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Authors
Angulo Chavira, Armando Quetzalcóatl
Castellón-Flores, Alejandra Mitzi
López-Santillán, Hillary
et al.

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Phono-semantic prediction during language comprehension: Effects of working memory

Armando Q. Angulo-Chavira (angulo-chavira@comunidad.unam.mx)
Facultad de Psicología, Universidad Nacional Autónoma de México

Alejandra Mitzi Castellón-Flores (mitzicastellon@comunidad.unam.mx)
Facultad de Psicología, Universidad Nacional Autónoma de México

Hillary López-Santillán (hillarylop98@gmail.com)
Facultad de Psicología, Universidad Nacional Autónoma de México

Natalia Arias-Trejo (nariast@unam.mx)
Facultad de Psicología, Universidad Nacional Autónoma de México

Abstract

There is strong evidence about the preactivation of semantic information but controversial results about phonological preactivation. This research explored the individual differences in phono-semantic preactivation using the visual world paradigm. Participants looked at four competitors (semantic, phonological, and two unrelated) while hearing highly constraining sentences. Moreover, they were evaluated in verbal and nonverbal speed processing and working memory. Our results showed a strong semantic prediction but an inhibition of the phonological effect. The semantic prediction was related to verbal and nonverbal working memory but not processing speed. The results were discussed in terms of lexical selection and inhibitory top-down influences.

Keywords: phonological preactivation, semantic preactivation, individual differences.

Introduction

Prediction plays an important role in language comprehension When reading or listening, the anticipation of the upcoming word facilitates comprehension by decreasing the cognitive load while increasing the processing speed (Huettig, 2015; Kuperberg & Jaeger, 2016; Pickering & Gambi, 2018). However, the mechanisms involved in selecting predicted information are still poorly understood. Previous research demonstrated the prediction of different levels of linguistic information before encountering predictable input. Strong converging research exists about the preactivation of semantic (Altmann & Kamide, 2007; Grisoni et al., 2017, 2021; Mani & Huettig, 2012) and syntactic (Martin et al., 2018; Wicha et al., 2004) information based on the sentence context.

More controversial is the prediction of the phonological and orthographic word form. In a pioneer work, (DeLong et al., 2005) presented highly constraining sentence context (e.g., *the day was breezy, so the boy went outside to fly…*). Crucially, the continuation of these sentence contexts was a highly predictable article and noun (e.g., a kite) or a less predictable plausible continuation but with a different article (e.g., an airplane). Results showed higher event-related potential responses when the article was incongruent with the predicted word than when it was congruent, revealing that the subject predicted the phonological word form of the expected word. This effect has been fully (Yan et al., 2017), partially (Martin et al., 2013), and not replicated (Nieuwland et al., 2018) in different studies.

Furthermore, Kukona (2020) presented a highly constraining sentence such *In order to have a closer look, the dentist asked the man to open his mouth*. Simultaneously, they looked at a visual array containing either the target (e.g., mouth), a phonological cohort competitor (e.g., mouse), an unrelated object (e.g., bone) or other distractors. Before hearing the target word, they looked at the target visual referent and the phonological competitor. These results suggested that participants preactivate the phonological word form. Similarly, these results have been partially replicated by other research using the visual word paradigm (Ito et al., 2016, 2018).

In their theory of prediction during language comprehension, Pickering and Gambi (2018) offered some insights into the possible explanations for the lack of general predictive effects (not specifically for phonological effects). Contrary to the most radical postures about prediction (Clark, 2013), Pickering and Gambi (2018) argued that prediction in language comprehension is optional; therefore, it depends on time and cognitive resources. Furthermore, it could be a matter of selection processes (Dahan & Tanenhaus, 2004).

Pickering and Gambi (2018) hypothesized that prediction during language comprehension is mediated by the production system (see also Dell & Chang, 2014; Martin et al., 2018). Thus, predictions are created serially by selecting the conceptual representation from the meaning of the sentences, then the syntactic representation, and finally, the phonological representation. (Ito et al., 2016) found that highly constraining sentences produced electrophysiological facilitation in a short (500 ms) and long (700 ms) presentation rate when a semantically related word replaced the expected word. However, when a phonological-related word replaced

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it, the facilitation was presented only in the long presentation rate. The authors argued that the preactivation of the phonological representations is time-dependent. Noteworthy, other researchers have found phonological effects in similar experimental manipulations with similar or faster presentation rates (DeLong et al., 2019; Laszlo & Federmeier, 2009). Furthermore, some researchers deny that lexical access in the production system is strictly serial; instead, they propose cascading or parallel mechanisms (Dell, 1986).

