Adaptation to noisy language input in real time: Evidence from ERPs

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Abstract

Language comprehension often deviates from the literal meaning of the input, particularly when errors resembles more plausible alternatives. Such non-literal interpretations have been associated with a reduced N400 and increased P600, but it remains debated whether these effects reflect perceptual misrepresentation of the input or error correction. One way to tease apart these accounts is to examine how comprehenders adapt to a noisy linguistic environment. A perceptual error account predicts that increased exposure to noise leads to habituation to errors and more misperception, resulting in reduced N400 and P600 responses. In contrast, an error correction account predicts that comprehenders perform more error correction in noisy environments, leading to increased P600s, and potentially modulated N400s depending on the timing of the correction. In this study, we manipulated the proportion of errors in non-critical exposure sentences and measured ERP responses to different types of anomalies. The results replicated prior findings of reduced N400s for recoverable errors. Results in the P600 window were not replicated and it remains an open question which framework (error correction vs. perceptual error) best accounts for the data. Further, the results revealed substantial individual differences in processing words which may contain errors with implications for how participants adapted to additional noise in the environment.

Keywords: Language processing; Event-related potentials; Noisy-Channel; Perceptual Error; Language adaptation

Introduction

In everyday communication, language input is often noisy. Yet comprehenders are remarkably adept at understanding the meaning of a sentence given imperfect input. When reading *The storyteller could turn any incident into an amusing antidote*, a comprehender might interpret *antidote* as a more plausible alternative, *anecdote*. Language comprehension can deviate from the literal, compositional meaning of the input and arrive at a non-literal interpretation (Trueswell et al., 1993; Frazier & Rayner, 1982; MacDonald et al., 1994; Van Gompel et al., 2000; Bever, 1970; Ferreira & Clifton Jr, 1986; Pickering & Traxler, 1998; Levy et al., 2009; Ferreira et al., 2002). Importantly, the non-literal interpretation process is adaptive. When comprehenders are exposed to a linguistic environment with frequent noise (e.g. texts with typos or recoverable anomalies), they can adjust their processing strategies to rely more on prior knowledge and thus be more likely to interpret sentences non-literally.

Theoretical accounts generally agree that non-literal interpretations reflect a trade-off between perceptual input and prior expectations. However, they differ in terms of when and how prior knowledge influences comprehension. We distinguish three hypotheses regarding the timing of reinterpretation: (1) perceptual error, (2) pre-lexical error correction, and (3) post-lexical error correction. In the perceptual error account, prior expectations shape the perception of input itself. Comprehenders may misperceive noisy or ambiguous input as a more expected word, even before lexical retrieval. Evidence from speech perception and eye-tracking shows that prior knowledge can bias categorization of phonemes and visual word recognition (Ganong, 1980; Staub et al., 2024). The detection of error is adaptive: comprehenders may habituate to the presence of many non-standard forms given repeated exposure to noisy linguistic input and adjust their threshold for error up (Caffarra & Martin, 2019).

In contrast, comprehenders may rationally infer the intended meaning from noisy linguistic input by balancing reliance on prior probabilities and the likelihood of noise-induced corruptions (Levy et al., 2009; Levy, 2008; Gibson et al., 2013; Futrell & Gibson, 2017; Futrell et al., 2020; Ryskin et al., 2021; Zhang et al., 2023; Poppels & Levy, 2016). This inference process may occur either before lexical retrieval (pre-lexical correction) or after it (post-lexical correction). If correction occurs prior to lexical retrieval, comprehenders are expected to retrieve the meaning of the inferred word rather than that of the presented input, thereby reducing the processing effort required for lexical access. After repeated exposure to recoverable errors, comprehenders are more likely to attribute them to noise and infer something more plausible.

