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# Complexity trade-offs in language production across lexical, syntactic, and semantic domains

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**Abstract:** Language production includes multiple subsystems such as the lexical, syntactic, and semantic domains. These subsystems do not operate in isolation but instead interact during production. Previous research has documented complexity trade-offs, cases in which an increase in complexity in one linguistic domain tends to be accompanied by a reduction in others. However, existing studies have primarily focused on trade-offs between syntax and lexicon using small datasets. Our study is the first to extend research on trade-offs into the semantic domain. Two innovative semantic complexity indices (semantic specificity and semantic richness) are incorporated to offer insights into the interaction with semantic complexity. Additionally, we evaluate the effect of sentence length. We conduct Spearman correlation tests and fit generalized additive mixed models to assess the trade-offs. Our results provide converging evidence of complexity trade-offs in natural language production across lexical, syntactic, and semantic domains. We then confirm that longer sentences make complexity trade-offs more prominent. Complexity trade-offs may be attributed to the constraints imposed by the limitations of cognitive resources and the need for efficient communication. Our findings may represent a universal feature of languages, offering insights into how efficiency and human cognitive resources shape language production.

**Keywords:** complexity trade-off; semantic complexity; cognitive resources; efficient communication

## 1 Introduction

Language production incorporates multiple interconnected domains, such as syntax, lexicon, and semantics, each of which contributes to the overall form and information of an utterance (Benítez-Burraco et al. 2024). Previous research has shown that measures of complexity in these domains are often interrelated, such that an increase of complexity in one domain may be accompanied by a systematic decrease in others (Bentz et al. 2023; Fenk-Oczlon and Fenk 2014; Koplenig et al. 2017; Levy and Jaeger 2007; Rezaii et al. 2022). Such interactive patterns across different subsystems have been discussed in terms of complexity trade-offs in language production (Bentz et al. 2023; Fenk-Oczlon and Fenk 2014; Koplenig et al. 2017; Levy and Jaeger 2007; Rezaii et al. 2022). For example, Rezaii et al. (2022) used a frequency-based method to analyze the natural language productions of individuals with primary progressive aphasia (PPA) and controls without this condition. Their results showed that a syntax-lexicon trade-off not only existed in PPA group's utterances but also presented in the picture-describing task utterances of non-aphasic speakers. The authors suggest that such trade-offs may contribute to more efficient communication. In addition, the observed syntax-lexicon trade-off was discussed in relation to the accessibility of lexical items and syntactic structures, with the possibility that words and syntactic constructions draw on shared cognitive resources during utterance production. This line of research has advanced the study of complexity trade-offs within the production of a single language. In addition, more validation has been conducted by researchers on crosslinguistic comparisons (Bentz et al. 2023; Coloma 2017). For example, Bentz et al. (2023) used

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28 complexity-related indices to further investigate complexity trade-offs across 80 typologically diverse languages. Their findings revealed that the overall complexity across various domains (i.e., syntax, lexicon, and morphology) tends to be balanced within a similar range.

Trade-off effects have also been observed in second language (L2) production, particularly from a longitudinal perspective (Li and Sui 2025; Liu et al. 2025). Learners may prioritize certain aspects of language development over others (Robinson 2001, 2011). This phenomenon has been explored within the framework of Complex Dynamic Systems Theory, which conceptualizes language as an adaptive system comprising interacting subsystems, such as lexical and syntactic domains (De Bot et al. 2007; Larsen-Freeman 2020; Robinson 2011). For example, Liu et al. (2025) demonstrated compensatory growth between lexical and syntactic complexity, particularly of lower-proficiency learners. Among the most influential advances in recent L2 research is the emergence of the complexity, accuracy, and fluency framework (Robinson 2001; Skehan 1998). For example, Li and Sui (2025) investigated trade-off effects across lexical complexity, syntactic complexity, accuracy, and fluency in longitudinal L2 data, revealing that an increase in one domain often coincided with no change or a decrease in others.

