text lasting two to three minutes with many occurrences of the target phoneme. Participants were asked to listen for comprehension and to press a button every time they detected a given phoneme. The most commonly used procedure in the missing-letter effect field was utilized by contrasting frequent function words with less frequent content words. More specifically, they used two texts. In the first text, they contrasted the frequent French indefinite article *des* with less frequent content words like *duo* [duet], *don* [gift or donation], and *duc* [duke]. In all cases, the word began with the letter *d* and the phoneme /d/ was always associated to the letter *d* in the critical words. This text was intended to reproduce typical texts in which a few function words are repeated many times while content words appear less frequently. In the second text, the frequent function word *pour* [for] was contrasted with the less frequent content word *cour* [yard], both words end with the letter *r* and the phoneme /ʁ/. Contrary to the first text, both critical words in the second text were repeated equally as often. Results showed higher omission rates for target phonemes embedded in frequent function words than in less frequent content words. In addition, another group of participants read the same texts while searching for a target letter in the same critical words. With both texts, results revealed the typical missing-letter effect with more omissions for the target letter embedded in frequent function words than in less frequent content words. Most importantly, as shown in Figure 1, an item-based analysis revealed a strong correlation between the reading and the listening task. In other words, words eliciting the most omissions of the target letter were also more likely to elicit more omissions of the target phoneme.

The functional equivalence between the reading and listening tasks supports the idea that the *missing-letter effect* and the *missing-phoneme effect* highlight the same cognitive processes. Roy-Charland et al. (2007, 2009) proposed the Attentional-Disengagement (AD) model of the missing-letter effect. According to the AD model, attention is disengaged more rapidly from function than from content words and from high- than low-frequency words. Typically, it is assumed that function words are more predictable in text and predictability would speed up processing speed (e.g., Koriat & Greenberg, 1994). For their part, high-frequency words would be processed faster than low-frequency words because high-frequency words would require less activation to reach the selection threshold (e.g., Staub, 2020). Using eye movements, Staub showed a large impact of predictability and word frequency in reading continuous text with shorter fixations and a higher rate of skipping for high frequency words and highly predictable words compared to low-frequency words and less predictable words.

Within the AD model, an isolable search mechanism checks for the presence of the target while reading or listening. The probability of detecting the target is a function of the momentary strength of the target representation. Because attention would be disengaged more rapidly from function words and high-frequency words than from content words and low frequency words, omission rates would be higher for the former than the latter. In reading, this was shown to be the case even when the target is irrelevant to the reading task such as searching for a pink letter in a multi-color text in which each letter was printed in a different color (Saint-Aubin et al., 2020).

Saint-Aubin et al. (2016) suggested that the attentional disengagement depends on cognitive factors operating in a relatively parallel way whether reading or listening. Therefore, parallel findings are expected in the reading and the listening tasks.

Despite the elegant simplicity of the AD model, it could be argued that the similarities between the pattern of results for the reading and listening tasks are more apparent than real. We labeled this alternative possibility the distinct processes hypothesis. According to the distinct processes hypothesis, performance in the reading task could be due to attentional processes as suggested by the AD model. However, in listening, omissions of phonemes in function words would be due to a phenomenon called speech reduction. In casual speech, short function words frequently consist of just a few pitch periods which can be indistinguishable from the preceding context (Baese-Berk et al., 2016). In fact, when function words are coarticulated with the preceding syllables, it can be very difficult to identify the word sequence. As mentioned by Baese-Berk et al. (2016), this is well illustrated by the controversy about the missing “a” in Neil Armstrong’s famous quote (Waxman, 2019). Although the famous quote we all know is “that’s one small step for man, one giant step for mankind”, when he returned from space, Armstrong claimed that he had said “a man” instead of just “man” (Jones, 2012). In two experiments, Baese-Berk et al. (2016) examined this question. They concluded that the spectral distribution of *for* and of *for a* overlap substantially and that the perception of the two function words varies as a function of context. Armstrong’s quote nicely illustrates the potential confound. Readers would have missed the *a* in reading Armstrong’s quote because of attentional processes and listeners would have missed the phoneme /ə/ because of speech reduction due to its spectral distribution. In sum, the controversy about Armstrong’s quote supports the distinct processes hypothesis according to which the reading and listening tasks would highlight different processes.

The current study was aimed at testing whether the reading and the listening tasks called upon the same processes as suggested by the AD model (Roy-Charland et al., 2007) or different processes as suggested by the distinct processes hypothesis. We used two different strategies to test if the missing-letter effect and the missing-phoneme effect really highlight the same processes. First, we isolated the influence of frequency and syntactic role. Although the *missing-letter effect* has been observed when high- and low-frequency words were matched for word function, a similar study has not been conducted in the listening task. Second, we controlled for pre-processing of upcoming information using a rapid serial visual presentation (RSVP) paradigm in our reading task, and a novel rapid serial auditory presentation (RSAP) paradigm in our listening task.

Experiment 1

In Experiment 1, we carefully isolated the unique influence of both word function and word frequency in the reading task and, most importantly, in the listening task. In addition, we included one of the texts used by Saint-Aubin et al. (2016) to allow a direct replication of their findings. This additional condition was deemed necessary because the missing-phoneme effect has a potentially high theoretical impact but has only been reported once. According to the AD model, more omissions should be observed in the reading and the listening tasks when the target is embedded in function than in content words and in high- than low-frequency words. According to the distinct processes hypothesis, in the reading task, more omissions should be found with function and high-frequency words than with content and low-frequency words. However, in the listening task, there might be more omissions for function than for content words due to speech reduction, but omission rates should be similar for high- and low-frequency content words because content words are less likely to consist of just a few pitch periods which can be indistinguishable from the preceding context.

Method

Transparency and Openness. In both experiments, we report all manipulations and measures. All stimulus materials and data are available in the Open Science Framework repository, https://osf.io/c9kr7/?view_only=f4964d1f0d9746a2ba5c1fdeeecee8fb. [Note to the reviewers: This page will be made public once the manuscript has been accepted.] Study designs and analyses were not preregistered. All experiments were approved by the research ethics committee of the Université de Moncton.

Participants. For all experiments, sample size selection relied on *a priori* power calculations with G*Power 3.1 (Faul et al., 2007) based on the effect sizes observed by Saint-Aubin et al. (2016) and by Roy-Charland and Saint-Aubin (2006). With these effect sizes, at most 30 participants per detection task would be required to achieve 80% power at the .05 level of significance. Considering the novelty of the procedure, we decided to slightly overpower the sample. Therefore, 72 undergraduate students (52 women, 15 men, and 5 preferred not to say) volunteered to participate in this experiment in exchange of course credits. Thirty-six participants were randomly assigned to each condition. All participants were native French speakers and reported having normal hearing and normal or corrected-to-normal vision.

Materials. Two prose passages were used in this experiment: the *P* text and the *pour-cour* text. The *P* passage comprised 1117 words and the target letter was *p*. In the critical words of this text, the target letter *p* was always associated with the phoneme /*p* /. As shown in Table 1, the text comprised eight critical words with the target letter *p*. In addition, in all critical words, the target letter/phoneme was located at the beginning of the word and word length was controlled for. There were 10 occurrences of the frequent content word *près* (close) and 10 occurrences of the equally frequent function word *puis*. In French, *puis* is a function word coordinating two syntactic units (puis, n.d.). We also contrasted 15 occurrences of low-frequency content words with 15 occurrences of high-frequency content words. In both cases, the 15 occurrences were composed of multiple presentations of 3 different words. The target letter *p* was also embedded in 59 noncritical words.

The *pour-cour* text, used by Saint-Aubin et al. (2016), comprised 809 words, and the target letter was *r*. In the two critical words of this text, *pour* (for) and *cour* (yard), the target letter was always associated with the phoneme /ʁ/. The passage comprised a total of 32 critical words; 16 instances of the function word *pour*, with a frequency count of 6,200 occurrences per million, and 16 instances of the content word *cour,* with a frequency count of 105 occurrences per million according to Lexique 3 (New et al., 2004). Furthermore, the target letter *r* was embedded in 49 noncritical words. Within each text, each word containing the target letter or phoneme, critical or not, was separated from the previous and the subsequent one by at least four filler words in which the target was not embedded. Furthermore, the critical words were not included in the first and last sentence of the text, and they were never adjacent to a punctuation mark. These criteria are typical in well-designed studies of the missing-letter effect (see Guérard et al., 2012 and Smith & Groat, 1979, for the importance of these criteria).