One way to adjudicate between these accounts is to examine how adaptation to a noisy linguistic environment influences N400 and P600 amplitudes across error types. The N400 is commonly associated with lexical access and semantic integration(Kutas & Hillyard, 1980; Kutas & Federmeier, 2011), while the P600 is associated with reanalysis and revision (Van de Meerendonk et al., 2011; Vissers et al., 2006; Kolk et al., 2003; Van Herten et al., 2005a). For N400 component, both perceptual error and pre-lexical correction accounts predict that noise exposure lead to higher likelihood of non-literal form and therefore reduced N400 responses due to facilitated access to the non-literal form. If correction occurs after lexical retrieval, the N400 should be less sensitive to noise rate, or even increase, due to stronger activation of context-driven alternatives. For P600 component, under the perceptual error account, habituation to errors leads

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to less need for re-analysis and therefore a reduced P600. In contrast, pre-lexical and post-lexical correction accounts predict a larger P600 under high-noise conditions, reflecting increased effort to resolve the conflict between the perceived form and the inferred intended word.

The present study tests these predictions by manipulating the rate of noise in non-critical exposure sentences and examining ERP responses to recoverable and unrecoverable anomalies. As shown in Figure 1, we crossed error type conditions (within-subjects) with exposure groups (between-subjects). Participants saw four types of critical sentences: semantically implausible, syntactically incorrect, recoverable (semantically implausible but close to a plausible word), and Control sentences. Exposure conditions varied, with the *No Noise* group seeing error-free sentences and the *Noise* group encountering blatant typographical errors. The results do not cleanly adjudicate between error correction and perceptual error mechanisms but reveal substantial individual differences in comprehenders' processing strategies, which have implications for how they adapt to noise.

Method

Participants

We recruited 57 native English speakers from University of California Merced and surrounding communities. All participants were paid $12 per hour. The participants' ages ranged between 18-33 years old (mean = 21.6), and included 39 females. Nine subjects were not included because of low accuracy on comprehension questions (N = 3), low data quality or experimenter error (N = 3), no demographic information provided (N = 1), or incomplete data (N = 2). 48 subjects were included in the final analysis. All participants reported normal or corrected-to-normal vision and did not report cognitive impairment.

Experimental design

We crossed error type conditions (within-subjects) with exposure groups (between-subjects) (Fig. 1). We included four conditions with different types of sentences by manipulating the last word in the sentence. In Control condition, the target word is congruent with the preceding context (e.g. The storyteller could turn any incident into an amusing *anecdote*). In the Semantic condition, the target word is semantically implausible given the preceding context (e.g. *hearse*). In the Syntactic condition, the target word is syntactically incongruent with the preceding context (e.g. *anecdotes*). In the Recoverable condition, the target word is semantically implausible but orthographically close (as measured by Levenshtein distance) to the semantically plausible word from the Control condition (e.g. *antidote*).

We also manipulated the rate of errors that comprehenders are exposed to between subjects. In the *No noise* exposure group, exposure sentences did not contain errors (e.g. A bystander was rescued by the fireman). In the *Noise* exposure group, exposure sentences contained blatant typographical errors (e.g. A bystander was rescued by the *firetan*).

Materials

We adapted stimuli from Ryskin et al. (2021). There are 640 ten-word-long experimental sentences with 160 in each condition. The target word always appears at the end of the sentence. The target words in the semantic and recoverable conditions were used as target words in Control items for other items. Therefore the target words were identical across conditions. The experimental sentences were evaluated for cloze probability of the target word, acceptability, and recoverability of the intended word (see Ryskin et al., 2021, for more details). In the original study, there were 280 error-free ten-word-long filler sentences. In the current study, 40 of those filler sentences were used as exposure sentences. In the No Noise exposure condition, those sentences were unchanged. In the Noise exposure condition, errors were introduced on those 40 sentences. These involved changing one to six characters in a word to create a non-word in English. Half of the errors appeared at the end of the sentences, and the other appeared in the middle of the sentences. The distribution of edit distances between the Noise and No Noise exposure sentences was similar to the distribution between Control sentences and their counterparts in Syntactic and Recoverable conditions. All sentences are distributed into 8 lists following a Latin Square design, and the order of sentences was randomized for each participant.