In another vein, the phonological preactivation could be modulated by competition or inhibition processes. (Dell & O'Seaghdha, 1994) argued that inhibitory processes during production should affect phonological representations because it is necessary for articulation. Supporting evidence for this idea has been provided by Dahan and Tanenhaus, (2004). In a target-present visual world paradigm, they found that constraining a verb, but not neutral verbs, elicited looks toward the target referent but not to the phonological or semantic competitor. Although Dahan and Tanenhaus, (2004) analyzed only the period after the target presentation, subsequent work showed that there were also no phonological effects prior to the presentation of the target (Blomquist et al., 2023).

Blomquist et al. (2023) explained that the selection of the target word inhibits other phonological-related lexical candidates from increasing the accuracy of the target processing. This claim aligns with phonological preactivation in target-absent designs (Ito et al., 2018; Kukona, 2020). Additional support comes from a nonpredictive visual word paradigm with a target-absent set-up; they showed that semantic competitors exert a top-down suppression of the phonological effect (Chow et al., 2022). Similarly, Karimi et al. (2019) found a predictive fixation to the phonological-related referent (e.g., hammock) that could function as a correction of an erroneous noun (e.g., hammer). Still, this effect disappeared when a semantic competitor was introduced (e.g., nail). Noteworthy, they found the same semantic and phonological effects by using the target word in isolation. Therefore, it is still being determined to which extent participants used the sentence context or the bottom-up target processing to activate semantic and phonological information (but see Kukona (2020) for a discussion of spreading activation as a predictive mechanism).

Finally, Pickering and Gambi (2018) argued that prediction is hindered when there are low cognitive resources. For example, toddlers with low vocabulary (Borovsky et al., 2012; Mani & Huettig, 2012) and children with low reading skills (Mani & Huettig, 2014) failed to make semantic predictions. Also, children with Down syndrome failed to make contextual but not associatively semantic predictions (Angulo-Chavira et al., 2022). At a phonological level, several works revealed that non-native speakers failed in phonological prediction (Ito et al., 2018; Martin et al., 2013). Also, toddlers (Gambi et al., 2018) and older adults (DeLong et al., 2012) did not show signs of phonological prediction. Furthermore, Kukona et al. (2016) found that the rapid automatized naming task was related to inhibiting unplausible but perceptually-related competitors during predictive lexical selection.

The present study

The present study investigated the time course of phono-semantic activation and its relationship with verbal and nonverbal processing speed and working memory. Participants were presented with highly constrained auditory sentence context and a target-absent picture array including a semantic competitor, a phonological competitor and two unrelated competitors. We hypothesized that participants would look at both competitors, upon hearing a verb, but before presenting the target word. Also, this predictive effect would be mediated by general domain speed processing and working memory.

Method

Participants

A total of 39 undergraduate students participated in the experiment (M = 19.08 years, SD = 1.13). All participants were native Mexican Spanish speakers, had a normal or corrected-to-normal vision and reported the absence of any neurological, psychiatric or language problems.

Stimuli

The stimuli consisted of 32 sentences with a high cloze probability toward the final word (cloze >.88); 16 sentences were used as filler and 16 as experimental trials in the task. A young male recorded all sentences at his normal speech rate.

For each filler sentence, three phonological and semantically unrelated words were chosen. For the experimental sentences, four words were selected: 1) a phonological competitor with the same first syllable as the final word but semantically unrelated; 2) a semantic competitor from the same coordinate category but phonological unrelated; and 3-4) two semantic and phonologically unrelated words.

The referents of these competitor words were presented visually in a 2x2 array using realistic photographs taken from public libraries on the internet (Figure 1). Pictures names were evaluated by 70 young adults with 98.43% of accuracy. In the filler trials, the target was presented with three unrelated words. In the experimental trials, the target was absent, but the phonological, semantic, and unrelated competitors were shown.