For the reading task, each text was double-spaced. The *P* text contained 79 lines, whereas the *pour-cour* text contained 58 lines. As per standard procedures, in both texts, care was taken to avoid locating the critical word at the beginning or at the end of a line. For the listening task, each text was recorded in a professional studio by a media professional who was unaware of the study purpose. The narrator was simply instructed to read the passage in a neutral way. The recording of the *P* text lasted 5 minutes 59 seconds, while the recording of the *pour-cour* text lasted 5 minutes 6 seconds. Overall, in both texts, a minimum of 1396 ms separated the onset of each target phoneme.

Procedure. Participants were tested individually in a private room. The experimenter was present throughout the task to ensure compliance with the instructions. Participants were randomly assigned to the reading or the listening task with the constraint that overall, the same number of participants were assigned to each condition. Accordingly, they were either asked to read or to listen for comprehension while detecting the target letter or phoneme. Presentation order of the critical passages was the same for all participants: the *P* text was presented first, followed by the *pour-cour* text. This order was chosen because the *P* text is critical for testing the current hypothesis, while the *pour-cour* text was only included for the purpose of providing a direct replication of Saint-Aubin's et al. (2016) results. Therefore, the chosen order priories the text allowing new discoveries over the text providing a direct replication. To promote comprehension, participants were told that their comprehension would be assessed with multiple-choice questions. To familiarize participants with the reading task, they were given a short practice text composed of 369 words and asked to search for the target letter *a.* The letter *a* was embedded in 29 words. For the listening task, our previous study revealed the need for more practice (Saint-Aubin, et al., 2016). Accordingly, participants first listened to three practice sentences while searching for the appropriate phoneme. The target phoneme only occurred once in each sentence. The target phonemes were respectively: /k/, /l/ and /t/. Participants then listened to the recording of the practice text and searched for the phoneme /a/ embedded in 31 words.

In the reading task, participants were instructed to read the text and to circle, with a pen, all occurrences of the target letter. They were asked to read at their normal speed and not to backtrack to circle missed targets. Participants were also told that they had to read two passages and that those passages had different target letters. To promote reading for comprehension, before each experimental text, participants were informed that five comprehension questions would follow. These questions were about general facts found in the text (e.g., What job does the narrator have in this story?) and each question had three alternative answers.

In the listening task, participants were instructed to listen to the narration of the texts and to press the space bar immediately when they noticed the target phoneme. They were asked to respond as quickly and accurately as possible. Before starting the experiment, participants were told that they would have to answer five comprehension questions after each text. After the presentation of the instructions, participants pressed the space bar, and a blank screen appeared. The experimenter then announced the target phoneme for the text. To ensure proper perception of the target phoneme, the experimenter asked the participant to repeat it aloud. If the participant failed to produce the phoneme, the experimenter repeated it and the participant tried again to produce it. Once the target phoneme was correctly pronounced, the participant was asked to press the space bar to initiate the narration of the text. This procedure was repeated for the three practice sentences, the practice text and the two critical texts. During the narration of each text, the screen remained blank. Headphones were used to minimize interference.

Data analysis. In the reading task, an omission was credited when the participant failed to circle the target letter included in a critical word. It is worth noting that with the paper and pencil procedure, participants almost never circle a non target letter. In the listening task, a response was scored correct if it occurred between 150 ms and 1250 ms after the onset of the critical word. The lower limit was selected to ensure that responses were not due to guessing. The upper limit was selected because it is shorter than the shortest interval before the onset of another word in which the target phoneme is embedded (1396 ms). Moreover, the use of the 1250 ms criterion ensures comparability with the delay used in Experiments 2 and 3 with the rapid serial visual/auditory presentation procedure. In Experiments 2 and 3, 1250 ms is the longest possible interval for providing a response before the occurrence of another word with the critical letter. This upper limit is longer than the 929 ms used by Saint-Aubin et al. (2016) in their listening task in which over their two texts, 929 ms was the minimal duration separating the onset of each target phoneme. As in Saint-Aubin et al. and in previous studies with a rapid serial visual presentation procedure, it is impossible to attribute a false alarm to a specific non-critical word or to a specific word class (see, e.g., Saint-Aubin & Klein, 2001; Saint-Aubin et al., 2003). For example, consider the following example with the onset of each word in brackets: Jérémy [0 ms], continua [388] donc [840] de [1041] se [1124 ms] diriger [1297 ms] vers [1676 ms] le [1786 ms] bureau [1982 ms] d'Antoine [2251] [Jeremy continued to walk towards Antoine's desk]. If a response occurred at 1600 ms, it could have been a false alarm of 303 ms to the preceding word "diriger" or a false alarm of 476 ms to the preceding word "se" or a false alarm of 559 ms to the preceding word "de" or even a false alarm of 1212 ms to the preceding word "continua" because none of these words contain the target phoneme /p/, but one could not chose among those options because of the nature of the stimulus presentation. As such, we categorized any response within our 1250 ms criterion of a target-containing word as a hit, and categorized any target-containing word that did not have a corresponding response within that window as an omission. Response times were not analysed because there were too few observations per condition to produce reliable estimates given the high omission rate, which is the standard and expected finding.

Following the recommendations of Jaeger (2008) and Dixon (2008), because for each occurrence of the target letter, a binary response choice is available (detection or omission), logistic mixed effects models were used to analyse the proportion of omissions. This procedure ensures appropriate statistical tests of the hypotheses. Participants and word occurrences were considered as random effects. The analyses were computed with the *glmr* function in the *lme4* package (Bates et al., 2014) in the R statistical software (Version 3.6.2; R Core Team, 2020). As suggested by Bates et al. (2014), for each analysis, we considered whether a model including the independent variables as random factors provided a better fit than a model considering them exclusively as fixed factors. Fit was estimated by comparing resulting deviance in each model, and only the best fitting model is reported.

Results

The mean proportion of omissions for the target letter or phoneme embedded in the critical words are presented in Figure 2 as a function of the text (*pour-cour* vs. P passage), task (reading vs. listening), and word function (function vs. content) or word frequency (function vs. content). These proportions were computed for each participant and each condition by dividing the number of omissions of each critical word by its number of occurrences in the text. An inspection of the figure reveals (a) a higher omission rate for the high-frequency function word *pour* than for the lower-frequency content word *cour*, (b) a higher omission rate for the high-frequency function words than for the high-frequency content words, and (c) a higher omission rate for high- than for low- frequency content words. The *pour-cour* text, and the effect of word function and of word frequency with the *p* passage were analysed separately with three separate logistic mixed effects models. For the *pour-cour* text, the best fitting model included random intercepts and slopes for participants and words. Results revealed significantly more omissions for the function word *pour* than for the content word *cour*, $\chi^2(1) = 89.78$, $p < .001$, and for the listening than the reading task, $\chi^2(1) = 32.13$, $p < .001$, and a significant interaction, $\chi^2(1) = 33.70$, $p < .001$, reflecting a larger missing-phoneme than missing-letter effect. Simple main effect tests indicated that the higher omission rate for *pour* than for *cour* was significant for the listening ($p < .001$) and the reading ($p < .001$) tasks. For the *p* passage, all analyses revealed that the best fitting model included random intercepts for participants and words. More specifically, for the effect of word function, results revealed significantly more omissions for function than for content words, $\chi^2(1) = 29.05$, $p < .001$, and for the listening than for the reading task $\chi^2(1) = 19.08$, $p < .001$, and a significant interaction $\chi^2(1) = 4.64$, $p = .03$. Simple main effect tests indicated that word function was significant in both the listening ($p < .001$) and the reading ($p < .001$) tasks. For the effect of word frequency, there was significantly more omissions for frequent than for rare words, $\chi^2(1) = 6.84$, $p = .009$, and for the listening than the reading task, $\chi^2(1) = 51.92$, $p < .001$. The interaction did not reach significance, $p = .20$.

Comprehension questions were then analysed. Typically, in the missing-letter effect literature, data about comprehension is not reported, as these questions are only included to promote reading for comprehension. However, in a few studies, comprehension performance was analysed to provide an independent assessment of the impact of text display or of the detection task on reading (see, e.g., Healy & Cunningham, 2004; Oliver et al., 2005; Redden et al., 2022; Saint-Aubin et al., 2020). Here, we analysed performance at the comprehension questions to provide a comprehensive investigation of the relationship between the reading and the listening task. Therefore, we merged the five questions of the *pour-cour* text with the five questions of the *P* text to test the effect of encoding task on comprehension. Participants' comprehension accuracy were high in both groups, with an average proportion of correct responses of .794 (SD

= .405) at the listening and of .797 (SD = .403) at the reading task. Results of the logistic mixed effects model with participants and questions as random effects failed to reveal a significant difference between the encoding tasks, χ^2 (1) = 0.01, p = .917. Furthermore, in both cases, accuracy was significantly greater than chance level (.33), both ts(35) > 20.95, ps < .0001.