Procedure

Comprehenders completed questionnaires about demographic information (language background, familial handedness, past brain injuries). Participants were instructed to sit in a quiet room and read sentences while EEG signals were recorded. The sentences were presented word by word at the center of the screen. At the beginning of each trial, a fixation cross was presented for 1000ms, followed by a blank screen for 500ms. Each word was presented for 400ms, followed by an inter-stimulus interval of 100ms. The last word had an additional 800ms interval. There were ten breaks over the course of the experiment. One third of the trials were followed by yes/no comprehension questions to keep participants engaged. There were no more than three consecutive trials with a question, and no more than 20 consecutive trials without a question. The correct answer for half of the questions was "yes".

EEG recording and analysis

The EEGs were recorded with a Brain Vision actiCHamp Plus System (Brain Products GmbH) with 64 active electrodes. A separate vertical EOG (VEOG) electrode was attached below the left eye. Two horizontal EOG (HEOG) electrodes were placed at the outer canthus of both left and right eyes, and one was placed on the cheek near the chin. The electrode Cz was referenced online during recording. Continuous data were

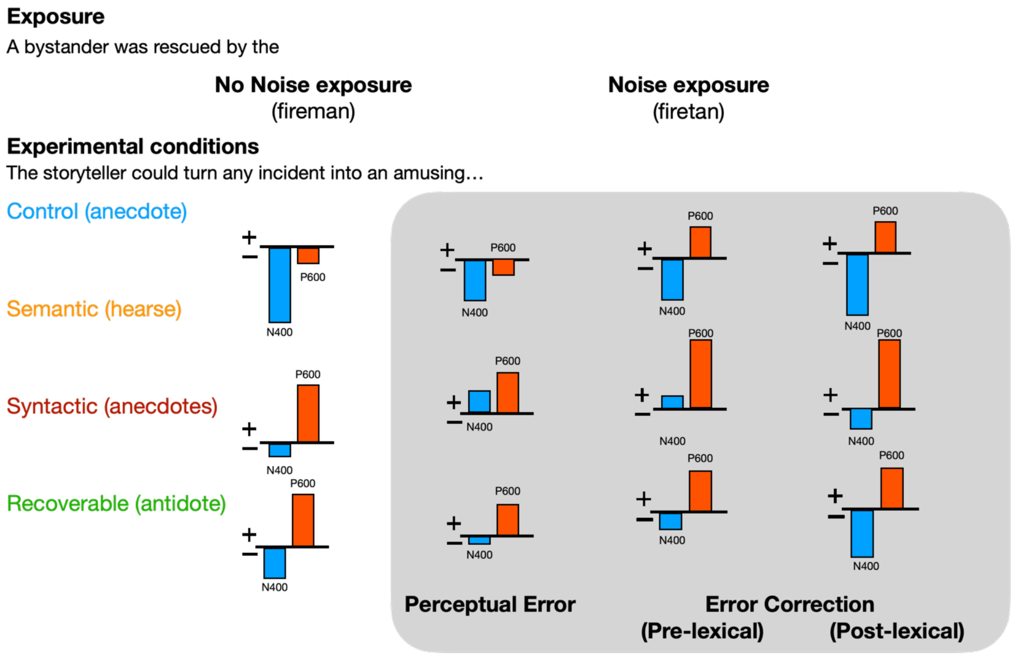

Figure 1: An illustration of the experimental design and predictions for ERP patterns according to error correction (pre- and post-lexical) and perceptual error frameworks. After Noise exposure, N400 is increased in post-lexical correction framework; otherwise reduced. P600 is reduced in perceptual error account; otherwise increased.

digitized using the BrainVision Recorder with a sampling rate of 1000Hz. The entire recording lasted for about 60 minutes.