While these studies offer an insightful avenue to understand complexity trade-offs, the intricacies of complexity trade-offs in L1 single-language production remain largely unexplored. First, previous studies (see the study of Rezaii et al. 2022) have had limited access to more extensive language materials from cognitively healthy people, leaving open the question of how broadly trade-offs generalize to large-scale corpora of cognitively healthy speakers. Second, previous studies have primarily focused on complexity trade-offs within the domains of lexicon and syntax (Bentz et al. 2023; Rezaii et al. 2022), while the role of semantic complexity has received little attention. Given that semantic domain constitutes a central component of utterance meaning, incorporating semantic complexity is necessary for a more comprehensive understanding of trade-offs in language production. Third, sentence length has been shown to significantly relate to various linguistic properties, suggesting that it may modulate the strength or presence of complexity trade-offs. Despite its potential importance, the relationship between trade-offs and sentence length has not yet been investigated.

The present study addresses these limitations through a corpus-based investigation of complexity trade-offs in language production. The trade-off phenomenon may exist not only between lexical and syntactic domains, but also extends to semantic domains. We aim to examine whether trade-offs among lexical, syntactic, and semantic complexity measures can be observed in large-scale production data, and whether these relationships vary as a function of sentence length. To summarize, the study aims to address the following research questions (RQs):

RQ1: Does complexity trade-off exist in language production? If so, how does complexity across different domains interact to reflect trade-offs in language production?

RQ2: Does sentence length influence the presence and degree of complexity trade-offs in language production?

# 2 Materials and methods

## 2.1 Data

We used BNC Baby (2005, version 2) as our data. BNC Baby is a principled sample of the British National Corpus. It contains four major text types in modern English: fiction, news stories, academic texts, and informal conversations. The majority of the materials in BNC Baby belongs to the written genre, with only approximately 10 percent representing spoken language. To examine the influence of sentence length, we divided BNC Baby texts into three subgroups: short sentences (shorter than 10 words), medium-length sentences (between 10 and 30 words), and long sentences (longer than 30 words). Sentences that were too short (4 words or fewer) or too long (200 words or more) were excluded to improve the reliability of our analysis. Very short sentences often lead to structural oversimplification (Ferrer-i-Cancho and Gómez-Rodríguez 2019), and excessively long sentences were likely to exhibit inappropriate sentence segmentation. In addition, each sentence was labeled with its corresponding text ID. The dataset for our analysis contains 231,940 sentences and approximately 3.8 million words. The number of sentences in the short (below 10 words), medium-length (between 10 and 30 words), and long

(above 30 words) groups were 81,433, 123,634, and 26,873, respectively. We employed the Python package spaCy to parse sentences and extract the necessary information for calculating complexity indices.

## 2.2 Statistical methods

We employed two methods to quantify complexity trade-offs in language production: correlation analysis and predictive modeling. Based on the view that language operates as a complex adaptive system (Beckner et al. 2009), nonlinear relationships may exist between different complexity domains. We used Spearman's rank correlation coefficient to test the correlations between complexity indices, as it is well suited for capturing such nonlinear correlations. In addition, generalized additive mixed models (GAMMs) were employed to model the relationships between complexity indices.[1] We aimed to predict the syntactic complexity measure using metrics from the lexical and semantic domains. In addition, we treated individual texts (text ID) as random effects, as each text typically corresponds to a different speaker (or writer). This approach serves as a practical proxy for controlling speaker-level variability. Given the advantages of GAMMs to capture nonlinear interactions between continuous predictors, we first conducted GAMMs analysis with interaction terms incorporating sentence length. Such analysis could provide solid evidence for whether sentence length moderates the effects of other variables on syntactic complexity. Then, for convenient analysis, a series of GAMMs was fitted across different sentence groups (i.e., short, medium, and long sentences). The explained variance reported by the GAMMs provides insight into both the presence and the degree of complexity trade-offs in language production.

## 2.3 Complexity trade-offs measurement

The core focus and key challenge of our study is the measurement of complexity across different domains, specifically the lexical, syntactic, and semantic domains. The complexity measurement framework is illustrated in Figure 1.