Overall, both passages showed a large missing-letter effect and missing-phoneme effect. The same pattern of omissions was found in both tasks with an effect of word function and of word frequency. Furthermore, as observed by Saint-Aubin et al. (2016) with the *pour-cour* text, the missing-phoneme effect was larger than the missing-letter effect. Finally, the data obtained from the comprehension questions showed that both groups had similar and strong understanding of the text.

Discussion

Results of Experiment 1 are clear. First, we replicated the results of Saint-Aubin et al. (2016) with more misses in the reading and listening tasks for the frequent function word *pour* than for the less frequent content word *cour*. In the context of the replication crisis, it is reassuring that the built-in replication worked so well. Second, and most importantly, results revealed that whether reading or listening, both word frequency and word function contributed to misses. This study provides the first demonstration of a word frequency effect and a word function effect in the phoneme-detection task. Our results fit nicely within the AD model, according to which reading or listening should elicit faster attentional disengagement from function than from content words and from high- than low-frequency words. However, no support was found for the distinct processes hypothesis because there were both a frequency based and a syntactically based missing-phoneme effect, even if speech reduction is less likely for content words.

Experiment 2

In the second experiment, we further tested the process communality between reading and listening. In both cases, it is well-known that upcoming items can be pre-processed with only partial sensory information; a phenomenon known as parafoveal processing in reading and speech reduction in aural language processing. In reading, parafoveal processing refers to the extraction of visual information in the word n+1 while the word n is fixated. While meaningful linguistic information can be obtained when the to-be-read material is not foveated, the visual acuity is poorer and the processing of the word is less efficient (Eskenazi & Folk, 2015). Similarly, in the aural language, coarticulation refers to changes in speech articulation due to the acoustic properties of subsequent phonemes. The phonetic reduction resulting from coarticulation is more likely to be misperceived by the listener due to a reduction of acoustic-phonetic substance in comparison to more hyperarticulated words (Salverda et al., 2014). For instance, in reading the sentence “I was there for a whole month”, readers are likely to fixate the word *for* and then word *whole*. In this case, it is assumed that the word *a* was processed in the parafovea while fixating the word *for*. Similarly, while listening to the narration of the sentence, due to coarticulation, there would be a phonetic reduction in which the function word *a* would become spectrally indistinguishable from the preceding context provided by the word *for*. Therefore, the identification of the word *a* would be based on very limited input information resulting in highly variable perceptions among listeners (Baese-Berk et al., 2016). In sum, the quality of the visual or auditory input is affected by parafoveal processing and coarticulation, respectively.

Recognizing the impact of parafoveal preview in reading, it has been suggested that the missing-letter effect could be a by-product of eye movements (Corcoran, 1966; Greenberg et al., 2004; Healy et al, 1987; Hadley & Healy, 1991). In effect, eye movement studies have shown that function words are more frequently skipped in reading than content words, implying that they are more frequently identified in the parafovea during the fixation of the preceding word (see Gauthier et al., 2000). All major models of eye-movement control in reading suggest that skipping derives from partial processing of information in the parafovea. For instance, according to parallel processing models of eye movements, such as SWIFT (Engbert et al., 2005), skipped words are not as fully processed as fixated words (Eskenazi & Folk, 2015). Serial processing models, such as the E-Z Reader (Reichle & Drieghe, 2013), also suggest partial processing of skipped words based on parafoveal information. For instance, the E-Z Reader model assumed that parafoveal processing of an upcoming word can be sufficient to complete the early lexical processing stage (i.e., the familiarity check), and therefore the upcoming word can be skipped. This is why easy words (i.e., high frequency, short, function words) are more often skipped than difficult words (i.e., low frequency, long, content words). Importantly, both serial and parallel processing models assumed that skipped words are not fully processed. The partial lexical processing of skipped words would make the detection of an embedded target letter harder.

Saint-Aubin and Klein (2001) conducted the first study in which eye movements were monitored while readers read a continuous text for comprehension and searched for a target letter. Results revealed that participants made 15% fewer fixations on the critical function word *the* than on the control content words (see also, Roy-Charland et al., 2007). However, contradicting the hypothesis that the missing-letter effect is a by-product of eye movements, Saint-Aubin and Klein observed more omissions for the function word *the* than for content words both when the target words had been fixated and when they had been skipped.

To further clarify the role of eye movements in the missing-letter effect, following the pioneer work of Healy et al. (1987), Saint-Aubin and Klein (2001; Redden et al., 2022) used an RSVP procedure in which words are presented one at a time at the center of a computer screen. This procedure is used to prevent parafoveal processing, while allowing participants to achieve normal comprehension (Potter et al., 1980). With this procedure, each word, be it a function or a content word, is fixated for its entire presentation duration (Saint-Aubin et al., 2010). Saint-Aubin and Klein showed that with a presentation duration similar to that of the usual duration of fixations in reading (250 ms per word), the usual pattern of omissions found with the paper and pencil procedure is found with the RSVP procedure. Furthermore, Saint-Aubin and Klein (2004) reported an almost perfect correlation between the paper and pencil method and the RSVP method when measurement errors were considered. Therefore, the missing-letter effect does not seem to be impacted by parafoveal pre-processing of upcoming words.

While a missing-letter effect has been found when controlling for the impact of parafoveal processing with the RSVP procedure, a similar examination has never been done with the listening task by controlling for coarticulation. Therefore, in Experiment 2, we tested whether the missing-phoneme effect was also independent of pre-processing upcoming information. To answer this question, we used the Rapid Serial Auditory Presentation (RSAP) procedure developed by Franco et al. (2015) to study statistical learning in speech segmentation. With this procedure, each word is recorded separately as a single token and all words are presented for the same duration. For words with a shorter pronunciation, silence is added at the end to ensure a constant presentation rate. The phenomenological experience is like listening to a robotic voice.

According to the AD model, attention would be disengaged faster from function than from content words and from high- than low-frequency words irrespective of presentation condition (e.g., Redden et al., 2022). Therefore, a missing-letter effect in reading and a missing-phoneme effect in listening should be observed. Alternatively, according to the distinct processes hypothesis, the missing-phoneme effect would be due to the pre-processing of upcoming information in which function words are less likely to be fully articulated. In this context, with an RSAP allowing each word to be fully articulated, the missing-phoneme effect should disappear.

Method

Participants. Seventy-two undergraduate students (64 women and 8 men) from Université de Moncton volunteered to participate in this experiment in exchange of course credits. Thirty-six participants were randomly assigned to each condition. All participants were native French speakers and reported having normal hearing and normal or corrected-to-normal vision. None took part in the previous experiment.

Materials and Procedure. The texts were the same as those used in Experiment 1, and their presentation order was counterbalanced across participants. For the reading task, the texts were presented with an RSVP procedure. After reading the instructions, the participant pressed the space bar, and the presentation of the first text began. With this procedure, words were presented one at a time in the center of the computer screen at a rate of four words per second (250 ms on, 0 ms off). Participants had to press the space bar every time they detected the target letter, and no feedback was given. Response latencies were measured from the onset of a critical word until the participant pressed the space bar. After reading the first text, participants answered five multiple-choice questions about it. When ready, participants pressed the space bar to initiate the presentation of the second text. The presentation of the *p* passage lasted 4 minutes 49 seconds, while the presentation of the *pour-cour* text lasted 3 minutes 35 seconds.

For the listening task, all words were recorded individually using Léo's voice on the Text-to-Speech website (retrieved from https://ttsdemo.com/). The audio files were recorded using the SoundTap software (NCH Software, version 3.04) and modified with the Audacity software (Audacity, 2.1.0). To develop a procedure similar to the RSVP procedure used in the reading task, all audio files were modified so that each word was presented for a fixed duration of 700 ms. This duration was selected because the pronunciation of most words was shorter than 700 ms and the distribution of pronunciation durations showed an abrupt drop after 700 ms. Therefore, this was the shortest possible duration without having to compress the auditory signal of too many words. When a word pronunciation duration was under 700 ms, silence was added to produce a file with a duration of 700 ms. Overall, when considering both texts, 3.3% of the words (64 words out of 1926) were longer than 700 ms (705ms to 1136 ms). Therefore, the pronunciation speed of these words was accelerated to achieve a duration of 700 ms. It is worth noting that none of the 64 words requiring acceleration was a critical word. Each text was presented aurally using headphones, while the computer screen remained blank. Participants had to press the space bar every time they detected the target phoneme, and no feedback was provided. The aural presentation of the *p* passage lasted 14 minutes and 40 seconds, while the aural presentation of the *pour-cour* text lasted 10 minutes and 50 seconds. With this procedure, the shortest duration separating the pronunciation of two words containing the target phoneme was of 2800 ms in the *p* passage and of 3500 ms in the *pour-cour* text.