In two pilot studies, the predictive effects of the competitors were tested using a similar experimental design but with the presentation of the phonological or semantic competitor separately. Participants (n = 32) from the pilot studies looked more at the phonological and semantic competitors before the final target word was heard. Hence, our experimental sentences and competitors elicited phonological and semantic preactivation.

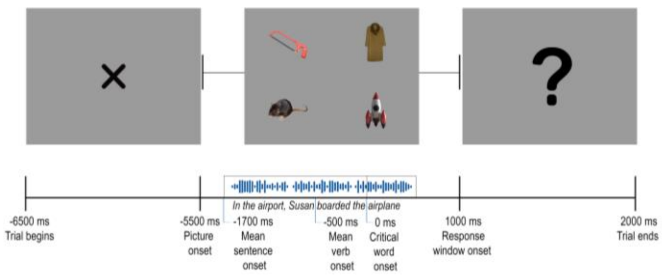

Figure 1: Example of an experimental trial.

Experimental design

Each trial lasted 7,500ms, but at all times they were relative to the onset of the final word (0ms). From -6500ms to -5500ms, a fixation point was shown; from -5500ms to 1000ms, the visual competitors and auditory sentences were presented; and from 1000ms to 2000ms, a question mark was displayed. On average, sentences were presented from -1700ms to 500ms. Participants were asked to press a green button if the target was present and a red button if the target was absent when the question mark appeared. The behavioural task aimed to maintain the participant's attention.

Cognitive assessment

To explore individual differences in the effect of phonological and semantic competition, we performed five cognitive assessments that were applied. We evaluated the processing speed and working memory in verbal and nonverbal tasks. The rationale was to test domain-specific effects assessing cognitive processes previously associated with language prediction (Huettig & Janse, 2016).

The verbal speed processing task was measured for semantic and phonological verbal fluency (Ostrosky-Solís et al., 1998). In the former, participants were asked to say as many animals as they could. In the latter, they had to say as many words with /f/ as possible. Both tasks lasted one minute.

For non-verbal speed processing, we used the Coding (Wechsler, 2008). Participants were asked to match a series of numbers with their corresponding symbols presented in a sample. They had to match as many symbols as they could in two minutes.

The verbal and nonverbal working memory was assessed using the reverse digit (Wechsler, 2008) retention test and Corsi's blocks (Ostrosky-Solís et al., 1998), respectively. In this task, the experimenter listed a series of numbers or pointed to a series of blocks, and the participant was asked to repeat the sequence in inverse order. The score was the length of the longest sequence that the participant remembered correctly.

Procedure

After written consent was obtained, participants performed the experimental task. They were seated at approximately 60 cm on a 1920x1080 pixels screen in a noise-reduced cubicle. Gaze data were recorded using a Tobii TX300 with a sample rate of 300 Hz. The experimental task was presented in Tobii Pro Lab. The session started with three test trials. Then, participants performed a 5-point calibration procedure, followed by the experimental task. Later, the cognitive assessment was performed in a different room.

Data processing and statistical analysis

All data processing and statistical analysis were performed in R (CoreTeam, 2020). Fixations were computed using the Tobii I-VT Fixation Filter independently for each competitor. Data containing less than 50% valid samples during the competitor presentation period were excluded.

We averaged the fixation over two windows: the prediction (-350 to 0ms) and the integration (0 to 350ms) windows. This window was based on the verb onset of the sentences, and previous predictive phonological effects (Ito et al., 2018; Li et al., 2022). Also, enough time to measure any bottom-up phonological effect (Huettig & McQueen, 2007).

A binomial mixed effect model was performed. The probability of fixation was our dependent variable. The fixed factors were the competitor (unrelated, phonological, and semantic) and window (prediction and integration). The random factors were the random intercepts and slopes of the fixed factors (Competitor*Window) on the Subject and Items. To keep the 'maximum' random structure without convergence failures, the correlation matrix of the model was deleted (Barr, 2008).

The individual differences were tested by measuring the fit of the model (via log-likelihood comparison) when cognitive assessments were independently added to the model.

Results

The binomial mixed effect model (Table 1, Figure 2) showed that the semantic competitor had a higher fixation probability than the unrelated competitors, independently of the window ($p = 0.03$). Furthermore, there was an interaction between the phonological competitor and the window ($p = 0.04$), revealing that the difference between the phonological competitor was higher in the integration than the prediction window. No other effect or interaction was significant ($p > 0.25$).