For the lexical and syntactic domains, we adopted the frequency-based method introduced by Rezaii et al. (2022), which includes calculating the average frequency of content words (word frequency) and the average frequency of syntactic rules (syntax frequency). Here, "freq(x)" refers to the frequency with which a given word or syntactic structure appears across the entire corpus. To avoid the adverse effects of outlier frequencies, all frequency values were log-transformed (Baayen and Divjak 2017). The approach was chosen for two reasons. First, the frequency measures themselves are highly effective and widely applied in much linguistic and cognitive science research (Brysbaert and New 2009; Diessel 2007). Second, the work of Rezaii et al. (2022) has demonstrated their validity and effectiveness. Higher frequency indicates lower complexity in lexical/syntactic domains. In addition, considering that content words typically serve as the core information in a sentence, we calculated the average frequency based only on content words. We also computed the average frequency for all words, and the results were highly similar. These additional results are presented in the Supplementary Materials. To capture the lexicon-syntax trade-off in language production, a negative correlation between word frequency and syntax frequency is expected.

For the semantic domain, we employed indices proposed by Lei et al. (2024), since they can directly reflect and quantify semantic complexity. The first metric, semantic specificity, is measured by calculating the average number of senses of nouns and verbs in a single utterance. A decrease in this metric implies that words convey more precise meanings, which is associated with higher complexity in the semantic domain. We expect a negative correlation between syntax frequency and semantic specificity. The second metric, semantic richness, reflects the informativeness of the semantic content conveyed by a sentence. We calculated semantic richness as the sum of the occurrence probabilities of nouns in the text. This noun-based approach is grounded in the consideration that

**1** While Pearson correlation tests and linear modeling were initially used, preliminary findings indicated that an unavoidable nonlinear relationship existed between the complexity indices. See detailed results in the Supplementary Materials.