The familiarization procedure was the same as in Experiment 1 using the RSVP procedure for the reading task and the RSAP procedure for the listening task. In both conditions, participants were told that they had to press the space bar as fast as possible each time they noticed the target letter or phoneme.

Results

With the RSVP and RSAP procedures, an omission was credited if no response occurred between 150ms and 1250ms after the onset of the critical word. The lower limit was selected to remove guesses and random responses. In total, 31 omissions were removed because the response time was shorter than 150 ms. This represents 0.52% of all trials (31 trials / 5976 trials [72 participants x 83 critical words]). The upper limit was set to ensure that a response was emitted before the presentation of another word with the target letter with an RSVP procedure (see Saint-Aubin et al., 2003, 2010, for similar criterion).

An inspection of Figure 3 reveals that, as in Experiment 1, in Experiment 2, there were more omissions of the target when it was embedded in the frequent function word *pour* than in the less frequent content word *cour,* in the function word *puis* than in the equally frequent content word *près*. However, the effect of word frequency did not emerge. The *pour-cour* text, and for the *p* passage, the effect of word function and the effect of word frequency were analysed with three separate logistic mixed effects models. All three analyses revealed that the best fitting model included random intercepts for participants and words. For the *pour-cour* text, there was significantly more omissions for the function word *pour* than for the content word *cour*, $\chi^2(1) = 15.48$, $p < .001$ and for the listening than for the reading task, $\chi^2(1) = 4.96$, $p = .026$, but the interaction did not reach significance, $p = .96$. For the effect of word function with the *p* passage, there was also significantly more omissions for the function than for the content word, $\chi^2(1) = 9.25$, $p = .002$, and for the listening than for the reading task $\chi^2(1) = 4.06$, $p = .044$, but the interaction did not reach significance, $p = .25$. For the effect of word frequency with the *p* passage, neither the main effect of word frequency ($p = .62$), nor the main effect of task ($p =$

.056) reached significance. Furthermore, the interaction between the type of task and word frequency failed to reach significance (p = .48).

Participants' comprehension accuracy were analysed by merging the five comprehension questions of each text. Results revealed that the average proportion of correct responses was high in both the RSVP (M =.82, SD =.39) and RSAP (M=.87, SD=.33) tasks. The logistic mixed effects model with participants and questions as random effects reveals a marginally significant advantage of the auditory version over the visual version of the task, $\chi^2(1) = 3.80$, $p = .051$. In both cases, accuracy was greater than chance level (.33), both ts(35) > 24.65, ps < .0001.

Discussion

Experiment 2 eliminated the possibility that participants can pre-process the next word with parafoveal vision in the reading task or coarticulation in the listening task. Once again, results revealed the same pattern of omissions: In both tasks, target letters and target phonemes were missed more often in function words than in equally frequent content words. This word function effect with the RSVP and RSAP procedures is a new finding. The word function effect with the RSVP procedure nicely extends previous findings observed in English (Redden et al., 2022; Saint-Aubin & Klein, 2001; Saint-Aubin et al., 2010) and French (Saint-Aubin et al., 2003) when contrasting frequent function words with less frequent content words.

Surprisingly, in Experiment 2, the word frequency effect was neither observed in the reading, nor in the listening task. At first glance, the lack of a frequency effect is surprising. In Experiment 1 with parafoveal processing and coarticulation, a substantial word frequency effect was observed, albeit smaller than the word function effect. In addition, Saint-Aubin et al. (2003) found a word frequency effect using an RSVP procedure. However, the absence of a word frequency effect in our study using the same RSVP procedure may be explained by word function as a confounding variable in the study of Saint-Aubin et al. In effect, in the text used by Saint-Aubin et al., the 24 occurrences of content words were composed of 9 different words for which there were between 1 and 4 occurrences. Although the 9 words were all content words, they do not belong to the same lexical category; there were 4 nouns, 3 verbs, and 2 adjectives. Furthermore, word frequency systematically varied across word categories with verbs being the most frequent, followed by adjectives and then nouns with, for instance, an average of 1064 occurrences per million for verbs and 36 occurrences per million for nouns (New et al., 2004). Therefore, in Saint-Aubin et al.'s (2003) study, the word frequency effect could in fact be due to word function.

The loss of the word frequency effect when parafoveal preview and coarticulation are eliminated can reveal the dependence of these effects on the pre-processing of upcoming information. In the eye movement literature, the longer fixations on low-frequency words compared to high-frequency words is a benchmark effect (see, e.g., Staub, 2020; Staub et al., 2010). Under this view, the frequency-based missing-letter effect would be a by-product of pre-processing upcoming information. This would fit nicely with some models of the missing-letter effect such as the parafoveal processing hypothesis (Hadley & Healy, 1991), but would be incompatible with the AD model which suggests that omissions and eye movements are due to attentional control processes—so the missing-letter effect would be defined by word function or word frequency (Roy-Charland et al., 2007). Similarly, it has been suggested that high-frequency words are easier to coarticulate than low-frequency words (Miller & Roodenrys, 2012; Woodward et al., 2008). It has further been shown that the information derived from coarticulation can be used on-line to speed up the recognition of spoken words. Again, this pre-processing of upcoming information would be contrary to the predictions of the AD model.

The lack of a word frequency effect within the RSVP and RSAP procedures could also be due to some peculiarities of the selected words, to some hidden factors in text construction, or to individual differences. These unnoticed characteristics of the reading material would interact with pre-processing of upcoming information and mask the true effect of word frequency. In the memory literature, some key effects were impossible to replicate with new items, suggesting that they were due to some specific properties of the original items (Bireta et al., 2021; Lovatt et al., 2000). Because, unlike word function, word frequency is entirely a property of the items, it is necessary to replicate the (lack of) word frequency effect by using a new word set. Furthermore, in the missing-letter effect literature, it has been shown that omission rate on content words can vary as a function of subtle differences in text structure (Koriat & Greenberg, 1996; Moravsick & Healy, 1998). These text structure differences that were not controlled for in the previous experiments—as they are usually ignored in the literature—could account for the loss of the word frequency effect with the RSVP and RSAP procedures (but see, Healy, 1976 for a well-controlled demonstration of a word frequency effect with a scrambled text).

In addition to reading material, the lack of a word frequency effect could be due to individual differences. A century ago, Preston (1935) already showed that frequency effects in a naming task negatively correlated with vocabulary. In other words, participants with a large vocabulary exhibited the smallest frequency effect. Since the publication of this pioneer work, the reduced word frequency effect among individuals with larger vocabulary has been repeatedly observed with various experimental paradigms (see, Brysbaert et al., 2018, for an overview). For instance, using the English Lexicon Project database with almost four million trials in a naming and a lexical decision task based on 1,200 participants, Yap et al. (2012) observed a reduced word frequency effect among individuals with more extensive vocabulary. Therefore, due to sampling variance, the lack of a frequency effect in Experiment 2 may have been due to the larger vocabulary of those participants compared to those in Experiment 1.

Experiment 3

In Experiment 3, we further tested the word frequency effect with an RSVP and an RSAP procedure by implementing the most stringent controls ever used in the missing-letter effect literature and by using new word sets. More specifically, we refined our control of the linguistic context surrounding target words. In 1996, Koriat and Greenberg discovered the enhancement effect: In the reading task, the probability of omitting the target letter is higher for content words preceded by a content than by a function word. In addition, Moravcsik and Healy (1998) showed a subtle syntactic effect. Readers omit a target letter more frequently when it is embedded in a content word located in an object phrase than in a subject phrase. Therefore, in Experiment 3, high- and low-frequency words were yoked in pairs. Each member of the pair was embedded in a sentence with the same structure. In other words, the preceding word was the same and the role within the sentence (subject or object) was the same. For instance, in the sentences, "Cathy took some time to settle on the *kind* of special treat that she might make," and "She would even try to replace the *spud* with a new one," the paired target words "kind" and "spud" are preceded by the same functor and are both within the object of the sentence. To improve the sensitivity of our analyses, we increased the number of occurrences of the critical words in the text by using 50 occurrences of low-frequency words and 50 occurrences of high-frequency words, instead of 15 in each category as was done in Experiment 1 and 2. Finally, to reduce the risk of having a sample of participants with large vocabulary, our participants were drawn from a crowdsourcing platform, as previous studies showed that non-university participants exhibit lower performance at a variety of language related tasks (e.g., Kuperman & Van Dyke, 2011).

According to the AD model, a frequency based missing-letter and missing-phoneme effect should be observed (Roy-Charland et al., 2007; Saint-Aubin et al., 2016). In this context, the failure to observe a frequency effect in Experiment 2 would entirely be due to the uncontrolled factors. In contrast, according to the distinct processes hypothesis, there should only be a missing-letter effect, because the missing-phoneme effect would be driven by pre-processing of upcoming information that is controlled for with the RSAP procedure.