Table 1. Main binomial mixed effect model

Fixed factor	*β*	*SE*	*Z*	*p*
Intercept	-1.345	0.124	-10.827	<0.001
Phonological	-0.216	0.208	-1.039	0.298
Semantic	0.668	0.325	2.057	0.039
Window	-0.099	0.087	-1.133	0.257
Phonological:Window	0.377	0.189	1.999	0.045
Semantic:Window	0.078	0.259	0.304	0.761

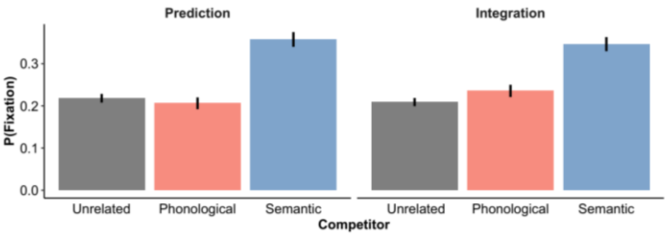

Figure 2. Main comparison among competitors.

The model comparison (Table 2) showed that only the verbal working memory (Digit retention) significantly increased the main model's fit (p = 0.003). However, the model with nonverbal working memory (Corsi's blocks) also was marginally significant (0.058).

Table 2. Model comparison for individual differences.

Models	*logLik*	X^2	*df*	*p*
Main model	-143696			
Semantic fluency	-143694	4.455	6	0.615
Phonological fluency	-143691	10.921	6	0.090
Coding	287839	9.2901	6	0.157
Digit retention	-143687	19.207	6	0.003
Corsi's blocks	-143690	12.181	6	0.058

In a further exploration of the significant models, we found an interaction among verbal working memory, semantic competitor, and window (β = -0.84, SE = 0.20, Z = 4.03, p < 0.001). This result indicated that participants with higher working memory looked more to the semantic competitor in the predictive window but less in the integration window (Figure 3). Other significant effects mimicked the results of the main model.

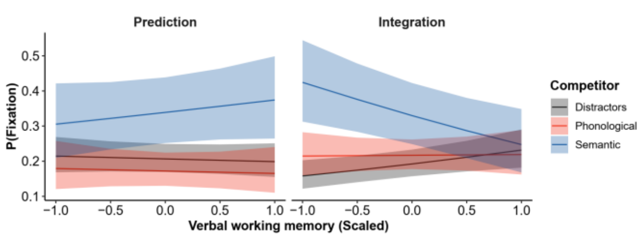

Figure 3. Predicted fixation probabilities for the effect of verbal working memory on the experimental effects.

By contrast, the marginally significant model showed a three-way interaction among nonverbal working memory, window, and both phonological (β = -0.47, SE = 0.24, Z = -1.94, p = 0.051) and semantic (β = -0.64, SE = 0.20, Z = -3.11, p = 0.001) competitors (Figure 4). Similarly to verbal working memory, participants with high nonverbal working memory looked less at the semantic competitor in the integration window. Crucially, they tend to look more at the phonological competitor in the prediction window, but they look at it less in the integration window. They also look more to the unrelated competitor in the integration window.

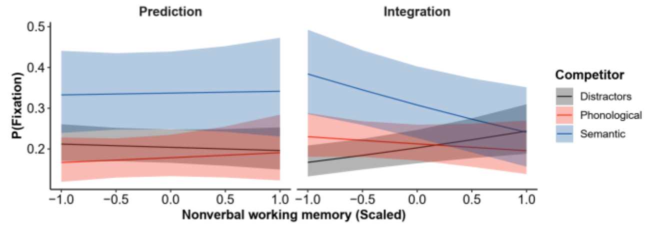

Figure 4. Predicted fixation probabilities for the effect of nonverbal working memory on the experimental effects.

Discussion

The present research investigated individual differences in phono-semantic preactivation. In a target-absent visual world paradigm, highly constraining sentence contexts were presented together with four competitors: semantic, phonological, and two unrelated. These participants also performed verbal and nonverbal processing speed and working memory tasks.