All EEG data was processed in MATLAB using EEGLAB and ERPLAB (Brunner et al., 2013; Lopez-Calderon & Luck, 2014). The data was filtered offline with a 0.1Hz high-pass filter and a 30Hz low-pass filter with 48 dB per Octave and downsampled to 500Hz. The EEG signals were re-referenced to the average of two mastoid channels TP9 and TP10. Independent Component Analysis (ICA) was performed to correct eye movement and other artifacts. Long breaks (more than 10 seconds between two events) and sections with excessive movements (a threshold of $500\mu V$ with a window size of 1000ms) were removed before ICA to avoid potential interference. Components with ocular and muscle artifacts were removed after visual inspection. After ICA correction, we epoched data with a time window between -200ms before the word onset and 1000ms after the word onset. Baseline correction was performed relative to the -200ms-0ms time window. Epochs exceeding $\pm 100\mu V$ were rejected using a peak-to-peak moving window approach, with a moving window size of 200ms and a 100ms step between successive windows.

We analyze mean N400 and P600 amplitudes elicited by critical words over fifteen pre-determined centro-parietal electrodes (Cz, CPz, Pz, C1, CP1, P1, C2, CP2, P2, C4, CP4, P4, C3, CP3, P3). Following prior research, we selected 300-500ms for the N400 time window and 600-900ms for the P600 time window (Ryskin et al., 2021). For each time window, we calculated the mean amplitude elicited by each target word for each subject. We analyze the results in a linear mixed effect model as shown in Eq. 1. The main effects include dummy-coded variables *Condition* with Control condition as the reference level, and *Exposure* with No Noise exposure as the reference level. The model includes random intercepts and slopes for participants, items and electrodes.

$$\begin{aligned}\text{Amplitude} \sim\ & \text{Condition} * \text{Exposure} + (1 + \text{Condition} \mid \text{subject}) \\ & + (1 + \text{Condition} * \text{Exposure} \mid \text{item}) \\ & + (1 + \text{Condition} * \text{Exposure} \mid \text{electrode})\end{aligned} \tag{1}$$

Results

Participants answered the comprehension questions accurately most of the time. All subjects included in the analysis had an accuracy rate over 75%, with an average accuracy rate of 88.5% (SD: ± 5.8%)

N400 Fig. 2 shows the average ERP waveforms to target words by condition for fifteen electrodes for *No Noise* and *Noise* exposure conditions. Fig. 3 shows the topographic maps of ERP amplitude difference between critical conditions and Control condition in the 300-500ms N400 time window and 600-900ms P600 time window. As expected, in the No Noise exposure condition, the N400 responses were larger (more negative) in the Semantic condition than in the Control condition ($\beta = -1.41$, $t = -3.18$, $p < .01$), and there was no significant difference between Syntactic and Control conditions ($\beta = -0.19$, $t = -0.58$, $p = .56$). There was also

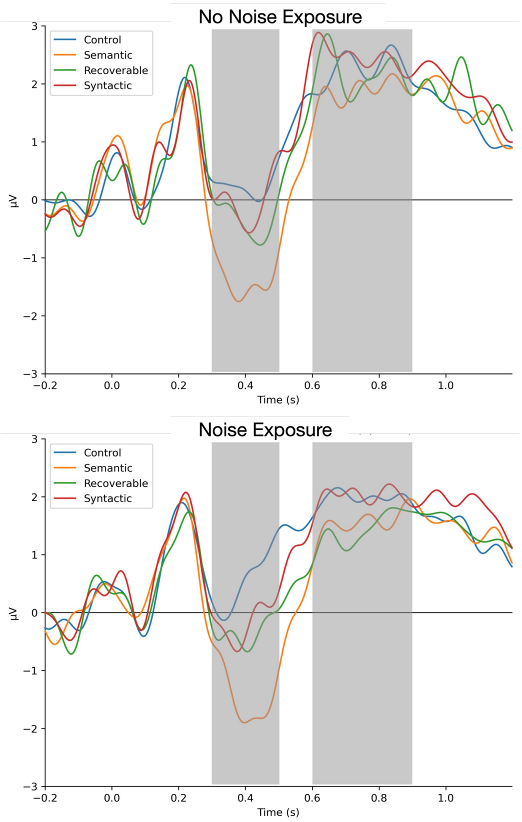

Figure 2: Grand-averaged ERP waveforms to the target words at 15 central-posterior electrodes in No Noise (top) and Noise (bottom) exposure conditions.