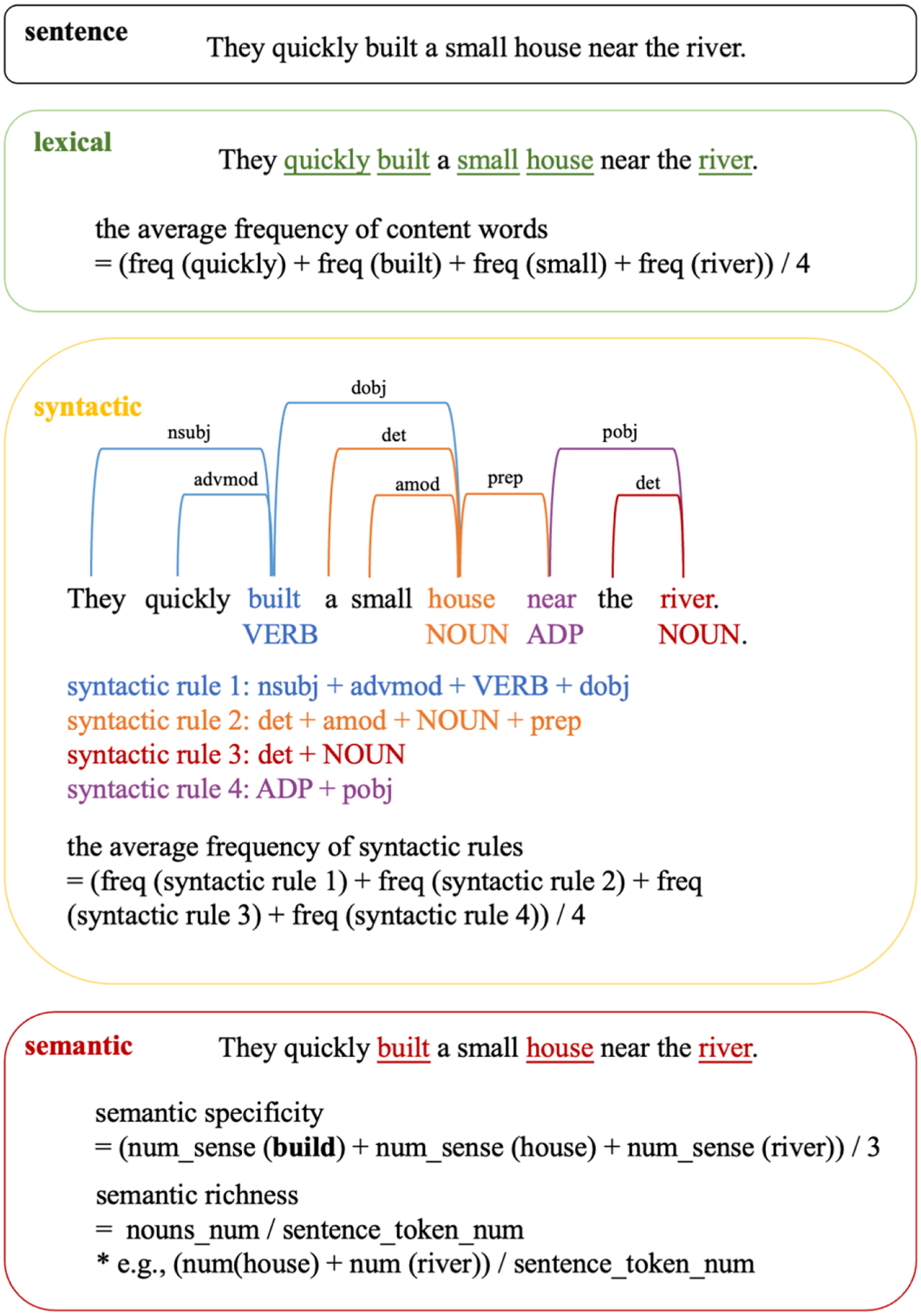


**Figure 1:** The complexity measurement framework demonstrated with an example sentence.

semantic richness should capture the amount of information an utterance conveys or the breadth of semantic topics it encompasses. Since nouns are central to encoding and transmitting core concepts and topics within a sentence, they can serve as reliable indicators of semantic content (Lei et al. 2023, 2024). Higher semantic richness

reflects greater information density in a sentence, indicating increased complexity in the semantic domain. Accordingly, we expect a positive correlation between the average frequency of syntactic rules and semantic richness.

To ensure reproducibility, we provide detailed explanations with formulas and well-commented codes for each metric in the Supplementary Materials.

# 3 Results

## 3.1 RQ1: The existence and interaction of complexity trade-offs in language production

The results of the Spearman correlation tests among all sentences and different length groups are presented in Table 1. The results of GAMMs to predict the syntax frequency with different complexity indices and their interaction with sentence length are reported in Table 2.

We found the expected evidence supporting the existence of complexity trade-offs in language production.

First, Spearman correlation tests indicate that syntax frequency is significantly negatively correlated with word frequency and semantic specificity, with coefficients of −0.362 and −0.155, respectively ($p < 0.001$). Additionally, syntax frequency is significantly positively correlated with semantic richness, with a coefficient of 0.559 ($p < 0.001$).

Second, the GAMMs results show that complexity indices from the lexical and semantic domains provide moderate explanatory power for predicting syntactic frequency. For models containing one metric, semantic specificity is the most influential, accounting for 37.6 % of the variance in syntactic frequency in Model 3. This is followed by word frequency, which explains 25.4 % of the variance in Model 1. Semantic specificity ranks third, contributing 25.0 % in Model 3, only slightly less than word frequency.

The results of both the correlation tests and the model predictions align with our previous expectations. That is, our results provide evidence that when syntactic structures become more complex, lexical and semantic complexities tend to decrease, presenting complexity trade-offs.

## 3.2 RQ2: The influence of sentence length on complexity trade-offs

Our findings highlight the impact of sentence length on complexity trade-offs. As shown in Table 1, the correlations for all indices are weakest in the short-sentence group, with the correlation for semantic specificity even being negligible ($r = -0.035$). As sentence length increases, the correlations become significantly stronger. The medium- and long-sentence groups exhibit relatively high correlations. These findings suggest that sentence length plays a crucial role in complexity trade-offs. To be more specific, complexity trade-offs are less pronounced in short sentences compared to longer ones.

The interaction effects between sentence length and complexity metrics, as shown in Table 2, are statistically significant. These findings indicate that sentence length interacts with other complexity metrics, contributing to

**Table 1:** Coefficients of the Spearman correlation tests.

| Indices correlated to syntax frequency | All sentences | Short sentences (<10 words) | Medium-length sentences (10–30 words) | Long sentences (>30 words) |
|---|---|---|---|---|
| word frequency | −0.362 | −0.245 | −0.402 | −0.365 |
| semantic specificity | −0.155 | −0.035 | −0.235 | −0.276 |
| semantic richness | 0.559 | 0.492 | 0.572 | 0.524 |

*Note*. The *p* values are all smaller than 0.001.