Method

Participants. Seventy-two volunteers (57 women, 13 men, 1 other gender, 1 prefer not to report) from an online collection agency, Prolific (https://www.prolific.co/), participated and were paid £2.00. Thirty-six participants were randomly assigned to each condition. Participants had to be between 18 and 30 years old; to be from the United States; to have English as their first language, normal or corrected-to-normal vision, a Prolific approval rate of at least 90%, and not to have reading or writing related disorders, cognitive impairments or dementia. Participants gave their free and informed consent and none of them took part in the previous experiments.

Materials. One prose passage was used in this experiment: the *D* text. The *D* passage comprised 1547 words and the target letter was *d*. In the critical words of this text, the target letter *d* was always associated with the phoneme / *d* /. As shown in Table 2, the text comprised 12 critical words with the target letter *d.* Word function and word length were controlled for by using only four-letter content words. The position of the target letter/phoneme was also controlled for, so that each high-frequency content word had an equivalent low-frequency content word with the target letter/phoneme in the same position. Half of the critical words had a high frequency with an average count of 269.24 occurrences per million in subtitles, and half of the critical words had a low frequency with an average count of 0.53 occurrence per million in subtitles according to SubtlexUS (Brysbaert & New, 2009). The target letter *d* was also embedded in 139 noncritical words.

We contrasted 50 occurrences of high-frequency content words with 50 occurrences of low-frequency content words. The number of occurrences of each critical content word is reported in Table 2. In both cases, the 50 occurrences of high- and low-frequency content words were composed of multiple presentations of six different words. For each pair of frequent-rare words, it was important that both pair members appear the same number of times in the subject of a sentence as in the object of a sentence (Moravcsik & Healy, 1998). In other words, since the frequent word *days* appeared one time in the subject and three times in the object, its paired rare word *dens* also appeared one time in the subject and three times in the object. It was also important that both pair members were preceded the same number of times by the same functor (Koriat & Greenberg, 1996). For instance, the frequent word *days* was preceded four times by “the”, twice by “their” and twice by “these”, its paired rare word *dens* was also preceded four times by “the”, twice by “their” and twice by “these”.

Within the text, each critical and noncritical word containing the target letter or phoneme was separated from the previous and the subsequent one by at least four filler words which did not contain the target. Furthermore, the critical words were nouns which could not also be verbs, and these were not included in the first and last sentence of the text nor were they ever adjacent to a punctuation mark (Guérard et al., 2012; Smith & Groat, 1979).

Procedure. Participants were randomly assigned to each condition. For the reading task, the *D* text was presented using the same RSVP procedure as in Experiment 2. Within this procedure, words were presented one at a time in the center of the computer screen at a rate of four words per second (250ms on, 0ms off). Participants had to press the space bar every time they detected the target letter, and no feedback was given. The presentation of the *D* passage lasted 7 minutes and 3 seconds. After the presentation of the *D* text, participants answered four multiple-choice questions about it to ensure their comprehension. These questions were about general facts found in the text and each question had four alternative answers.

For the listening task, all words were recorded individually using James' voice on the Text-to-Speech website (retrieved from https://ttsdemo.com/). Audio files were recorded using the SoundTap software (NCH Software, version 3.04) and modified with the Audacity software (Audacity, 2.1.0). As in Experiment 2, audio files were then modified so that each word was presented for a fixed duration of 700ms, with silence being added to words whose duration of pronunciation was under this threshold. We accelerated the pronunciation speed of 0.98% of the words (15 words out of 1547) which were longer than 700ms to achieve the required duration. None of the words requiring acceleration was a critical word. Each text was presented aurally while the computer screen remained blank. As in the reading task, participants were instructed to press the space bar every time they detected the target phoneme, and no feedback was provided. After reading the instructions, participants first listened to three practice trials while searching for a single occurrence of the phonemes /k/, /l/, and /t/, respectively. These three sentences were presented one word at a time, at the same rate as the *D* text. Participants then listened to practice text while searching for the phoneme /b/ embedded in 79 words. After the practice procedure, participants listened to the narration of the *D* passage, which lasted 18 minutes and 35 seconds, while searching for the phoneme /d/.

Results

As in Experiment 2, an omission was credited in the RSVP and RSAP procedures if no response occurred between 150ms and 1250ms after the onset of the critical word. In total, 56 omissions were not credited because the response time was shorter than 150 ms. This represents 0.77% of all trials (56 trials / 7200 trials [72 participants x 100 critical words]). Another 422 omissions were not credited because the response time was longer than 1250ms. This represents 5.86% of all trials (422 trials / 7200 trials [72 participants x 100 critical words]).

An inspection of Figure 4 reveals that there were more omissions of the target when it was embedded in the frequent words than in the rare words. This effect of word frequency was analysed with a logistic mixed effects model. The best fitting model included random intercepts for participants and words. There was significantly more omissions when the target was embedded in a frequent than in a rare word, $\chi^2(1) = 41.04$, $p < .0001$, but omission rate did not differ across tasks ($p = .95$), and the interaction between word frequency and task did not reach significance ($p = .96$).

Participants' comprehension accuracy were analysed by examining the four comprehension questions. Results revealed that the average proportion of correct responses was high in both the RSVP (M =.90, SD =.31) and RSAP (M=.89, SD=.32) tasks. Results of the logistic mixed effects model with participants and questions as random effects failed to reveal a significant difference between the encoding tasks, $\chi^2(1) = 0.45$, $p = .50$. In both cases, accuracy was significantly greater than chance level (.25), both ts(35) > 22.07, ps < .0001.

Item-Based Analysis. To further explore the relation between the reading and the listening tasks, we computed item-based correlations (see Saint-Aubin et al., 2016 and Saint-Aubin & Klein, 2004, for a similar procedure). Each occurrence of a critical word in which the target is embedded served as the basic unit of analysis. For each condition (natural listening and reading tasks for Experiment 1 and RSVP and RSAP for Experiment 2 and 3), we computed the average omission rate of each occurrence of a critical word across all participants. Data from Experiment 1 and Experiment 2 were analyzed together because they used the same materials. Since a new text was used for Experiment 3, the data from this experiment was analyzed separately. For the joint analysis of Experiments 1 and 2, each correlation is based on 82 observations (32 critical words in the pour-cour text and 50 critical words in the *p* passage). The six correlations are presented in Figure 5. As can be seen, all correlations between omission rates are large, varying between .55 and .69, significant, and of similar magnitude (Cohen, 1988). We used the same process to compute item-based correlations in Experiment 3 across the RSVP and RSAP tasks. In this case, the correlation is based on 100 observations (50 high-frequency words and 50 low-frequency words). As shown in Figure 6, the correlation between omission rates at the RSVP and RSAP tasks is moderate (.41) and significant (Cohen, 1988). Furthermore, an inspection of scatter plots in Figures 3 and 4 indicates that these correlations are not driven by outliers.

Discussion

Once more, in Experiment 3, the same pattern of results was observed with the reading and the listening tasks. This additional replication with a new language, participant pool, and testing environment further established the reproducibility of the phenomenon. As such, although results are not coming from different laboratories, our demonstration goes some way in meeting the criterion for establishing the new finding of a missing-phoneme effect in the list of benchmark findings (Oberauer et al., 2018).

Most importantly, we observed a word frequency effect which did not interact with task. The frequency-based missing-letter and missing-phoneme effect was predicted by the AD model but contradicts the predictions of the distinct processes hypothesis. The presence of this word frequency effect raises the issue of why we did not observe it in Experiment 2. Because with the same material, the word frequency effect was observed in Experiment 1, this null effect in Experiment 2 would have to derive from some peculiarities of the selected words or some hidden factors in text construction interacting with pre-processing of upcoming information. Although, it is not impossible, a more likely hypothesis is that participants in Experiment 2 had a larger vocabulary than those who took part in the other experiments. In support to this view, in previous studies using a lexical decision task, researchers observed a reduced word frequency effect among individuals with more extensive vocabulary (e.g., Yap et al., 2012).

In addition, it is worth reminding the reader that in Experiment 3, with more stringent controls in text construction, with two times more target words and with 3.3 times more occurrences than in Experiment 2, results revealed frequency-based missing-letter and missing-phoneme effects. Therefore, it is concluded that word frequency can influence omissions in the reading and listening tasks even after controlling for pre-processing of upcoming information. Considering that this paper was aimed at systematically investigating the relationship between the reading and the listening tasks, and given the parallel results between both tasks in all experiments, the fluctuations of the word frequency effect across experiments will not be further discussed.