no significant N400 effect elicited by the Recoverable condition (β $= -0.50$, $t = -1.24$, $p = 0.21$) in the No Noise exposure condition. There is no significant difference between No Noise and Noise exposure groups (β $= 0.18$, $t = 0.40$, $p = 0.68$) in the Control condition. Crucially, the interactions between target word conditions and exposure were also not significant (Semantic by Noise Exposure: β $= -0.11$, -0.17, $p = 0.86$, Recoverable by Noise Exposure: β $= -0.05$, $t = -0.08$, $p = 0.93$, Syntactic by Noise Exposure: β $= -0.30$, $t = -0.63$, $p = 0.52$).

Replicating Ryskin et al. (2021), we show that the N400 reduction in the Recoverable condition is related to the recoverability of the target word. Fig. 5 shows the relationship between the size of N400 effect of an experimental item (averaged across participants) and the recoverability of the given item, as measured by Levenshtein edit distance between the target word and its counterpart in the Control condition. The N400 is linearly related to the recoverability of the word ($r = -0.24$, $p < 0.001$). Items with a smaller edit distance from the Control counterpart (easier to recover) elicited a smaller N400 effect relative to Control.

In an exploratory analysis, to test whether any differences between exposure conditions may have emerged over the course of the experiment but not have been visible when averaging over the whole session, we examined the relationship between the magnitude of N400 effect and the presentation order of an item in the experiment (Fig. 4). In the No Noise exposure condition, N400 effects to semantic errors decreased (became less negative) as the experiment progressed (Semantic by Order: β $= 0.001$, $t = 3.23$, $p < 0.01$). In the Noise exposure group, the magnitude of N400 effects to recoverable and syntactic errors increased (more negative) as the number of presented errors increased (Recoverable by Order: β $= -.003$, $t = -6.06$, $p < 0.001$; Syntactic by Order: β $= -0.002$, $t = -2.94$, $p < 0.01$).

P600 Fig. 2 and Fig. 3 summarize the results in the P600 time window . In contrast to Ryskin et al. (2021), we did not find any significant ERP effects in P600 time window (600-900ms) across all conditions within No Noise exposure (Semantic: β $= -0.27$, $t = -0.67$, $p = 0.5$; Recoverable:β $= -0.005$, $t = -0.01$,$p = 0.98$; Syntactic: β $= 0.18$, $t = 0.50$, $p = 0.62$). There was no significant between No Noise and Noise exposure groups (β $= -0.49$, $t = -0.82$, $p = 0.41$). There was no significant interaction between target word conditions and exposure groups (Semantic by Noise Exposure: β $= 0.31$, 0.55, $p = 0.58$, Recoverable by Noise Exposure: β $= -0.15$, $t = -0.30$, $p = 0.77$, Syntactic by Noise Exposure: β $= 0.09$, $t = 0.16$, $p = 0.87$). There was no significant correlation between P600 effect size and word recoverability measured by Levenshtein edit distance ($r = -0.08$, $p = 0.08$).

Figure 4-bottom shows the relationship between the magnitude of P600 effect and the presentation order of an experimental item. In the No Noise exposure condition, there was no significant interaction between condition and exposure (all $0.1 < ts < 1$,all $ps > 0.32$). In the Noise exposure group, the magnitude of P600 effects to semantic and recoverable errors increased as the number of presented errors increased (Recoverable by Order: β $= 0.002$, $t = 3.66$, $p < 0.001$; Semantic by Order: β $= 0.002$, $t = 2.58$, $p < 0.01$).