**Table 2:** Model summary for the GAMMs fitted with different complexity indices.

| Model (explained variance) | Smooth term | *F* Value | *p* Value |
|---|---|---|---|
| Model 1 (25.4 %) | te (word frequency, sentence length) | 700.8 | <0.0001 |
| | s (text id) | 115.7 | <0.0001 |
| Model 2 (25.0 %) | te (semantic specificity, sentence length) | 597.3 | <0.0001 |
| | s (text id) | 179.1 | <0.0001 |
| Model 3 (37.6 %) | te (semantic richness, sentence length) | 3,658.7 | <0.0001 |
| | s (text id) | 108.3 | <0.0001 |

*Notes*. The smooth term "te (x)" introduces a nonlinear interaction of complexity metric by sentence length. The smooth term "s (text id)" denotes the by-text random intercepts.

**Table 3:** The explained variances of GAMMs.

| Metric | Short sentences (<10 words) | Medium sentences (10–30 words) | Long sentences (>30 words) |
|---|---|---|---|
| Word frequency | 13.6 % | 30.6 % | 38.2 % |
| Semantic specificity | 14.22 % | 29.0 % | 36.9 % |
| Semantic richness | 26.9 % | 43.5 % | 48.2 % |

*Note*. All GAMMs included "s (text id)" as a random effect.

trade-offs in complexity. In addition, we plotted contour plots to visualize the interaction effects between sentence length and complexity metrics, which are provided in the Supplementary Materials. To provide clearer interpretation, the results of separate GAMMs fitted for different sentence length groups are reported in Table 3.

The explained variances in Table 3 further support the sentence-length sensitivity. As sentence length increases, the fitted GAMMs explain more variances. While correlation analyses show that the medium-sentence group demonstrates the highest correlations for some metrics, the GAMMs results do not align with this pattern. As we expected, the models fitted for the long-sentence group achieve the highest predictive power. In particular, the explained variances for the medium- and long-sentence groups surpass those of the all-sentence group (see Table 2). These results indicate that complexity trade-offs become more pronounced in medium- and long-sentence contexts, with longer sentences yielding the most predictive models.

To illustrate the general trends of different complexity indices, we plotted all pairwise relationships across sentence-length groups. As shown in Figure 2, the colorful curve exhibits the fitted relationships, while each gray point represents a single sentence. First, based on the scatter plots and fitted curves in Figure 2, the main trends within the dense regions align with the direction (positive or negative) indicated by the Spearman correlation tests. This further provides evidence for the presence of trade-offs. Second, the scatter plots and curves by sentence-length groups show that, in the long-sentence group, the points are more densely clustered and the curve slopes are steeper, suggesting that the degree of trade-offs is greater in longer sentences.

# 4 Discussion

Below, we discuss our statistical results based on the research questions previously proposed.

In response to RQ1, our findings confirm the existence of trade-offs in language production. Extending the previous findings, two semantic indices provide converging evidence for complexity trade-offs across semantic and syntactic domains. When sentences carry more complex or infrequent syntactic structures, semantically specific words and more information density (or topic density) will not be conveyed simultaneously. This finding aligns with studies such as Levy and Jaeger (2007), which demonstrated that speakers tend to simplify syntactic complexity to prioritize information transmission. Moreover, the compensatory strategy between semantics and syntax has been well documented in research on agrammatic aphasia (Berndt et al. 1997; Hagoort et al. 2003). For agrammatic aphasia individuals, the use of semantically rich verbs and nouns serves as a compensatory strategy