Our results revealed a strong effect of semantic prediction but null phonological preactivation. After the presentation of the expected target, the semantic effect continued, and the bottom-up phonological effect emerged. Additionally, only working memory but no processing speed was related to our results. The semantic effect was particularly related to verbal and nonverbal working memory tasks, but the phonological effect was related only to nonverbal working memory. Participants with higher working memory tended to predict better but reduced the bottom-up processing.

The semantic predictive effect is similar to those reported in previous research (Li et al., 2022), ending after the presentation of the expected word onset. This strong effect is possibly related to the main goal of communication: understanding the meaning of the message. Therefore, it is possible that the meaning of the sentences pre-active more the semantic information (Li et al., 2022).

According to Pickering and Gambi (2018), phonological preactivation is optional and the late stage of lexical prediction. Hence, it is only carried out when there are time and cognitive resources. Our results partially support the optionality of phonological predictions. However, we attribute this result to lexical competition processes instead of temporal factors. Previous research has shown indirect evidence of phonological prediction in a normal presentation rate (DeLong et al., 2019). Moreover, our pilot studies (not presented here) showed that our stimuli elicited phonological preactivation (without the semantic competitor). Thus, our participants had enough time to make predictions, but there was an effect by introducing the semantic competitor.

In a nonpredictive experiment, Huettig and McQueen (2007) found that phonological activation depends on the preview of the pictures. When pictures were presented in a long (1,000 ms) but not short (200 ms) preview, the phonological cohort effects were presented. By contrast, Apfelbaum et al. (2021) showed that the bottom-up phonological effect is presented even with a null preview. Crucially, Apfelbaum et al. (2021) presented the phonological competitor in isolation. Chow et al. (2022) demonstrated that the inclusion of a semantic competitor explains the null phonological effect in the short preview in Huettig and McQueen (2007). Chow et al. (2022) claimed that the semantic competitor exerts a top-down inhibition over the phonological competitor when the preview is short.

The present research has a long preview (5,000 ms) before presenting the prediction point (the determinant). Thus, the phonological effect should be presented even with the introduction of the semantic competitor. An important difference between nonpredictive and predictive phonological effects is that the former is elicited by temporal ambiguity (Dahan & Tanenhaus, 2004). In contrast, in the latter, the phonological activation is created by predicting the expected word (Pickering & Gambi, 2018). In this regard, the suppression of the phonological competitor may be mediated by selecting the semantic competitor as the nearest candidate of the general meaning of the sentences. This interpretation is supported by target-present works where both semantic and phonological effects are suppressed when the target is selected from constrained verbs (Dahan & Tanenhaus, 2004). Another plausible explanation is that the predictive system always looks for information that allows accurate prediction; therefore, when the phonological competitor is presented in isolation, it takes its information to generate the prediction. In this sense, semantic competitors could be more informative cues; for example, in a sentence constrained toward edible nouns, the predictive system would prefer to active the category food rather than random words with a specific phoneme.

Regarding individual differences, we found that working memory is related to both semantic and phonological effects. This result is congruent with previous research on individual differences of prediction (Huettig & Janse, 2016; Otten & van Berkum, 2009). Since our task is mediated by visual and spatial attention, the nonverbal working memory would be related to the spatial location of the visual competitors. In contrast, verbal working memory maintains the lexical representation of the sentence context and the labels of the object on the screen. Importantly, the effect of working memory in the integration is higher than in the prediction window because participants with higher working memory tend to look less than those with lower working memory. This is an important distinction because prediction is performed to preprocess information to reduce the cost of processing the bottom-up stimulus. Thus, it is possible that participants with a higher working memory performed better predictive processing, taking advantage of their spatial and verbal representations.

Conversely, we failed to replicate the previous relationship between prediction and processing speed (Huettig & Janse, 2016). Theoretically, prediction makes language processing faster because stimuli are preprocessed. People with faster speed processing should predict fast. A possible explanation for our results is that processing speed affects the temporality but not necessarily the magnitude of the effect. Thus, a more fine-grained analysis considering the time is required.

Additionally, it is possible that we failed to observe an effect on the speed of processing because we had a small sample size. Usually, individual difference studies assess a large number of participants to have a good variability in their cognitive skills.

To summarize, we found two main results, semantic information elicited the inhibition of phonological one. Moreover, working memory is related to preactivating semantic information.

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