General discussion

The results of the current study confirm the reproducibility of the missing-phoneme effect with new texts, target phonemes, critical words, languages, presentation methods, and participants. This demonstration is important to establish that, as a newly discovered effect, the missing-phoneme effect does not depend on highly specific boundary conditions that could make it difficult, or even impossible, to replicate in other laboratories. Most importantly, in the current study, we showed that as observed in reading, the missing-phoneme effect is sensitive to both word function and word frequency. We further showed that in the listening task, neither the word function effect nor the word frequency effect is due to coarticulation. Finally, we showed that performance in the reading and listening tasks correlates well on an item-by-item basis.

According to the distinct processes hypothesis presented in the introduction, the missing-letter effect and the missing-phoneme effect would be driven by distinct processes. The missing-letter effect would be due to attentional factors as proposed by the AD model. However, the missing-phoneme effect would be due to speech reduction due to coarticulation. Under the distinct processes hypothesis, the missing-phoneme effect should only be observed in natural listening situations in which coarticulation plays a major role, but not when it is eliminated. As a reminder, in the aural language, as powerfully exemplified by the controversy about Neil Armstrong's famous quote, short function words often consist of a few pitch periods frequently indistinguishable from the preceding context (e.g., Baese-Bark et al., 2016). Therefore, in the original study of the missing-phoneme effect, the target phoneme could have been missed more frequently when it was embedded in a frequent function word because of its pronunciation. Here, the presence of a word frequency effect and word function effect when listening to the narration of a text would be more difficult to account for with this view because all critical words were 3 or 4 phoneme long. In addition, with the RSAP procedure preventing coarticulation in Experiments 2 and 3, the word function effect observed in Experiment 2 and the word frequency effect observed in Experiment 3 provide critical evidence against this explanation.

According to the AD model, both the missing-phoneme and missing-letter effect are driven by the allocation of attention and are not a by-product of the pre-processing of upcoming information. In support to this view, we observed substantial item-based correlations between both tasks and similar patterns of omissions. These similarities suggest that the missing-letter and missing-phoneme effects have the same cause, and it cannot be pre-processing of upcoming information. Saint-Aubin et al. (2016) proposed that errors in the reading and listening tasks are due to attentional processes. More specifically, they called upon the AD model of the missing-letter effect (Roy-Charland et al., 2007, 2009). According to the AD model, the proximal cause of omissions depends on when attention is disengaged from the word containing the target. More specifically, because function words are more predictable than content words (see, Roy-Charland et al., 2007 for an empirical demonstration), and because frequent words are identified faster than rare words—as evidenced by shorter fixation durations on frequent words (e.g., Staub, 2020; Staub et al., 2010; Slattery et al., 2007)—attention would be disengaged faster from function words and from frequent words. It is further assumed that the same pattern of attentional disengagement can be observed in the visual and auditory modality (Klein & Lawrence, 2011). Within the AD model, attention is driven by the primary reading or listening task, and not by the secondary search task (Redden et al., 2022). It is further assumed that information about the physical characteristics (visual or acoustic) of the word accumulates when attention is engaged on it. The internal representation starts to decay as soon as attention is disengaged from the word. The search mechanism operates by sampling at regular intervals from the accumulated information. Therefore, the higher the amount of information that is accumulated, the higher the probability of detecting the target. As such, the AD model can handle the current pattern of results.

The demonstration that reading and listening are based on common cognitive processes paves the way for new avenues of research. First, it has been shown that the magnitude of the missing-letter effect was related to reading skills among elementary school students (Drewnoswki, 1978; Saint-Aubin & Klein, 2008; Saint-Aubin et al., 2005). Compared to poor readers, good readers from grades 1 to 4 exhibited a larger missing-letter effect. In other words, the omission rate difference between function (*the, and, for*) and content words (e.g., *tag, ant, fun*) was larger among good readers (Saint-Aubin & Klein, 2008). Since it is well established that preschoolers can process phonemes, the missing-phoneme effect could be used to assess prereading skills for predicting later reading achievement. For instance, using a longitudinal design, Powell and Atkinson (2021) showed that phonological awareness assessed among 4 year old children predicted their subsequent reading achievement. However, as is usually the case, phonological awareness in their study was assessed for individual words. With our listening task, phonemes are processed in a meaningful context with a strong syntactic structure. Therefore, this task has the potential to add to the predictive power of current measures of phonological awareness.

As suggested during the review process, the missing-letter and missing-phoneme effects can improve the understanding of the cognitive processes associated with some physical limitations. More specifically, among blind participants, reciprocal effects have been found between phonological awareness and Braille reading skills with, for instance, the nature of the Braille orthography modulating phonological awareness skills (e.g., Dodd & Conn, 2000; Gillon & Young, 2002). Similarly, a recent eye-movement study comparing deaf and typical hearing participants revealed important differences in grammatical processing between both groups (Gómez-Merino et al., 2020). Interestingly, results suggest that the syntactic skills of deaf participants would have cascading effects in their sentence processing. In this context, the presence of a missing-phoneme effect with blind participants and of a missing-letter effect with deaf participants and blind participants—using the Braille system in the latter case—could help better understand the specificity of their language related cognitive processing.

A further research avenue derives directly from previous studies showing that the word frequency effect in reading tasks such as the naming task, the lexical decision task and eye movements in continuous reading are influenced by vocabulary size (e.g., Brysbaert et al., 2018; Kuperman & Van Dyke, 2011; Preston, 1935; Yap et al., 2012). Here, we hypothesized that vocabulary size could account for the disappearance of the word frequency effect in Experiment 2. However, a limitation of our study is the lack of a direct experimental test of this hypothesis. In light of previous inconsistencies of the word frequency effect in the missing-letter effect literature (e.g., Minkoff & Raney, 2000; Roy-Charland et al., 2022; Saint-Aubin et al., 2005; Smith & Groat, 1979), it would be worth systematically investigating the frequency-based missing-letter and missing-phoneme effects as a function of individual differences in vocabulary knowledge.

Conclusion

We established that the missing-phoneme effect is sensitive to word frequency and word function. Furthermore, we showed that the missing-phoneme effect is not a by-product of coarticulation. These results suggest that the missing-letter and missing-phoneme effects are derived from the same cognitive processes as suggested by the Attentional Disengagement model which successfully accounted for the results.

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Table 1

Critical words used in the P text.

Target words	Frequency per million	Number of occurrences within the text	Role	Frequency
Word Function				
Près [Adverb]	285.41	10	Content	Frequent
Puis [Conjunction]	272.77	10	Function	Frequent
Word Frequency				
Père [Father]	708.11	4	Content	Frequent
Peur [Fear]	307.23	6	Content	Frequent
Porte [Door]	536.96	5	Content	Frequent
Prune [plum]	0.55	6	Content	Rare
Pôle [pole]	2.77	4	Content	Rare
Pore [pore]	0.47	5	Content	Rare

Table 2

Critical words used in the d text of Experiment 3.

Target words	Frequency per million[1]	Number of occurrences within the text
High-frequency words		
Days	305.73	8
Food	154.43	9
Kind	590.69	8
Lady	217.08	8
Road	111.94	9
Word	235.55	8
Low-frequency words		
Dens	0.29	8
Bard	0.80	9
Spud	0.92	8
Suds	0.47	8
Rind	0.27	9
Curd	0.43	8

[1] Frequencies were taken from the $SUBTLEX_{WF}$ measure in the $SUBTLEX_{US}$ database.