Individual differences In previous studies, the processing of syntactic and recoverable semantic violations has been linked to the P600 as well as to a left anterior negativity effect (Hagoort et al., 1993; A. Kim & Osterhout, 2005; Van Herten et al., 2005b; Friederici et al., 2004). More importantly, the processing mechanisms of semantic and morphosyntactic violations have been shown to vary to a great extent between individuals, depending on various individual differences such as processing strategies, language experience and proficiency, and working memory (Tanner & Van Hell, 2014; Tanner, 2019; A. E. Kim et al., 2018). It is possible that in our study, the absence of P600 effects and exposure effects reflects different processing and adaptation strategies across participants. Some participants might show primarily (sustained) N400 effects and some participants might show P600s for syntactic and recoverable violations. Visual inspection suggests substantial variation in ERP effects across subjects.

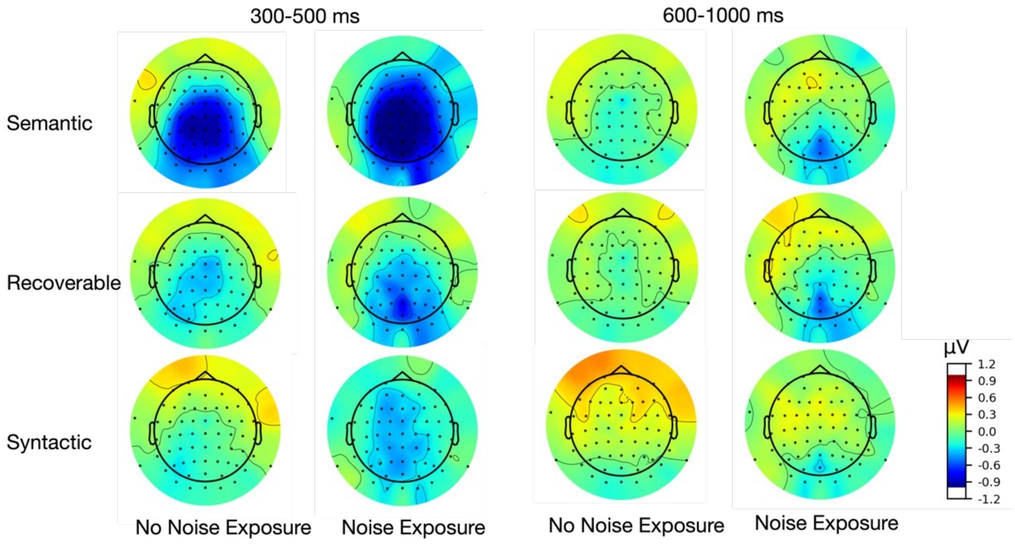

Figure 3: Topographic maps of ERP amplitude differences for the Semantic condition (top), Recoverable condition (middle) and Syntactic condition (bottom) relative to Control condition in 300-500ms (left) and 600-900ms time window (right).