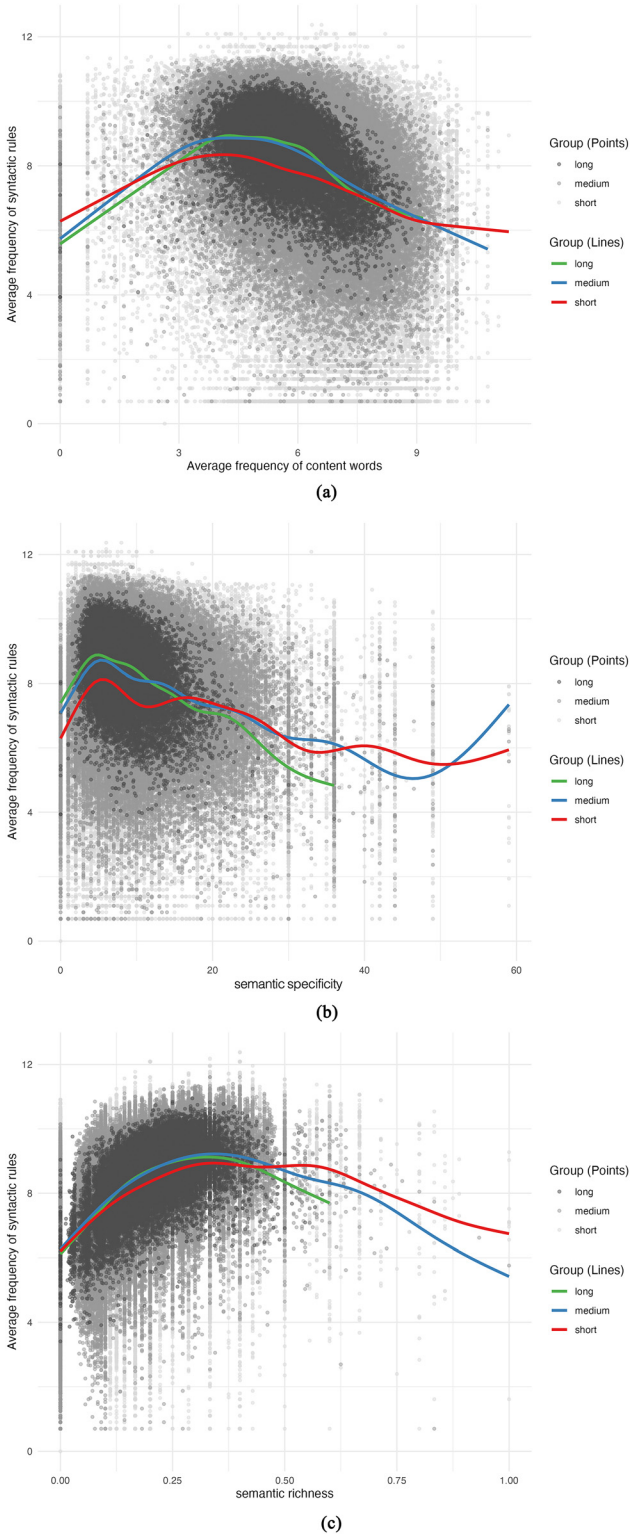


**Figure 2:** The pairwise relationships between the indices across sentence-length groups: (a) relationship between word frequency and syntactic frequency; (b) relationship between semantic specificity and syntactic frequency; and (c) relationship between semantic richness and syntactic frequency.

to mitigate their syntactic deficits. Similarly, studies under the Complex Dynamic Systems Theory in L2 production reveal trade-offs across linguistic subsystems. Our study extends these insights to non-aphasic L1 speakers, providing the first evidence that similar trade-offs operate in L1 non-aphasic speakers' production.

Our findings on complexity trade-offs may be interpreted from several perspectives. It should be noted that the following perspectives are presented only as a possible explanatory framework, rather than being directly verified by our findings.

First, consistent with the principle of least effort (Chao and Zipf 1950), language production exhibits complexity trade-offs designed to optimize communication efficiency for both information producers and perceivers. Producers tend to select language elements that minimize their retrieval effort, such as high-frequency syntactic structures, but perceivers favor elements that are easier to understand in order to reduce ambiguity, such as semantically specific words. This mutual balancing of effort helps facilitate effective communication.