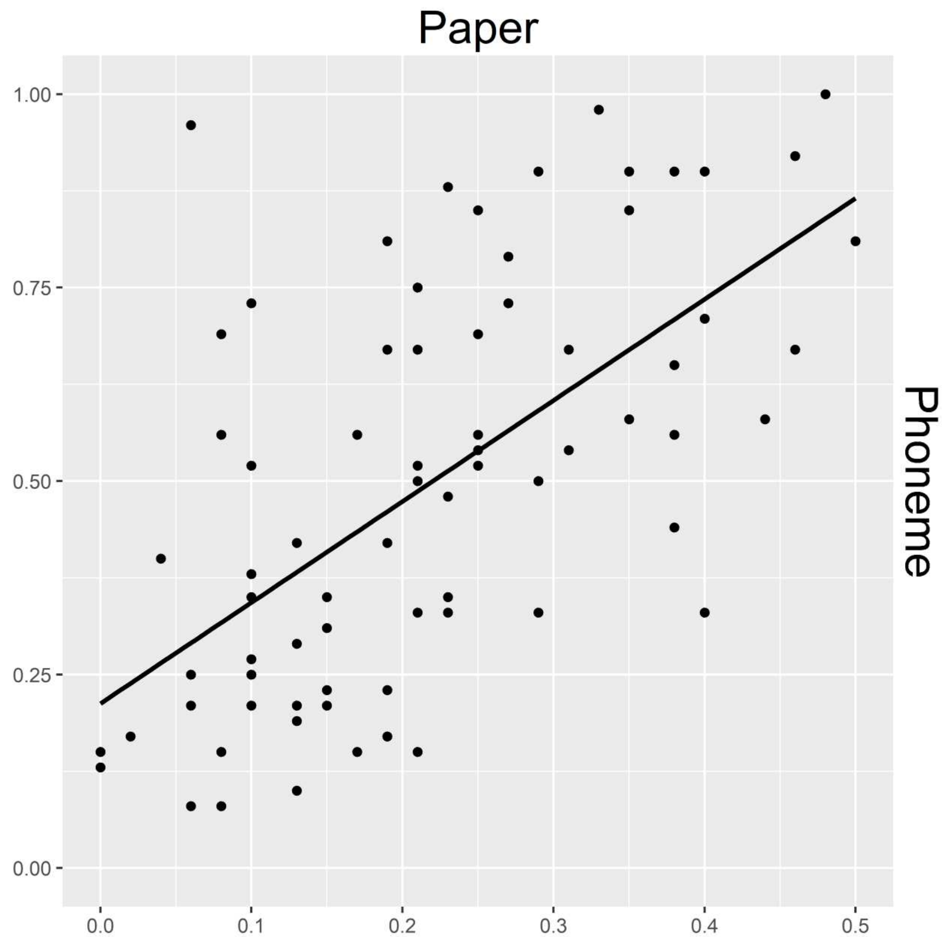

Figure 1. Reproduction of the scatter plot with best-fitted regression line from Saint-Aubin et al. (2016), demonstrating the relationship between mean omission rate on the listening task and mean omission rate on the reading task for each target-containing word.

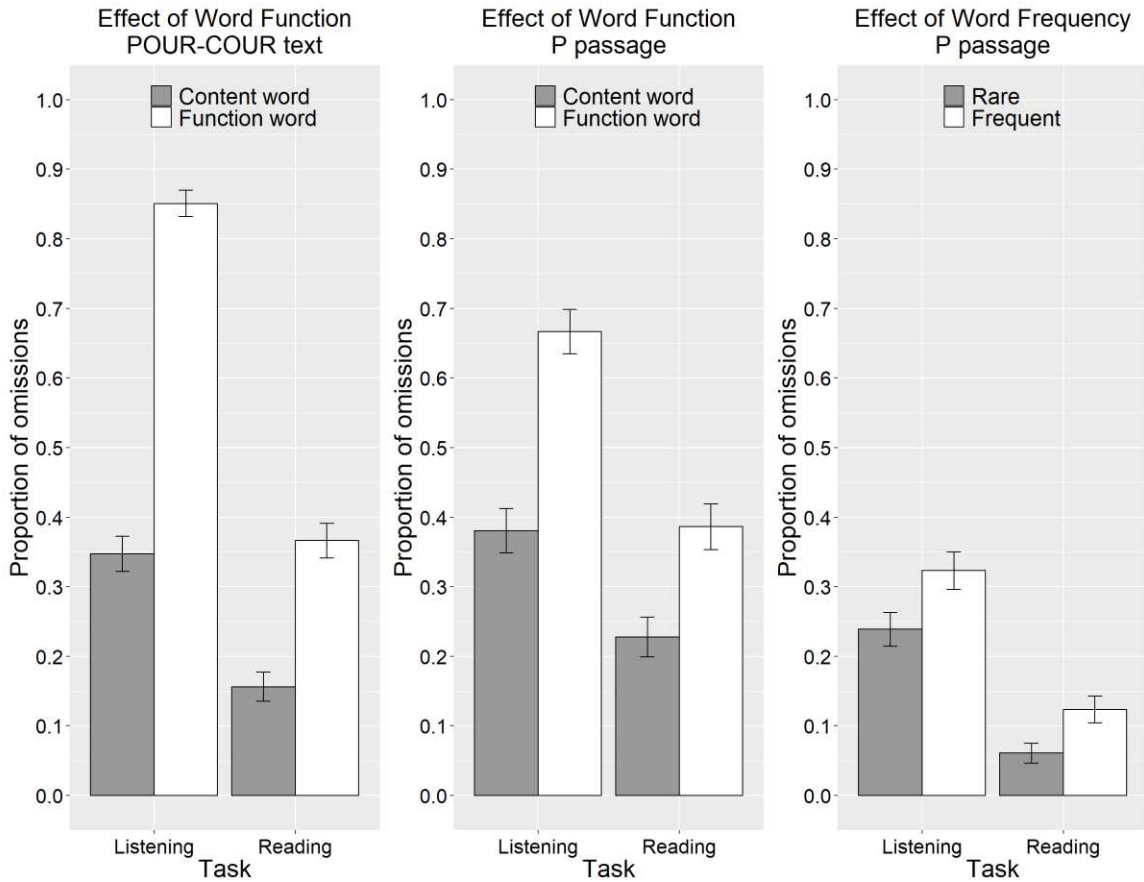

Figure 2. Mean proportion of omissions in Experiment 1 as a function of the text (*Pour-Cour* vs. *P* passage), task (listening vs. reading), and target (function or frequent vs. content or rare). Error bars represent 95% within-participant confidence intervals computed according to Morey's (2008) procedure.

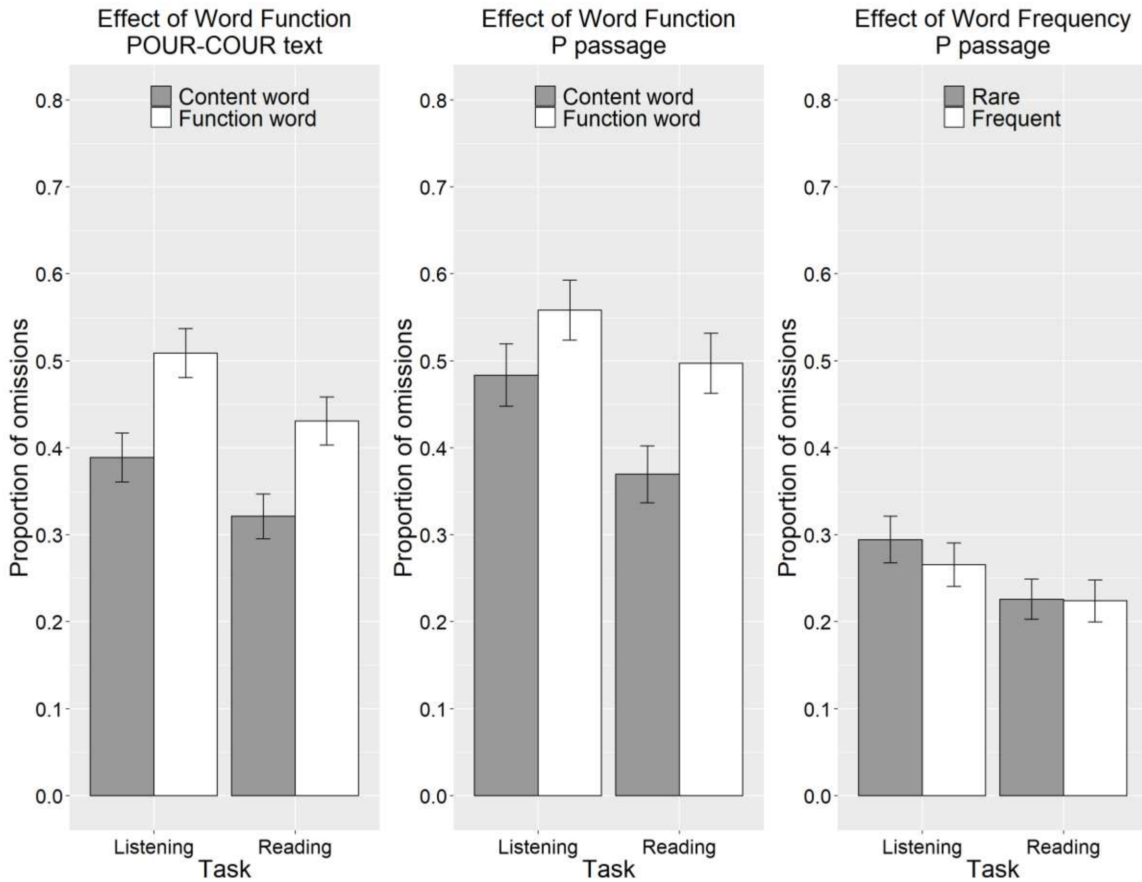

Figure 3. Mean proportion of omissions in Experiment 2 as a function of the text (*Pour-Cour* vs. *P* passage), task (listening vs. reading), and target (function or frequent vs. content or rare). Error bars represent 95% within-participant confidence intervals computed according to Morey's (2008) procedure.