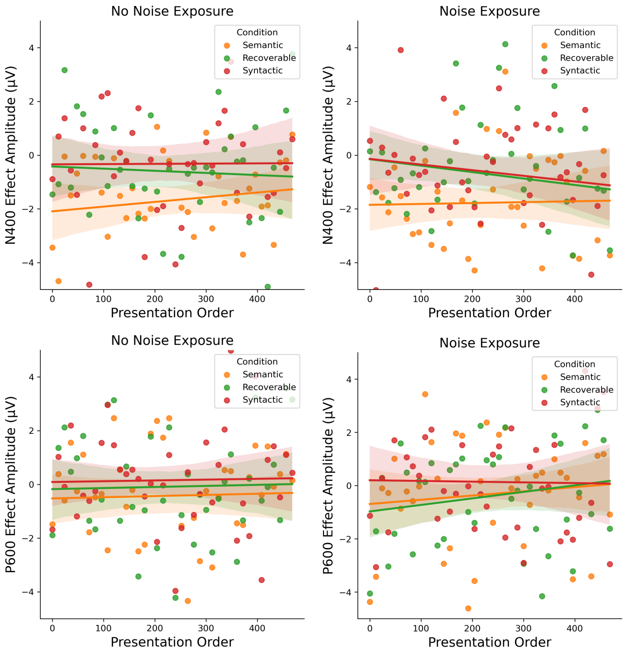

Figure 4: The relationship between presentation order of the item and N400 effect amplitude (top) / P600 effect amplitude (bottom) across critical conditions in No Noise exposure (left) and Noise exposure groups (right). Each point represents N400 or P600 effect amplitude (Critical condition minus Control condition) averaged across subjects, items, and electrodes presented within a given range of order.

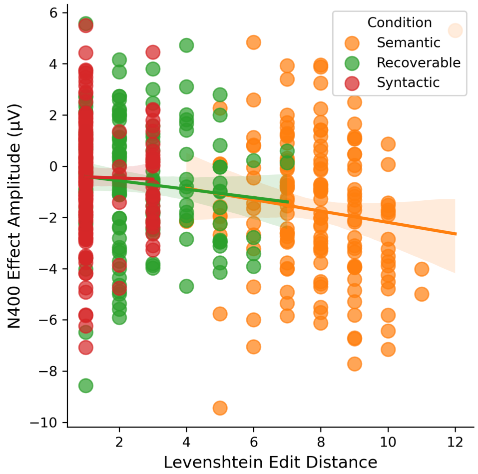

Figure 5: The relationship between average N400 effects for each item (e.g., "antidote") in each experimental condition and Levenshtein edit distance between that item and its counterpart in the Control condition (e.g., "anecdote").

Given the potential impact of individual differences on the N400 and late ERP components, we investigate the relationship between N400 effects and P600 effects by subject. In Fig. 6, each dot represents the ERP effect magnitude for each subject averaged across items and across electrodes. We find a trade-off between N400 and P600 effect magnitudes (absolute effect size), where the N400 effect magnitude is negatively related to the size of P600 effect across all violations ($r = -0.52$, $p < 0.001$). The result suggests substantial individual differences in the neural profiles when processing similar linguistic violations: some subjects showed more N400-like responses (above dashed line), whereas less subjects showed primarily P600 effects (below dashed line).

We further investigated how individuals with different neural profiles might adapt to a noisy linguistic environment differently. We classified participants into *syntax-insensitive* and

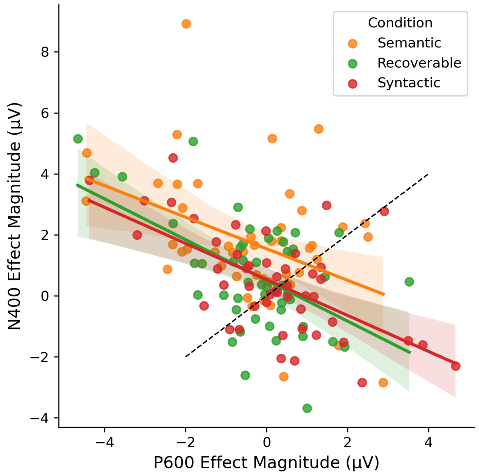

Figure 6: The relationship between N400 and P600 effect magnitudes across subjects. Dashed line indicates equal N400 and P600 effect sizes. Subjects below and to the right showed a predominant P600 effect.

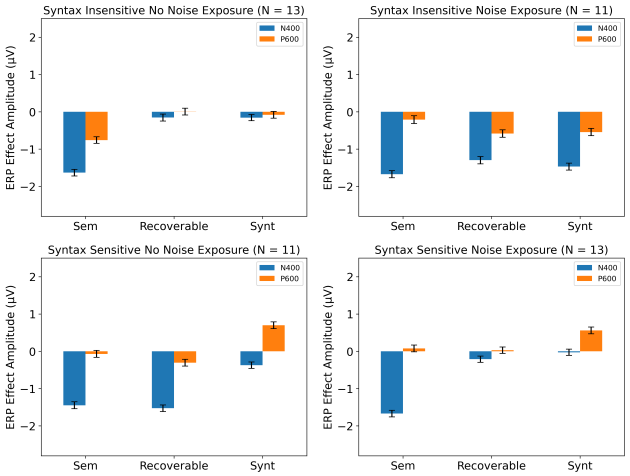

Figure 7: ERP effect amplitudes in the second half of the experiment across conditions for “syntax-insensitive” (top) and “syntax-sensitive” (bottom) comprehenders in No Noise (left) and Noise (right) exposure groups.