Second, from the cognitive resource optimization perspective (Jaeger and Tily 2011), human language use is often discussed in relation to the limited capacity for processing information (Baddeley 1986, 2012, 2020), which may give rise to strategies for distributing processing demands more efficiently. The trade-offs observed in the present study are consistent with this view. Higher levels of complexity could be associated with greater cognitive demands in certain subsystems. In particular, the complexity indices adopted in our study are frequently discussed in relation to processing and retrieval difficulty. For example, frequency-based measures have been widely associated with lexical and syntactic retrieval, with more frequent words or constructions being retrieved more easily during grammatical encoding (Bock 1986; Brysbaert and New 2009; Kelly et al. 1986). Similarly, producing semantically specific words requires greater cognitive effort, as producers must carefully select words to convey specific information (Almor 1999; Kennette and Wurm 2016; Kounios and Holcomb 1994). Higher semantic richness also reflects an increase in the information density of the sentence. Against this background, the observed complexity trade-offs may be interpreted as reflecting strategies to distribute cognitive demands efficiently. Our findings support this view, demonstrating that information producers balance cognitive effort by adjusting the complexity of linguistic elements. Specifically, when sentences exhibit high complexity in one dimension, producers compensate by incorporating simpler elements in other dimensions. Importantly, this interpretation should be treated with caution. Language production is a highly complex process, and the notion of limited cognitive resources adopted here is intended as a broad, functional characterization rather than a specification of underlying mechanisms. The present corpus-based findings do not allow us to determine how such trade-offs arise during production, nor whether they reflect specific cognitive processes. Further evidence from psycholinguistic and behavioral experiments will be necessary to clarify how and when complexity trade-offs emerge in language production.

To address RQ2, it is noteworthy that complexity trade-offs become more pronounced in longer sentences. The significance of sentence length has long been emphasized in quantitative linguistic studies, such as dependency distance minimization (Jiang and Liu 2015). Similarly, our study revealed a comparable sensitivity, where trade-offs were less evident in shorter sentences compared to longer ones. This pattern may be interpreted from the perspective of cognitive resource limitations. Longer sentences are often associated with higher overall processing demands, whereas shorter sentences may place fewer constraints on language production (Gibson et al. 2019). Shorter sentences naturally ease the cognitive load for producers, allowing for greater flexibility in the arrangement of words and syntax (Lei and Wen 2020).

Another point that is worth noting is the presence of complexity trade-offs in the written mode. Previous research has highlighted that complexity trade-offs are particularly evident in tasks such as picture descriptions, where language production tends to be unstructured and spontaneous (Rezaii et al. 2022). However, our finding underscores that the phenomenon is not confined to spoken language but extends to written language as well. One possible explanation is that writing and speaking share the same underlying cognitive mechanisms, as both depend on working memory for the maintenance and manipulation of linguistic units (Kellogg 1996, 2001; Olive 2014). However, speaking is typically immediate and linear, whereas writing incorporates additional processes of reflection and revision (Kellogg 2001). Studies have demonstrated that the cognitive cost of language production is higher in writing compared to speaking (Bourdin and Fayol 1994; Kellogg 2001). Writing requires greater planning and organization, consuming more cognitive resources and executive control demands (Bourdin and Fayol 1994;

Kellogg 2001). In addition, trade-offs in the written mode may also be influenced by comprehension-related considerations. Writing often incorporates self-editing and revision (Flower and Hayes 1981), during which producers may adjust linguistic choices in response to discourse-level organization and anticipated reader comprehension. Such sensitivity to discourse structure may further contribute to the observed distribution of complexity across domains.

## 5 Limitations and future research

Several limitations of the present study are discussed below. First, our basic analytic unit is the sentence, which is more suitable for written data. Taking sentence as the unit of analysis is debated for spoken data, since the concept of sentence is decided by transcribers rather than speakers. Second, our analyses are conducted solely at Marr's computational level, which fundamentally entails the description of statistical patterns evident in corpus data. Any claim that language producers actively trade off complexity across subsystems due to cognitive capacity limitations would necessitate an algorithmic-level explanation that specifies the cognitive processes underlying such trade-offs. Algorithmic-level explanations would require identifying the linguistic representations engaged during production, detailing how these representations are processed, and clarifying the sequence of processing. Addressing these issues would necessarily require carefully designed behavioral experiments with appropriate control of variables.

Our findings also offer valuable insights for future corpus-based research on complexity trade-offs in language production. First, future research could apply the methods used here to other languages to identify potential language universals. Second, further investigation of this phenomenon is warranted with the use of alternative or more robust complexity indices. Indices that reflect morphological and phonological features could offer a broader perspective. Third, several influential factors were beyond the scope of the present study. Variables such as the type of task required in language production, the speaker's age, or their language proficiency may significantly affect complexity trade-offs (Kormos 2023; McLaughlin et al. 2021). Exploring how these variables interact with complexity across linguistic domains could deepen our understanding of the underlying mechanisms.

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