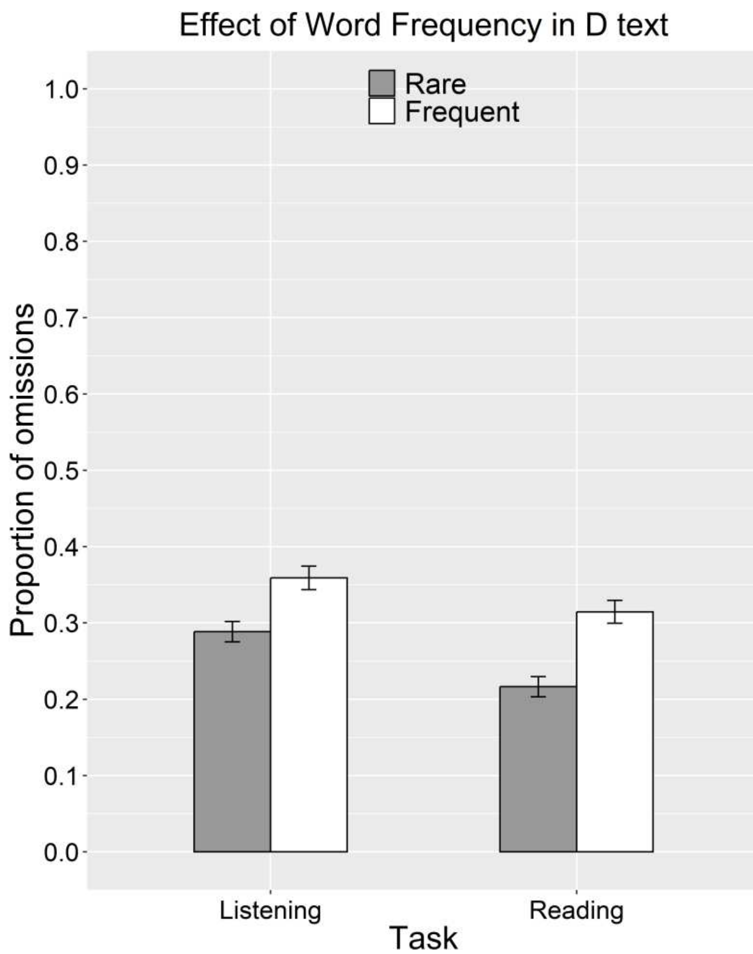

Figure 4. Mean proportion of omissions in Experiment 3 as a function of the task (listening vs. reading), and word frequency (frequent vs. rare). Error bars represent 95% within-participant confidence intervals computed according to Morey's (2008) procedure.

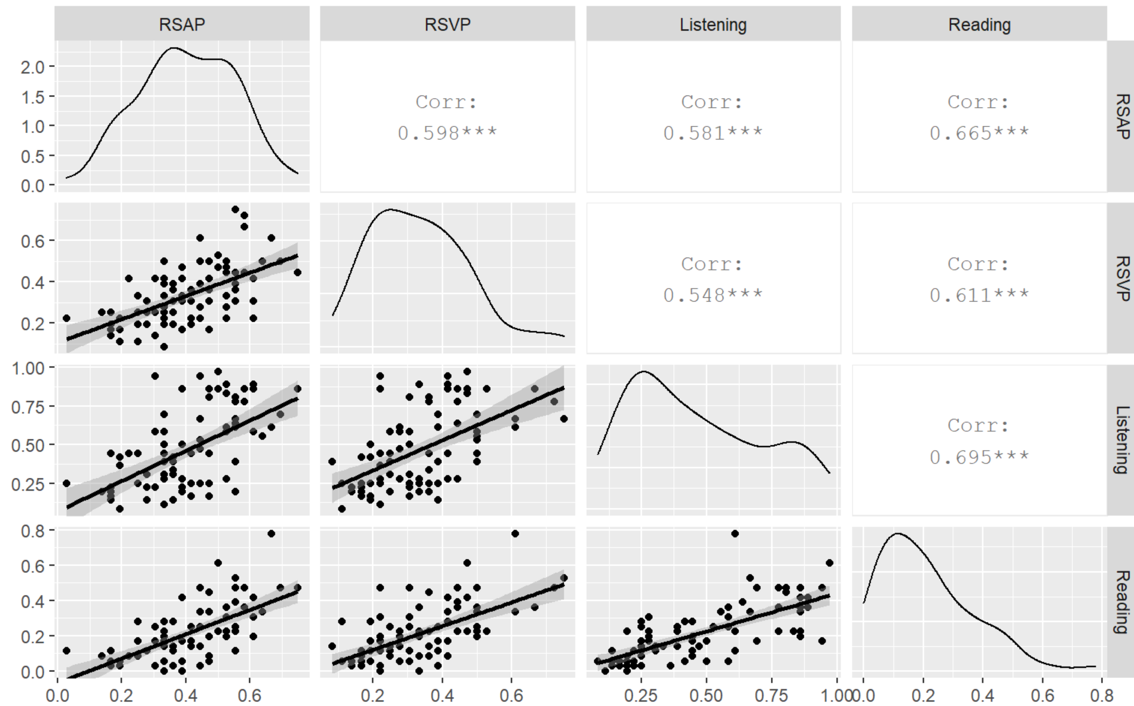

Figure 5. Scatter plot matrix with best fitting regression lines, density plots, and item-based correlations, illustrating the relation between mean proportion of omissions for each target containing word in both the *pour-cour* text and the *P* passage in the four detection tasks used here; the two detection tasks used in Experiment 1 (reading and listening) were combined with the two detection tasks used in Experiment 2 (RSVP and RSAP).

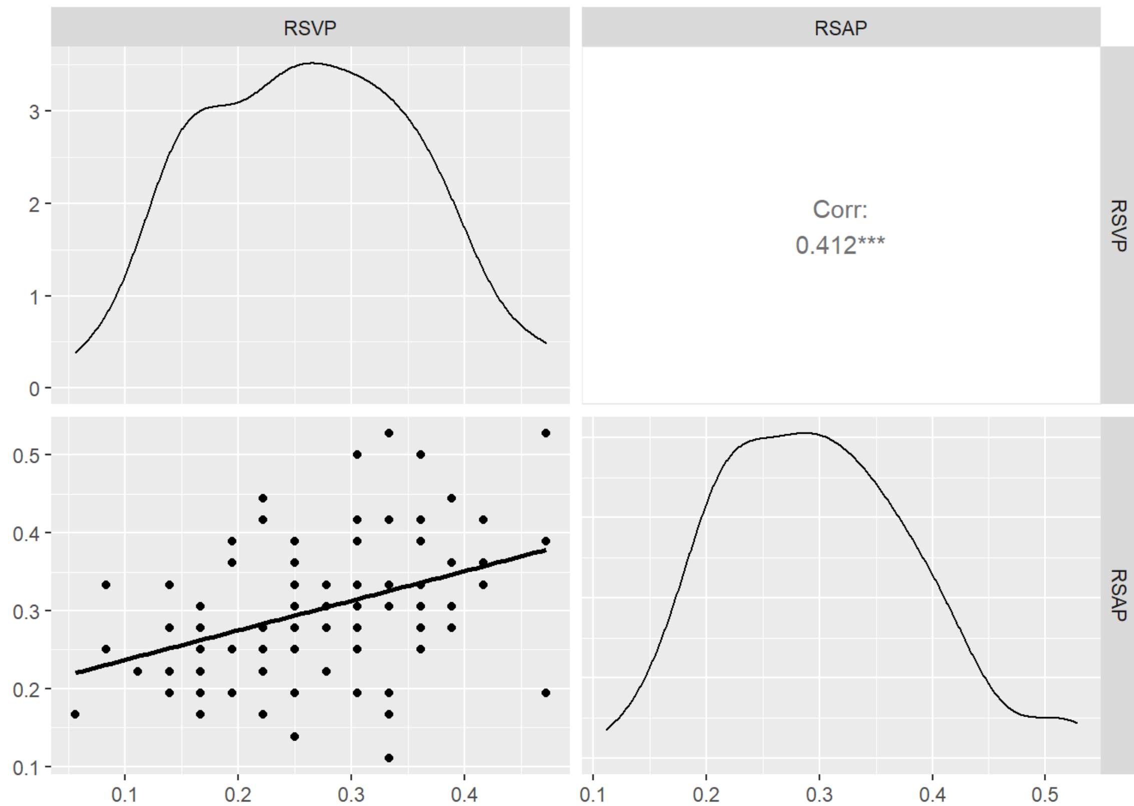

Figure 6. Scatter plot matrix with best fitting regression lines, density plots, and the correlation, illustrating the relation between mean proportion of omissions for each target containing word in the *D* text in both the RSVP and RSAP tasks.