syntax-sensitive comprehenders by the magnitude of P600 effect in the Syntactic condition in the first one hundred trials of the experiment. Syntax-insensitive comprehenders are those who have a smaller P600 effect (cut-off threshold $= 1.8\mu V$) in the first part of the study, suggesting they did not notice the syntactic violations. Syntax-sensitive comprehenders have greater P600 effects to syntactic violations in the first part of the experiment. We then compared the N400 and P600 effects between syntax-sensitive and syntax-insensitive comprehenders across the two exposure conditions elicited by stimuli presented in the rest of the experiment (Figure 7).

For syntax-insensitive comprehenders who showed more negativity when processing syntactic errors in the first part, the N400 effects elicited by recoverable ($\beta = -1.14, t = -6.14, p < 0.001$) and syntactic errors ($\beta = -1.31, t = -7.08, p < 0.001$) increased (more negative) after being exposed to errors. The magnitude of the P600 effect elicited by recoverable ($\beta = -0.58, t = -3.04, p < 0.01$) and syntactic errors ($\beta = -0.46, t = -2.40, p < 0.05$) decreased (more negative) in Noise exposure, whereas the P600 amplitude to semantic errors increased after erroneous exposure ($\beta = 0.54, t = 2.82, p < 0.01$). For the syntax-sensitive comprehenders, the N400 effects in Recoverable ($\beta = 1.21, t = 7.44, p < 0.001$) and Syntactic conditions ($\beta = 0.35, t = 1.98, p < 0.05$) decreased (more positive) after exposed to errors. In the P600 time window, there was no significant interaction between target word condition and exposure group.

Discussion

This study investigated how comprehenders adapt to noisy linguistic environments, particularly when exposed to ”recoverable” errors—errors that are semantically anomalous but phonologically similar to plausible alternatives. We compared the neural responses to different types of critical sentences (Semantic, Syntactic, Recoverable and Control) when exposed to sentences with or without errors. Consistent with previous studies, we found that the N400 effect is reduced when a presented semantic violation is orthographically or phonologically related to a more predictable target (A. Kim & Osterhout, 2005; Hoeks et al., 2004; Van Herten et al., 2005b; Ito et al., 2016), and that the N400 effect size is modulated by the recoverability of the target word (Ryskin et al., 2021).

By manipulating the proportion of errors in exposure sentences, we tested whether neural responses to recoverable errors are best explained by three frameworks. We found that in Noise exposure group, N400 effects to recoverable and syntactic errors increased over the time of exposure and P600 effects to semantic and recoverable errors increased. This is consistent with post-lexical error correction account. The evidence also suggests an important role for individual differences in processing strategies. Participants with stronger syntactic sensitivity (as indexed by P600 effects in early trials) exhibited reduced N400 responses to recoverable and syntactic violations after noisy exposure, consistent with pre-lexical correction or perceptual error accounts, whereas those with weaker syntactic sensitivity demonstrated increased N400 responses, consistent with a post-lexical correction account. The P600 responses exhibited a more complex pattern not predicted by any accounts alone.

Our findings highlight the complexity of adaptation to linguistic noise and underscore the importance of considering individual differences when evaluating processing mechanisms. These results contribute to our understanding of language comprehension under uncertainty and suggest that multiple mechanisms: error correction, perceptual adaptation, and individual cognitive strategies—interact dynamically in response to noisy input.

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